COMPARISON OF BEHAVE: FIRE BEHAVIOR PREDICTION AND FUEL MODELING SYSTEM PREDICTIONS WITH OBSERVED FIRE BEHAVIOR VARYING BY SEASON AND FREQUENCY

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ABSTRACT

Managers are increasingly using computer models to predict prescribed fire behavior in various seasons and under different fuel conditions. Because fire behavior is related to fire effects on vegetation, validation of computer models will help understand possible outcomes and increase planning efficacy. Better predictions of fire behavior also will aid in management of risk associated with prescribed burning. We compared fire behavior predicted with BEHAVE, fire behavior and fuel modeling system, using standard and site-specific customized fuel models with observed fire behavior of strip headfires. These fires were observed in shortleaf pine (*Pinus echinata*)–dominated stands managed as pine–grassland stands for the endangered red-cockaded woodpecker (*Picoides borealis*). We evaluated the accuracy of fuel models across different seasons and fire return intervals.

Fuels in all stands tended to be heterogeneous and discontinuous, with fuel loads differing considerably between growing and dormant seasons and time since burned both in weight and composition. Fuel models varied in accuracy depending on fuel loading and season of fire. Therefore, multiple fuel models were required to more accurately characterize fire behavior across fire seasons and fire return intervals. All fuel models failed to produce accurate predictions for fireline intensity and rate of spread. All fuel models tended to overpredict fireline intensity on low-intensity fires and underpredict fireline intensity on high-intensity fires. The firing pattern we chose may have influenced the accuracy of predictions, but we were unable to detect appreciable changes in wind speed due to presumed convective influences of backing and headfires approaching each other. Additional BEHAVE fuel models for a wider range of fuel conditions show some promise in providing managers with more realistic predictions of fire behavior under variable fuel conditions. However, field validation for specific sites is imperative.

keywords: Arkansas, ecosystem restoration, fire behavior, fire ecology, fire models, *Pinus echinata,* prescribed burning, shortleaf pine.

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INTRODUCTION

Fire is a natural and dynamic force that played a major role in presettlement landscape development in both forest and rangeland communities worldwide (Christensen et al. 1981, Gill 1981, Wright and Bailey 1982, Chandler et al. 1983, Bigalke and Willan 1984, Kruger 1984, Pyne 1984, Sparks and Masters 1996). However, fire control and prevention has altered many of these fire-derived communities, often causing many plant and animal species dependent on these communities to decline or become endangered. Land managers throughout the world attempt to restore and maintain relicts of these communities by initiating prescribed fire to meet specific objectives such as endangered species management, manipulation of community composition, fire hazard reduction, wildlife habitat improvement, control of woody or invasive species, and seedbed preparation (Van Lear 1985, Waldrop et al. 1992, Wilson et al. 1995, Masters et al. 1996).

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Computer models utilizing on-site environmental data to predict common fire behavior parameters can be used before fire ignition, providing managers with insight on the probability of achieving desired objectives, possibility of escapes, and equipment required to suppress the fire front (Raybould and Roberts 1983, Andrews and Bradshaw 1990). BEHAVE is a wildland fire behavior and fuel modeling system developed by the U.S. Department of Agriculture, Forest Service to provide real-time fire behavior predictions of large-scale wildland fires or prescribed natural fires (Burgan and Rothermel 1984, Andrews 1986, Andrews and Chase 1989). However, when used with caution, BEHAVE can be utilized for fire behavior training, dispatch of crews for initial attack, and prescribed fire planning (Andrews 1986, Andrews and Chase 1989, Andrews and Bradshaw 1990).

BEHAVE is equipped with 13 standard fuel models and the capability of customizing site-specific fuel models (Andrews 1986, Andrews and Chase 1989). Standard fuel models vary according to fuel type, fuel load, and fuel structure and in their relative sensitivity to live fuel moisture. However, fuels are dynamic and describing them often requires more than one fuel model, depending on management history—particularly fire regime, the season of fire, fuel bed depth, and subsequent weather conditions. Furthermore, a standard fuel model may not adequately characterize a site; therefore, managers may need to modify a model for their particular situation. Managers must be aware of the complexity of fuels and be capable of choosing the appropriate fuel model for a given situation.

Many land managers and researchers are beginning to apply fire in different seasons and with fires of varying intensities to accomplish management objectives (Robbins and Myers 1992, Glitzenstein et al. 1995). Fire behavior characteristics may be used to predict the influence on herbaceous and woody vegetation (Engle et al. 1996, Sparks 1996, Sparks et al. 1999). Accurate fire behavior predictions can thus be used to define burning windows and potential habitat change for management of endangered species such as the red-cockaded woodpecker (*Picoides borealis*) (Sparks et al. 1999). Currently, research and experience with prescribed fire at times other than the late dormant season is limited. Therefore, managers are faced with uncertain liability risks from fire escapes, residual smoke, and uncertain management outcomes when using prescribed fire for endangered species management. However, fire behavior systems such as BEHAVE maybe useful for increasing the efficacy of prescribed fires and reducing liability (Masters and Engle 1994). Predictive fire behavior systems such as BEHAVE were developed for use in continuous fine fuels under wildfire situations. Therefore, these systems must be validated before fire management decisions are based on predicted outcomes.

Our primary objective was to evaluate the accuracy of BEHAVE's predictions by determining the most appropriate fuel model for thinned stands of shortleaf pine (*Pinus echinata*) managed as a pine–grassland community for the red-cockaded woodpecker. We also used the SITE module of the Fire 1 program in BEHAVE to predict dead fine fuel moisture (Andrews 1986) for comparative purposes because some prescribed burners may not monitor fine fuel moisture. We also wanted to determine the efficacy of using a single fuel model in different seasons.

