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Evaluation of FOFEM Fuel Loads and Consumption Estimates in Pine-Oak Forests and Woodlands of the Ouachita Mountains in Arkansas, USA

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Accurate fuel load and consumption predictions are important to estimate fire effects and air pollutant emissions. The FOFEM (First Order Fire Effects Model) is a commonly used model developed in the western United States to estimate fire effects such as fuel consumption, soil heating, air pollutant emissions, and tree mortality. However, the accuracy of the model in the eastern United States has not been well tested. As a result, managers are turning to locally collected data sets from eastern forests to improve the accuracy of FOFEM and other models. FOFEM lacks local fuel load and consumption data for the Ouachita Mountains, an area with nearly 50,000 ha prescribe burned annually. In this study, we compared fuel loads and consumption using field-collected data with data predicted by FOFEM. We determined fuel loads before and after 15 prescribed fires by sampling live fuels, down woody debris, litter, and duff in three cover types (oak forest, pine-oak forest, and pine woodland) on the Ouachita National Forest in Arkansas. Default estimates of litter and duff fuel load in FOFEM were up to 346 and 1,307% greater than field estimates, respectively. FOFEM estimates of 10-hour, 1-hour, and litter fuel consumption were up to 182, 150, and 46% greater, respectively, than field-measured consumption. These overestimations of fuel load and consumption could result in overpredictions of air pollutant emissions and reduce the area of habitat restored and maintained by prescribed burning as fire managers seek to comply with air quality standards.

Keywords: fire effects models, fire emissions, Fuel Characteristic Classification System, shortleaf pine

Fuel load and consumption predictions are critically important for accurate assessment of fire effects and air pollutant emissions on wildland and prescribed burns (Ottmar 2014, Urbanski 2014). These predictions are especially needed in the eastern United States where prescribed burning is widely used for ecosystem restoration, hazardous fuel reduction, wildlife habitat improvement, and seedbed preparation (Elliott et al. 1999, Guldin et al. 2004, Andre et al. 2009, Melvin 2012) and where compliance with air quality standards is required by many states (Riebau and Fox 2010). Field measurements of air pollutant emissions and fire effects are costly and time intensive (Akagi et al. 2014); therefore, fire managers rely on models to provide this information. Fuel load inputs and consumption algorithms are important components of many fire effects models because they relate directly to air pollutant emissions (Ward and Hardy 1991, Wiedinmyer et al. 2006), fire severity (Chafer et al. 2004), hazardous fuel reduction (Pollet and Omi 2002), and tree mortality (Varner et al. 2005, 2007, Jenkins et al. 2011). Burn programs depend on the accuracy of these decision support models to determine when burns can occur, how much area can be burned, and what the potential fire effects are.

Fire has played a vital role in the maintenance of many forest communities in the Ouachita Mountains of western Arkansas and eastern Oklahoma, which have a historical fire return interval of approximately 7 years (Foti and Glenn 1991). Between 2007 and 2011, the Ouachita National Forest (Ouachita NF) burned an average of 49,821 ha annually (US Department of

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This article uses metric units; the applicable conversion factors are: meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; centimeters (cm): 1 cm = 0.39 in.; megagrams (Mg): 1 Mg = 2,204.6 lb; hectares (ha): 1 ha = 2.47 ac.

Table 1. Three forest cover types in the Ouachita Mountains and the corresponding FOFEM cover-type classifications using the SAF/SRM, NVCS, and FCCS terminology.

Cover type	FOFEM cover-type classification
Oak forest	
SAF/SRM	052 White Oak-Black Oak-Northern Red Oak
NVCS	*Quercus alba*-(*Quercus rubra*-*Carya* spp.)
FCCS	123 White oak-northern red oak-black oak-hickory forest
Pine-oak forest	
SAF/SRM	076 Shortleaf Pine-Oak
NVCS	*Pinus echinata* Forest
FCCS	281 Shortleaf pine-post oak-black oak
Pine woodland	
SAF/SRM	075 Shortleaf Pine
NVCS	*Pinus echinata* Woodland
FCCS	422 Post oak-shortleaf pine/bluestem-Indiangrass savannah

Agriculture [USDA] Forest Service 2011). With increasingly stringent regulation of air pollutant emissions (Environmental Protection Agency 1996, 1998), burn programs have been targeted for their contribution to these emissions and to climate change. For this reason, managers have sought to improve the accuracy of model predictions.

The FOFEM (First Order Fire Effects Model) was developed to provide reliable predictions of wildland and prescribed fire effects (Reinhardt et al. 2001, Reinhardt 2003) and is widely used by managers in the United States (Miller and Landres 2004). Fuel loading and model algorithms in FOFEM were created from published studies, unpublished reports, and anecdotal information. Estimates of fuel loading and consumption, however, lack validation in many regions of the United States, especially the Southeast. In Arkansas, fuel loading estimates exist in the Arkansas smoke management guidelines (Arkansas Forestry Commission 2007), but the origin of these estimates is unclear. No published data on fuel loads and consumption in the Ouachita Mountains exist. If fire effects models such as FOFEM are being used to determine management actions (e.g., number of hectares that can be burned while remaining in compliance with air quality standards), it is critical that these models be validated with local fuel loading by cover type.

Recent studies have tested the accuracy and assumptions of fire effects models in forest communities of the eastern United States and have begun to fill gaps in the data on which the models are based. Prichard et al. (2014) studied pine forests in Florida, Georgia, and South Carolina and mixed hardwood forests in Kentucky, Ohio, and Virginia. They found that FOFEM offered reliable predictions of live fuel (herbs and shrubs) and 1-hour fuel consumption, but the model's predictions for woody fuel, litter, and duff consumption should be improved. Reid et al. (2012) found that default fuel loads of litter in native longleaf pine (*Pinus palustris* Mill.) and old-field loblolly pine (*Pinus taeda* L.)-shortleaf pine (*Pinus echinata* Mill.) communities in FOFEM were significantly less than observed fuel loads, whereas default fuel loads of duff were significantly greater than observed fuel loads. Reid et al. (2012) also found that FOFEM overpredicted fuel consumption of litter and herbs when custom fuel loads were used.

