AN EVALUATION OF HARDWOOD FUEL MODELS FOR PLANNING PRESCRIBED FIRES IN OAK SHELTERWOOD STANDS

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Abstract.—The shelterwood burn technique is becoming more accepted and used as a means of regenerating eastern mixed-oak (*Quercus* spp.) forests on productive upland sites. Preparation is important to successfully implement this method; part of that preparation is selecting the proper fuel model (FM) for the prescribed fire. Because of the mix of leaf litter and logging slash, FMs 6, 8, 9, 10, and 11 may be appropriate representations of oak shelterwood stands for planning prescribed fires. This study compares fire behavior in oak shelterwood stands to BehavePlus-generated predictions for these FMs. BehavePlus most accurately predicted flame lengths and rates of spread with FM 11. When FM 6 was used, BehavePlus overestimated fire behavior. With FMs 8 and 9, BehavePlus consistently underestimated fire behavior, and with FM 10 BehavePlus produced overestimations and underestimations with no discernible pattern. When planning prescribed fires in oak-dominated shelterwood stands, resource managers should use either FM 11 to predict average fire behavior or FMs 6 and 9 to predict maximum and minimum fire behaviors.

INTRODUCTION

Throughout the eastern United States, resource managers increasingly use prescribed fire to regenerate, restore, and sustain upland oak (*Quercus* spp.) forests (Dickinson 2006, Hutchinson 2009, Van Lear and Brose 2002, Yaussy 2000). A popular regeneration method to use when oak seedlings are dense is to proceed with stand renewal via the shelterwood-burn technique (Brose et al. 1999, Van Lear and Brose 2002). This technique entails integrating a moderate- to high-intensity prescribed fire between the first and final removal cuts of a two-step shelterwood sequence (Brose et al.1999, Van Lear and Brose 2002). Because of the harvest – burn – harvest order of this method, identifying the fuel model (FM) that accurately portrays an oak shelterwood stand is necessary to plan a safe and successful prescribed fire.

An FM is a numerical description of the herbaceous and woody material available for burning in fire-prone ecosystems. These models provide fuel data for fire behavior prediction systems (Pyne et al. 1996). FMs contain parameters for loading the four fuel diameter classes (Fosberg 1970), height of the fuel bed, surface area to volume ratio, and moisture of extinction threshold. Rothermel (1972) developed the first 11 FMs (3 grass, 2 shrub, 3 timber, and 3 logging slash) for use in his fire spread model, and Albini (1976) added 2 additional shrub models. Anderson (1982) published a photo series describing these 13 FMs in detail. That series is widely used to help select the appropriate model for many common fire-prone ecosystems. Scott and Burgan (2005) developed 40 more FMs to supplement the original 13 FMs. These new FMs cover unrepresented fuel types and include dynamic moisture content for live herbaceous vegetation.

One purpose of FMs is to use them, in conjunction with topographic and weather data, in fire behavior prediction systems such as BEHAVE (Andrews 1986, Andrews and Chase 1989) and FARSITE (Finney 1998). These computer-based systems generate estimates of several fire-line characteristics (flame length [FL], rate of spread [ROS], and heat energy output) that are critical

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to successfully implementing a prescribed fire or safely suppressing a wildfire. These fire behavior prediction systems can also be used to determine which FM is the most accurate representation of a fire-prone ecosystem. Testing of the common hardwood FMs in this manner is limited.

Grabner et al. (2001) used Behave to generate ROS predictions for FMs 1 (short grass), 2 (timber and grass), 3 (tall grass), and 9 (loose leaf litter) in oak savannas in Missouri. They found that Behave generated reasonable ROS estimates for all FMs at wind speeds slower than 10 feet per minute, but at faster wind speeds Behave accurately predicted ROS for FM 2 only. In North Carolina, Phillips et al. (2006) used FARSITE to determine which FM portrayed mountain laurel (*Kalmia latifolia*), an ericaceous shrub that forms thickets in mixed-oak forests of the Appalachian Mountains. They found that none of the shrub FMs were viable representatives of mountain laurel thickets and concluded that a custom FM needed to be developed for that plant community.