METHODS

Study Area

Our study sites were located on the Poteau Ranger District of the Ouachita National Forest (ONF) (approximately 34°54′N, 94°04′W) in Scott County of west-central Arkansas. The ONF was within the 2,280,000-ha Ouachita Mixed Forest–Meadow Provide and comprised 648,000 ha throughout the Ouachita Mountains in Arkansas and Oklahoma (Neal and Montague 1991, Bailey 1995). The Ouachita Mountains were east-to-west trending, strongly dissected, and ranged in elevation from 150 to 790 m (Fenneman 1938). Soils in the Ouachita Mountains developed from sandstone and shales and were thin and drought-prone. The climate of the area was semi-humid to humid, with hot summers and mild winters.

Our study focused on stands under active management for the endangered red-cockaded woodpecker within the 40,000-ha Pine-Bluestem Ecosystem Renewal Area (Wilson et al. 1995, Masters et al. 1996). Management consisted of thinning midstory and codominant pine and hardwood trees, also known as wildlife stand improvement (WSI). Dormant-season prescribed burning every 3 y followed WSI. Three-year fire intervals were the most common after WSI, but intervals varied from 1 to 4 y. We randomly chose 12 stands that had been burned previously in the dormant season between 1 and 5 times at 3-y intervals (Table 1).

Shortleaf pine was the dominant overstory tree species in all stands (Table 1). Codominant and intermediate overstory species included post oak (*Quercus stellata*), blackjack oak (*Q. marilandica*), white oak (*Q. alba*), northern red oak (*Q. rubra*), black oak (*Q. velutina*), black hickory (*Carya texana*), and mockernut hickory (*C. tomentosa*). Woody resprouts and shrubs (≤3 m) dominated the understory of these stands. The dominant understory species included poison ivy (*Toxicodendron radicans*), low-bush huckleberry (*Vaccinium pallidum*), blackberry (*Rubus* spp.), Virginia creeper (*Parthenocissus quinquefolia*), New Jersey tea (*Ceanothus americanus*), muscadine (*Vitis rotundifolia*), post oak, white oak, and shortleaf pine (Sparks 1996).

Treatments

We applied 5 treatments in a completely randomized fashion, with 2 treatments consisting of late growing-season fires, and 3 treatments of dormant-season fires. Treatments were as follows:

1) Late growing-season burn (G30; *n* = 4): 30 mo after previous dormant-season burn;

2) Dormant-season burn (D36; $n = 4$): 36 mo after previous dormant-season burn;
3) Late growing-season burn (G43; $n = 2$): 43 mo after previous dormant-season burn;
4) Dormant-season burn (D48; $n = 2$): 48 mo after previous dormant-season burn;
5) Dormant-season burn (D12; $n = 2$): 12 mo after previous dormant-season burn.

The G43 and D48 treatments differed from the G30 and D36 treatments in that experimental prescribed burns were applied after 4 growing seasons and 3 growing seasons, respectively. The G43, D48, and D12 treatments were added to test fuel model flexibility under different fuel loads.

We conducted late growing-season burns between 1200 and 1800 hours on 10–13 September 1994 and 14–15 October 1995 (Table 1). During this study, these were the earliest dates we could get a fire to readily spread in these stands; these burns were conducted well before leaf drop, and herbaceous and woody species were living. We initiated dormant-season prescribed fires between 1000 and 1800 hours on 31 March–2 April 1995 and 2–4 March 1996 (Table 1). We ignited backfires and allowed them to burn >50 m into the stand before igniting strip headfires and sampling fire behavior parameters of the strip headfires.

Table 1. Characteristics of stands used to compare BEHAVE predicted and observed fire behavior in the Ouachita Mountains of Arkansas, 1994–1996.

Stand	Treatment	Fire date	Months since last fire	Stand size (ha)	Stand elevation (m)	Slope (%)	Mean basal area (m^2/ha)	Mean height (m)	Mean DBH[a] (cm)	Mean crown length (m)	Mean crown diameter (m)	Mean canopy cover (%)
1257	D48	2 Mar 1996	48	18.2	335	9	14	17.0	32.6	9.0	7.1	68
1257	D36	2 Apr 1995	36	16.2	305	7	20	15.5	31.5	7.0	6.3	88
1257	D12	2 Mar 1996	12	16.2	305	7	20	16.0	32.5	7.0	6.4	81
1257	G30	12 Sep 1994	30	16.2	292	13	18	20.5	32.3	9.5	6.1	81
1259	G30	13 Sep 1994	30	16.2	305	9	17	21.5	33.4	10.0	6.5	72
1265	G43	14 Oct 1995	43	16.2	335	4	23	21.5	29.7	9.0	5.7	93
1274	G43	15 Oct 1995	43	17.8	305	15	26	23.0	27.6	10.0	5.2	92
1274	D36	1 Apr 1995	36	16.2	336	7	25	16.5	28.2	7.0	5.3	94
1274	D12	4 Mar 1996	12	16.2	336	7	25	16.5	28.2	7.0	5.3	84
1274	G30	10 Sep 1994	30	24.3	338	3	23	22.0	30.7	10.0	6.1	87
1289	D36	1 Apr 1995	36	16.2	335	7	17	15.0	29.1	6.0	5.4	82
1289	G30	11 Sep 1994	30	13.8	333	8	17	21.0	32.8	9.0	5.9	81
1313	D48	3 Mar 1996	48	26.7	305	8	23	15.0	26.9	7.0	4.9	84
1313	D36	31 Mar 1995	36	13.8	305	7	24	15.0	27.9	6.5	5.4	90

[a] Abbreviation: DBH, diameter at breast height.