We assessed the accuracy of fuel load and fuel consumption estimates derived from FOFEM for three fire-adapted cover types found on the Ouachita NF of Arkansas: oak (*Quercus* spp. L.) forest, shortleaf pine-oak forest, and shortleaf pine woodland (Table 1). We estimated fuel load and fuel consumption during prescribed fires using field-measured data and compared these values with those derived from FOFEM. Conversations with local fire managers lead us to hypothesize that preburn fuel loads in FOFEM cover types were greater than field-measured fuel loads except for those fuelbeds where FOFEM cover types were lacking data. Personal observations led us to hypothesize that FOFEM overestimated the consumption of 1- and 10-hour fuels and litter.

The objectives of this research were to develop appropriate fuel load estimates for use in decision support models in the Ouachita Mountains and to test the ability of FOFEM to predict fuel consumption using these fuel loads. Our results have implications for developers of decision support models and resource managers in Arkansas who desire accurate predictions of fire effects.

Methods

Study Site

We conducted our study on the Mena-Oden and Poteau-Cold Springs Ranger Districts of the Ouachita NF, where we randomly selected 15 high-priority burn units from the 30 planned burn units (Table 2). The Ouachita NF is located in the Ouachita Mountains of western Arkansas and eastern Oklahoma. Ridges are underlain by Pennsylvanian and Mississippian sandstone, with shale valleys dominated by clayey colluviums.

The vegetation cover in the region is oak, pine-oak, and pine woodlands and forests (USDA Forest Service 1999). Forest cover types had a closed canopy (>70% canopy cover) with little herbaceous cover (<25%). Pine-oak forest was predominantly pine with an oak component, and oak forest was oak-dominated, sometimes with a pine component. The pine woodland was open forest (<70% canopy cover) with substantial herbaceous cover (>25%). Shortleaf pine was the dominant species and often found with other hardwoods such as oak and hickory. The most prevalent oaks on the Ouachita NF were white oak (*Quercus alba* L.), northern red oak (*Quercus rubra* L.), post oak (*Quercus stellata* Wangenh.), and black oak (*Quercus velutina* Lam.), and hickory species included mockernut hickory (*Carya alba* [L.] Nutt. ex Elliott) and black hickory (*Carya texana* Buckley) (Mayo and Raines 1986).

Fuel Loading

Fuel loads were estimated using planar-intercept methods for down woody debris and depth measurements for litter and duff (Brown 1974, Ottmar and Andreu 2007). Transects ($n = 120$) were systematically established in 15 burn units (4–10 per burn unit). Each burn unit had a different percentage of the three cover types. We established a total of 40 transects in each of the three cover types. Each transect was 15.24 m long and permanently marked with rebar at each end. We used variable radius plots, located at the beginning of each transect, to obtain estimates of basal area (BA) and characterize species composition. Variable radius plot sampling was conducted using a 2.3 m^2/ha prism. Information on tree species composition was used to assign cover types.

Before and after each prescribed burn, we tallied dead and down woody fuel that bisected each transect. In the first 1.83 m of the transect, we tallied 1- and 10-hour woody fuels (≤0.64 cm and >0.64–≤2.54 cm diameter, respectively). In the first 3.66 m of the transect we tallied 100-hour fuels (>2.54–≤7.62 cm diameter). These fuels (1-, 10-, and 100-hour fuels) were considered fine woody fuel (FWF). For large woody fuel (LWF) (>7.62 cm diameter) we recorded diameter and decay class (sound or rotten, as in Brown 1974) and whether it was hardwood or pine, along the entire

Table 2. Weather parameters during burning, fuel loads, and consumption, and burn history of burn units on the Ouachita National Forest in Arkansas, 2010–2013.

Burn unit	Date burned	Max temp (° C)	Min RH	10-hr FM (%)	DSLR (amt)	KBDI	BI	Preburn*	Consumed*	No. previous burns	Yr since burn	Area (ha)
								. . . .(Mg/ha)	. . . .			
Brushy Bee	Mar. 16, 2010	22	34	8	4 (0.15)	57	23	22.28 ± 8.81	5.60 ± 1.68	1	14	356
Potter	Mar. 18, 2010	18	37	8	6 (0.15)	67	26	27.37 ± 15.78	10.11 ± 3.03	0	>20	125
Grapevine	Apr. 1, 2010	27	29	7	7 (2.79)	71	32	17.19 ± 10.24	7.96 ± 1.93	3	3	785
Buffalo 6	Apr. 10, 2010	24	17	6	7 (2.95)	84	38	26.88 ± 11.72	8.61 ± 5.58	0	>20	387
Harvey Ridge	Apr. 12, 2010	27	27	6	9 (2.74)	107	32	20.69 ± 14.37	3.18 ± 1.73	6	3	265
RCE 6	Apr. 12, 2010	27	27	6	9 (2.74)	107	32	24.36 ± 5.45	14.01 ± 4.26	0	>20	148
Muddy Mt.	Mar. 12, 2011	23	18	8	3 (0.89)	70	32	17.13 ± 17.28	4.53 ± 1.35	3	5	949
Cow Creek	Feb. 25, 2012	17	20	5	4 (0.28)	55	29	24.61 ± 7.55	7.20 ± 4.33	4	4	454
Robertson	Feb. 25, 2012	17	20	5	4 (0.28)	55	29	23.00 ± 13.74	10.54 ± 4.51	4	4	499
Blackfork 21	Feb. 26, 2012	18	16	5	5 (0.28)	60	42	33.98 ± 30.22	6.28 ± 2.38	4	4	748
Stevens	Mar. 6, 2013	13	21	5	7 (0.89)	22	34	15.53 ± 6.68	7.49 ± 2.53	2	3	727
RCB 7	Apr. 22, 2013	23	25	7	2 (1.40)	92	35	20.49 ± 11.79	4.60 ± 3.38	4	7	185
RCB 8	Apr. 22, 2013	23	25	7	2 (1.40)	92	35	10.00 ± 10.60	4.15 ± 2.85	4	7	169
RCE 12	Apr. 22, 2013	23	25	7	2 (1.40)	92	35	13.79 ± 9.77	6.05 ± 1.97	5	7	296
Henry Mt. 3	Apr. 30, 2013	30	29	7	2 (1.40)	98	34	24.79 ± 10.87	7.67 ± 2.67	4	3	287

