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The Effectiveness and Limitations of Fuel Modeling Using the Fire and Fuels Extension to the Forest Vegetation Simulator

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Fuel treatment effectiveness is often evaluated with fire behavior modeling systems that use fuel models to generate fire behavior outputs. How surface fuels are assigned, either using one of the 53 stylized fuel models or developing custom fuel models, can affect predicted fire behavior. We collected surface and canopy fuels data before and 1, 2, 5, and 8 years after prescribed fire treatments across 10 national forests in California. Two new methods of assigning fuel models within the Fire and Fuels Extension to the Forest Vegetation Simulator were evaluated. Field-based values for dead and downed fuel loading were used to create custom fuel models or to assign stylized fuel models. Fire was simulated with two wind scenarios (maximum 1-minute speed and maximum momentary gust speed) to assess the effect of the fuel model method on potential fire behavior. Surface flame lengths and fire type produced from custom fuel models followed the fluctuations and variability of fine fuel loading more closely than stylized fuel models. However, results of 7 out of 10 statistical tests comparing surface flame length between custom and stylized fuel models were not significant ($P < 0.05$), suggesting that both methods used to assign surface fuel loads will predict fairly similar trends in fire behavior.

Keywords: prescribed fire, custom fuel model, California, fire behavior modeling

During the 2000 fire season, wildland fires burned large areas in the western United States, resulting in large fire suppression expenditures. In response, the National Fire Plan (US Department of the Interior, US Department of Agriculture 2000) and 10-Year Comprehensive Strategy (US Department of the Interior, US Department of Agriculture 2002) funded and implemented fuel treatment projects intended to decrease hazardous fuels and mitigate unwanted, large wildland fires (Stephens and Ruth 2005). The National Fire Plan created interagency performance measures designed to provide accountability of hazardous fuel treatment projects; however, the evaluation of the treatments themselves, via the National Fire Plan Operations and Reporting System, was performed sparingly or not at all (US General Accounting Office 2004).

In a synthesis of fuel treatment effectiveness, Omi and Martinson (2009) evaluated more than 1,200 publications. Within the synthesis, 60 publications evaluated fuel treatments burned by wildland fire and of those only 19 included controls and data that made quantitative analysis possible. Given the challenges of evaluating fuel treatment effectiveness with observed wildland fire, managers and researchers use fire behavior modeling systems as a proxy for wildland fire (van Wagtendonk 1996, Harrington et al. 2007, Stephens et al. 2009). Fuel treatments evaluated in this manner are subject to the limitations of the input data and fire behavior modeling systems used to assess effectiveness via predicted fire behavior metrics (Scott 2006). For instance, a suggested best practice to model fuel treatment effectiveness with custom fuel models is to fully disclose all inputs and assumptions to defend these studies, thereby building trust among the wildland fire community (Varner and Keyes 2009).

A fuel model is a set of fuel parameters used to characterize a surface fuelbed less than 1.83 m (6 ft) in depth, which may then be used to predict fire behavior using fire models (Rothermel 1972). Fuel model parameters include dead and live surface fuel loads (Mg/ha), surface area to volume ratio (SAV, cm^2/cm^3), heat content (kJ/kg), fuelbed depth (m), and dead fuel moisture of extinction (%) (Albini 1976, Anderson 1982, Scott and Burgan 2005). Dead surface fuel loads defined by particle size classes range from 0 to 0.64 cm

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(1 hour and litter); 0.65 to 2.54 cm (10 hours); and 2.55 to 7.62 cm (100 hours). The size class intervals, 1 hour, 10 hours, and 100 hours, correspond to average moisture time lag classes and are an indication of how long it takes a fuel to lose approximately 63% of the difference between its initial moisture content and its equilibrium moisture content (Deeming et al. 1972). Live fuels less than 6 mm in diameter are divided into live herbaceous fuels including grasses and forbs and live woody fuels including shrubs. Measured fuel loads should reflect the fuels that propagate fire spread, such as dead and downed woody fuels less than 7.62 cm in diameter and branches, stems, and leaves within live vegetation less than 1.63 cm in diameter (Burgan and Rothermel 1984). The SAV ratio describes the size of individual fuel particles that are used to weight fuel loads within each size class to determine rate of spread (Rothermel 1972). Fine fuels such as grasses have higher SAV ratio values conducive to higher rates of spread. Heat content defines the amount of heat required to raise 0.45 kg (1 lb) of dry wood from air temperature to ignition temperature (Burgan and Rothermel 1984). The heat content of live and dead fuels can be used to fine tune the fire behavior of custom fuel models (Scott and Burgan 2005). Fuelbed depth in combination with total fuel load is used to compute bulk density and is a measure of the oven-dry weight of fuel per volume of the fuelbed. Dead fuel moisture of extinction is the highest average dead fuel moisture in which a fire will no longer burn. Fuel models commonly used in humid environments with higher values of dead fuel moisture of extinction will continue to spread even as dead fuel moisture increases, compared with fuel models with lower values for moisture of extinction (Burgan and Rothermel 1984).

The Rothermel (1972) rate of spread model uses fuel models to produce quantitative values of spread representing mean values for the given fuel and environment. Predicted fire behavior is assumed to be fully established and growing at a steady state. The model assumes that continuous fuels are well mixed (i.e., shrub, grass, and litter) and spread homogeneously throughout the fuelbed. Stylized fuel models (Anderson 1982, Scott and Burgan 2005) are most frequently used to propagate fire spread using the Rothermel model. The original 13 stylized fuel models were developed to represent fire behavior during the severe period of the fire season and were organized into four groups: grass, shrub, timber, and slash (Albini 1976, Anderson 1982). Scott and Burgan (2005) published an additional 40 stylized fuel models designed to represent a wider range of fuel types and fire behavior compared with the original 13 fuel models. The 40 fuel models are split into the dominant fire-carrying fuel type including grass, grass/shrub, shrub, timber litter, timber understory, and slash/blowdown.

