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Evaluating fuel complexes for fire hazard mitigation planning in the southeastern United States

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ABSTRACT

Fire hazard mitigation planning requires an accurate accounting of fuel complexes to predict potential fire behavior and effects of treatment alternatives. In the southeastern United States, rapid vegetation growth coupled with complex land use history and forest management options requires a dynamic approach to fuel characterization. In this study we assessed potential surface fire behavior with the Fuel Characteristic Classification System (FCCS), a tool which uses inventoried fuelbed inputs to predict fire behavior.

Using inventory data from 629 plots established in the upper Atlantic Coastal Plain, South Carolina, we constructed FCCS fuelbeds representing median fuel characteristics by major forest type and age class. With a dry fuel moisture scenario and 6.4 km h^{-1} midflame wind speed, the FCCS predicted moderate to high potential fire hazard for the majority of the fuelbeds under study. To explore fire hazard under potential future fuel conditions, we developed fuelbeds representing the range of quantitative inventory data for fuelbed components that drive surface fire behavior algorithms and adjusted shrub species composition to represent 30% and 60% relative cover of highly flammable shrub species.

Results indicate that the primary drivers of surface fire behavior vary by forest type, age and surface fire behavior rating. Litter tends to be a primary or secondary driver in most forest types. In comparison to other surface fire contributors, reducing shrub loading results in reduced flame lengths most consistently across forest types. FCCS fuelbeds and the results from this project can be used for fire hazard mitigation planning throughout the southern Atlantic Coastal Plain where similar forest types occur. The approach of building simulated fuelbeds across the range of available surface fuel data produces sets of incrementally different fuel characteristics that can be applied to any dynamic forest types in which surface fuel conditions change rapidly.

1. Introduction

Fire is an integral process in forests of the southeastern United States (Keeley et al., 2009; Robbins and Myers, 1992). With departures from historically frequent, low-intensity fires and widespread conversion to pine plantations, the composition, structure and arrangement of southeastern fuels were drastically altered, as were potential wildland fire behavior and effects (Outcalt and Wade, 2004). Southeastern land managers have been using prescribed fire and other vegetation/fuel management techniques for decades in an attempt to mitigate wildland fire behavior, enhance timber resources, improve wildlife habitat for hunting and conservation goals, and promote restoration of southern pine forests (Robbins and Myers, 1992; Sparks et al., 1999). However, concerns about pollutant and smoke emissions, budget constraints, and the perceived danger of using prescribed fire in close proximity to the wildland–urban interface necessitate the prioritization of areas where prescribed fire will be used for hazardous fuel reduction.

Wildfire hazard assessments are used to prioritize fuel treatments and require a detailed characterization of fuelbed components to predict potential fire behavior and effects. Fuel conditions can be highly variable in southeastern forests and are dependent on land use history, site productivity and management treatments including thinning, herbicide application, chipping, pine straw raking, and prescribed burning (Foster et al., 2003; Hiers et al., 2009; Mitchell et al., 2006). The frequency and seasonality of prescribed fire also creates variation in fuels (Robbins and Myers, 1992).

Due to the high spatial and temporal variability in fuel conditions in the southeastern United States, coarse-scale fire risk assessment tools such as LANDFIRE and the Southern Wildfire Risk

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Assessment (SWRA) may not be sufficient for fire hazard assessments at the operational level. Both of these tools use satellite imagery to assign stylized fire behavior fuel models (Anderson, 1982; Scott and Burgan, 2005) to represent surface fuels across the landscape and are most appropriate for use at the state or regional level or for incident response planning. The Fuel Characteristic Classification System (FCCS) offers over 200 default fuelbeds and can be used to build an unlimited number of fuelbeds from regional or local inventory data. In addition, the system treats surface fuels as four distinct layers (shrubs, non-woody fuels, woody fuels <7.6 cm, and litter), rather than homogenized, single layer units, which provides a much finer level of detail and facilitates operational level assessments of surface fuels and fire behavior (Riccardi et al., 2007). Because FCCS also allows inputs of inventoried vegetation/fuel data it can be used to compare and catalog fuelbed changes due to canopy and surface fuel treatments for mitigation planning and reporting (Ottmar et al., 2007). The FCCS uses a modified Rothermel approach to calculate surface fire behavior (SFB), crown fire, and available fuel potentials scaled on an index from 0 to 9 (Rothermel, 1972; Sandberg et al., 2007b), and surface fire behavior including reaction intensity, flame length, and rate of spread (Sandberg et al., 2007a).

In this study, the objectives were to (1) use inventory data to define current fuel complexes and assess current wildfire hazard based on predicted surface fire behavior under dry fuel moisture values in several southern forest types and (2) assess potential future wildfire hazard in these forests using simulated fuelbeds representing a wide range of surface fuel complexes. Using the suite of simulated fuelbeds for each forest type, we determined surface fuel targets that would reduce SFB to acceptable levels and surface fuel parameters that drive SFB in each forest type.

2. Materials and methods

2.1. Study area

The Savannah River Site (SRS) is situated along the Savannah River in the Upper Coastal Plain and Sandhills provinces of South Carolina (Fig. 1). The site is a US Department of Energy (DOE) facility and contains approximately 71,224 hectares of forestland, composed of 50,024 ha of pine (*Pinus* spp.) forests, 4328 ha of mixed pine-hardwood forest, 16,769 ha of hardwood forest, and 2702 ha of cypress-tupelo (*Taxodium distichum – Nyssa biflora*) forest (USDE, 2005). Much of the site is actively managed to improve wildlife habitat and to reduce hazardous wildland fuels. According to Kilgo and Blake (2005) approximately 27,000 ha of upland forests are managed to improve habitat for red-cockaded woodpeckers (RCW, *Picoides borealis*) which require open forests of mature live trees for cavity nests and foraging (James et al., 2001; Walters et al., 2002). Management activities on RCW colony and recruitment sites include thinning, reducing midstory vegetation and prescribed burning. On 5665 ha, which are part of the DOE Set-Aside Program, very little management takes place (Kilgo and Blake, 2005). Prescribed burning is limited on forested areas near major infrastructure and roads, however, other hazardous fuel reduction techniques, such as thinning for biomass production, may be used within those areas.

2.2. Data analysis

We developed a matrix framework for surface fire behavior based on the Fuel Characteristic Chart thresholds used to make fire-fighting deployment decisions (Andrews and Rothermel, 1982) and the experience of SRS fire managers. The matrix defines rate of spread (ROS) and flame length (FL) ranges for low (0–3.4 m min^{-1}, 0–0.6 m), moderate (3.4–6.7 m min^{-1}, 0.6–1.2 m), high (6.7–13.4 m min^{-1}, 1.2–2.4 m), and extreme (13.4–26.8 m min^{-1}, 2.5–4.9 m (or higher)) surface fire behavior for seven forest types/structures important on Savannah River Site, each with up to four age classes: clearcut (CC < 5 years); cypress-tupelo (CT <50 years, CT >50 years) and catastrophic damage (CAT 30–50 years and >50 years); pine (Pine 5–20 years, 21–40 years, 41–60 years, and >60 years), pine-hardwood (PHW 5–20 years, 21–40 years, 41–60 years, and >60 years), hardwood (HWD 5–20 years, 21–40 years, 41–60 years, and >60 years), and longleaf pine-scrub oak (LPO 5–20 years, 21–40 years, 41–60 years, and >60 years). Flame length was used to determine placement of fuelbeds within SFB rating levels.

To construct FCCS fuelbeds representing average conditions within each forest type-age class category, we used data from 629 forest inventory plots sampled in 1999–2002 (see Parresol et al., 2012a, for sampling methodology). Because the forest types in the matrix were broader than the stand types designated for each plot, we grouped all pine stand plots (slash (*Pinus elliottii*), longleaf (*P. palustris*), loblolly (*P. taeda*), sand (*P. clausa*) and shortleaf (*P. echinata*) pines), all pine-hardwood stand plots (shortleaf pine-oak (*Quercus* spp.), loblolly pine-hardwoods, southern red oak (*Q. falcata*)-yellow pine, white oak (*Q. alba*)-black oak (*Q. velutina*)-yellow pine and longleaf pine-hardwoods (in part)), and all upland and lowland hardwood stand plots. Plots for the longleaf pine-scrub oak forest type were selected from the longleaf pine-hardwoods plots and scrub oak plots, based on overstory dominance of longleaf pine and understory composition

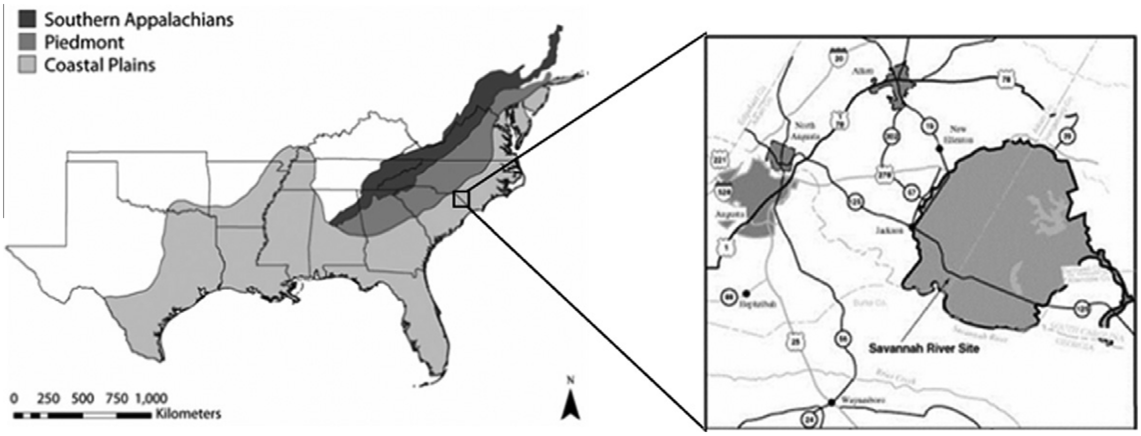

Fig. 1. Location of the study area, Savannah River Site, within the Coastal Plain of the Southeastern United States.

consistent with sandhill vegetation. Cypress-tupelo plots were maintained as a separate forest type. We selected the most similar FCCS fuelbed to each forest type-age class, or an average of several FCCS fuelbeds (Table 1), and used median and range values from the inventory data as FCCS mode and range inputs of fuel parameters for which inventory data were collected (Table 2).