Max temp, maximum temperature; Min RH, minimum relative humidity; 10-hr FM, lowest 10-hour fuel moisture during the burn; DSLR(amt), days since last rain (amount in centimeters), No. previous burns, number of burns in the last 20 years; Yr since burn, years since last burn.
[a] Data are means ± 2 SE.

15.24-m transect. Before and after each prescribed burn, we sampled depth of litter and duff (to the nearest 0.25 cm) in the same location in an exposed profile using a trowel and ruler at 10 points along each transect.

We used FEAT/FIREMON Integrated (FFI) software (Lutes et al. 2009) to quantify pre- and postburn fuel loads for all 120 transects. We entered local litter and duff bulk density (mass per unit volume [Mg/ha/cm]) values into FFI to convert depth to loading (Mg/ha). These values were 1.22 Mg/ha/cm for litter and 4.27 Mg/ha/cm for duff in oak forests and 1.80 Mg/ha/cm for litter and 5.66 Mg/ha/cm for duff in both pine-oak forests and pine woodlands (Ottmar and Andreu 2007). We used wood density, quadratic mean diameter, and nonhorizontal correction values of eastern species to calculate pre- and postburn FWF and LWF loading (Green et al. 1999).

Because of time constraints, we collected live fuel samples in plots adjacent to only 60 of the 120 transects, with 20 plots in each cover type. Live fuels were grasses, forbs, and small woody plants attached to the ground in various stages of senescence. Five collection plots were located at 3.05-m intervals along two parallel transects that were located 3.05 m on either side of the transect. We collected preburn data on the right side of the transect and postburn data on the left. At each plot, we clipped combustible live fuels of ≤0.64 cm in diameter that were attached to the ground in a 0.91-m × 0.91-m area. All collected samples were placed in paper bags and oven-dried at 80° C for at least 72 hours to obtain dry weight. Because we did not separate herbaceous fuels from shrubs, we used data from Masters et al. (1996) to estimate the proportion of herbaceous versus woody vegetation in the three cover types. In pine-oak and oak forests, we estimated that herbaceous fuels comprised 48% and shrubs comprised 52% of the live ground cover, whereas the ratio was 54 to 46% in woodlands, respectively (Masters et al. 1996). We adjusted our live fuel load (Mg/ha) by these ratios for herbaceous fuels and shrubs on each transect.

Fuel consumption was estimated by subtracting postburn fuel loads from preburn fuel loads on each transect. The postburn load for a fuel type was occasionally higher than the preburn load, similar to the results of other studies (Scholl and Waldrop 1999). This may have occurred because (1) fuels that were LWF measured preburn became 100-hour fuels postburn, 100-hour fuels became 10-hour fuels and so on; (2) FWF and LWF may have fallen on the transect after the burn; (3) some partially obscured woody fuel may have only been revealed postburn; and (4) distinguishing litter from duff in the half centimeter transition zone may have varied with observer. In instances where fuel loading increased postburn, we changed the fuel consumption to zero, except when fuel clearly changed size classes. We changed negative consumption to zero in 1% of litter, 13% of 1- and 10-hour fuel, 10% of 100-hour fuel, 8% of solid LWF, 3% of rotten LWF, and 26% of duff measurements. While over a quarter of the duff measurements increased postburn, the increase amounted to an average of only 0.29 cm or 1.63 Mg/ha.

Data Analysis

FOFEM is a fire effects model used to estimate fuel consumption, emissions, soil heating, and tree mortality. It requires plot-level fuel load inputs (biomass per unit area) of common fuel components (1-, 10-, and 100-hour fuels; ≥7.62 cm LWF; and herbaceous, shrub, and canopy fuels). It also allows for input of fuel characteristics such as size class distribution of LWF and percentage of LWF that are rotten, moisture content of fuel, and season of burn (Lutes et al. 2012). FOFEM includes default loading for each fuel component by cover type, or users can supply local information. FOFEM assumes 100% consumption of litter and herbaceous fuel and uses empirically derived regression models based on geographic regions to determine shrub and duff consumption. FOFEM uses BURNUP, a mechanistic fuel consumption model, to estimate woody fuel consumption (Albini and Reinhardt 1995, Lutes 2013).

FOFEM provides fuel loads for several cover-type classifications (cover types), including Society of American Foresters/Society of Range Management (SAF/SRM), National Vegetation Classification System (NVCS), and Fuel Characteristic Classification System (FCCS) (Ottmar et al. 2007, Prichard et al. 2013). FOFEM has three levels of preburn fuel loads for the SAF/SRM cover types: light, typical, and heavy (Lutes et al. 2012). The typical level is the default. FCCS has only one level of fuel loads. Because each cover type uses its own nomenclature, we selected the most applicable

Table 3. BA of plots by burn unit and cover type in the Ouachita National Forest, Arkansas, 2010–2013.