Fuel Sampling

We sampled fuels <1 h before burning at 3 random locations within each stand. At each location, we harvested all fuels ≤1.5 m in height in four to ten 0.5 × 0.5-m quadrats at 5-m intervals, parallel to the fire front. We hand-separated fuels into 1-h (<0.6 cm diameter) dead, fine live fuels (all live grasses, forbs, and foliage combined <0.6 cm diameter), and 10-h (0.6–2.5 cm diameter) dead components. We weighed fuels immediately after clipping. After burning, we collected fuel residue at locations paired with pre-fire fuel samples by sampling all residual dead and live vegetation <2.5 cm in diameter to a height of 1.5 m. All fuel samples were dried at 70°C to a constant weight. Fuel moisture was calculated on a dry-weight basis. We also determined fuel moisture of 10-h fuels using standard fuels sticks and a protimeter.

We calculated fuel energy by selecting 3 random samples of dried fuels from each stand burned during the dormant season of 1995 and late growing season of 1994 ($n = 24$). We combined all fuel classes sampled for each pre-burn observation, ground samples to a fine powder, and compressed them into 1-g pellets. These pellets were then combusted in a bomb calorimeter to determine high heat of combustion.

Meteorological Data

We measured relative humidity, temperature, cloud cover, and wind speed at sunrise, 1400 hours, and sunset the day before the burn, the day of the burn, and the day after the burn. We also recorded weather observations immediately before igniting the fire, as we

Table 2. Range of fuel and weather conditions during prescribed fires on wildlife stand improvement areas in Ouachita National Forest, western Arkansas, 1994–1996.

Parameter	Treatment[a] D36		G30		D48		G43		D12	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Fuel load (kg/ha)										
Fine live fuels	73	422	320	1,890	75	330	363	1,010	81	250
1-h dead fuels	6,580	11,350	4,860	9,340	8,900	13,810	7,420	8,460	5,910	9,140
10-h dead fuels	200	1,730	156	2,510	340	1,570	77	1,700	175	1,550
Post-burn residue	3,230	6,740	2,430	9,870	5,170	9,560	3,430	6,050	5,450	8,970
Fuel moisture (%)										
Fine live fuels	45	163	92	133	114	184	86	127	133	194
1-h dead	9	45	8	28	12	28	6	15	15	24
10-h dead	6	55	6	58	28	48	8	62	19	50
Weather conditions										
Air temperature	12	24	27	31	12	16	19	26	10	19
6-m wind speed (km/h)	0	13	3	9	2	7	0	5	0	4
Relative humidity (%)	22	48	46	57	26	51	20	31	32	49
Cloud cover (%)	0	70	0	30	0	10	0	0	0	90

[a] Treatment: D12, dormant-season burn 12 mo after previous dormant-season burn ($n = 6$); D36, dormant-season burn 36 mo after previous dormant-season burn ($n = 12$); D48, dormant-season burn 48 mo after previous dormant-season burn ($n = 6$); G30, late growing-season burn 30 mo after previous dormant-season burn ($n = 12$); G43, late growing-season burn 43 mo after previous dormant-season burn ($n = 6$).

observed fire behavior parameters, and immediately upon completion of the fire. We measured wind at 2 m using a totalizing anemometer. We used observed wind speeds to estimate wind speed at 6 m (Albini and Baughman 1979). We used a belt weather kit to determine other weather parameters. We verified our observations with weather data from the Poteau Ranger District Headquarters in Waldron, Arkansas, and the National Weather Service in Tulsa, Oklahoma, for Fort Smith observations (Table 2).

Stand Characteristics

We characterized the canopy species within each stand before burning. In September 1994 and in March and April, 1995, we sampled 30 points at 30-m intervals on 2–4 randomly spaced lines perpendicular to the contour. In October 1995 and March 1996, we sampled 20 locations within each stand. At each sampling location, we estimated canopy cover with a spherical densiometer (Avery 1967), tree and crown height using a clinometer, crown diameter, and diameter at breast height for the closest tree in each sampling quarter. We estimated mean tree height and the ratio of crown length to tree height and crown length to crown diameter from these observations for use in the SITE module of BEHAVE 4.1.

Fire Behavior Observations

We recorded rate of spread, flame length, flame depth, and residence time near all 3 fuel sampling locations. Before headfire ignition, we placed 3 sets of 2-m freestanding stakes, with referenced heights marked at 0.5-m intervals, at 5 m apart and perpendicular to the fire front. Three observers estimated fire behavior parameters by observing and timing the fire as the fire front passed each set of stakes, as described by Rothermel and Deeming (1980). We repeated this procedure ≥ 2 times at 3 locations within each stand ($n \geq 18$), as logistically possible. Observed and predicted fire behavior parameters and data for each fire front observed are included in Sparks (1996).