Plot data included canopy tree measurements, a vegetation profile (small trees, shrubs and herbaceous vegetation), and litter and duff measurements. Inventory data were summarized and the median values were used directly for canopy trees, snags, woody loadings, and litter and duff depths. Data for shrubs, non-woody vegetation and small understory trees were summarized from vegetation profile data, which were collected within height zones and organized by broad species classes for which a percent cover was visually estimated; species were listed in order of importance within the broad species classes. These data had to be parsed out for entry in the proper FCCS fuel strata (Table 3). For fuel parameters not measured, default values in the original FCCS fuelbeds were used or changed to ‘not present’ in the case of woody fuel accumulations, stumps, lichen, moss, and squirrel middens. If inventory plots were not available for a forest type-age class, the most similar FCCS fuelbed was used with no adjustments or was augmented with supplemental regional data (Table 1).

Median fuelbeds were constructed to reflect the current fire hazard on SRS. To estimate potential future fire hazard and conditions created through potential fuel reduction treatments, median fuelbeds were used as the foundation from which an array of fuelbeds was constructed for each forest type-age class. To build the arrays we selected increments for each quantitative surface fuel parameter and some levels of qualitative parameters and combined all values in new fuelbeds representing possible combinations of surface fuels across the range of inventory data (Table 2). Inventory plots included a wide range of data values that represent fuel accumulations in largely unmanaged set-aside areas and

Table 1
Number of forest inventory plots, Fuel Characteristic Classification System (FCCS) base fuelbed(s) and supplemental data sources used to build median fuelbeds by forest type and age class.

Forest type-age class[a]	# of plots	FCCS base fuelbed (for some default values)	Supplemental data sources[b]
CC <5	12	Fuelbed 196: Loblolly pine/Bluegrass forest (clearcut, 2–10 years)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
CAT 30–50	0	Fuelbed 241: Longleaf or Loblolly pine forest (windthrow from hurricane, 65 years)	Wade et al. (1993) and Vihnanek et al. (2009) (HURR1); Species information from Pine 21–40 and PHW 21–40 for canopy, shrub and non-woody
CAT >50	0	Fuelbed 241: Longleaf or Loblolly pine forest (windthrow from hurricane, 65 years)	Wade et al. (1993) and Vihnanek et al. (2009) (HURR4); Species information from SRS Pine and PHW 41–60 and >60 for canopy, shrub and non-woody
CT <50	0	Fuelbed 288: Cypress-Tupelo forest (>70 years)	FIA data (FT 607, <50 years, SC, *Taxodium distichum* >0; 21 plots) for canopy and snag data. Used CT >50 and for shrub, non-woody and as guide for woody, litter and duff – altered for younger stand
CT >50	5	Fuelbed 288: Cypress-Tupelo forest (>70 years)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
Pine 5–20	124	Fuelbed 178: Loblolly – Shortleaf forest (10–15 years)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
Pine 21–40	86	Average of fuelbeds 156, 157, 161, 162, 178, 182, 188, 190, 191, 282, and 291	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
Pine 41–60	216	Average of fuelbeds 156, 157, 161, 162, 178, 182, 188, 190, 191, 282, and 291	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
Pine >60	27	Average of fuelbeds 156, 157, 161, 162, 178, 182, 188, 190, 191, 282, and 291	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
PHW 5–20	1	Fuelbed 178: Loblolly – Shortleaf forest (10–15 years)	FIA data (FT 160, 404, 406, 409, age ⩾5 and ⩽20, SC, *Pinus taeda* >50; 105 plots) for canopy and snag data. PHW 41–60 as guide for shrub, non-woody. CC <5, PHW 21–40, and PHW 41–60 as guides for woody, litter and duff
PHW 21–40	3	Fuelbed 157: Loblolly-Shortleaf-Mixed hardwoods forest (45+ years)	FIA data (FT 160, 404, 406, 409, age >20 and ⩽40, SC, *Pinus taeda* ⩾50; 83 plots) for canopy and snag data. PHW 41–60 as guide for shrub, non-woody, woody, litter and duff – altered for younger stands
PHW 41–60	9	Fuelbed 157: Loblolly-Shortleaf-Mixed hardwoods forest (45+ years)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
PHW >60	5	Fuelbed 157: Loblolly-Shortleaf-Mixed hardwoods forest (45+ years)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed.
LPO 5–20	2	Fuelbed 184: Longleaf pine – Turkey oak forest	FIA data (FT 403, age ⩾5 and ⩽20, SC, *Pinus palustris* >0; 19 plots) for canopy and snag data. Ottmar et al., 2003 (SH05, 11) with LPO 21–40 as guides for woody, litter and duff
LPO 21–40	7	Fuelbed 184: Longleaf pine – Turkey oak forest	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
LPO 41–60	7	Fuelbed 184: Longleaf pine – Turkey oak forest	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
LPO >60	2	Fuelbed 184: Longleaf pine – Turkey oak forest	FIA data (FT 403, age >60, SC, *Pinus palustris* >0 19 plots) for canopy and snag data. Ottmar et al., 2003 (SH08, 09, 10) and Glitzenstein et al., 1995 as guides for woody, litter, and duff. Left snags, shrubs, and non-woody as in plot data
HWD 5–20	2	Average of fuelbeds 275, 180, 123 (upland hardwoods) and 129, 283 (bottomland hardwoods)	FIA data (FT 508, age ⩾5 and ⩽20, SC, *Liquidambar styraciflua* >0; 82 plots) and CC <5, PHW 5–20, HWD 21–40 as guides for canopy. Snags from plot data. HWD 21–40 as guide for shrub and non-woody. CC <5, PHW 5–20, HWD 21–40 as guides for woody, litter and duff
HWD 21–40	18	Average of fuelbeds 275, 180, 123 (upland hardwoods) and 129, 283 (bottomland hardwoods)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
HWD 41–60	60	Average of fuelbeds 275, 180, 123 (upland hardwoods) and 129, 283 (bottomland hardwoods)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed
HWD >60	43	Average of fuelbeds 275, 180, 123 (upland hardwoods) and 129, 283 (bottomland hardwoods)	Median fuelbed values for all quantitative inputs available in SRS data. Other values from base fuelbed

[a] See Section 2.2 in the text for descriptions of forest type abbreviations.

[b] SRS, Savannah River Site; FIA, Forest Inventory and Analysis; FT, forest type; SC, South Carolina; HURR, hurricane; SH, sandhill.

Table 2
Surface fuel input value median, range and increment used to build Fuel Characteristic Classification System (FCCS) simulated fuelbeds by forest type-age class. Canopy and ground fuels were not modified in simulated fuelbeds.