Cover type	Burn unit	No. plots	Pine BA	Oak BA	Other BA	Total BA
			(m^2/ha)			
Oak forest	Blackfork	7	0.98 ± 0.98	15.42 ± 1.30	1.64 ± 0.97	18.04 ± 1.37
	Brushy Bee	3	3.06 ± 0.77	17.60 ± 1.53	0.77 ± 0.77	21.42 ± 0.77
	Cow Creek	2	5.74 ± 1.15	10.33 ± 3.44	0 ± 0.00	16.07 ± 2.30
	Harvey Ridge	1	4.59 ± 0.00	9.18 ± 0.00	0 ± 0.00	13.78 ± 0.00
	Muddy Mt.	4	0.57 ± 0.57	18.37 ± 3.87	2.87 ± 1.72	21.81 ± 3.57
	Potter	4	5.74 ± 2.39	9.18 ± 2.48	1.14 ± 0.66	16.07 ± 1.62
	Robertson	4	5.74 ± 0.66	16.65 ± 5.33	0 ± 0.00	22.39 ± 5.25
	Stevens	10	2.07 ± 0.93	14.69 ± 1.85	3.44 ± 1.20	20.20 ± 1.40
	Grapevine	3	1.53 ± 1.53	14.54 ± 2.03	2.30 ± 1.33	18.37 ± 0.00
	Buffalo 6	1	4.59 ± 0.00	4.59 ± 0.00	11.48 ± 0.00	20.66 ± 0.00
	RCE 6	1	2.30 ± 0.00	9.18 ± 0.00	0 ± 0.00	11.48 ± 0.00
Pine woodland	Blackfork	3	19.13 ± 0.77	1.53 ± 0.77	0 ± 0.00	20.66 ± 1.33
	Cow Creek	4	16.07 ± 2.81	4.02 ± 2.55	0 ± 0.00	20.09 ± 1.96
	Harvey Ridge	9	11.23 ± 2.49	1.79 ± 0.51	0.51 ± 0.51	13.52 ± 2.75
	Henry Mt. 3	6	14.16 ± 1.10	0.77 ± 0.77	0 ± 0.00	14.92 ± 1.75
	RCB 7	5	13.78 ± 1.03	1.84 ± 0.86	0 ± 0.00	15.61 ± 1.13
	RCB 8	8	13.78 ± 0.75	0.29 ± 0.29	0 ± 0.00	14.06 ± 0.68
	RCE 12	5	17.45 ± 3.60	3.21 ± 1.17	0 ± 0.00	20.66 ± 2.62
Pine-oak forest	Brushy Bee	7	10.82 ± 2.05	6.89 ± 1.23	2.62 ± 0.78	20.34 ± 2.21
	Cow Creek	2	11.48 ± 2.30	9.18 ± 4.59	0 ± 0.00	20.66 ± 6.89
	Potter	6	16.07 ± 3.65	4.21 ± 1.72	2.68 ± 1.82	22.96 ± 4.59
	Robertson	4	18.94 ± 1.10	9.76 ± 3.16	0 ± 0.00	28.70 ± 3.44
	Grapevine	1	6.89 ± 0.00	4.59 ± 0.00	2.30 ± 0.00	13.78 ± 0.00
	Buffalo 6	9	19.39 ± 3.18	3.06 ± 0.86	0 ± 0.00	22.45 ± 2.67
	Henry Mt. 3	2	14.92 ± 5.74	2.30 ± 2.30	0 ± 0.00	17.22 ± 3.44
	RCE 6	9	21.17 ± 2.38	8.42 ± 1.88	1.28 ± 0.56	30.86 ± 1.96

Data are means ± SE.

SAF/SRM, NVCS, and FCCS cover type for each of the three Ouachita NF cover types (Table 1). We chose to compare our field-measured fuel data with only the SAF/SRM and FCCS cover types because the NVCS default fuel loads were similar to typical SAF/SRM fuel loads.

Our analyses were based on 15 prescribed burns in the Ouachita NF. All burns were conducted under moderately dry conditions between 11:00 am and 6:00 pm. Mean temperature during burns was 22° C (range, 13–30° C), mean relative humidity was 25 (range, 16–34), mean fuel moisture was 7% (range, 5–8%), mean Keetch-Byram drought index (KBDI) was 75 (range, 22–107), and mean burn index (BI) was 33 (range, 23–42) (Table 2). FOFEM can be run under four moisture settings determined by 10-hour fuel moisture (FM10): wet (FM10 = 22%), moderate (FM10 = 16%), dry (FM10 = 10%), and very dry (FM10 = 6%). Although average FM10 for our burns was closer to the very dry setting (6%), average KBDI was low for all burns. Because KBDI has a greater effect on larger woody fuels and duff and FOFEM assumes 100% consumption of smaller fuels (shrubs, herbs, litter, and 1-hour and 10-hour fuels) at the dry fuel moisture setting, we chose to run FOFEM at the dry setting rather than the very dry setting, which would have unjustifiably increased consumption of duff and larger woody fuels.

We determined BA (m^2/ha) at the start point of each transect and used a combination of these data and stand-level data from FSVeg (USDA Forest Service 2015) to determine the cover type. The BA averaged 18.21 (±1.06 SE) in oak forests, 22.12 (±1.98) in pine-oak forests, and 17.07 (±1.23) in pine woodlands (Table 3). Oak forests were predominantly composed of oak (white, northern red, southern red [*Quercus falcata* Michx.], post, and black) but had a component of pine, hickory, and blackgum (*Nyssa sylvatica* Marshall). Pine-oak forests were composed of shortleaf pine and oak species (white, northern red, and southern red) as well as hickory, black gum, and sweetgum (*Liquidambar styraciflua* L.). Pine woodlands were composed of predominately shortleaf pine with a smaller component of oak (white, northern red, and post).