There are some challenges when either a stylized or custom fuel model is used to characterize surface fuels due to the necessity of scaling from a fine-scale heterogeneous fuelbed to a value representing stand-level surface fuels (McHugh 2006, Harrington et al. 2007). Common fuel inventory protocols, such as the FEAT and FIREMON Integrated (FFI) ecological monitoring utilities (Lutes et al. 2006, 2009), collect surface and canopy fuels on a smaller plot scale than the stand level that is commonly referred to when fire behavior is evaluated. Site-specific fuel models must represent a broad range of conditions, given the variability of fuelbed depth, composition, and quantity (Burgan and Rothermel 1984), because real fire behavior will be affected by the variability of fuels, weather, and topography that are not taken into account with fire behavior modeling systems (Fulé et al. 2001).

The Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003, Rebain 2010) to the Forest Vegetation Simulator (FVS) (Dixon 2002, Crookston and Dixon 2005) uses surface fuel loading and stand characteristics to select one or more of the 53 stylized fuel models to simulate fire behavior. Johnson et al. (2011) evaluated fuel treatment effectiveness using the FFE-FVS fuel model logic that assigned variant-specific fuel loads to one or more of the stylized 13 fuel models, and they reported limited capability to detect fuel treatment effectiveness for surface fuel treatments. Seli et al. (2008) addressed these fuel modeling limitations by developing new logic in FFE-FVS to select one of the 53 stylized fuel models to evaluate fuel treatments and their influence on large fire growth over time. Constants for shrub loading and fuelbed depth with modifications based on time since treatment, forest type, and canopy cover were variables used to select the final fuel models to partially address the problematic lack of understory vegetation modeling within FFE-FVS. Both studies identified limitations with traditional methods used to assign fuel models. More recently, FFE-FVS provides two additional alternatives to assign surface fuel models, which is the focus of this analysis. Managers can use their measured values of downed woody fuel loading derived from fuel inventories to guide the selection of a stylized fuel model or create custom fuel models used directly to predict fire behavior (Rebain 2010).

Federal land management agencies are emphasizing measurable and quantifiable methods to evaluate whether a fuel treatment is effective for mitigating unwanted fire behavior (Forest Service Manual 2012). In response, monitoring protocols and databases were developed to measure and store inventory data to evaluate how the manipulation of surface and canopy fuels change fire behavior. The FFI provides monitoring protocols and a database to store fuels inventory data that allows managers to quickly quantify surface and canopy fuel parameters important for fire behavior prediction (Lutes et al. 2009). The FFI is commonly used to store National Park Service monitoring data, whereas Field Sampled Vegetation (FS-Veg) stores National Forest inventory data (USDA Forest Service 2013). These databases are now linked with programs such as FFE-FVS or FuelCalc (Reinhardt et al. 2006) allowing the use of field-based fuels inventory data to create custom fuel models or assign stylized fuel models that traditionally required extensive expertise of fire behavior and fuel simulation programs. The new logic in FFE-FVS presents an opportunity for fire managers to objectively represent surface fuel loads as fuel models rather than using more traditional and subjective methods to assign surface loads to fuel models. Other studies have subjectively assigned stylized fuel models even when field-based fuel loading values existed to create custom fuel models (Stephens et al. 2009, Vaillant et al. 2009a, 2009b). What was lacking was a consistent and quantitative approach to the use of field-based values for custom fuel model creation, which is now available in FFE-FVS. In the future, the Fuel Characteristic Classification System (Ottmar et al. 2007) will link to FFE-FVS and provide more opportunities for custom fuel modeling using field-based fuels inventory data (Johnson 2012).

The objective of this study was to test an alternative to the traditional method of assigning fuel models used by FFE-FVS. Surface fuel loads, derived from field-based data and collected before and after prescribed fire, were directly used to assign a stylized fuel model or create a custom fuel model to evaluate the effectiveness of prescribed fire treatments. It was hypothesized that there would be no difference between surface flame lengths and fire type when either

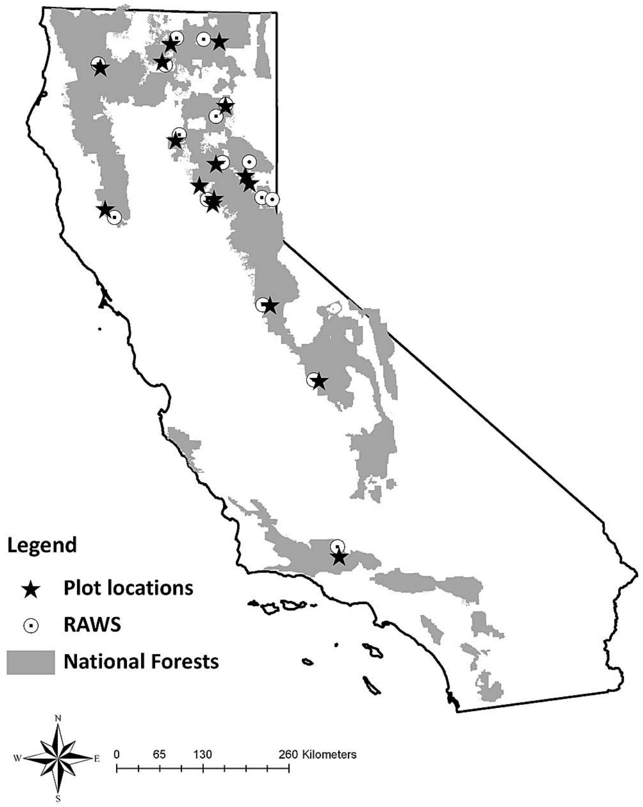

Figure 1. Map of plot locations and RAWS in California National Forests.

custom or stylized fuel models were used to simulate potential wildfire behavior.