Forest type-age class[a]	Values	Shrub cover (%)	Shrub height (m)	Non-woody cover (%)	Non-woody height (m)	Litter cover (%)	Litter depth (cm)	Drape (Y,N)[b]	Litter arrangement (N, F, P)[c]	Number simulated fuelbeds
Pine 5–20	Median	44	1.1	10	0.8	100	2.8	Y	F, P	2304
	Range	1–100	0.3–3.1	0–83	0.2–3.1	12.5–100	2.0–5.1			
	Increment	33	1.4	27	0.9	40	2.5			
Pine 21–40	Median	33	0.8	3.5	0.6	100	3.3	Y	F, P	1296
	Range	1–100	0.2–5.8	0–82	0.1–1.8	75–100	0.3–7.6			
	Increment	33	2.4	40	0.9	25	3.8			
Pine 41–60	Median	43	0.7	3	0.6	100	3.3	Y	F, P	2592
	Range	0.5–100	0.2–4.0	0–54	0.2–3.1	25–100	0.3–10.2			
	Increment	33	2	18	1.5	37	5.1			
Pine >60	Median	46	0.6	5.5	0.3	100	3.1	Y	F, P	1728
	Range	Mar–92	0.3–1.8	0–100	0.2–3.1	85–100	1.0–7.6			
	Increment	33	0.9	33	0.9	15	3.8			
PHW 5–20	Median	50	0.8	16.5	0.6	100	2.8	N	F, P	1728
	Range	10–95	0.6–4.6	5–40	0.2–1.2	60–100	2.5–7.6			
	Increment	28	1.8	12	1.1	20	1.8			
PHW 21–40	Median	50	0.6	10	0.5	100	3.3	Y	F, P	864
	Range	25–95	0.5–4.6	2.2–95	0.3–0.6	80–100	2.5–7.6			
	Increment	18	0.8	25	0.2	20	5.1			
PHW 41–60	Median	43	0.6	2.4	0.3	100	2.8	Y	F, P	1536
	Range	15–71	0.3–21.3	0.4–38	0.2–2.0	80–100	0.5–3.6			
	Increment	18.6	2	12.6	0.9	20	3.1			
PHW >60	Median	8	1.5	1	3	100	3.6	N	F, P	1536
	Range	1.5–73	0.4–3.7	0–23	0.3–0.6	80–100	1.0–5.1			
	Increment	25	1.2	7	0.3	20	2.5			
LPO 5–20	Median	39	0.6	44	0.6	88	2.8	Y, N	F, P	576
	Range	25–95	0.5–4.6	20–50	0.5–0.9	75–100	1.3–4.1			
	Increment	13	0.6	10	0.5	25	2.8			
LPO 21–40	Median	35	0.6	12	0.6	100	4.1	Y, N	F, P	1151
	Range	24–96	0.5–0.9	May–41	0.6–0.9	50–100	1.3–4.6			
	Increment	25	0.2	20	0.3	50	3.3			
LPO 41–60	Median	33	1.22	1	0.3	100	4.1	Y, N	F, P	1536
	Range	8–63	0.3–2.0	0–12	0.2–0.8	88–100	3.8–5.1			
	Increment	18	0.8	13	0.5	12	1.3			
LPO >60	Median	37	0.6	1	0.6	100	5.1	Y, N	F, P	1296
	Range	25–50	0.3–2.4	0.5–95	0.2–0.9	25–100	2.8–7.6			
	Increment	15	0.9	10	0.5	10	5.1			
HWD 5–20	Median	43	0.7	29	0.6	100	3.3	Y, N	N, F, P	1728
	Range	30–56	0.6–4.6	7.5–50	0.5–0.9	90–100	2.5–3.8			
	Increment	10	0.6	20	0.5	10	1.3			
HWD 21–40	Median	39	1.2	11	0.6	100	3.6	N	N, F	1728
	Range	3–100	0.3–3.4	0–81	0.1–3.1	75–100	1–5.1			
	Increment	32	1.5	27	1.5	25	2			
HWD 41–60	Median	46	0.9	6	0.6	100	3.3	N	N, F	3456
	Range	1–100	0.2–3.7	0–100	0.1–2.1	25–100	0.3–6.6			
	Increment	29	1.2	29	0.9	35	3.1			
HWD >60	Median	49	1.2	17	0.6	100	3.1	N	N, F	3456
	Range	1–100	0.4–3.4	1–100	0.2–2.4	12.5–100	0–5.1			
	Increment	33	1.5	33	1.1	29.2	2.4			
CAT 30–50	Median	30	0.6	4	0.5	100	3.3	Y, N	N, F, P	2916
	Range	20–90	0.3–2.4	2–90	0.2–0.6	75–100	1.3–3.8			
	Increment	35	1.1	40	0.2	25	1.3			
CAT >50	Median	20	0.6	2.5	0.5	100	3.3	Y, N	N, F , P	2916
	Range	20–90	0.3–2.4	2–90	0.2–0.6	75–100	1.3–3.8			
	Increment	35	1.1	40	0.2	25	1.3			
CT <50	Median	5	1.5	2	1.5	100	2.5	N	N	1296
	Range	2–25	1.5–9.1	2–40	0.3–1.5	0–100	0–5.1			
	Increment	11.5	4.6	13	0.6	33	2.4			
CT >50	Median	5	1.5	2	1.5	100	3.6	N	N	1728
	Range	0.1–72	0.2–10.4	0.1–28	0.2–1.5	50–100	2.5–6.1			
	Increment	23.9	3.4	8.3	0.6	25	1.8			
CC <5	Median	34	0.8	30	0.7	60	0.8	N	N, P	3456
	Range	2–100	0.3–1.2	10–100	0.3–1.2	0–100	0–3.8			
	Increment	33	0.5	30	0.5	33	1.8			

[a] See section 2.2 in the text for descriptions of forest type abbreviations.
[b] Y, yes; N, no.
[c] N, normal; F, fluffy; P, perched.

Table 3
Data source, calculations used to modify measured data, and units by input variable used to build median fuelbeds in the Fuel Characteristic Classification System (FCCS).

Input variables[a]	Data source	Calculations and data conversions[b]	Units
Total canopy cover	Maximum of overstory, midstory or understory covers	None	%
Overstory tree cover, height, density, dbh, and hlc	Median value for each forest type-age class from inventory data based on crown class	Percent cover: crown-diameter prediction models for dominant and co-dominant tree species	%, m, # ha^{-1}, cm, m
Midstory tree cover, height, density, dbh, and hlc	Median value for each forest type-age class from inventory data based on crown class	Percent cover: crown-diameter prediction models for intermediate tree species	%, m, # ha^{-1}, cm, m
Understory tree cover, height, density, dbh, and hlc	Median value for each forest type-age class from inventory data based on crown class	Percent cover: crown-diameter prediction models for suppressed tree species *Trees from vegetation profile:* Trees >1.37 m tall added to understory data; assigned dbh 1.27 cm; assumed 1 individual per species Height = $tuhz * 0.75$ hlc (if in more than 1 hz) = $blhz + 0.75\ (tlhz - blhz)$ hlc (if in 1 hz) = $bhz + 0.25(thz - bhz)$	%, m, # ha^{-1}, cm, m
Snag density, diameter, and height; three decay classes	Median value for each forest type-age class from inventory data	None	# ha^{-1}, cm, m
Ladder fuels	Estimated from plot photos, understory data and vines in shrub layer	None	Present or not present
Shrub cover, height, and percentage live	Median value for each forest type-age class from inventory data	Percent cover = $(\sum(hzp * \sum scp))/100$ Height = $(\sum(thz * hzp))/\sum hzp$ Percent live: default 50%	%, m,%
Shrub species and relative cover	Used first two species from each broad species class and height zone	Assigned weight of 60% to first species and 40% to second species; if only one species, assigned 100% Weighted cover (each species) = $hzp * scp * aw$ Relative cover (each species) = $WC/(\sum WC) * 100$ If species occurred in more than one height zone, used largest relative cover calculated for that species	%
Needle drape	Default values assigned to each forest type-age class	None	Present or not present
Non-woody cover, height, and percentage live	Median value for each forest type-age class from inventory data	Percent cover = $(\sum(hzp * \sum bcp))/100$ Height = $(\sum(thz * hzp))/\sum hzp$ Percent live: default 25%	%, m,%
Non-woody species and relative cover	Used first two species from each broad species class and height zone	See procedures for shrub relative cover above	%
Non-woody loading	Median value of calculated loadings	Allometric equations based on percent cover	Mg ha^{-1}
Fine woody fuel loading; three size classes	Median value for each forest type-age class from inventory data	None	Mg ha^{-1}
Large woody fuel loading; three size classes	Median value for each forest type-age class from inventory data	None	Mg ha^{-1}
Rotten large fuel loading	Median value for each forest type-age class from inventory data	None	Mg ha^{-1}
Litter depth and cover	Median value for each forest type-age class from inventory data	Percent cover: percentage of subplots with litter present	cm,%
Litter arrangement and types	Default values assigned to each forest type	None	None
Duff depth and cover	Median value for each forest type-age class from inventory data	Percent cover: percentage of subplots with duff present Depth: divided total duff depth by 2 for upper and lower duff	cm,%
Basal accumulation radius, depth, percent of trees affected	Estimated from plot photos. If present, used values from base FCCS fuelbed	None	cm, cm,%

[a] dbh, diameter at breast height; hlc, height to live crown; snag decay classes: (1) new sound snags, (2) older snags without fine branches but coarse branches and bark intact, (3) old rotten snags with no bark intact; fine fuel size classes: (1) 0–0.6 cm, (2) 0.6–2.4 cm, (3) 2.5–7.6 cm; large fuel size classes: (1) 7.6–23 cm, (2) 23–51 cm, 3) >51 cm.

[b] tuhz, top of upper height zone; blhz, bottom of lower height zone; tlhz, top of lower height zone; bhz, bottom of height zone; thz, top of height zone; hzp, height zone percent cover; scp, species class percent cover; aw, assigned weight (0.4, 0.6, or 1); WC, weighted cover; allometric biomass equations for non-woody loadings from Siccama et al. (1970) and Whittaker (1966) for forbs and Ohmann et al. (1981) for grasses and grass-likes; diameter-crown models to calculate canopy stratum percent cover from Bechtold (2003).

stands close to infrastructure where fire has been excluded for decades as well as actively managed conditions. Small woody fuels were held at the median value for the simulated fuelbeds because previous test runs showed that woody fuels were not important determinants of SFB in the forest types evaluated in this study. Non-woody loadings were calculated based on the cover times height relationship to loading from the median fuelbed in each forest type-age class. The arrays of fuelbeds used the 'average' shrub composition (i.e., first two species from each broad species class with calculated relative cover) from the median fuelbed. In addition, based on comparisons of predicted surface fire behavior from median fuelbeds with prescribed fire observations, we also constructed each array with 30% and 60% of highly flammable shrub species (e.g., wax myrtle (*Morella cerifera*) or saw palmetto (*Serenoa repens*)) to capture a wider range of potential ecological variability. Typically, no highly flammable shrub species occur in cypress-tupelo forests, so fuelbeds with altered shrub compositions were not constructed for this forest type.

We used the FCCS to calculate surface fire behavior (reaction intensity, flame length, and rate of spread) for each fuelbed using a custom moisture scenario based on 97th percentile weather conditions (fuel moisture contents: 1 h fuels 5%, 10 h fuels 6%, 100 h fuels 11%, 1000 h fuels 15%, herbaceous vegetation 113% and shrubs 113%), a 6.4 km h^{-1} midflame wind speed, 0% slope and percent live of 50% for shrubs and 25% for non-woody fuels. Fuelbeds were selected based on predicted flame length to populate each cell of the surface fire behavior matrix. Some cells were left unpopulated because available data and observations by fire managers indicated that the level of fire behavior was not ecologically feasible in a particular forest type-age class.

To determine drivers of surface fire behavior within each forest type, we calculated the percent of total reaction intensity (RI) contributed by each surface fuel parameter for each array fuelbed then compared the average percent of RI for each parameter within each forest type-age class. To determine wildfire mitigation fuel load targets we examined mean and 95% confidence intervals for each surface fuel parameter in each forest type-age class.

Several fuelbeds with 60% relative cover of highly flammable shrub species are included in the matrices for each forest type representing extreme SFB, however, reaction intensity and fuel load target results for fuelbeds with 60% highly flammable shrubs will not be reported here because this shrub composition is not widespread on Savannah River Site.