We calculated fireline intensity by Byram's (1959) formula ($I_B = hwr$), where I_B is frontal fire intensity (kW/m); h is net heat of combustion (kJ/kg), obtained by adjusting fuel high heat of combustion for fuel moisture and heat of vaporization; w is fuel consumed (kg/m^2), calculated as pre-burn fuel load minus post-burn residual fuel; and r is rate of spread (m/s). We estimated the total energy released in the active flame front, or heat per unit area (H_a; kJ/m^2), by dividing fireline intensity (kW/m) by rate of spread (m/min) (Rothermel and Deeming 1980). We determined reaction intensity (I_R; kW/m^2), or the rate of energy release per unit area of flaming zone, by dividing fireline intensity (kW/m) by flame depth (m) (Albini 1976, Alexander 1982).

Creating Custom Fuel Models

We used TSTMDL in BEHAVE to create a site-specific, static fuel model for each treatment type ($n = 5$), by adjusting the values of the Southern Rough model (fuel model 7). We used the fuels sampled in each stand to represent fuel load. We calculated depth of the fuel bed in NEWMDL and used this value in TSTMDL. After customizing fuel model 7, we used TSTMDL to test the model against observed fire behavior using environmental data we collected. We fine-tuned extinction moisture, fuel load, and fuel depth (Table 3) to produce accurate and consistent results for a variety of environmental conditions.

BEHAVE Predictions

The mathematical model used to calculate surface fire spread and intensity in BEHAVE is intended pri-

Table 3. Fuel model descriptors for standard and custom fuel models used to model fire behavior in the Ouachita Mountains, Arkansas, 1994–1996.

		Fuel load (Mt/ha)					Surface-to-volume ratio (1/cm)				
Model	Treatment[a]	1-h	10-h	100-h	Live herbaceous	Live woody	1-h	Live herbaceous	Live woody	Fuel depth (cm)	Extinction moisture (%)
7	All	2.54	4.20	3.37	0.00	0.83	57	6	51	76.2	40
8	All	3.37	2.25	5.61	0.00	0.00	66	6	6	6.1	30
9	All	6.54	0.93	0.34	0.00	0.00	82	6	6	6.1	25
10	All	6.74	4.49	11.23	0.00	4.49	66	6	49	30.5	25
Custom	G30	7.62	1.12	1.01	0.90	1.12	57	6	51	28.96	27
Custom	D36	8.96	1.12	0.52	0.00	0.83	57	6	51	60.9	45
Custom	G43	7.84	1.57	0.90	0.90	1.12	57	6	51	29.57	29
Custom	D12	5.60	0.67	0.45	0.00	0.83	57	6	51	24.38	25
Custom	D48	9.52	1.90	0.90	0.00	0.83	57	6	51	67.06	40

[a] Treatment: D12, dormant-season burn 12 mo after previous dormant-season burn (*n* = 6); D36, dormant-season burn 36 mo after previous dormant-season burn (*n* = 12); D48, dormant-season burn 48 mo after previous dormant-season burn (*n* = 6); G30, late growing-season burn 30 mo after previous dormant-season burn (*n* = 12); G43, late growing-season burn 43 mo after previous dormant-season burn (*n* = 6).

marily for the prediction of fire behavior parameters on the flame front of a headfire carried by fine fuels (Rothermel 1983). Therefore, we only compared observed fire behavior parameters of headfires with BEHAVE predictions. We modeled fire behavior using the SITE module of the FIRE1 program in BEHAVE 4.1 (Andrews 1986). We were interested in predictions from several possible fuel models; therefore, we used our custom fuel model and standard fuel models 7, 8, 9, and 10 described by Anderson (1982) that best fit the fuel characteristics of the study area. We considered standard fuel model 5 but excluded it from consideration because the woody vegetation in our stands did not have the same characteristics of structure and a considerable amount of the dead fuel was composed of pine needles, which are somewhat volatile compared to other fuels. We used 1-h dead and fine live fuel moisture from collected fuel samples; 10-h fuel moisture from fuel sticks and protimeter readings observed on-site; we estimated 100-h fuel moisture based on 1- and 10-h fuel moisture and weather conditions. We supplied all environmental variables, stand characteristics, and weather observations for each fire subsample within a stand as prompted by the SITE module. BEHAVE predicted fireline intensity, heat per unit area, reaction intensity, flame length, and rate of spread for each fire location within all stands.

We used simple linear regression to determine if fuel models in BEHAVE were accurate predictors over the range of observed fire behavior by pairing observed and predicted fire behavior parameters for each fire subsample. We tested the slope of the linear regression line (i.e., BEHAVE-predicted fire behavior versus observed fire behavior) for equality to 1, with the *y*-intercept forced to 0. A model was determined accurate when the slope was not significantly different from 1 at a significance level of 0.05. To determine fuel model accuracy at all levels of observed behavior, we inspected the R^2 for the model and plotted the residuals. We also validated the average accuracy of BEHAVE predictions of flame length and fireline intensity with Fisher's exact test by defining categorical variables from the fire behavior characteristics chart (Rothermel 1983).

RESULTS AND DISCUSSION

Fuel loads varied considerably, while mean fuel moisture was relatively similar across all treatments and within stands (Table 2; see Appendix A for mean fuel conditions for each fire run sampled for each stand). Fuel moisture was underpredicted considerably by fuel sticks deployed within a stand and the protimeter when compared with actual measurements, but estimates from fuel sticks and the protimeter were similar. We found that heat of combustion varied from 14,300 to 19,520 kJ/kg (Table 4) for a percent difference from the often used standard of 18,620 kJ/kg (Pyne et al. 1996) of −23.2 to 4.8, respectively. Al-

Table 4. Mean fuel energy (kJ/kg) sampled prior to growing-season (September 1994) and dormant-season (March 1995) prescribed burns in Ouachita National Forest, Arkansas.