Oak shelterwoods are another environment that may not be adequately characterized by any of the hardwood FMs, because two major fuel types are present: leaf litter and dry logging slash. This study analyzes data from Brose (1997) using BehavePlus (Andrews et al. 2005) to determine which of the 13 standard FMs (Anderson 1982) is the most accurate representation of oak shelterwood stands undergoing regeneration via the shelterwood-burn technique. I limited my pool of potential FMs to the original 13 because these are widely used by wildland fire professionals. I also focused only on FMs that are either commonly used to represent hardwood environments or were relatable to partly cut stands. Selected FMs include FM 6 (hardwood slash), FM 8 (compacted leaf litter), FM 9 (loose leaf litter), FM 10 (litter and timber), and FM 11 (light logging slash). Finally, I focused on FL and ROS because these are of utmost importance to wildland fire professionals in the region. Knowing which FM to use when planning prescribed fires in oak shelterwoods will help resource managers more safely and successfully use the shelterwood-burn technique when regenerating mixed-oak forests on productive upland sites.

METHODS

Study Site

The field portion of this study was conducted at the Horsepen Lake Wildlife Management Area in the Piedmont of central Virginia. This area consists of broad, gently rolling hills on sandy loam soils (Reber 1988). The climate is warm continental with 50 inches of precipitation distributed evenly throughout the year and an average growing season of 190 days. The area is presently owned and managed by the Virginia Department of Game and Inland Fisheries (VDGIF).

In 1994, three oak shelterwood stands on productive upland soils (oak site index$_{50}$ ranged from 70 to 80 feet) were selected for an oak regeneration study (Brose 1997). The VDGIF created these shelterwoods between 1990 and 1992 by salvaging trees that had been injured or killed by an ice storm in 1989. Harvesting reduced basal areas to an average of 50 square feet per acre in each shelterwood. Slash was left in place after the harvest. Each shelterwood was 20-50 acres and was dominated (67 percent of residual basal area) by four upland oak species: black (*Q. velutina*), northern red (*Q. rubra*), scarlet (*Q. coccinea*), and white (*Q. alba*). Other hardwoods present in these stands included American beech (*Fagus grandifolia*), blackgum (*Nyssa sylvatica*), flowering dogwood (*Cornus florida*), hickory (*Carya* spp.), red maple (*Acer rubrum*), and yellow-poplar (*Liriodendron tulipifera*).

Table 1.—Site attributes of the nine oak shelterwood burn units in central Virginia and the dates, times, and preburn weather conditions of the nine prescribed fires. These data were used in the BehavePlus program to predict flame length and rate of spread for each of the five hardwood fuel models examined in this study.

Attribute/condition	Prescription fire 1	Prescription fire 2	Prescription fire 3
Slope (%)	10	5	5
Aspect	NE	E	E
Burn date	25 Feb 1995	27 Feb 1995	27 Feb 1995
Time of burn	1300	1100	1430
Air temperature (°F)	46	43	48
Relative humidity (%)	26	52	44
Wind direction	NW	E	E
Wind speed (mph)	4	1	2
Cloud cover (%)	0	100	100
	Prescription Fire 4	Prescription Fire 5	Prescription Fire 6
Slope (%)	7	5	10
Aspect	E	SW	E
Burn date	26 Apr 1995	26 Apr 1995	26 Apr 1995
Time of burn	2000	1630	1830
Air temperature (°F)	68	73	70
Relative humidity (%)	28	20	20
Wind direction	SW	SW	SW
Wind speed (mph)	1	5	3
Cloud cover (%)	0	0	0
	Prescription Fire 7	Prescription Fire 8	Prescription Fire 9
Slope (%)	3	10	5
Aspect	NE	W	NW
Burn date	24 Aug 1995	24 Aug 1995	24 Aug 1995
Time of burn	1630	1430	1230
Air temperature (°F)	92	95	95
Relative humidity (%)	46	44	46
Wind direction	SW	SW	SW
Wind speed (mph)	0	5	8
Cloud cover (%)	0	0	0

Fuel Sampling Procedures

Each shelterwood stand was divided into four equally sized units; three units were designated for burning in different seasons (spring, summer, and winter). Near the center of each burn unit, a 100-foot × 150-foot plot, visually judged to represent average fuel conditions, was located for measuring the flaming front. The slope and aspect of each burn unit were determined with a clinometer and compass, respectively (Table 1).