3. Results

3.1. Current wildfire risk assessment: median fuelbeds

Predicted SFB for median fuelbeds in all Pine age classes fell within the high matrix level with predicted flame lengths of 1.4–1.5 m (Table 4). PHW fuelbeds spanned moderate and high SFB ratings in the matrix, with predicted flame lengths of 1.0 m for fuelbeds >60 years old to 1.6 m for 41–60 year old fuelbeds. LPO fuelbeds had predicted flame lengths of 1.2–2.1 m and HWD fuelbeds had flame lengths of 0.8–1.3 m. CC and CT fuelbeds fell within the low rating of SFB with predicted flame lengths of 0.6 and 0.4–0.5, respectively. CAT fuelbeds had high SFB rating with predicted flame lengths of 2.2 and 2.3 m for 30–50 year old and >50 year old fuelbeds, respectively.

Table 4
Surface fire behavior results and Fuel Characteristic Classification System (FCCS) fire potentials for SRS median fuelbeds compiled from plot data.

Forest type-age class[a]	# of plots	FPC[b]	FL[b] (m)	ROS[b] (m min^{-1})	RI[b] (kW m^{-2})
Pine 5–20	124	552	1.4	2.2	927.8
Pine 21–40	86	542	1.4	2.3	928.8
Pine 41–60	216	533	1.5	2.3	962.7
Pine >60	27	543	1.5	2.3	987.8
PHW 5–20	1	532	1.5	2.2	1258.7
PHW 21–40	3	522	1.5	2.2	1211.6
PHW 41–60	9	632	1.6	2.9	1106.4
PHW >60	5	522	1.0	2.2	562.1
HWD 5–20	2	531	1.3	1.7	1102.3
HWD 21–40	18	521	0.9	1.8	527.1
HWD 41–60	60	522	0.8	1.7	480.4
HWD >60	43	512	0.9	1.7	597.0
LPO 5–20	2	531	1.2	2.0	843.3
LPO 21–40	7	542	1.5	2.2	1171.0
LPO 41–60	7	842	1.9	4.9	925.2
LPO >60	2	942	2.1	5.6	987.9
CT 0–50	0	433	0.5	1.1	181.9
CT >50	5	422	0.4	1.2	161.0
CC <5	12	321	0.6	0.5	542.7
CAT 30–50	0	725	2.3	3.4	1570.9
CAT >50	0	637	2.2	3.2	1538.5

[a] See Section 2.2 in the text for descriptions of forest type abbreviations.

[b] FPC, FCCS fire potential code; FL, flame length; ROS, rate of spread; RI, reaction intensity.

3.2. Surface fire behavior matrix

An example surface fire behavior matrix, representing pine forest age classes with fuelbeds spanning the range of potential surface fire behavior is presented in Table 5. In general higher surface fire behavior depends on fuel accumulation, in the form of needle drape and litter, increased shrub loading and relative cover of accelerant shrub species. In our matrix fuelbeds, a decrease in non-woody loading is associated with higher surface fire behavior, reflecting that with increases in shrub loading, there is typically a decrease in non-woody loading. Matrices for the other forest types are not included here, but the results are similar. An exception is in HWD and PHW fuelbeds where switch cane (*Arundinaria gigantea*) can produce a dense, tall non-woody stratum that significantly increases SFB.

3.3. Drivers of surface fire behavior

Reaction intensity was used to assess which surface fuel parameters (shrubs, non-woody fuels, woody fuels <7.6 cm, or litter) drive surface fire behavior in each forest type in our study area (Table 6 for fuelbeds with average shrub composition; see Table A.1 in the appendix for reaction intensity data for simulated fuelbeds with 30% highly flammable shrub species composition.). In terms of percent of RI contributed by each surface fuel stratum, the main drivers of SFB in all pine forest age classes are litter and shrubs (which includes needle drape where present). Shrubs contribute between 22% and 74% of RI and litter contributes between 10% and 60% of RI across all pine forest age classes. Non-woody fuel tends to become a more important contributor to RI at the extreme SFB level in all pine age classes. Woody fuels <7.6 cm are more important at the low end of the SFB spectrum in Pine forests, contributing up to 18% of total RI.

In PHW fuelbeds, surface fire behavior in 5–20 and 21–40 year age classes is strongly driven by shrub and litter fuels, which together contribute between 72% and 100% of total RI in those classes. In PHW 41–60, non-woody and shrub fuels dominate SFB, together contributing between 72% and 87% of RI. In PHW >60 fuelbeds, litter and non-woody are the primary drivers of SFB, contributing between 74% and 86% RI. Woody fuels <7.6 cm are not important drivers of SFB in PHW forests, contributing 8% or less to total RI. None of our simulated fuelbeds for 5–60 year old pine-hardwood forests produced low SFB estimates. In addition, extreme SFB was not produced by simulated PHW >60 year old fuelbeds.

Reaction intensity in longleaf pine-oak forests is generally dominated by shrub and litter fuels. Non-woody fuels are also important in the younger age classes, but are less important in LPO forest >60 age class. Woody fuels <7.6 cm contribute 10% to total RI in LPO 5–20 year age class, but are not important contributors to SFB in other LPO age classes. No simulated fuelbeds produced extreme SFB in LPO forests younger than 60 years. In addition, no low estimated SFB was produced by LPO 41–60 fuelbeds.

The main drivers of SFB in HWD 5–20 fuelbeds are shrub and litter fuels. In the other three HWD age classes, shrubs and litter contribute between 63% and 82% of total RI at low SFB, while non-woody fuels drive SFB (up to 70% of total RI) at the higher end of the SFB spectrum. Woody fuels <7.6 cm contributed up to 15% of total RI in the low range of the SFB of HWD forests >20 years, but was not important at the higher end of SFB spectrum for HWD forests. Simulated HWD 5–20 fuelbeds did not produce extreme SFB, nor did HWD 21–40 fuelbeds, unless accelerant shrubs were included.

Table 5
Pine forest surface fire behavior matrix. Fuelbeds within each surface fire behavior rating for each age class with rate of spread (ROS) and flame length (FL) outputs and a description of surface fuel parameters. In each age group, the first row is the median fuelbed, the second row is the plot fuelbed with highest predicted FL, and the other 4 rows are simulated fuelbeds selected to represent each surface fire behavior rating.

Forest type-age[a]	FB #[c]	Surface fire behavior ratings[b]				Surface fuel parameter summary[d]	
		Low	Moderate	High	Extreme		
Pine 5–20	1106	ROS 2.3		FL 1.4		Shrub: 44% cover, 1.1 m; needle drape; no accelerant shrubs	Non-woody: 10% cover, 0.8 m; Litter: 100% cover, 2.8 cm, normal
	Plot 4232			ROS 6.4	FL 2.7	Shrub: 43% cover, 4.7 m; needle drape; 54.5% accelerant shrubs	Non-woody: 2% cover, 4.6 m; Litter: 100% cover, 4.7 cm; normal
	1138	FL 0.5 ROS 0.6				Shrub: 60% cover, 0.6 m; no needle drape; no accelerant shrubs	Non-woody: 15% cover, 0.2 m; Litter: 50% cover, 1.3 cm; normal
	1139	ROS 1.6	FL 1.0			Shrub: 27% cover, 0.9 m; no needle drape; 30% accelerant shrubs	Non-woody: 15% cover, 0.2 m; Litter: 75% cover, 2.5 cm; normal
	1140		ROS 4.0	FL 2.1		Shrub: 34% cover of 1.7 m; needle drape; 60% accelerant shrubs	Non-woody: 1% cover, 0.2 m; Litter: 100% cover, 4.6 cm; normal
	1141		ROS 6.6		FL 3.0	Shrub: 70% cover of 3.0 m; needle drape; 60% accelerant shrubs	Non-woody: none; Litter: 100% cover, 7.6 cm; normal
Pine 21–40	1107	ROS 2.3		FL 1.4		Shrub: 33% cover, 0.8 m, needle drape; no accelerant shrubs	Non-woody: 4% cover 0.6 m; Litter: 100% cover, 3.3 cm, normal
	Plot 4153			ROS 7.9	FL 2.8	Shrub: 18% cover, 1.8 m; needle drape; 59% accelerant shrubs	Non-woody: 0.2% cover, 1.8 m; Litter: 100% cover, 3.6 cm, normal
	1142	FL 0.5 ROS 0.6				Shrub: 34% cover, 0.2 m; no needle drape; 30% accelerant shrubs	Non-woody: 40% cover, 0.2 m; Litter: 75% cover, 0.8 cm; normal
	1143	ROS 1.2	FL 0.8			Shrub: 34% cover, 0.5 m; no needle drape; 30% accelerant shrubs	Non-woody: 40% cover, 0.2 m; Litter: 100% cover, 1.3 cm; normal
	1144	ROS 2.4		FL 1.5		Shrub: 40% cover, 1.5 m; needle drape; 30% accelerant shrubs	Non-woody: 20% cover 0.1 m; Litter: 100% cover, 2.5 cm; normal
	1145		ROS 4.2		FL 2.6	Shrub: 40% cover, 1.5 m; needle drape; 60% accelerant shrubs	Non-woody: 10% cover, 0.1 m; Litter: 100% cover, 7.9 cm; fluffy
Pine 41–60	1108	ROS 2.3		FL 1.5		Shrub: 43% cover, 0.7 m; needle drape; 5% accelerant shrubs	Non-woody: 3% cover, 0.6 m; Litter: 100% cover, 3.3 cm, normal
	Plot 4029			ROS 6.7	FL 2.7	Shrub: 22% cover, 1.7 m; needle drape; 59% accelerant shrubs	Non-woody: 1% cover, 1.5 m; Litter: 100% cover, 3.8 cm, normal
	1146	FL 0.4 ROS 0.4				Shrub: 35% cover, 0.3 m; no needle drape; 30% accelerant shrubs	Non-woody: 30% cover, 0.2 m; Litter: 75% cover, 0.3 cm; normal
	1147	ROS 1.7	FL 1.2			Shrub: 35% cover, 0.9 m; needle drape; 30% accelerant shrubs	Non-woody: 20% cover, 0.2 m; Litter: 75% cover, 0.8 cm; normal
	1148		ROS 3.4	FL 2.0		Shrub: 50% cover, 1.5 m; needle drape; 60% accelerant shrubs	Non-woody: 10% cover, 0.2 m; Litter: 100% cover, 5.1 cm; normal
	1149		ROS 4.2		FL 2.6	Shrub: 80% cover, 1.8 m; needle drape; 60% accelerant shrubs	Non-woody: 5% cover, 0.2 m; Litter: 100% cover, 10.4 cm; fluffy
Pine 60+	1109	ROS 2.3		FL 1.5		Shrub: 46% cover, 0.6 m; needle drape; no accelerant shrubs	Non-woody: 6% cover, 0.3 m; Litter: 100% cover, 3.0 cm, normal
	Plot 1174			ROS 8.9	FL 2.8	Shrub: 32% cover, 1.6 m; needle drape; 32% accelerant shrubs	Non-woody: 100% cover, 1.6 m; Litter: 100% cover, 5.5 cm; normal
	1150	FL 0.6 ROS 0.8				Shrub: 10% cover, 0.5 m; no needle drape; 30% accelerant shrubs	Non-woody: 33% cover, 0.2 m; Litter: 100% cover, 2.5 cm; normal
	1151	ROS 2.1	FL 1.2			Shrub: 30% cover, 1.2 m; no needle drape; 30% accelerant shrubs	Non-woody: 25% cover 0.2 m; Litter: 100% cover, 8.6 cm; normal
	1152		ROS 3.3	FL 2.0		Shrub: 60% cover, 1.5 m; needle drape; 60% accelerant shrubs	Non-woody: 15% cover, 0.2 m; Litter: 100% cover, 8.6 cm; perched
	1153		ROS 4.6		FL 3.0	Shrub: 80% cover, 1.8 m; needle drape; 60% accelerant shrubs	Non-woody: 10% cover, 0.2 m; Litter: 60% cover, 1.3 cm; normal