We considered burn units to be random blocks and transects to be subsamples. Not all cover types were present on all burn units, resulting in an unbalanced, incomplete block design. We used generalized least squares (GLS) methodology (Littell et al. 2006, p. 44–56, Spilke et al. 2005) with burn unit as a random blocking factor to calculate GLS mean fuel loads and consumption for each cover type. We tested the accuracy of FOFEM default fuel loads for each fuel component in the SAF/SRM and FCCS cover types. We considered the FOFEM default values to be accurate if they fell within the 95% confidence interval (±2 SE) of the means from our field-measured values. We obtained predicted consumption from FOFEM 6.0 by running the model for each of our preburn transects and collection plots separately, which resulted in 120 FOFEM consumption predictions for each fuel load component, except herbs and shrubs for which only 60 runs were made. We compared actual consumption with predictions from FOFEM in each cover type using a repeated-measures analysis and GLS methodology (Spilke et al. 2005, Littell et al. 2006) with burn unit as a random blocking factor. For each fuel component, we modeled the repeated factor (field versus FOFEM) with both a compound symmetry and unstructured covariance matrix and used a likelihood ratio test to select the appropriate covariance structure. If the test was not significant ($P > 0.05$), the model with compound symmetry covariance was used. We used a Kenward-Roger correction for denominator degrees of freedom for repeated measures to avoid inflated type I error (Littell et al. 2006). Because this resulted in 10 tests for each cover type, we adjusted the P values with the false discovery rate technique (Benjamini and Hochberg 1995). We corrected within cover types because separate recommendations were expected for each group (Benjamini and Hochberg 1995).

Table 4. GLS analysis of preburn fuel loads and fuel consumption in the Ouachita NF, Arkansas, 2010–2013.

	Oak forest		Pine-oak forest		Pine woodland	
Fuel type	Preburn (Mg/ha)	Consumption (%)	Preburn (Mg/ha)	Consumption (%)	Preburn (Mg/ha)	Consumption (%)
Plots*						
Shrub	0.11 ± 0.02	7.74 ± 21.35	0.18 ± 0.02	42.05 ± 22.15	0.43 ± 0.02	66.13 ± 21.61
Herb	0.11 ± 0.02	31.44 ± 15.75	0.18 ± 0.02	38.48 ± 17.15	0.38 ± 0.02	66.51 ± 16.65
Planar intercepts†						
Solid LWF	9.77 ± 2.73	5.01 ± 5.09	4.28 ± 2.78	11.12 ± 5.32	6.10 ± 2.76	14.52 ± 5.23
Rotten LWF	0.90 ± 0.36	13.43 ± 8.21	1.19 ± 0.36	23.93 ± 8.18	0.78 ± 0.36	14.38 ± 8.12
100-hr	3.54 ± 0.96	23.33 ± 6.36	5.49 ± 1.01	22.90 ± 6.36	3.77 ± 0.99	9.77 ± 6.36
10-hr	1.30 ± 0.27	25.76 ± 7.85	1.61 ± 0.27	29.91 ± 7.99	0.65 ± 0.27	23.42 ± 7.91
1-hr	0.34 ± 0.04	22.80 ± 8.88	0.36 ± 0.04	43.86 ± 9.06	0.16 ± 0.04	41.11 ± 8.89
Litter	3.43 ± 0.25	82.84 ± 4.35	3.61 ± 0.27	89.27 ± 4.90	2.08 ± 0.27	81.34 ± 5.00
Duff	3.52 ± 0.76	16.63 ± 4.33	10.04 ± 0.83	23.81 ± 4.64	3.99 ± 0.83	21.11 ± 4.60
Intercept total	22.87 ± 3.12	38.46 ± 4.90	26.61 ± 3.16	42.14 ± 5.38	17.44 ± 3.14	37.16 ± 5.43
Total*	22.04 ± 4.80	38.29 ± 4.90	28.76 ± 4.84	42.29 ± 5.41	22.89 ± 4.77	37.46 ± 5.43
Litter depth (cm)†	2.77 ± 0.15	84.72 ± 5.05	2.01 ± 0.15	87.36 ± 5.46	1.14 ± 0.15	81.52 ± 5.43
Duff depth (cm)†	0.81 ± 0.15	16.46 ± 5.36	1.78 ± 0.15	23.94 ± 5.73	0.71 ± 0.15	18.89 ± 5.68

Data are means ± SE.
* $n = 20$ per cover type.
† $n = 40$ per cover type.

Results

Preburn Fuel Loading

Solid LWF contributed 33–62% of the preburn fuel loading from down woody debris, but <15% of solid LWF in each cover type was consumed during prescribed burns (Table 4). Litter comprised only 12–15% of the preburn fuels on transects but had the highest percent consumption (>80%) of all fuelbeds. Total fuel consumption ranged from 37 to 42% of preburn fuel loading (Table 4).

FCCS default fuel loads greatly exceeded field estimates for most fuel loads in oak and pine-oak forest (Figure 1). In the oak forest, FCCS default fuel loads were greater than field estimates for shrubs (6,627%), rotten LWF (99%), 10-hour (107%), 1-hour (297%), litter (346%), duff (1307%), and total fuel (305%) loads. In the pine-oak forest, FCCS defaults were greater than field estimates for shrubs (983%), solid LWF (418%), 1-hour fuels (275%), litter (203%), duff (176%), and total fuel loading (156%). In the pine woodland, FCCS defaults were greater than field estimates for herbs (813%), litter (135%), and duff (448%) but less for all woody fuels. In all cover types, SAF/SRM default loads of FWF were less than or not different from field-measured loads (Figure 1). SAF/SRM default shrub loads were 4,755% greater than field estimates in the pine-oak forest. SAF/SRM duff load was greater in all cover types (oak = 155%, pine-oak = 27%, and pine woodland = 237% greater), whereas default litter load was 31% greater than field estimates in the oak forest but 44% less in the pine-oak forest.