Methods

Background

Surface and canopy fuels data used in this analysis were acquired from a subset of the USDA Forest Service Pacific Southwest Fuel Treatment Effectiveness and Effects Study (Vaillant et al. 2009a) in which 39 unique plots were monitored for 8 years posttreatment. A total of 142 plots representing pretreatment ($n = 39$), 1 year posttreatment ($n = 37$), 2 years posttreatment ($n = 36$), 5 years posttreatment ($n = 8$), and 8 years posttreatment ($n = 22$) were sampled from 16 projects to summarize surface and canopy fuels before and after prescribed fire treatments (Figure 1). All posttreatment data were sampled from the original 39 plots. Not all plots have data for all posttreatment intervals because not enough time had passed since treatment; the plot was subsequently retreated or burned in a wildfire, or the interval fell within a 2-year period (2007–2008) during which no sampling occurred because of a lack of funding. Consequently, only 8 plots from 5 of the original 16 projects were sampled for remeasurements 5 years posttreatment.

Three to six plots were established on a specific fuel treatment project, belonging to any of 10 national forests in California (Klamath, Lassen, Los Padres, Mendocino, Plumas, Shasta-Trinity, Modoc, Sierra, Stanislaus, and Tahoe National Forests). The plots are represented by four different FVS variants: Inland California and Southern Cascades (CA), South Central Oregon and Northeast California (SO), Klamath Mountains/North Coast (NC), and Western Sierra Nevada (WS). Dominant overstory tree species included Jeffrey pine (*Pinus jeffreyi* Balf.), ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), white fir (*Abies concolor* (Gord. & Glend.), incense cedar (*Calocedrus decurrens* [Torr.] Florin), and California black oak (*Quercus kelloggii* Newberry). Detailed information about the study and site descriptions can be found in Vaillant et al. (2009a).

Field Sampling

Surface fuels include dead and downed woody fuels as well as live and dead shrub and herbaceous fuels. Counts of downed woody fuels were inventoried using the line intercept method (Van Wagner 1968, Brown 1974), along two to four 15.24-m transects. Litter and fuelbed depth were recorded at 10 equidistant points along the same transect. Fuelbed depth is the vertical distance from the bottom of the litter layer to the highest intersected dead and downed fuel particle along a vertical plane extending the length of the fuel transect (Brown 1974). Live and dead shrub species, range (dm), and height (cm) were sampled along a 50-m transect. Five 1-m × 1-m quadrats along one to two 50-m transects were used to collect herbaceous and grass species, cover class, and status. Six cover classes were ocularly estimated to quantify herb and grass cover by species: 0–5%; 6–25%; 26–50%; 51–75%; 76–95%; and 96–100%, separated by live and dead status (Daubenmire 1959).

Canopy fuels were composed of overstory trees ($\geq$15 cm dbh measured at 1.4 m), poles ($\geq$2.5 cm and less than 15 cm dbh), and seedlings ($<$2.5 cm dbh). Fixed area nested plots sized 0.1, 0.025, and 0.005 ha were used to sample overstory trees, poles, and seedlings, respectively. With few exceptions, height (m), height to live crown base (m), dbh (cm), and species were recorded for all live overstory trees and poles. Seedlings were tallied by species, vigor, and height class. Both surface and canopy fuel monitoring protocols were based on the National Park Service monitoring handbook (US Department of the Interior, National Park Service 2003). Detailed descriptions of the field sampling are available in Fites-Kaufman et al. (2007).

FFE-FVS

The FFE-FVS was used to create custom fuel models and assign stylized fuel models to each plot to model potential fire behavior. The FVS is a stand-level distance-independent forest growth and treatment simulator (Dixon 2002, Crookston and Dixon 2005). The FFE is one of the many extensions available to FVS and simulates fuel dynamics and potential fire behavior, leveraging existing fire behavior models (Rothermel 1972, Van Wagner 1977, Alexander 1988, Scott and Reinhardt 2001). The FFE-FVS requires plot (i.e., location, elevation, slope, and initial fuel loads by size class) and individual tree data to initiate a simulation. All live overstory trees, poles, and seedlings require a dbh, height, and crown ratio (calculated from tree height and height to live crown base measurements) to compute their biomass. Seedlings were assigned a crown ratio and dbh value based on height, because these values were not collected in the field. The crown ratio and dbh values assigned were 100% and 0.25 cm for seedlings $<$1.52 m, 75% and 1.27 cm for seedlings 1.52 to 3.05 m, and 50% and 2.29 cm for seedlings $>$3.05 m. Overstory trees and poles with missing height values were assigned values by FVS using the NOHTDREG keywords (Van Dyck 2006).

Plot-level canopy bulk density (CBD) and canopy base height (CBH) were estimated in nonuniform stands (Sando and Wick 1972) for overstory trees, poles, and seedlings greater than 0.3 m. CBD is the mass of available fuel per unit canopy volume and a bulk property of a stand used to determine the threshold for active crown

Table 1. Fuel moisture and wind speed from five candidate fires.

Date of fire start	Fire name	Fire size (ha)	Fuel moisture						10-min average wind (km/hr)
			1-hr	10-hr	100-hr	1,000-hr	Live H	Live W	
			. . . .	. . . .	. . . . . .	(%)	. . . . . .	. . . .	
Aug. 31, 1987	Paper	21,427	3	4	5	8	NA	70	13
Aug. 14, 1996	Rogge	8,478	3	3	6	17	30	131	8
July 26, 2009	Knight	2,481	4	5	5	6	30	70	11
Sept. 7, 1992	Ruby	1,400	5	5	8	9	30	70	10
July 20, 2003	Mountain	1,250	6	6	6	7	30	70	10
Average			4	5	6	9	30	82	10

Fuel moisture averages from the above and wind speed derived from five candidate fires were used in a potential fire simulation in FFE-FVS for one project. Average wind speed was adjusted (Crosby and Chandler 2004) for two wind scenarios: probable maximum 1-minute speed; and probable maximum momentary gust speed. NA, not applicable; Live H, live herbaceous; Live W, live woody.

fire behavior (Van Wagner 1977, Alexander 1988, Scott and Reinhardt 2001). In FFE-FVS, CBD is derived from the maximum 4.5 m (15 ft) deep running mean of CBD for layers 0.3 m (1 ft) thick (Beukema et al. 1997, Scott and Reinhardt 2001). CBH is the lowest height above which at least 0.011 kg/m^3 (0.0007 lb/ft^3) of CBD is present (Scott and Reinhardt 2001) and is a necessary value to predict the transition of surface to passive crown fire behavior (Van Wagner 1977).