[a] See Section 2.2 in text for descriptions of forest type-age class abbreviations.

[b] Flame length (FL) determines the surface fire behavior rating; low is 0–0.6 m, moderate is 0.6–1.2 m, high is 1.2–2.4 m, extreme is 2.4–4.9 m (or higher). For rate of spread (ROS) ratings, low is 0–3.4 m min^{-1}, moderate is 3.4–6.7 m min^{-1}, high is 6.7–13.4 m min^{-1}, extreme is 13.4–26.8 m min^{-1}.

[c] FB, Fuel Characteristic Classification System fuelbed number.

[d] Woody fuels <7.6 cm were not included in the surface fuel summary; they were not major contributors to SFB in most forest types.

In CT <50 fuelbeds, the shrub stratum is the main contributor to RI at all SFB levels and becomes more dominant at higher levels. RI in CT >50 fuelbeds was strongly dominated by litter at the lowest SFB rating and by shrubs at all other ratings. Extreme SFB was not reached for CT <50 fuelbeds.

As expected, small woody fuels played a larger role in driving SFB in clearcut and catastrophic damage fuelbeds contributing up to 38% of RI at lower SFB ratings, but surprisingly, were not main contributors to RI at the higher end of the SFB spectrum (<20% of RI at high and extreme SFB ratings). In general, SFB in clearcut forests is driven by non-woody and litter fuels. RI in catastrophically damaged forests is driven by litter and woody fuels at the lower end of the SFB spectrum and by shrubs and litter at the higher end. None of our simulated fuelbeds for catastrophically damaged forests produced low SFB estimates.

3.4. Management targets for surface fire behavior reduction

Table 6 lists the mean and 95% confidence interval of surface fuel loading data for simulated fuelbeds with average shrub com-

Table 6

Summarized results for all simulated fuelbeds with average shrub composition by forest type-age class and surface fire behavior rating. Mean fuel loadings ($\mathrm{Mg\ ha^{-1}}$) with 95% confidence intervals and percent of total reaction intensity for each surface fuel stratum. Mean loadings of small woody fuels (<7.6 cm) were not included because they were not important drivers of surface fire behavior in most forest types on our study site.

Forest type-age class[a]	SFB rating[b]	Fuelbeds #	Mean fuel loadings and 95% CI			Percent of total reaction intensity			
			Shrub	Non-woody	Litter	Shrub	Non-woody	Small woody	Litter
Pine 5–20	Low	44	3.4 +/− 0.0	0.4 +/− 0.2	2.7 +/− 0.6	27%	10%	3%	60%
	Moderate	839	5.4 +/− 0.1	0.6 +/− 0.1	3.4 +/− 0.2	43%	11%	2%	44%
	High	1373	6.1 +/− 0.1	0.9 +/− 0.1	4.4 +/− 0.1	39%	15%	1%	45%
	Extreme	48	8.5 +/− 0.7	2.6 +/− 0.2	4.6 +/− 0.7	32%	30%	0%	38%
Pine 21–40	Low	40	3.4 +/− 0.0	0.6 +/− 0.3	0.3 +/− 0.1	28%	25%	14%	33%
	Moderate	216	5.8 +/− 0.4	0.4 +/− 0.1	0.5 +/− 0.1	74%	11%	4%	11%
	High	751	6.6 +/− 0.2	1.0 +/− 0.1	5.9 +/− 0.4	39%	18%	2%	41%
	Extreme	289	7.9 +/− 0.4	2.2 +/− 0.2	6.3 +/− 0.4	27%	26%	1%	47%
Pine 41–60	Low	118	3.4 +/− 0.0	0.7 +/− 0.2	0.3 +/− 0.0	41%	24%	18%	17%
	Moderate	418	6.0 +/− 0.2	0.5 +/− 0.1	0.9 +/− 0.2	69%	14%	6%	10%
	High	1344	6.2 +/− 0.2	1.3 +/− 0.1	7.8 +/− 0.4	34%	21%	2%	43%
	Extreme	712	7.4 +/− 0.2	3.3 +/− 0.2	8.3 +/− 0.4	24%	36%	1%	39%
Pine >60	Low	15	3.4 +/− 0.0	0.1 +/− 0.1	1.1 +/− 0.3	37%	4%	12%	46%
	Moderate	195	5.0 +/− 0.2	0.3 +/− 0.1	1.3 +/− 0.1	61%	9%	6%	24%
	High	781	5.5 +/− 0.1	1.0 +/− 0.1	6.4 +/− 0.4	38%	19%	3%	40%
	Extreme	737	5.9 +/− 0.1	3.8 +/− 0.2	6.6 +/− 0.3	22%	41%	1%	36%
PHW 5–20	Low	0	na	na	na	na	na	na	na
	Moderate	3	5.1 +/− 2.9	0.1 +/− 0.0	2.3 +/− 0.0	44%	4%	4%	48%
	High	1635	7.3 +/− 0.2	0.6 +/− 0.0	6.6 +/− 0.2	40%	13%	3%	44%
	Extreme	90	12.5 +/− 0.7	2.0 +/− 0.1	6.2 +/− 0.8	37%	27%	1%	35%
PHW 21–40	Low	0	na	na	na	na	na	na	na
	Moderate	138	5.8 +/− 0.2	0.9 +/− 0.1	1.5 +/− 0.0	45%	24%	3%	29%
	High	707	5.9 +/− 0.1	0.6 +/− 0.0	6.9 +/− 0.3	41%	12%	1%	45%
	Extreme	19	6.1 +/− 0.7	0.0 +/− 0.0	4.5 +/− 0.0	34%	0%	0%	66%
PHW 41–60	Low	0	na	na	na	na	na	na	na
	Moderate	337	6.0 +/− 0.2	0.4 +/− 0.0	0.6 +/− 0.0	66%	18%	5%	11%
	High	952	6.8 +/− 0.2	1.6 +/− 0.1	2.9 +/− 0.2	41%	31%	2%	26%
	Extreme	247	7.6 +/− 0.4	6.0 +/− 0.2	2.8 +/− 0.3	22%	65%	1%	12%
PHW >60	Low	293	1.3 +/− 0.1	0.6 +/− 0.1	0.9 +/− 0.1	18%	32%	8%	42%
	Moderate	569	1.5 +/− 0.1	0.6 +/− 0.1	3.5 +/− 0.3	14%	26%	5%	55%
	High	674	1.6 +/− 0.1	1.0 +/− 0.1	6.2 +/− 0.2	9%	29%	5%	57%
	Extreme	0	na	na	na	na	na	na	na
LPO 5–20	Low	34	2.1 +/− 0.2	0.4 +/− 0.0	0.7 +/− 0.0	32%	27%	10%	31%
	Moderate	334	3.5 +/− 0.2	0.6 +/− 0.0	2.5 +/− 0.2	36%	22%	5%	36%
	High	208	5.4 +/− 0.2	0.6 +/− 0.0	4.5 +/− 0.4	44%	15%	4%	37%
	Extreme	0	na	na	na	na	na	na	na
LPO 21–40	Low	184	1.5 +/− 0.1	0.2 +/− 0.0	1.3 +/− 0.1	29%	18%	10%	43%
	Moderate	612	3.2 +/− 0.2	0.3 +/− 0.0	3.2 +/− 0.2	39%	14%	5%	42%
	High	356	4.8 +/− 0.1	0.3 +/− 0.0	4.9 +/− 0.3	44%	10%	3%	42%
	Extreme	0	na	na	na	na	na	na	na
LPO 41–60	Low	0	na	na	na	na	na	na	na
	Moderate	585	1.1 +/− 0.1	0.4 +/− 0.0	5.4 +/− 0.2	11%	17%	3%	69%
	High	951	3.8 +/− 0.1	0.7 +/− 0.0	5.1 +/− 0.2	36%	18%	2%	45%
	Extreme	0	na	na	na	na	na	na	na
LPO >60	Low	2	1.0 +/− 1.1	0.0 +/− 0.0	1.4 +/− 0.0	16%	0%	0%	84%
	Moderate	597	2.1 +/− 0.1	0.2 +/− 0.0	5.5 +/− 0.4	24%	9%	2%	65%
	High	696	4.0 +/− 0.1	0.2 +/− 0.0	6.3 +/− 0.3	35%	5%	1%	59%
	Extreme	1	4.9 +/− 0.0	0.0 +/− 0.0	4.3 +/− 0.0	39%	0%	0%	61%
HWD 5–20	Low	72	1.0 +/− 0.1	0.1 +/− 0.0	6.2 +/− 0.9	36%	9%	4%	51%
	Moderate	1476	2.6 +/− 0.1	0.5 +/− 0.0	5.3 +/− 0.2	36%	24%	8%	32%
	High	180	4.3 +/− 0.0	0.6 +/− 0.1	4.3 +/− 0.4	48%	18%	5%	29%
	Extreme	0	na	na	na	na	na	na	na
HWD 21–40	Low	403	1.2 +/− 0.1	0.1 +/− 0.0	5.7 +/− 0.4	32%	6%	11%	50%
	Moderate	705	3.0 +/− 0.2	0.5 +/− 0.1	7.3 +/− 0.3	36%	21%	5%	37%
	High	620	3.0 +/− 0.2	3.6 +/− 0.1	7.1 +/− 0.3	17%	66%	1%	16%
	Extreme	0	na	na	na	na	na	na	na
HWD 41–60	Low	1107	1.4 +/− 0.1	0.2 +/− 0.0	5.4 +/− 0.4	35%	15%	15%	34%
	Moderate	1540	2.7 +/− 0.1	0.8 +/− 0.0	8.2 +/− 0.3	30%	34%	5%	31%
	High	792	3.2 +/− 0.2	2.8 +/− 0.1	8.8 +/− 0.4	19%	65%	1%	15%
	Extreme	17	6.4 +/− 0.7	4.1 +/− 0.0	13.3 +/− 2.2	25%	64%	1%	10%
HWD >60	Low	950	1.2 +/− 0.1	0.2 +/− 0.0	4.7 +/− 0.3	30%	22%	15%	33%
	Moderate	1310	3.7 +/− 0.2	0.9 +/− 0.1	6.2 +/− 0.2	37%	33%	5%	26%
	High	1015	4.8 +/− 0.2	2.7 +/− 0.1	6.6 +/− 0.3	29%	57%	1%	13%
	Extreme	181	5.6 +/− 0.6	4.9 +/− 0.1	8.3 +/− 0.7	21%	70%	0%	9%