	Fire 1		Fire 2		Fire 3	
Stand[a]	Pre-burn	Post-burn	Pre-burn	Post-burn	Pre-burn	Post-burn
1257D	17,021.98	18,154.89	18,519.68	19,105.83	19,069.70	17,269.50
1257G	17,623.87	17,276.33	17,793.44	17,160.52	14,915.81	17,750.06
1259G	15,476.50	15,250.80	14,467.57	17,785.07	18,666.72	16,137.27
1274D	17,349.22	19,520.03	18,110.76	14,311.95	17,400.09	14,380.23
1274G	18,254.87	18,965.95	17,111.79	17,904.98	17,031.74	14,300.73
1289D	16,788.91	16,004.46	18,442.85	17,685.21	16,988.15	15,954.55
1289G	16,286.74	19,894.21	15,768.91	18,591.78	16,555.40	18,818.45
1313D	18,702.23	18,174.48	18,250.01	15,146.42	18,304.36	18,617.19

[a] Abbreviations: D, dormant-season burn; G, growing-season burn.

exander (1982) suggested that most fuels were within 10% of this figure and that the influence of that amount of variation on fireline intensity is small relative to other parameters. Thus, theoretically our actual heat of combustion on the low end should result in actual fireline intensity to be lower than predicted fuel model outputs using the standard. Weather parameters varied such that we had a good range of conditions under which to compare model performance (Table 2).

Fuels in all stands tended to be heterogeneous and discontinuous, with occasional exposed rock, patches of dense grass, deep pine needles, residual thinning slash, and occasional fallen snags. Fuels in the late growing-season treatments were even more heterogeneous because of patchy distribution of live understory vegetation such as green patches of panicgrass (*Panicum* spp.) basal rosettes interspersed with dense clumps of woody vegetation.

The SITE module of the FIRE1 program in BEHAVE is based on Rothermel's (1972) model and Albini's (1976) additions. It was developed for predicting fire behavior of wildland fires in relatively homogeneous, porous fuels (Rothermel 1983). The program is intended to characterize fine fuels and describe headfires (Rothermel 1983, Andrews 1986). In discontinuous and heterogeneous fuels, the model can produce erroneous predictions (Sneeuwjagt and Frandsen 1977, Brown 1982). Brown (1982) found Rothermel's model accurately predicted rate of spread in sagebrush (*Artemisia* spp.) fuel types; however, the model produced erroneous predictions of flame length and intensity. Sneeuwjagt and Frandsen (1977) determined the model was useful in predicting fire behavior in grasslands but expressed concern about flame length and combustion zone depth inaccuracies. Therefore, part of the variation between observed and predicted fire behavior may be attributed to fuel bed continuity and relative homogeneity.

Our derivation of fireline intensity from estimates of flame length showed a considerable underestimation of fireline intensity compared with actual measurements of inputs for Byram's equation. Plots of residuals for predicted fireline intensity showed that variability of predictions increased with increasing intensity of fires (i.e., longer flame lengths) (Figure 1). Estimates of fireline intensity derived from flame lengths of headfires are problematic because of the subjectivity in estimating headfire flame lengths.

Application of Fuel Models across Seasons

Fire behavior parameters predicted with standard fuel models were constant for all treatments regardless of fuel loads and season of fire, while observed parameters varied depending on the season of the fire and fuel loads (Figure 2a–e). This constancy is linked to the static nature of the fuel models selected to best represent the stand characteristics of the study area, which were not most sensitive to live fuel moisture or loading. Fuels are dynamic, and change by seasons and with time since fire (see Sparks 1996, Sparks et al. 2002). For example, a larger proportion of the fuels are dormant or ''cured'' during dormant-season fires. Second, woody species in the understory are primarily deciduous; therefore, when they are dormant there is an increase in solar radiation and wind exposure on the fuels (Sparks 1996, Sparks et al. 2002). Further, structure of the fuel beds change with each growing season post-fire. Each fuel model is designed to function in a specific fuel type; as fuel characteristics change, so must the fuel models used to predict fire behavior. Therefore, it is essential for managers to understand the dynamics of fuels and which fuel model is appropriate for a given situation (Andrews 1986, Andrews and Chase 1989). Managers must also consider that fuel characteristics in a given stand can change through time, requiring managers to shift to different fuel models to adequately predict the fire behavior for the site for any given time. To appropriately choose a fuel model, managers should use TSTMDL in BEHAVE to validate a fuel model for their particular fuel type (Burgan and Rothermel 1984).

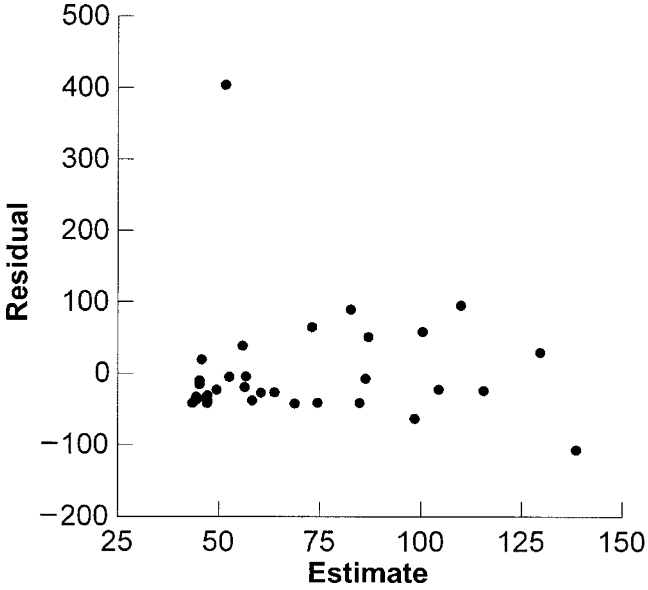

Fig. 1. Regression analysis showing plots of residuals against predicted values of fireline intensity derived from estimates of flame lengths on a series of prescribed burns on the Ouachita National Forest, Arkansas, 1994–1996.