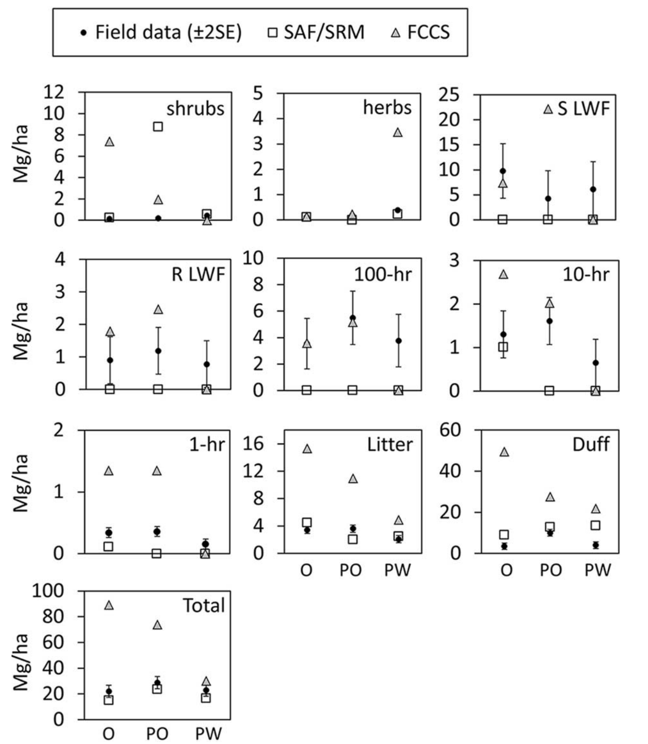

Figure 1. A comparison of field-collected preburn fuel load (±2 SE) and default fuel loads found in FOFEM for three cover types. Field data were measured on the Ouachita NF in Arkansas, 2010–2013. O, oak forest; PO, pine-oak forest; PW, pine woodland.

Fuel Consumption

In all cover types, FOFEM-predicted consumption was either greater than or similar to field-measured consumption (Table 5). In the oak forest, FOFEM-predicted consumption was greater than field-estimated consumption for herb (200%), 10-hour (156%), 1-hour (150%), and litter (20%) loads (Figure 2). In the pine-oak forest, FOFEM-predicted consumption was greater for 100-hour (78%), 10-hour (182%), 1-hour (113%), litter (11%), duff (70%), and total fuel (37%) loads. In the pine woodland, FOFEM-predicted consumption was greater for herbs (54%), 100-hour (241%), 10-hour (96%), 1-hour (78%), and litter (18%) loads (Figure 2).

Discussion

The lack of studies to adequately inform fuel cover classification models, at least in the Ouachita Mountains Ecoregion, is evident by the overestimation of default preburn fuel loads for most fuelbed components found in FOFEM. Our preburn fuel loads of 22 to 29 Mg/ha were similar to those for other studies in pine and oak ecosystems. Scholl and Waldrop (1999) found average preburn fuel loads of 19–24 Mg/ha in loblolly and longleaf pine forest in the

Table 5. GLS estimates of FOFEM- and field-estimated fuel consumption in the Ouachita National Forest, Arkansas, 2010–2013.

Fuel type	Oak forest FOFEM dry	Oak forest Field	Oak forest P*	Pine-oak forest FOFEM dry	Pine-oak forest Field	Pine-oak forest P	Pine woodland FOFEM dry	Pine woodland Field	Pine woodland P
	.......(Mg/ha).......			........(Mg/ha)........			.......(Mg/ha).......		
Plots†									
Shrub	0.00 ± 0.01	0.02 ± 0.03	0.4197	0.16 ± 0.07	0.10 ± 0.04	0.3871	0.23 ± 0.05	0.29 ± 0.05	0.2342
Herb	0.09 ± 0.02	0.03 ± 0.02	0.0014	0.22 ± 0.08	0.09 ± 0.03	0.0594	0.37 ± 0.04	0.24 ± 0.04	0.0004
Transects‡									
LWF R	0.61 ± 0.15	0.68 ± 0.20	0.4990	0.40 ± 0.24	0.24 ± 0.18	0.4299	0.13 ± 0.04	0.26 ± 0.08	0.1749
LWF S	3.61 ± 2.01	0.80 ± 0.20	0.2288	0.91 ± 0.67	0.82 ± 0.67	0.9025	0.59 ± 0.22	1.37 ± 0.47	0.1749
100-hr	2.01 ± 0.65	0.91 ± 0.65	0.0686	4.61 ± 1.15	2.59 ± 1.15	0.0029	2.80 ± 0.64	0.82 ± 0.23	0.0106
10-hr	1.10 ± 0.37	0.43 ± 0.29	0.0014	1.55 ± 0.26	0.55 ± 0.26	0.0002	0.57 ± 0.12	0.29 ± 0.12	0.0091
1-hr	0.35 ± 0.03	0.14 ± 0.03	0.0006	0.32 ± 0.04	0.15 ± 0.04	0.0002	0.16 ± 0.02	0.09 ± 0.02	0.0004
Litter	3.31 ± 0.16	2.76 ± 0.16	0.0006	3.88 ± 0.23	3.51 ± 0.23	0.0002	2.11 ± 0.13	1.79 ± 0.13	0.0004
Duff	0.86 ± 0.19	0.63 ± 0.19	0.2519	4.04 ± 0.41	2.37 ± 0.41	0.0002	1.27 ± 0.30	0.87 ± 0.19	0.1749
Intercept total	11.48 ± 2.29	5.59 ± 0.77	0.0334	15.71 ± 1.68	10.30 ± 1.32	0.0002	7.58 ± 0.92	2.44 ± 0.57	0.0746
Total†	12.04 ± 4.16	5.86 ± 1.11	0.2099	17.63 ± 1.96	12.84 ± 1.96	0.0119	9.63 ± 1.63	6.83 ± 0.80	0.1749

Data are means ± SE.
* P values were adjusted with the false discovery rate technique (Benjamini and Hochberg 1995).
† $n = 20$ per cover type.
‡ $n = 40$ per cover type.

upper Piedmont of South Carolina. Kolaks (2004) estimated preburn fuel loads of 17–18 Mg/ha in the mixed hardwood forests of the Missouri Ozarks. Thus, an overestimation of default preburn fuel loads may exist across a wider range of cover classifications. This overestimation will result in higher predictions of air pollutant emissions as fuel loads directly relate to these emissions (Sandberg et al. 2002). FOFEM's overestimation of duff consumption will further exacerbate this overprediction.