We used Sierra Nevada coefficients (Van Wagtendonk et al. 1996, 1998) to convert counts of downed woody fuel particles and litter depth to biomass estimates. The FFE-FVS does not use field-based values of live herbaceous or live woody fuel loading to develop custom fuel models or to select a stylized fuel model. Instead, these values are calculated based on the geographic location (variant), overstory species, and canopy cover of the stand. Live woody load computed in FFE-FVS included shrub fuels plus the foliage and half of the fine branchwood of all seedlings $<$0.3 m. Seedlings taller than 0.3 m were represented as part of the canopy fuel estimates and were not included in live woody fuel loading.

The FFE-FVS performs potential fire behavior calculations before litter fall and random crown breakage but after decay is simulated. To perform fire behavior calculations on inventory year data, it was necessary to hold these processes stable so that our original surface fuel values were used in the fire behavior calculations. We used DUFFPROD and FUELDCAY keywords to eliminate change to the initial inventory.

Modeled Loads to Custom and Stylized Fuel Models

The FIRECALC keyword within FFE-FVS was used to initiate a new logic to either create custom fuel models from field-based values of dead fuel loading and modeled live fuel loads or assign a stylized fuel model using the same information. For custom fuel models, default values were applied by FFE-FVS for the SAV ratio, bulk density, and heat content. Default bulk densities were 1.6 kg/m^2 (0.1 lb/ft^3) for live fuels and 12.0 kg/m^2 (0.75 lb/ft^3) for dead fuels. Initial values used for the SAV ratio (cm^2/cm^3) by size class were 65.62 (1 hour), 3.58 (10 hours), 0.98 (100 hours), 59.06 (live herbaceous), and 49.21 (live woody). Initial default values for the SAV ratio in combination with oven-dry fuel load per size class were used to create a characteristic SAV ratio for dead and live fuels (Burgan and Rothermel 1984). Default heat content was 18,593 kJ/kg (8000 BTU/lb). For all stylized and custom fuel models, the standard value for total mineral content was 5.55%, the effective mineral content was 1%, and the oven-dry fuel particle density was 513 kg/m^3 (32 lb/ft^3) (Rothermel 1972, Scott and Burgan 2005). Stylized fuel models were assigned using a two-step process that limited the number of fuel models available based on climate type, major fire-carrying fuel type, and the fuel model set (13, 40, or 53 stylized fuel models). Next, a departure index (DI) was used to determine how similar the selected fuel models were in step 1 to the modeled loads based on the characteristic SAV ratio, fine fuel load, and bulk density (Rebain 2010). The STATFUEL keyword was used to select only one fuel model as opposed to two or more.

Modeling Potential Weather and Fire in FFE-FVS

Wind and fuel moisture data were acquired from the most representative remote automated weather stations (RAWS) that had at least 10 years of data and resided in an elevation similar to that recommended by fire managers (Figure 1). Given the proximity of some projects to each other, only 12 total RAWS stations were used to acquire data for 16 different projects. Weather files from each RAWS were acquired from the National Interagency Fire Management Integrated Database via the Kansas City Fire Access Software (KCFAST) (USDA Forest Service 2010) and were imported into FireFamily Plus (version 4.1.0.0 Beta; Bradshaw and Termenstein 2009). Fire occurrence data from 1960 to 2011 were also acquired

Table 2. Average and range of fuel moisture and wind speed used for potential fire simulations in FFE-FVS.

Time period	Fuel moisture (percent)					Wind	
	1-hr	10-hr	100-hr	Live H	Live W	1-min speed	Momentary gust speed
	. . . .	. . . .	(%)	. . . .	. . . .	. . . .	(km/hr) . . . .
P00	4 (3–6)	4 (3–7)	6 (5–9)	34 (30–51)	71 (60–87)	18 (10–27)	35 (24–47)
P01	4 (3–6)	4 (3–7)	6 (5–9)	34 (30–51)	70 (60–87)	19 (10–27)	35 (24–47)
P02	4 (3–6)	5 (3–7)	6 (5–9)	34 (30–51)	71 (60–87)	18 (10–27)	35 (24–47)
P05	3 (3–4)	4 (3–5)	6 (5–7)	30 (30–30)	69 (60–82)	18 (14–27)	34 (29–47)
P08	4 (3–6)	4 (4–7)	6 (5–8)	35 (30–51)	70 (60–87)	18 (10–27)	35 (24–47)

Data are means (ranges). Values are summarized by time since prescribed fire treatment and include pretreatment (P00), 1 year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08).