Accuracy of Fuel Models

We examined four standard fuel models (i.e., 7, 8, 9, and 10) that best fit the fuel characteristics of the study area and a separate fuel model customized for each treatment (Table 3). Fuel models 8 and 9 produced unrealistic predictions for all fire behavior parameters regardless of season, and because these fuel models do not consider live fuels—so in essence are dormant-season fuel models—we discarded them from further analysis. None of the fuel models, either standard or customized, produced accurate estimates of all fire behavior parameters across all treatments (Figure 2). Fuel models varied in accuracy depending on fuel loading and season of fire. Therefore, multiple fuel models were required to accurately characterize all fire

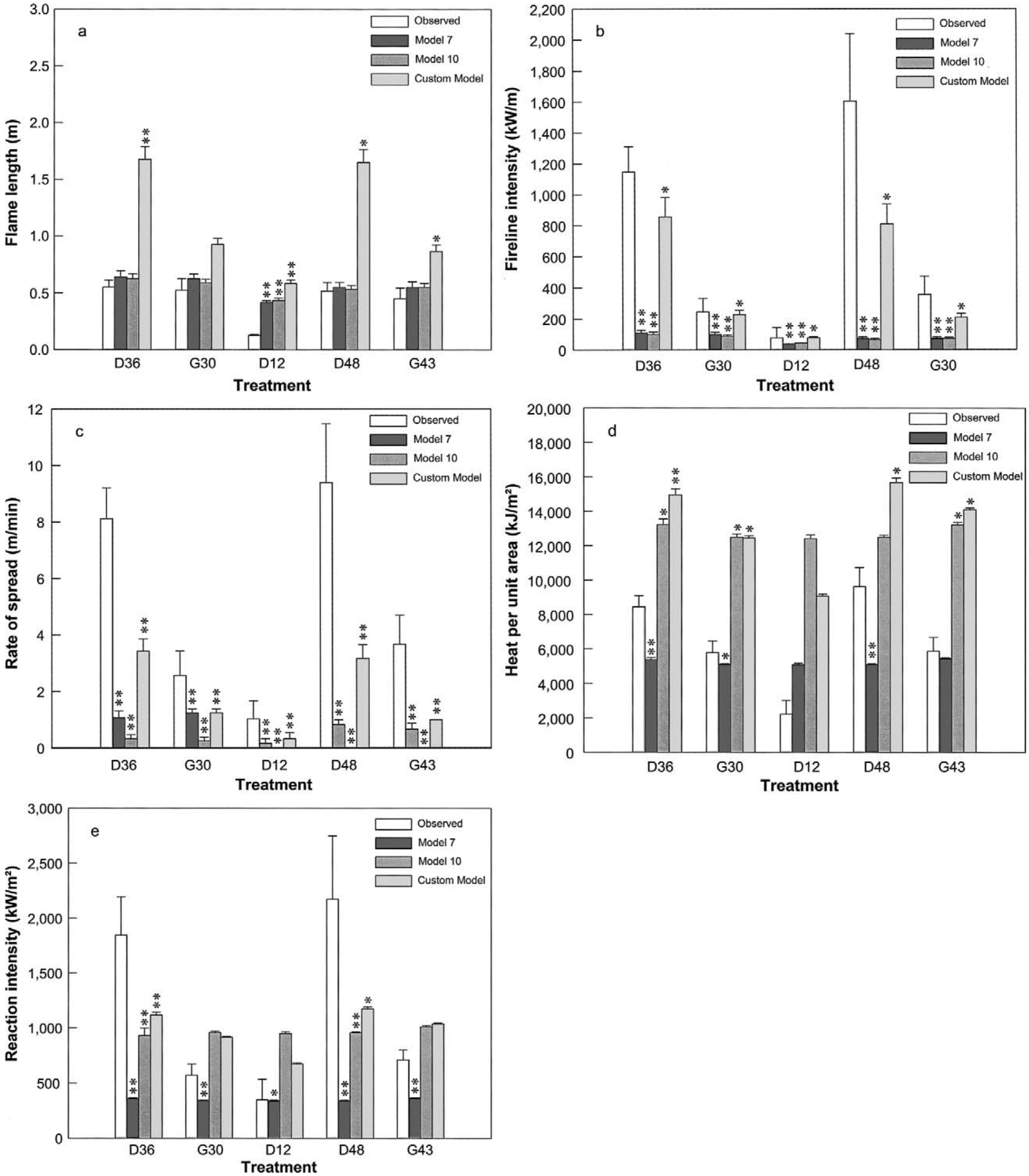

Fig. 2. Means and standard errors by treatment for (a) flame length (m), (b) fireline intensity (kW/m), (c) rate of spread (m/min), (d) heat per unit area (kJ/m^2), and (e) reaction intensity (kW/m^2), Ouachita Mountains, Arkansas, 1994–1996. Asterisks indicate regression results (H_0: slope = 1, given *y*-intercept = 0): * = P = 0.05 to 0.001, ** = $P \leq 0.001$; no asterisk indicates $P \geq 0.05$ (that the model prediction accurately represents observed fire behavior). Treatment: D12, dormant-season burn 12 mo after previous dormant-season burn (n = 6); D36, dormant-season burn 36 mo after previous dormant-season burn (n = 12); D48, dormant-season burn 48 mo after previous dormant-season burn (n = 6); G30, late growing-season burn 30 mo after previous dormant-season burn (n = 12); G43, late growing-season burn 43 mo after previous dormant-season burn (n = 6). Bars are +1 SE.