Typical SAF/SRM Cover Type

Typical SAF/SRM preburn fuel loads underestimated woody fuel and overestimated duff compared with field-measured estimates in all cover types. The underprediction of some fuel components and overprediction of others resulted in similar total preburn fuel loads in all cover types, but consumption of individual fuel components may have disproportionate effects on fire behavior and predicted emissions (Ottmar 2014). For example, the overprediction of duff in all cover types would lead to significantly higher predicted emissions because FOFEM considers duff to be consumed by smoldering combustion. Under dry scenarios, FOFEM predicts the amount of particulate matter produced per unit biomass in smoldering combustion as 9 times greater than flaming combustion (Lutes et al. 2012). Duff loads for all default cover types were greater than field-measured loads (3–9 Mg/ha greater). If these typical fuel loads are used, overestimates of emissions could be 27–81 times higher than reality. At the same time, data for 1-, 10-, and 100-hour fuel loads and LWF do not exist for most typical SAF/SRM fuel loads. This lack of data results in an underestimation of air pollutant emissions and causes erroneous assertions of healthy air quality.

FCCS Cover Type

FCCS overestimated litter and duff in all cover types in the Ouachita NF by 3–12 and 18–46 Mg/ha, respectively. Lydersen et al. (2014) also found that FCCS overestimated fuel loads. A possible reason is that cover types in FCCS have extensive geographic ranges, and fuels can vary within these geographic areas (Brown and Bevins 1986, Clinton et al. 1998, Sandberg et al. 2002, McDaniel et al. 2012). However, error in fuel loading accounts for 80% of the error in emissions (Sandberg et al. 2002). The US Environmental Protection Agency is currently using FCCS fuel loads in models (e.g., BlueSky) to determine air pollutant emissions across the United States (Larkin et al. 2009). In addition, the *"Criteria Pollutant Modeling Analysis for Arkansas"* (ICF International 2014) used 2005 and 2008 National Emissions Inventory data sets to develop base-year emissions inventory inputs for Community Multi-Scale Air Quality regional scale modeling. These fuel load overestimates could impede the implementation of burn programs (Kobziar et al. 2015) and reduce the area burned across the United States as fire managers seek to comply with air quality standards. These burns are critical for the reduction of hazardous fuels, preparation of seedbeds, and restoration and maintenance of habitat for rare, threatened, and endangered species such as the red-cockaded woodpecker (*Picoides borealis*) in the Southeast and in the Ouachita NF in particular (Sparks et al. 1999, Kelly et al. 2004). To properly use FCCS, developers recommend creating customized fuelbeds in FCCS and importing those into FOFEM (or other fire effects models) before running the model (Ottmar et al. 2007) to provide more accurate estimates of fuel consumption and air pollutant emissions. The data presented in this article can be used to create a site-specific fuelbed for the Ouachita Mountains that will more appropriately represent the fuel loads present in these cover types and result in more accurate model predictions.

Field-Measured Inputs to FOFEM

FOFEM estimates of LWF consumption were not different from field-measured estimates in any forest type. Prescribed burns in the Ouachita NF most often occur in the late winter and early spring when log fuel moisture is high (16–20%) and KBDI is low (<150). As a result, few LWFs are consumed in prescribed burns. In addition, the patchy distribution of LWF across the landscapes makes assessment more difficult than that of other fuelbed components (Jenkins et al. 2004).

FOFEM consumption estimates based on field-measured fuel loads overestimated consumption of 100-hour fuels in pine-oak forest and pine woodland. Prichard et al. (2014) found that field-measured consumption of 100-hour fuels was not correlated with FOFEM predictions in pine sites in Florida, Georgia, and South Carolina or hardwood sites in Kentucky, Ohio, and Virginia.