(*continued on next page*)

Table 6 (*continued*)

Forest type-age class[a]	SFB rating[b]	Fuelbeds #	Mean fuel loadings and 95% CI			Percent of total reaction intensity			
			Shrub	Non-woody	Litter	Shrub	Non-woody	Small woody	Litter
CT 0–50	Low	868	1.6 +/− 0.1	0.3 +/− 0.0	7.0 +/− 0.4	37%	26%	10%	27%
	Moderate	384	4.2 +/− 0.2	0.3 +/− 0.0	9.7 +/− 0.6	54%	22%	5%	19%
	High	44	7.3 +/− 0.4	0.4 +/− 0.1	10.5 +/− 1.6	72%	11%	1%	16%
	Extreme	0	na	na	na	na	na	na	na
CT >50	Low	355	0.1 +/− 0.0	0.1 +/− 0.0	11.1 +/− 0.4	9%	10%	11%	70%
	Moderate	821	3.7 +/− 0.2	0.2 +/− 0.0	11.8 +/− 0.3	47%	17%	15%	21%
	High	437	12.3 +/− 0.5	0.1 +/− 0.0	11.7 +/− 0.4	80%	4%	3%	13%
	Extreme	115	18.5 +/− 0.7	0.0 +/− 0.0	12.1 +/− 0.7	91%	0%	0%	9%
CC <5	Low	484	0.9 +/− 0.1	0.4 +/− 0.0	0.6 +/− 0.1	24%	34%	25%	17%
	Moderate	1829	1.9 +/− 0.1	0.8 +/− 0.0	3.3 +/− 0.2	24%	30%	10%	36%
	High	1128	2.6 +/− 0.1	1.3 +/− 0.1	4.7 +/− 0.2	22%	32%	5%	41%
	Extreme	15	3.0 +/− 0.9	2.6 +/− 0.0	3.8 +/− 1.5	17%	43%	2%	38%
CAT 30–50	Low	0	na	na	na	na	na	na	na
	Moderate	96	1.0 +/− 0.1	0.2 +/− 0.0	2.2 +/− 0.2	15%	11%	37%	37%
	High	2280	3.8 +/− 0.1	0.6 +/− 0.0	4.2 +/− 0.1	30%	18%	20%	32%
	Extreme	540	6.7 +/− 0.2	1.2 +/− 0.1	5.2 +/− 0.3	36%	25%	12%	27%
CAT >50	Low	0	na	na	na	na	na	na	na
	Moderate	71	0.9 +/− 0.1	0.2 +/− 0.0	2.2 +/− 0.2	15%	11%	38%	36%
	High	2130	3.6 +/− 0.1	0.6 +/− 0.0	4.1 +/− 0.1	29%	19%	20%	32%
	Extreme	715	6.4 +/− 0.1	1.2 +/− 0.1	5.1 +/− 0.2	35%	26%	13%	26%

[a] See section 2.2 in text for descriptions of forest type-age class abbreviations

[b] SFB ratings are based on flame length thresholds: low is 0–0.6 m, moderate is 0.6–1.2 m, high is 1.2–2.4 m, extreme is 2.4–4.9 m (or higher). SFB, surface fire behavior; na, not applicable (no fuelbeds resulted in estimated flame lengths within specified level of SFB).

position within each age class and SFB matrix rating, providing targets for fuel reduction treatments. For example, in Pine 21–40 fuelbeds, reducing shrub loading by 26%, from 7.8 to 5.8 Mg ha^{-1}, should reduce SFB from extreme to moderate. The arithmetic means were calculated for each surface fuel parameter individually, but realistically most management treatments would reduce more than one fuel component which would likely result in a larger decrease in SFB. Woody fuels <7.6 cm were not included in this section of the table since they were not major contributors to SFB in most forest types. See Table A.1 for surface fuel loading data for simulated fuelbeds with 30% highly flammable shrub species composition.

4. Discussion

4.1. Current wildfire hazard assessment: median fuelbeds

As estimated by predicted flame lengths in our median fuelbeds calculated at a dry fuel moisture scenario, current wildfire hazard on Savannah River Site ranges from low to high across all forest types. Forest fuelbeds with high predicted flame lengths (all pine age classes, pine-hardwoods less than 60 years, and longleaf pine-oak forests greater than 20 years) contain continuous litter cover and moderate shrub cover with needle drape. The oldest pine-hardwood age class fuelbeds had moderate flame lengths, which is apparently related to lower shrub and non-woody cover under the denser canopy stratum. Five to twenty year old longleaf pine-oak forests also had moderate predicted flame lengths, which appear to be related to relatively thin, discontinuous litter (2.8 cm, 88% cover) and the absence of needle drape. Surprisingly, the young hardwood median fuelbed had a high predicted flame length, which is apparently related to higher non-woody and shrub cover than in older hardwood fuelbeds and also the presence of loblolly pine seedlings in the shrub layer (which are designated highly flammable in the FCCS). While the plots were classified as hardwood forests, they had rather high relative cover of pines in the midstory and understory of the canopy, so needle drape was present on the shrubs. A larger sample size probably would have produced a purer hardwood composition which likely would have yielded lower surface fire behavior estimates more consistent with the other hardwood forest age classes. Low flame lengths were predicted for cypress-tupelo forests and clearcuts, which is consistent with the low surface fuel loads typically present in cypress-tupelo forests and young pine plantations which generally have surface fuel treatments before planting.

4.2. Surface fire behavior matrix

Fuelbeds for the pine forest surface fire behavior matrix were selected to represent a low to extreme SFB spectrum assuming a lack of management, so litter, shrub loading, composition of highly flammable shrubs and needle drape tend to increase while non-woody fuels decrease from low to extreme. This trend in selection criteria was applied in most forest type-age class matrices. In some cases in pine-hardwood or hardwood fuelbeds, extreme SFB was predicted only when a tall, dense non-woody layer was included. These fuelbeds represent ecotones between upland pine forests and pine-hardwood forests or bottomland hardwood forests, which often contain switch cane intermixed with wax myrtle or other shrubs, and can produce intense surface fires that can carry into adjacent forest stands (Chris Hobson, USFS Savannah River Fire Management Officer, personal communication).

The SFB matrix framework is flexible and could be altered for use in other areas by redefining the SFB ratings and forest types, if necessary. In addition, including multiple fuelbeds at each SFB rating for each forest type would provide managers an array of fuelbeds with different surface fuel complexes that produce similar SFB. For example, let us consider a fuelbed with dense, tall grasses or forbs, such as broomsedge (*Andropogon virginicus*) or dogfennel (*Eupatorium capillifolium*) and a fuelbed with moderate cover of highly flammable shrubs. Both fuelbeds might produce high predicted SFB and both could be included in the matrix to represent different understory conditions in the same forest type.