behavior parameters across fire seasons and fuel loads. Results on the efficacy of fuel models varied with the different statistical analyses (i.e., regression versus Fisher's exact test). For example, fuel model 7 appears to be the most accurate fuel model on average for predicting reaction intensity in the D12 treatment, but fuel model 10 and the custom fuel model are more accurate for analyzing specific fires (Figure 2e). Fuel model 7 would be effective from a management standpoint if numerous predictions were obtained throughout the

Table 5. The r^2-values by treatment and fire behavior parameters for linear regression of observed parameters versus predicted parameters, Ouachita Mountains, Arkansas, 1994–1996.

	Treatment[a] and model														
	D36			G30			D12			D48			G43		
Fire behavior parameter	7	10	Custom	7	10	Custom	7	10	Custom	7	10	Custom	7	10	Custom
Flame length (m)	0.90	0.87	0.90	0.72	0.71	0.72	0.95	0.96	0.94	0.90	0.90	0.92	0.93	0.90	0.90
Fireline intensity (kW/m)	0.75	0.70	0.80	0.63	0.60	0.61	0.19	0.21	0.18	0.72	0.72	0.74	0.77	0.71	0.73
Rate of spread (m/min)	0.77	0.47	0.85	0.54	0.37	0.54	0.01		0.02	0.65		0.82	0.84		0.72
Heat per unit area (kJ/m^2)	0.93	0.93	0.93	0.87	0.87	0.87	0.60	0.61	0.60	0.94	0.94	0.94	0.91	0.91	0.91
Reaction intensity (kW/m^2)	0.72	0.72	0.71	0.75	0.75	0.75	0.40	0.41	0.40	0.75	0.75	0.75	0.93	0.92	0.93

[a] Treatment: D12, dormant-season burn 12 mo after previous dormant-season burn ($n = 6$); D36, dormant-season burn 36 mo after previous dormant-season burn ($n = 12$); D48, dormant-season burn 48 mo after previous dormant-season burn ($n = 6$); G30, late growing-season burn 30 mo after previous dormant-season burn ($n = 12$); G43, late growing-season burn 43 mo after previous dormant-season burn ($n = 6$).

stand, but fuel model 10 and the custom fuel model would be more effective if a limited number of predictions were obtained.

Standard fuel models 7 and 10 produced accurate predictions of flame length for all treatments except the D12 treatment (Figure 2a). However, standard fuel models underestimated fireline intensity and rate of spread in all treatments except for the D12 treatment, for which the customized fuel models and fuel models 7 and 10 predicted fireline intensity similar to observed fireline intensity (Figure 2b, c). Fuel model 7 produced accurate predictions of heat per unit area more often than other models for late growing-season fires, while custom fuel models tended to overpredict heat per unit area (Figure 2d, e). Fuel model 7 was most effective at predicting reaction intensity of D12 stands, while fuel model 10 and the custom models proved more effective on average and on an individual basis for all other treatments (Figure 2e). Fuel models produced similar r^2-values within similar treatments (Table 5).

All fuel models failed to produce accurate predictions for fireline intensity and rate of spread (Figure 2b, c). Analysis of residuals indicated that all fuel models tended to overpredict fireline intensity on low-intensity fires while underpredicting on higher-intensity fires. We found an inconsistent relationship between observed and predicted fireline intensity based on low r^2-values for fireline intensity (Table 5). Observed rate of spread and fireline intensity may have been greater than predicted because the headfire may have been influenced by backing fires. Strip headfires were set and allowed to burn into backing fires, creating a situation similar to a ring fire, a common firing technique in the southeastern United States (Wade and Lunsford 1989). Wind speeds in the actively burning area can increase because of the convection created by ring fires (Wade and Lunsford 1989); we attempted to monitor these winds at 2 m, but were unsuccessful. Therefore, fire behavior may have been influenced by these convection winds not measured in our pre-burn weather observations. Adjustments to BEHAVE may be needed for this influence in small-scale ring fires (Masters and Engle 1994).

Because of the mountainous terrain of the region, wind speeds away from the fire were also variable in all stands, constantly shifting directions and varying speed. We attempted to monitor this variability but were unsuccessful. As a result of live vegetation in the growing season and variable shading from the dense midstory, fuel moisture was also quite variable within stands. A portion of the large variation between observed and predicted fire parameters was a result of the inherent variation of the advancing fire front, which varies with fuel moisture, and wind speed (Brown and Davis 1973, Trollope 1984).

In the D12 treatment, BEHAVE failed to produce accurate predictions and high r^2-values for nearly all fire behavior parameters (Table 5). Unlike other treatments, this treatment had only 1 y of fuel buildup, with fuels consisting primarily of freshly fallen conifer needles with little cured herbaceous material and hardwood leaf litter. Unweathered conifer needles, such as those found in this treatment, often act like 10-h timelag fuels or greater (Anderson 1990). Hartford and Rothermel (1991) noted unweathered organic coatings on freshly cast conifer needles as a likely cause of slow moisture response in the 1988 fires in Yellowstone National Park.