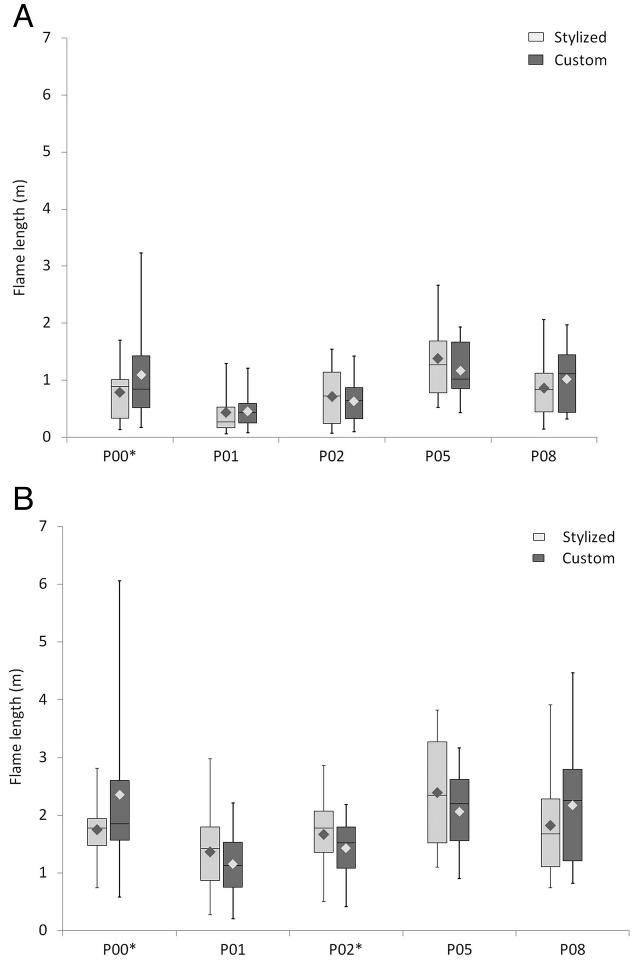

Figure 2. Predicted surface flame lengths (m) modeled with (A) the maximum 1-minute speed and (B) the maximum momentary gust speed between custom and stylized fuel models by time. Values are summarized by time since prescribed fire treatment and include pretreatment (P00), 1 year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08). Box and whisker plots display the 25th and 75th percentiles, with whiskers displaying the highest and lowest values. Both the 50th percentile (median line) and mean (diamond) are shown. Asterisks next to time since treatment represent significantly different results ($P < 0.05$).

from KCFAST and were used to identify the five largest fires that occurred adjacent to the projects. For each fire, daily fuel moisture and wind speed observations were acquired from the first day and were averaged to obtain representative 1-, 10-, and 100-hour live herbaceous and live woody fuel moisture values and 10-minute wind speed (Table 1). Because RAWS wind speed values represent 10-minute averages composed of lulls and gusts, we applied a wind gust estimation from Crosby and Chandler (2004) to better represent peak winds that could affect fire growth and intensity (Stratton 2006, Stephens et al. 2009). Maximum 1-minute speed ranged from 10 to 27 km/hour and maximum momentary gust speed ranged from 24 to 47 km/hour (Table 2). Adjustments made to the 10-minute average wind speeds (Crosby and Chandler 2004) resulted in the average increase of 7 km/hour for the maximum 1-minute speed and 23 km/hour for the maximum momentary gust speed. A calculated wind adjustment factor based on overstory canopy cover was used to adjust 6.1-m wind speeds to eye level (Rebain 2010).

In FFE-FVS, the POTFMOIS and POTFWIND keywords were used to assign the dead and live fuel moistures and two wind speed scenarios (as described above). Outputs were used to evaluate potential fire behavior pre- and posttreatment for stylized and custom fuel models (Table 2). Six-meter wind speed was the same for all time periods, but eye-level winds could vary because of changes in canopy cover posttreatment. Fuel moisture also remained constant for all the simulations and did not vary from changes in canopy cover, slope, aspect, or elevation. Foliar moisture was set to 100% as per FFE-FVS.

Data Analysis

We used generalized linear mixed models to analyze differences in surface flame length predictions created with custom versus stylized fuel models (PROC GLIMMIX, SAS version 9.3, 2010; SAS Institute, Inc., Cary, NC). We tested these differences separately for each time period (pretreatment and 1, 2, 5, and 8 years posttreatment) and also for each wind scenario (maximum 1-minute speed and the maximum momentary gust speed). Generalized linear mixed models are used to fit statistical models to data with correlations and for nonnormal responses (McCulloch and Searle 2001). We included project as the random factor, because plots were not truly independent. Surface flame lengths represent surface fire behavior independent of the predicted fire type; for example, if crown fire was predicted for a particular plot, only surface fire flame lengths would be reported.

Plots were tallied by predicted fire type defined as either surface or crown for each wind scenario and time period. Crown fire includes passive, active, and conditional crown fire. Passive crown fire occurs when surface fire intensity increases and causes the crown to burn, but the spread rate is too low to sustain active crowning. Passive crown fire is more likely when canopy base heights are low and canopy bulk density is too low to sustain active crowning (Van Wagner 1977). Active crown fire occurs when a surface fire is able to transition and sustain itself in the canopy (Van Wagner 1977). Conditional crown fire or conditional surface fire can sustain active crowning but cannot initiate to the crown. The fire must spread into the stand as an already-initiated crown fire (Scott and Reinhardt 2001).

The DI was computed to quantify the difference between custom and stylized fuel models for each plot separately. The DI is weighted by the characteristic SAV ratio, fuelbed bulk density, and fine fuel loads (Rebain 2010) (Equation 1)

$$\mathrm{DT} = 0.25 \cdot \left(\frac{\mathrm{SAV_{custom}} - \mathrm{SAV_{fm}}}{405.2}\right)^2 + 0.25\left(\frac{\mathrm{SD_{custom}} - \mathrm{SD_{fm}}}{0.3992}\right)^2 + 0.50 \cdot \left(\frac{\mathrm{FFL_{custom}} - \mathrm{FFL_{fm}}}{3.051}\right)^2 \quad (1)$$

where $\mathrm{SAV_{custom}}$ is the surface area/volume ratio ($\mathrm{ft^2/ft^3}$) of the modeled loads, $\mathrm{SAV_{fm}}$ is the surface area/volume ratio ($\mathrm{ft^2/ft^3}$) of the stylized fuel model, 405.2 is the standard deviation of the SAV ratio of the 53 stylized fuel models, $\mathrm{BD_{custom}}$ is the bulk density ($\mathrm{lb/ft^3}$) of the modeled loads, $\mathrm{BD_{fm}}$ is the bulk density ($\mathrm{lb/ft^3}$) of the stylized fuel model, 0.3992 is the standard deviation of the BD of the 53 stylized fuel models, $\mathrm{FFL_{custom}}$ is the fine fuel load (tons/acre), including fine dead, live herbaceous, and live woody fuels from the modeled loads, $\mathrm{FFL_{fm}}$ is the fine fuel loads (tons/acre) including fine