4.3. Drivers of surface fire behavior and target fuel loadings

Litter is a primary or secondary driver of predicted RI and provides much of the fuel loading in fuelbeds across all SFB matrix ratings in most forest types. This is consistent with litter loading and consumption data from SRS and other sites in the Southeast (Kilgo and Blake, 2005 (Table 3.2, summarized unpublished data by Hao et al.); McNab et al., 1978; Ottmar and Vihnanek, 2000; Ottmar et al., 2003; Scholl and Waldrop, 1999). Non-woody fuels are larger contributors to RI at the higher end of SFB in hardwood forests, despite the fact that litter loads are often much higher than shrub or non-woody fuels in these fuelbeds. In FCCS, broadleaf deciduous litter has a higher surface area to volume ratio and lower bulk density than pine litter, which reduces the contribution to RI for an equal fuel load. So while hardwood forests, which based on plot photos, were all sampled in the late fall or early winter, had some of the highest litter loads in our study, litter did not act as a primary driver of RI due to the properties assigned to it in our fuelbeds. Non-woody fuels were also important contributors to RI in clearcuts, which is consistent with early colonization by herbaceous species following removal of the tree canopy. Litter was the other main contributor to RI in clearcuts, which perhaps reflects the residual litter from the mature forest canopy before harvest; however, if prescribed fire were used during site preparation, the litter would have been removed. Twelve clearcut plots were included in our study; 10 of them were three years old or less and average time since last burn was 17.8 years, so litter from the previous forest would have been present, albeit compacted by harvesting equipment.

Small woody fuels were not important contributors to SFB in most forest types studied; however, they were important in some CC and CAT fuelbeds. Our predicted FL and ROS from CAT fuelbeds are lower than those reported by Wade et al. (1993). The small woody loadings in our fuelbeds were in the higher end of the range reported by Wade et al. (1993), however, the foliage loadings reported in that study (up to 38.7 Mg ha^{-1}) are not fully captured in our FCCS fuelbeds. The closest approximation to foliage on downed tree crowns in FCCS is shrub layer needle drape and adding drape only increases surface fuel loads by 3.4 Mg ha^{-1}. So, although the simulated fuelbeds contain wide ranges of shrub, non-woody and litter loads and needle drape, they did not approach the total surface fuel loadings reported by Wade et al. (1993). Manually increasing the loading of non-woody fuels, as a proxy for the fine fuel contribution by dead foliage on downed tree crowns, resulted in SFB predictions similar to those reported in the Wade et al. (1993) study. As the authors of that study conclude, reducing fine fuel loadings in post-hurricane fuel complexes should significantly reduce surface fire hazard.

In this analysis default FCCS litter bulk density values were used to represent southern litter, however, as mentioned above, our findings are similar to those of other fuel loading and consumption studies conducted in similar forests in the southeastern US. Although this is the case, FCCS developers are exploring the use of regional litter bulk density values (Ottmar and Andreu, 2007; Parresol et al., 2006) within FCCS to further refine the contribution of litter to potential fire behavior. While estimated loadings for shrub and non-woody fuels could likely be improved with more precise vegetation measures of each stratum rather than combined in a vegetation profile, in general, our predicted stratum loadings fit with those reported elsewhere (Ottmar and Vihnanek, 2000; Ottmar et al., 2003; Scholl and Waldrop, 1999). Therefore, our loadings for each forest type-age class and stratum should provide adequate targets for fuels management. While specific management treatments are not assigned to each fuel condition with this matrix approach, managers can determine which treatments will create fuel conditions similar to the fuelbeds predicted to yield target surface fire behavior.

We used a dry fuel moisture scenario and relatively high wind speed in this study to determine fuel complexes that are most likely to produce extreme SFB in a wildfire situation. We also determined the surface fuels that contribute most to SFB in each forest type and provide surface fuel target loadings to reduce wildfire behavior under those conditions. While our analysis is useful for fuel reduction planning, it does not address potential SFB from a wildfire or prescribed fire at other fuel moisture levels or wind speeds, which might produce different results in a similar analysis. Therefore, we are exploring the possibility of repeating our analysis using several sets of environmental variables to add to the applicability of our study. If our fuelbeds or methodologies were to be applied to another wildfire hazard assessment project, the environmental variables in the selected fuelbeds could be changed within FCCS to any set of custom fuel moistures or wind speeds that represent typical fire conditions of the project area.

4.4. Management applications

The median fuelbeds from this work are based on SRS inventory data coupled with regional data (default data from FCCS fuelbeds, FIA data and other regional studies). As such, these fuelbeds are analogous to the FCCS default fuelbeds and can be used across multiple spatial scales: from fine-scale assessments of fuel complexes of individual stands to broader-scale landscape analysis to prioritize areas where fuel reduction treatments are needed across an ownership or a region. For example, the median fuelbeds were used along with individual plot fuelbeds in a separate component of this project to map SFB across the SRS landscape in order to prioritize areas where fuel treatments should be located (Ottmar et al., 2012). In addition, Hollingsworth et al. (2012) used data-derived FCCS fuelbeds to create custom fuel models (Parresol et al., 2012b) as a basis for running FlamMap. They compared the outputs of flame length, rate of spread, crown fire activity and burn probability to those produced by using standard fuel models assigned to the landscape by LANDFIRE data (Reeves et al., 2009; Scott and Burgan, 2005) and Southern Wildfire Risk Assessment data (Buckley et al., 2006; Anderson, 1982).

Using management history or available surface fuel data, our simulated fuelbeds can be assigned to management compartments or stands by fuel loads of the strata that are most important to surface fire behavior in a given forest type. In this way, the assigned fuelbeds can be mapped across the landscape, giving a more detailed view of fuel loadings and fire behavior outputs at finer scales. Following this type of spatial analysis in which areas are prioritized for fuel reduction treatment, our results identifying the drivers of surface fire behavior in different forest types can aid in determining which fuel types should be targeted in hazardous fuel mitigation projects. Similarly our results of target surface fuel loads will be useful for determining how much fuel to remove in order to reduce SFB to a desired or acceptable level. For example, if an area of pine forest greater than 60 years old is predicted to have extreme surface fire behavior it would likely be selected for fuel reduction treatment. In this case, Table 6 reports that non-woody fuel or litter is likely to be the main driver of surface fire behavior since those strata contribute most to reaction intensity, 41% and 35% of total RI, respectively. Table 6 also shows that by reducing litter by 81%, from 6.6 to 1.3 Mg ha^{-1}, or non-woody fuel by 92%, from 3.8 to 0.3 Mg ha^{-1}, predicted surface fire behavior could be reduced to the moderate level. Therefore, some combination of herbicide, pine straw raking, or prescribed fire should be considered to reduce potential SFB in this hypothetical area.

The surface fire behavior matrix results from this study can be used to assess current predicted SFB at fine to moderate scales. The composition and structure of surface fuels across the matrix can be compared to surface fuels either visually, for fine scale applications, or based on surface fuel data, for broader scale applications, in order to determine the potential SFB level. In this way, the SFB matrix could be used in a manner similar to the natural fuels photo series (e.g., Ottmar and Vihnanek, 2000; Ottmar et al., 2003). As noted in the discussion section, including more fuelbeds within each SFB rating is possible. This would give a more complete set of potential fuel characteristics to apply to a given management area or landscape.

In summary, we created a catalog of thousands of simulated fuelbeds that can be used to represent fuel conditions and predict surface fire behavior throughout the Atlantic Coastal Plain. Because these fuelbeds are based on inventory data and the contribution of each surface fuel stratum is considered separately in FCCS, they provide a more robust tool for assessing fuel reduction options for treatment planning than stylized fuel models. In addition, the fuelbeds can be used to provide inputs for other fire and environmental modeling packages such as Consume (Prichard et al., 2006), BlueSky (Pouliot et al., 2005), and the First Order Fire Effects Model (Reinhardt et al., 1997). This set of simulated fuelbeds includes a wide range of fuel conditions in several age classes, therefore, the fuelbed matrices and stratum loading results from this project should sufficiently represent surface fuel conditions throughout the southern Atlantic Coastal Plain where similar forest types occur. Our pine forest data set is quite large and with the additional sets of fuelbeds built with 30% and 60% relative cover of highly flammable shrub species, could be used to represent a wide range of surface fuel conditions in pine forests throughout the southern coastal plain region (see Fig. 1). Our approach of building simulated fuelbeds across the range of available surface fuel data produces sets of incrementally different data-derived fuelbed characteristics to assess wildfire hazard and can be applied to dynamic forest types in any geographic area. We believe this approach offers land owners a detailed and focused method to prioritize and plan fuel treatments at fine to moderate operational scales in a way that approaches reliant on remotely sensed data cannot.

Median fuelbeds and the matrix for each forest type-age class from this project can be accessed from the FCCS website (http://www.fs.fed.us/pnw/fera/fccs/downloads.shtml). Contact the corresponding author to obtain the larger sets of simulated fuelbeds.

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Appendix A

Table A.1. Summarized results for all simulated fuelbeds with 30% relative cover of highly flammable shrubs by forest type-age class and surface fire behavior rating. Mean fuel loadings (Mg ha^{-1}) with 95% confidence intervals and percent of total reaction intensity for each surface fuel stratum. Mean loadings of small woody fuels (<7.6 cm) were not included because they were not important drivers of surface fire behavior in most forest types on our study site.