MANAGEMENT IMPLICATIONS

If BEHAVE can accurately predict fire behavior parameters before ignition, managers can prescribed burn with more efficacy and yet reduce the risks involved. Fireline intensity, heat per unit area, and reaction intensity relate to fire effects on vegetation (Van Wagner 1973, Rothermel and Deeming 1980, Alexander 1982, Wright and Bailey 1982, Wade 1986, Engle et al. 1996). Wade (1986) recommended using fireline intensity for correlating fire behavior effects above the flame zone, reaction intensity within the flame zone, and heat per unit area for belowground effects. Flame length, which is related to fireline intensity, is a good predictor of scorch height on conifers (Van Wagner 1973). Fireline intensity and flame length are also excellent indicators of the difficulty of control, potential for escapes, and equipment required for suppression (Roussopoulos and Johnson 1975, Rothermel 1983, Pyne et al. 1996). With accurate fuel models, prescribed burn practitioners can set goals and identify parameters within which a given heat per unit area, reaction intensity, and fireline intensity will best achieve their management objectives. Using the fire behavior characteristics chart (Rothermel 1983), practitioners can also determine the equipment required to suppress or maintain the fire fronts.

Headfires with fireline intensity <345 kW/m (flame length <1.2 m) can generally be attacked at the head by persons using hand tools (Rothermel 1983). Headfires with a fireline intensity >345 kW/m (flame length <2.5 m) are too intense for direct attack on the head by persons using hand tools and require equipment such as plows, dozers, pumpers, and retardant aircraft (Rothermel 1983). Our fires produced intensities and flame lengths in both of these categories (Figure 2a, b). In treatments D48 and D36, fuel models 10 and 7 were more accurate than custom fuel models at predicting flame length within the correct fire behavior classification ($P \leq 0.001$). However, custom fuel models were more accurate than other models at predicting fireline intensity in treatments D36 and D48 ($P \leq 0.001$).

CONCLUSIONS

BEHAVE can provide accurate predictions of fire behavior for use in defining prescribed burning windows when the proper fuel model is selected. This is particularly important when managing for endangered species because specific fire behavior parameters may be used to predict the influence on habitat variables. However, managers must proceed with caution because the appropriate fuel model varies with season of fire and fuel loading. Therefore, managers must identify or customize the appropriate fuel model. Furthermore, fuel model accuracy varies among fire behavior parameters, so managers should use more than one fuel model to predict relevant fire behavior parameters and to produce a range of fire behavior within which a specific fire may fall. Because fuels vary widely between seasons, managers should interpret predictions with caution and perform multiple analyses for each burn situation. The additional fuel models for a wider range of fuel conditions in BehavePlus 3.0.2 (Scott and Burgan 2005), plus the greater flexibility for inputs of actual values for various fuel parameters, show promise in providing managers with more realistic predictions of fire behavior under variable fuel conditions. However, field validation for specific sites is imperative.

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Appendix A. Mean fuel conditions during prescribed fires in wildlife stand improvement areas, Ouachita National Forest of western Arkansas, 1994–1996.

		Moisture (%)			Fuel load (kg/ha)			
Stand[a]	Fire	1-h dead	Fine live	10-h dead	1-h dead	Fine live	10-h dead	Post-burn residual
1257CD	1	23	184	37	10,070	294	350	5,980
	2	24	135	48	12,030	198	340	6,900
	3	24	114	39	13,805	188	1,565	6,485
1257D	1	16	120	28	9,960	200	687	4,472
	2	11	63	14	10,013	153	1,727	6,740
	3	9	45	6	10,728	160	200	6,673
1257G	1	11	101	18	9,344	1,074	2,511	6,820
	2	11	121	43	8,656	732	1,902	9,868
	3	12	121	53	9,102	1,053	1,029	8,520
1259G	1	14	101	22	8,080	1,072	1,056	5,712
	2	8	113	40	7,668	889	728	4,892
	3	10	115	31	8,888	1,416	848	6,240
1265CG	1	13	104	40	7,293	423	350	5,153
	2	14	127	36	8,460	827	857	6,053
	3	10	127	19	8,083	363	1,703	5,200
1274CG	1	10	113	51	7,613	495	77	5,747
	2	6	86	8	7,432	650	643	5,627
	3	11	110	17	7,527	1,007	703	3,433
1274D	1	12	128	26	9,247	73	1,080	3,993
	2	15	117	15	8,413	307	1,140	5,147
	3	16	120	14	6,767	283	577	6,107
1274G	1	15	105	23	7,896	870	1,212	6,256
	2	25	117	29	6,136	942	1,573	4,564
	3	8	102	11	4,864	816	280	2,432
1289D	1	22	143	29	8,180	220	1,380	4,987
	2	45	117	55	6,580	263	963	3,273
	3	20	163	45	8,260	380	1,113	3,233
1289G	1	28	92	29	8,492	1,018	1,752	5,304
	2	12	94	40	5,940	1,227	883	4,227
	3	24	100	58	5,592	1,892	156	6,028
1313CD	1	28	128	33	13,305	330	910	9,555
	2	21	114	28	8,895	75	960	5,165
	3	12	153	38	13,465	145	1,070	8,015
1313D	1	19	113	26	9,300	422	474	4,336
	2	18	138	33	10,180	366	1,436	5,448
	3	29	143	31	11,352	200	720	6,300

[a] Abbreviations: D, dormant-season burn; G, growing-season burn.