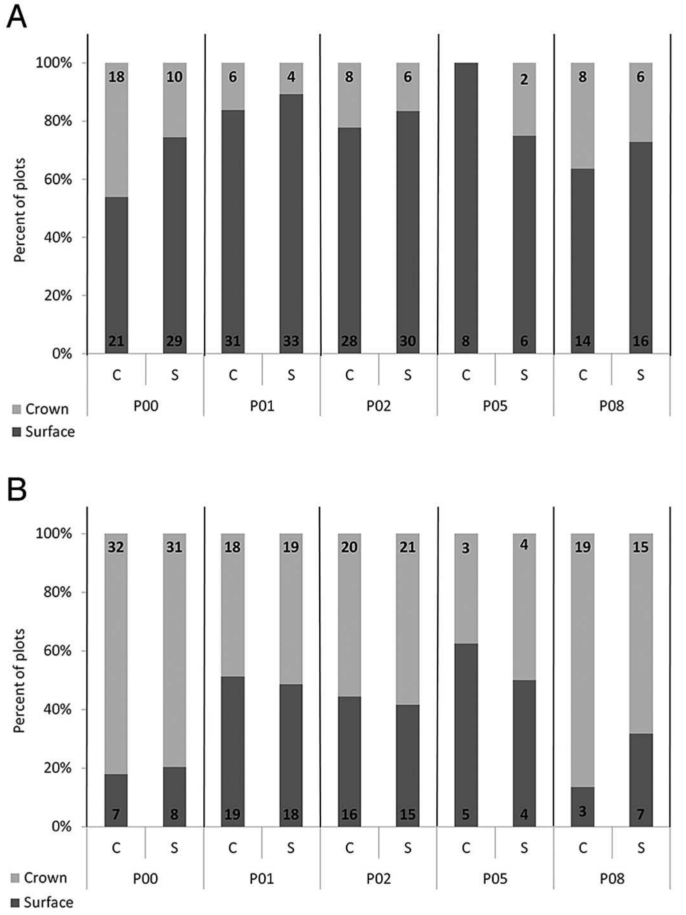

Figure 3. Predicted fire type (surface or crown) modeled with (A) the maximum 1-minute speed and (B) the maximum momentary gust speed with custom (C) and stylized (S) fuel models by time since treatment: pretreatment (P00), 1-year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08). Crown fire includes passive, active, and conditional crown fire types. The numbers in the bars represent the number of plots with either predicted surface or crown fire.

dead, live herbaceous, and live woody fuels associated with the stylized fuel model, and 3.051 is the standard deviation of the fine fuel load of the 53 stylized fuel models.

DI values for each selected stylized fuel model were summarized by time period to evaluate the similarities of the fine fuels, SAV ratio, and bulk density between stylized and custom fuel models. Mean and range of the DI by time period regardless of the selected stylized fuel model were also summarized.

Results

Fire behavior predicted from both custom and stylized fuel models followed fairly similar trends through time. Both methods produced a decrease in average surface fire flame lengths and less crown fire 1 year after prescribed fire followed by a general increase in fire behavior beginning 2 years after prescribed fire (Figures 2 and 3). Seven of the 10 surface flame length comparisons were not significant ($P < 0.05$) (Table 3). Surface flame lengths simulated with custom fuel models were significantly higher ($P < 0.05$) than those for stylized fuel models for only pretreatment plots when modeled with maximum 1-minute speed (Table 3; Figure 2A). Surface flame lengths between custom and stylized fuel models were significantly different ($P < 0.05$) for pretreatment and 2 years posttreatment plots when modeled with maximum momentary gust speed (Table 3; Figure 2B). The largest difference for average surface flame length between custom and stylized fuel models was 0.6 m, which occurred for the pretreatment time period modeled with the maximum momentary gust speed. Despite similarities of fire behavior outputs, surface flame lengths produced from custom fuel models followed the fluctuations and variability of fine fuel loading more closely than stylized fuel models (Figures 2 and 4).

Fire type did not differ by more than 20% for either method when modeled with each wind scenario (Figure 3). Custom fuel models generally produced more crown fire than stylized fuel models, especially for pretreatment and 8-year posttreatment time periods when average surface flame lengths were also highest. Custom fuel models resulted in 20% (eight plots) more crown fire for pretreatment data modeled with the maximum 1-minute speed compared with fire type predicted from stylized fuel models (Figure 3A). Predicted fire type as a result of maximum momentary gust speed did not differ between custom and stylized fuel models by more than one plot, except the 8-year posttreatment time period for which custom fuel models resulted in 18% (4 plots) more predicted crown fire than stylized fuel models (Figure 3B).

The pretreatment plots had the highest average DI, suggesting a greater difference between fuel model methods than any of the posttreatment plot averages (Table 4). Stylized fuel model TL9 was selected more than any other stylized fuel model (11 plots) for the pretreatment time period and had the highest average DI of 2.44. Most of the differences between custom and stylized fuel models can be attributed to higher litter and 1-hour fuel loading for custom fuel models. The difference between stylized fuel model TL9 and the custom fuel models can be attributed to these differences in fine fuel loading. At least 30% of the 1- and 2-year posttreatment plots were represented with stylized fuel models that had some portion of live fuel loading (Table 4). In contrast, measured values of live fuel loading are lowest for these same time periods (Figure 5). Five- and 8-year posttreatment time periods have less than 14% of the stylized fuel models with a live fuel component, yet measured values of live fuels increase for these time periods (Table 4; Figure 5).