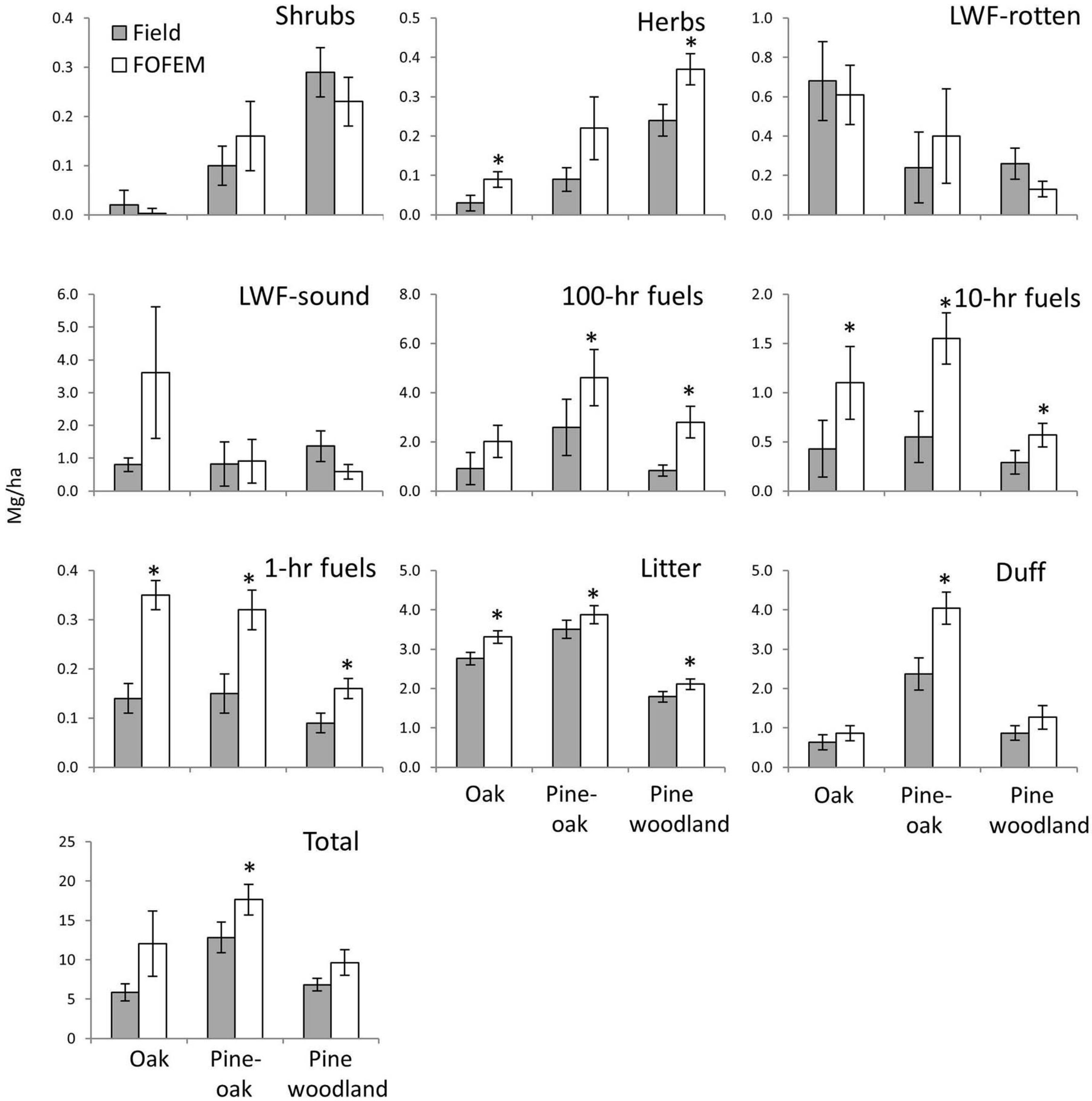

Figure 2. Comparison of field-measured fuel consumption and FOFEM-predicted fuel consumption in three cover types (oak forest, pine-oak forest, and pine woodlands) after prescribed burns in Arkansas, 2010–2013 (n = 40 for all fuel types except Shrubs, Herbs, and Total for which n = 20).

FOFEM assumes 100% consumption of 1- and 10-hour fuels. We found that FOFEM overestimated consumption of 1- and 10-hour fuels in all cover types. Prichard et al. (2014) found that FOFEM estimates of 1-hour fuel consumption was correlated with field measures in pine sites, but FOFEM overestimated 1-hour fuel consumption in mixed hardwood sites. For 10-hour fuel consumption in pine sites, Prichard et al. (2014) found no relationship between predicted and measured values, but in hardwood cover types, FOFEM overestimated consumption.

Like Reid et al. (2012) and Prichard et al. (2014), we found that FOFEM estimates of litter consumption were higher than field-measured estimates. This discrepancy may be the result of the heterogeneous nature of fire and fuels found within burn units (Hiers et al. 2009). Although fire consumes most litter and live fuels, there are often patches that do not burn or that burn with varying levels of consumption. Reinhardt (2003) acknowledges that FOFEM is not designed to account for patchy or discontinuous burns and notes that results should be weighted according to the area burned. At the same time, areas that burn with lower severity can leave recognizable needle and leaf pieces. In the postburn measurement, this would be considered litter, therefore resulting in less than FOFEM-predicted 100% consumption of litter, even in areas that have burned.

FOFEM overpredicted duff consumption in the pine-oak forest, but not in the oak forest or in the pine woodland. This is most likely due to higher preburn duff loads in the pine-oak forest combined with low KBDI during the prescribed burns. Duff consumption adds significantly to air pollutant emissions (Reid et al. 2012, Ottmar 2014). Therefore, the more duff a cover type has, the greater the potential overprediction of fuel consumption and air pollutant emissions. Currently, developers of FOFEM are collecting data from cover types with higher duff loads that burn under the typical winter/spring conditions and that can have low FM10 as well as low KBDI, to test the duff consumption algorithm in FOFEM (Duncan Lutes, Ecologist, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT, pers. comm., May 11, 2015).

The current use of cover types such as FCCS and SAF/SRM in fire and landscape assessment models like Consume 3.0 (a model that predicts fuel consumption and emissions) (Prichard et al. 2006), BlueSky Playground (a model that predicts smoke emissions) (Larkin et al. 2009), and IFTDSS (Interagency Fuel Treatment and Decision Support System) (Rauscher and Drury 2014) emphasizes the need for accurate preburn fuel load and consumption estimates. Fuel load estimates and consumption algorithms are major components in these models (Drury et al. 2014, Lydersen et al. 2014, Urbanski 2014) and greatly influence their estimates of air pollutant emissions. Ensuring that these inputs are accurate will be critical for assessing and maintaining fire-adapted ecosystems and the fire management programs that maintain them, across the United States and more widely.

Conclusions

Although fuel loads can be variable, characterizing appropriate loads within a cover type is critical to accurately model fire effects and air pollutant emissions. We found that the default cover classifications for FCCS and SAF/SRM cover types in FOFEM had greater duff loads than field-measured data in all cover types. Compared with other fuelbed components, greater duff inputs result in disproportionally greater air pollutant emissions when FOFEM or other decision support models are run using these defaults. We also found that FOFEM overestimated consumption of duff in the pine-oak forest, as well as litter and 1- and 10-hour fuel consumption across all cover types. The combined effect of overestimating preburn fuel loads and using an algorithm that overestimates consumption might result in drastically higher predictions of air pollutant emissions which might prevent the restoration and maintenance of fire-adapted ecosystems, as fire managers seek to comply with air quality regulations. We hope our results and other existing data sets in the eastern United States will improve preburn data found in cover-type classifications and improve the consumption algorithms within FOFEM and other fire effects models.

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