Forest type-age class[a]	SFB rating[b]	Fuelbeds #	Mean fuel loadings & 95% CI			Percent of total reaction intensity			
			Shrub	Non-woody	Litter	Shrub	Non-woody	Small woody	Litter
Pine 5–20	Low	32	3.4 +/– 0.0	0.3 +/– 0.2	2.8 +/– 0.7	23%	7%	4%	66%
	Moderate	1506	5.9 +/– 0.1	0.6 +/– 0.0	4.0 +/– 0.1	48%	10%	2%	41%
	High	602	7.3 +/– 0.3	1.2 +/– 0.1	4.1 +/– 0.2	45%	16%	1%	38%
	Extreme	164	10.0 +/– 0.5	2.0 +/– 0.1	4.6 +/– 0.4	43%	22%	0%	34%
Pine 21–40	Low	32	3.4 +/– 0.0	0.8 +/– 0.3	0.3 +/– 0.1	21%	26%	15%	39%
	Moderate	121	4.8 +/– 0.4	0.4 +/– 0.2	0.6 +/– 0.2	72%	10%	5%	13%
	High	701	7.0 +/– 0.3	0.9 +/– 0.1	5.0 +/– 0.4	52%	15%	2%	31%
	Extreme	442	10.2 +/– 0.5	1.9 +/– 0.2	6.3 +/– 0.4	39%	21%	1%	40%
Pine 41–60	Low	100	3.4 +/– 0.0	0.6 +/– 0.2	0.3 +/– 0.0	41%	22%	19%	18%
	Moderate	257	5.2 +/– 0.3	0.6 +/– 0.2	0.9 +/– 0.3	71%	14%	5%	10%
	High	1354	6.8 +/– 0.2	1.1 +/– 0.1	7.0 +/– 0.4	45%	17%	3%	36%
	Extreme	881	9.0 +/– 0.3	3.0 +/– 0.1	8.0 +/– 0.4	33%	32%	1%	34%
Pine >60	Low	8	3.4 +/– 0.0	0.1 +/– 0.1	0.7 +/– 0.0	45%	4%	12%	38%
	Moderate	50	3.5 +/– 0.0	0.4 +/– 0.1	1.3 +/– 0.2	58%	13%	6%	23%
	High	846	5.7 +/– 0.2	0.7 +/– 0.1	5.7 +/– 0.4	49%	14%	3%	34%
	Extreme	824	6.3 +/– 0.2	3.7 +/– 0.2	6.4 +/– 0.3	28%	38%	1%	33%
PHW 5–20	Low	0	na	na	na	na	na	na	na
	Moderate	250	1.4 +/– 0.1	0.3 +/– 0.1	5.3 +/– 0.4	15%	10%	5%	69%
	High	1421	5.3 +/– 0.2	0.7 +/– 0.0	6.9 +/– 0.2	27%	15%	3%	55%
	Extreme	57	14.4 +/– 0.6	1.7 +/– 0.2	6.3 +/– 1.0	44%	19%	1%	36%

Appendix A (*continued*)

Forest type-age class[a]	SFB rating[b]	Fuelbeds #	Mean fuel loadings & 95% CI			Percent of total reaction intensity			
			Shrub	Non-woody	Litter	Shrub	Non-woody	Small woody	Litter
PHW 21–40	Low	0	na	na	na	na	na	na	na
	Moderate	104	5.8 +/– 0.3	0.7 +/– 0.1	1.5 +/– 0.0	53%	18%	2%	26%
	High	647	6.2 +/– 0.1	0.7 +/– 0.0	6.4 +/– 0.3	48%	12%	1%	38%
	Extreme	113	6.8 +/– 0.4	0.2 +/– 0.1	8.0 +/– 0.8	46%	2%	0%	52%
PHW 41–60	Low	0	na	na	na	na	na	na	na
	Moderate	141	5.7 +/– 0.3	0.5 +/– 0.1	0.6 +/– 0.1	66%	20%	6%	8%
	High	1031	7.8 +/– 0.2	1.2 +/– 0.1	2.5 +/– 0.1	55%	22%	2%	21%
	Extreme	364	9.7 +/– 0.5	5.1 +/– 0.2	2.8 +/– 0.3	32%	55%	1%	12%
PHW >60	Low	212	1.3 +/– 0.2	0.6 +/– 0.1	0.8 +/– 0.1	22%	24%	6%	48%
	Moderate	538	2.3 +/– 0.2	0.7 +/– 0.1	2.9 +/– 0.2	20%	31%	8%	41%
	High	786	3.1 +/– 0.2	0.9 +/– 0.0	6.0 +/– 0.2	18%	23%	5%	55%
	Extreme	0	na	na	na	na	na	na	na
LPO 5–20	Low	21	1.8 +/– 0.2	0.4 +/– 0.1	0.7 +/– 0.0	34%	25%	10%	30%
	Moderate	252	3.2 +/– 0.2	0.6 +/– 0.0	2.2 +/– 0.2	39%	21%	6%	34%
	High	303	5.3 +/– 0.2	0.6 +/– 0.0	4.0 +/– 0.3	50%	15%	3%	32%
	Extreme	0	na	na	na	na	na	na	na
LPO 21–40	Low	141	1.5 +/– 0.1	0.2 +/– 0.0	1.2 +/– 0.1	32%	18%	10%	41%
	Moderate	530	3.0 +/– 0.2	0.3 +/– 0.0	3.2 +/– 0.2	40%	13%	5%	41%
	High	480	5.0 +/– 0.1	0.3 +/– 0.0	4.3 +/– 0.3	52%	9%	3%	36%
	Extreme	0	na	na	na	na	na	na	na
LPO 41–60	Low	0	na	na	na	na	na	na	na
	Moderate	514	1.2 +/– 0.1	0.4 +/– 0.0	5.4 +/– 0.4	14%	15%	3%	68%
	High	1014	4.1 +/– 0.1	0.7 +/– 0.0	5.1 +/– 0.2	40%	16%	2%	42%
	Extreme	8	4.8 +/– 0.2	0.0 +/– 0.0	5.9 +/– 2.7	59%	0%	0%	41%
LPO >60	Low	0	na	na	na	na	na	na	na
	Moderate	481	2.4 +/– 0.1	0.3 +/– 0.0	4.1 +/– 0.4	28%	11%	3%	58%
	High	717	4.0 +/– 0.1	0.3 +/– 0.0	6.8 +/– 0.3	38%	8%	2%	53%
	Extreme	98	5.2 +/– 0.2	0.0 +/– 0.0	8.4 +/– 0.9	47%	0%	0%	53%
HWD 5–20	Low	72	1.0 +/– 0.1	0.1 +/– 0.0	6.2 +/– 0.9	36%	9%	4%	51%
	Moderate	1433	2.6 +/– 0.1	0.5 +/– 0.0	5.3 +/– 0.2	36%	24%	8%	32%
	High	223	4.3 +/– 0.0	0.6 +/– 0.0	4.4 +/– 0.3	49%	17%	5%	28%
	Extreme	0	na	na	na	na	na	na	na
HWD 21–40	Low	299	0.7 +/– 0.1	0.1 +/– 0.0	5.7 +/– 0.5	29%	8%	12%	51%
	Moderate	688	2.8 +/– 0.2	0.5 +/– 0.1	7.0 +/– 0.3	40%	19%	5%	35%
	High	622	4.8 +/– 0.3	2.5 +/– 0.1	6.9 +/– 0.3	35%	46%	1%	18%
	Extreme	119	5.6 +/– 0.7	5.4 +/– 0.2	8.8 +/– 0.7	24%	65%	1%	10%
HWD 41–60	Low	895	1.0 +/– 0.1	0.2 +/– 0.0	5.1 +/– 0.4	32%	17%	16%	35%
	Moderate	1545	3.0 +/– 0.1	0.7 +/– 0.0	7.9 +/– 0.3	38%	29%	6%	28%
	High	972	5.0 +/– 0.2	2.3 +/– 0.1	8.7 +/– 0.4	34%	49%	1%	15%
	Extreme	44	8.6 +/– 0.7	3.9 +/– 0.2	11.7 +/– 1.5	38%	52%	1%	10%
HWD >60	Low	872	1.0 +/– 0.1	0.3 +/– 0.0	4.7 +/– 0.3	28%	23%	15%	34%
	Moderate	1293	3.4 +/– 0.2	1.0 +/– 0.1	6.1 +/– 0.3	38%	31%	5%	25%
	High	1106	6.2 +/– 0.3	2.4 +/– 0.1	6.5 +/– 0.3	40%	45%	1%	13%
	Extreme	185	8.7 +/– 0.7	4.3 +/– 0.2	8.6 +/– 0.7	38%	53%	0%	9%
CC <5	Low	441	0.8 +/– 0.1	0.4 +/– 0.0	0.6 +/– 0.1	23%	34%	26%	17%
	Moderate	1819	2.0 +/– 0.1	0.7 +/– 0.0	3.2 +/– 0.2	26%	29%	10%	35%
	High	1177	2.7 +/– 0.1	1.3 +/– 0.1	4.6 +/– 0.2	24%	32%	5%	39%
	Extreme	19	3.3 +/– 0.8	2.6 +/– 0.1	4.0 +/– 1.4	20%	42%	2%	36%
CAT 30–50	Low	na	na	na	na	na	na	na	na
	Moderate	65	0.9 +/– 0.1	0.2 +/– 0.0	2.1 +/– 0.3	17%	11%	37%	36%
	High	1690	3.3 +/– 0.1	0.6 +/– 0.0	4.0 +/– 0.1	31%	18%	20%	32%
	Extreme	1161	7.0 +/– 0.1	0.9 +/– 0.0	4.8 +/– 0.2	45%	18%	13%	24%

(*continued on next page*)

Appendix A (*continued*)

Forest type-age class[a]	SFB rating[b]	Fuelbeds #	Mean fuel loadings & 95% CI			Percent of total reaction intensity			
			Shrub	Non-woody	Litter	Shrub	Non-woody	Small woody	Litter
CAT >50	Low	0	na	na	na	na	na	na	na
	Moderate	44	0.8 +/– 0.1	0.2 +/– 0.0	2.0 +/– 0.3	15%	10%	38%	36%
	High	1591	3.1 +/– 0.1	0.6 +/– 0.0	4.0 +/– 0.1	29%	18%	21%	32%
	Extreme	1281	6.7 +/– 0.1	1.0 +/– 0.0	4.7 +/– 0.2	44%	19%	13%	24%

[a] See section 2.2 in text for descriptions of forest type-age class abbreviations.

[b] SFB ratings are based on flame length thresholds: low is 0–0.6 m, moderate is 0.6–1.2 m, high is 1.2–2.4 m, extreme is 2.4–4.9 m (or higher). SFB, surface fire behavior; na, not applicable (no fuelbeds resulted in estimated flame lengths within specified level of SFB).

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