Discussion

The FFE-FVS fuel modeling method provides an opportunity for managers to create custom fuel models or assign stylized fuel models from measured values obtained from inventory data. Fire behavior predicted from uncalibrated custom fuel models needs to be analyzed carefully (Varner and Keyes 2009, Cruz and Alexander 2010). These custom fuel models have not been calibrated and may not represent realistic fire behavior. However, custom fuel models showed fairly similar trends of fire behavior through time compared with those for stylized fuel models and appeared to better reflect the increase of fine fuels that would intuitively result in an increase of fire behavior. The similarity of the fire behavior in addition to the lack of statistically significant results for average surface flame lengths suggests that either custom or stylized fuel models represented the relative change of fire behavior as a result of prescribed fire in similar ways. Analyzing fire behavior created from custom fuel models is most useful to compare relative values of predicted fire behavior as a result of some type of management activity like a fuel treatment through time. There is both an art and science that is necessary to develop custom fuel models and the utility of the output is dependent on the understanding of the assumptions and

Table 3. Results from the generalized linear mixed model estimating differences between average surface flame lengths generated from custom and stylized fuel models by time with the maximum 1-minute speed and maximum momentary gust speed.

			Custom			Stylized			
Scenario	Time period	*n*	Mean	Range	SE	Mean	Range	SE	*P* value
			(m)						
Maximum 1-min average speed	P00	39	1.1	0.2–3.2	0.1	0.8	0.1–1.7	0.1	0.0020*
	P01	37	0.5	0.1–1.2	0.1	0.4	0.1–1.3	0.1	0.6911
	P02	36	0.6	0.1–1.4	0.1	0.7	0.1–1.5	0.1	0.0973
	P05	8	1.2	0.4–1.9	0.2	1.4	0.5–2.7	0.3	0.2144
	P08	22	1.0	0.3–2.0	0.1	0.8	0.1–2.1	0.1	0.0625
Maximum momentary gust speed	P00	39	2.4	0.6–6.1	0.2	1.8	0.7–2.8	0.1	0.0022*
	P01	37	1.2	0.2–2.2	0.1	1.4	0.3–3.0	0.1	0.0848
	P02	36	1.4	0.4–2.2	0.1	1.7	0.5–2.9	0.1	0.0062*
	P05	8	2.1	0.9–3.2	0.3	2.4	1.1–3.8	0.4	0.2748
	P08	22	2.2	0.8–4.5	0.2	1.8	0.7–3.9	0.2	0.1274

Average, range, and SE values are summarized by time since the prescribed fire treatment and include pretreatment (P00), 1 year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08).

* *P* values are significant ($P < 0.05$).

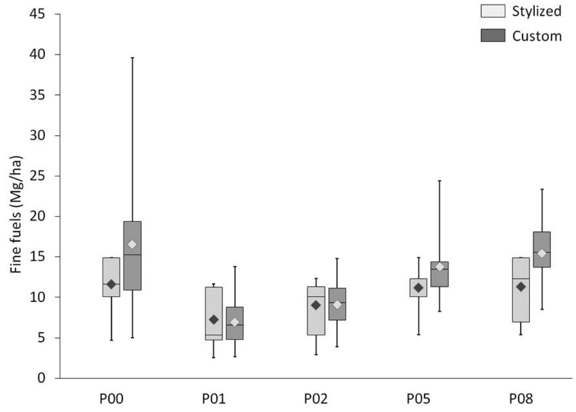

Figure 4. Comparison of fine fuel loading (Mg/ha) between custom and stylized fuel models by time since treatment: pretreatment (P00), 1 year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08). Fine fuel loading includes litter and 1-hour dead fuels, live herbaceous, and live woody fuels. Box and whisker plots display the 25th and 75th percentiles, with whiskers displaying the highest and lowest values. Both the 50th percentile (median line) and mean (diamond) are shown.

limitations of the fire models that will be used to predict fire behavior.

One limitation of using FFE-FVS to assign custom fuel models is that modeled loads for live herbaceous and woody fuel are used instead of field-based values. The FFE-FVS-derived live fuel loads remained fairly constant regardless of the time since treatment (Figure 5) because the actual prescribed fire treatments did not change overstory canopy cover enough to affect the calculation of live fuel loading. Field-based fine fuels decreased posttreatment and began to increase by 2 years posttreatment (Figure 4). Consequently, the shift in the ratio of live to dead fuels resulted in the 1-year posttreatment plots being represented by the highest percentage of stylized fuel models with live fuels (Table 4). In contrast, the actual field-based values for live fuel loads remained low 1 year posttreatment (Figure 5), suggesting that the lack of understory vegetation modeling in FFE-FVS could lead to erroneous stylized fuel model selections. Efforts are underway to include live fuel dynamics in FFE-FVS, so that better estimates can be used for future fire behavior modeling (Stephanie Rebain, Forest Management Service Center, pers. comm., Nov. 15, 2012).

Although the process to develop custom fuel models is becoming more efficient, there is still some debate on how fuel parameters that compose custom fuel models are quantified and calibrated (Cruz and Alexander 2010). The FFE-FVS provides the option to include biomass estimates of seedlings less than 1.8 m in height as part of the surface or canopy fuels, using variant-specific, small tree equations primarily from Brown (1978) to estimate biomass. We chose to represent seedlings less than 1.8 m and greater than 0.3 m as part of the canopy fuels because seedlings have similar morphology and are measured and calculated like trees rather than shrubs. There are limitations with this method. When many seedlings are present, their contribution to plot-level canopy biomass estimations can result in low values of canopy base height because of the method used to calculate this metric (Sando and Wick 1972). Fire type in these cases is usually predicted to be crown fire, which may be unrealistic, because a large enough gap between the seedlings and overstory canopy would preclude the transition from surface to crown fire.

Fuel moisture and wind values used in the simulation were based on data from the first day of historical large fire events. The first day of the fire may not be the largest day of fire growth; however, these fires escaped initial firefighting attack efforts. Consequently, the fuel moisture and wind speed should represent the kind of conditions to test the effectiveness of a fuel treatment for mitigating unwanted fire behavior. Many fuel treatment effectiveness studies have used some level of percentile fuel moisture and wind for their fire simulation (Stephens and Moghaddas 2005, Schmidt et al. 2008, Stephens et al. 2009). We originally tried this approach and found that the simultaneous occurrence of 90th percentile fuel moisture with 90th percentile wind historically happened less than 0.8% of the time, suggesting that this was not a realistic portrayal of conditions that should be used to evaluate fuel treatment effectiveness. However, dead and live fuel moisture values are subject to all the limitations in the National Fire Danger Rating System. The ranges of dead fuel moistures were generally low, from 3 to 9% for 1- to 100-hour size classes. Likewise, the ranges of live fuel moistures were also very low, from 30 to 51% for the live herbaceous and 60 to 87% for the live woody fuel moisture. The low live fuel moisture values used in the fire simulation represent mostly fully cured fuels, which will contribute to greater fire spread and intensity especially for stylized fuel

Table 4. DI comparison between custom and stylized fuel models, for which a higher DI signifies the stylized and custom fuel models are more different.

		DI			Stylized fuel model composition	
Time period	Fuel model	*n*	Mean	Range	Live/dead	Dead
P00		**39**	**0.83**	**0.00–6.79**		
	5 Brush	1	0.26	0.26–0.26	X	
	122 GS2	1	0.22	0.22–0.22	X	
	142 SH2	10	0.32	0.02–0.52	X	
	186 TL6	3	0.16	0.02–0.41		X
	189 TL9	11	2.44	0.44–6.79		X
	202 SB2	7	0.03	0.00–0.11		X
	203 SB3	6	0.22	0.14–0.35		X
P01		**37**	**0.17**	**0.01–0.46**		
	5 Brush	2	0.15	0.10–0.19	X	
	10 Timber	1	0.17	0.17–0.17	X	
	121 GS1	1	0.18	0.18–0.18	X	
	122 GS2	5	0.41	0.26–0.46	X	
	141 SH1	3	0.17	0.03–0.28	X	
	142 SH2	9	0.25	0.01–0.44	X	
	185 TL5	3	0.12	0.11–0.12		X
	186 TL6	8	0.03	0.01–0.07		X
	202 SB2	5	0.03	0.01–0.10		X
P02		**36**	**0.1**	**0.01–0.52**		
	5 Brush	1	0.2	0.20–0.20	X	
	10 Timber	2	0.06	0.02–0.10	X	
	122 GS1	1	0.39	0.39–0.39	X	
	142 SH2	6	0.19	0.01–0.37	X	
	161 TU1	2	0.27	0.03–0.52	X	
	186 TL6	7	0.05	0.01–0.23		X
	202 SB2	14	0.03	0.01–0.07		X
	203 SB3	3	0.14	0.12–0.16		X
P05		**8**	**0.24**	**0.04–1.17**		
	186 TL6	1	0.14	0.14–0.14		X
	189 TL9	1	1.25	1.25–1.25		X
	202 SB2	2	0.06	0.04–0.07		X
	203 SB3	4	0.13	0.07–0.23		X
P08		**22**	**0.33**	**0.00–0.98**		
	142 SH2	2	0.33	0.19–0.48	X	
	164 TU4	1	0.16	0.16–0.16	X	
	186 TL6	6	0.34	0.11–0.80		X
	189 TL9	7	0.54	0.33–1.06		X
	203 SB3	6	0.23	0.14–0.32		X

Values are summarized by time since prescribed fire treatment and include pretreatment (P00), 1 year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08). Stylized fuel models, composed of either a combination of live and dead surface fuels compared with only dead surface fuels are distinguished, which can affect predicted fire behavior.

Bold values signify the summary for each time period.

models with higher live fuel loading (Scott and Burgan 2005, Jolly 2007).

Conclusion

We generally found good agreement between custom and stylized fuel models with the methods presented in this analysis. Users that apply their own SAV ratios or calculated values for bulk density may find that their results will have greater variability than results shown here. Live fuel loads differed between those generated from FFE-FVS and field-based values. Users that have stands with a considerable portion of live fuel loading should apply the fuel model logic in FFE-FVS with caution, understanding the limitations. Custom fuel models were better able than stylized fuel models to represent fine fuel loading associated with prescribed fire treatments and the accumulation of fine fuels after the treatment. However, both custom and stylized fuel models resulted in similar enough predicted fire behavior to suggest that both are adequate options to evaluate fuel treatment effectiveness.

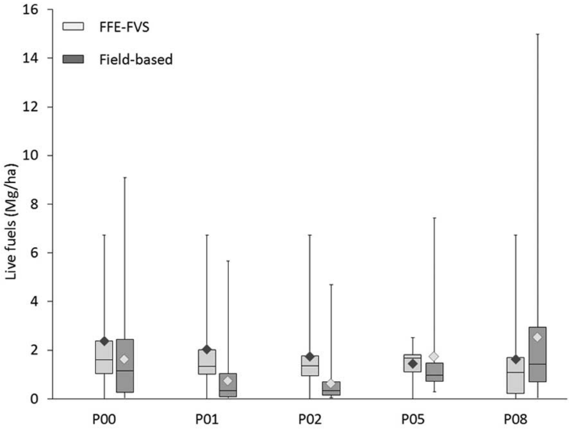

Figure 5. Comparison of live fuel loading (Mg/ha) between FFE-FVS modeled live fuel loads and field-based values by time since treatment: pretreatment (P00), 1 year posttreatment (P01), 2 years posttreatment (P02), 5 years posttreatment (P05), and 8 years posttreatment (P08). Box and whisker plots display the 25th and 75th percentiles, with whiskers displaying the highest and lowest values. Both the 50th percentile (median line) and mean (diamond) are shown.

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