Within each fire behavior plot, 11 fuel inventory transects were systematically installed to uniformly sample the area. Each transect was 50 feet long and was inventoried for woody fuels using the planar-intersect method (Brown 1974). Sound woody fuels (those not in an advanced state of decay) were tallied by the time-lag size classes of Fosberg (1970). One-hour fuels were smaller than 0.25 inch in diameter; 10-hour fuels were 0.25 to 1 inch in diameter. These two size classes were tallied along the proximal 6-foot section of each transect. Hundred-hour fuels were 1-3 inches in diameter and were tallied along the distal 12-foot section of each transect. Fuels larger than 3-inch diameter and rotten woody fuels of all sizes were ignored because these are not used in the standard FMs (Anderson 1982). For each transect, the woody fuel counts in each time-lag class were converted to tons per acre using established fuel equations (Brown 1974) and hardwood-specific gravities (Anderson 1978). For each fire behavior plot, a mean fuel loading for each time lag class was calculated by summing the appropriate loading of each transect and dividing by the number of transects.

Litter loading was measured by collecting two 1.36-square-foot samples per transect of the Oi and Oe horizons. Samples were collected near the midpoint and distal end of each transect. The samples included the leaf litter, dead herbaceous plants, and woody material smaller than 1 inch in diameter found among the leaves. Live herbaceous matter was excluded because it is not part of the selected FMs (Anderson 1982). Samples were dried at 122 °F for 72 hours then weighed on an electronic scale to the nearest 0.1 ounce. The masses of the two leaf litter samples from each transect were averaged, and the average was converted to tons per acre. Transects in the winter and spring burn units were inventoried for litter fuels and woody fuels in February 1995; those in the summer burn units were inventoried in August 1995.

Several weeks before each prescribed fire, I placed a 10-hour fuel moisture stick in each fire behavior plot so it could acclimate to the environmental conditions. Within 1 hour before each prescribed fire, the fuel moisture stick was weighed with a hand scale to determine the percent moisture content. One-hour fuel moisture content was calculated from the 10-hour fuel moisture content using conversion tables in the Fireline Handbook (National Wildfire Coordinating Group 1989). Fuel moisture for the 100-hour fuels was measured using a moisture probe by sampling twelve 100-hour fuels suspended within 1 foot of the ground.

The Prescribed Fires

VDGIF personnel conducted each prescribed fire in accordance with department policy and state law. The fires occurred on February 25 and 27 (winter), April 26 (spring), and August 24 (summer), 1995. Weather was monitored with a belt weather kit. Air temperature, cloud cover, relative humidity, wind direction, and wind speed were recorded at the beginning of each prescribed fire (Table 1).

All prescribed fires were lighted using drip torches in a strip head-fire ignition pattern beginning at the downwind side of the burn block. Initial strips were 5-10 feet apart, but these widened to 150 feet once the control lines were secured. As ignitors neared the fire behavior plot, a strip was lighted 20-30 feet outside the plot on the downhill or upwind side and allowed to burn through the plot. FLs were measured (in feet) by photographing the flaming front as it passed five trees previously marked with paint at 1-foot intervals to a height of 5 feet (Rothermel and Deeming 1980). ROS was calculated by marking, timing, and measuring five 2-minute runs with a stopwatch. The five FL measurements were combined to calculate a mean FL for each prescribed fire. Similarly, a mean ROS was calculated for each prescribed fire based on the five ROS measurements of that burn.

Statistical Analysis

For the initial comparison of FMs 6, 8, 9, 10, and 11 to the oak shelterwoods, I used T-tests with unequal variances (Ott 1993) to test whether published fuel loadings and fuel-bed depths (Anderson 1982) were different from the mean fuel loadings and fuel-bed depths found in the oak shelterwoods. I further compared the five FMs by using analytical techniques developed by Smith and Rose (1995) and Sneeuwjagt and Frandsen (1977). I used BehavePlus (Andrews et al. 2005) to predict the average FL and ROS for each of the nine prescribed fires based on each of the five FMs and the weather conditions, site characteristics, and fuel moistures recorded just before each prescribed fire. The nine predicted FL and ROS outputs of each FM were then regressed on the mean FL and ROS measurements of the nine prescribed fires. Scatter plots were used to graphically represent the deviation of the BehavePlus-generated FL and ROS predictions for each FM from the actual measured values. Perfect agreement between predicted and measured FL and ROS values resulted in a diagonal line with an intercept of zero (0) and a slope of one (1). Deviation from this optimal line showed where a FM overestimated or underestimated FL and ROS.

I used regression on the observed and predicted FL and ROS values to determine their linear equations and coefficients of variation (r^2). This value provides a measure of consistency; a higher r^2 indicates more consistency among the predicted outputs than a lower r^2 (Smith and Rose 1995, Sneeuwjagt and Frandsen 1977). Finally, I calculated the mean relative difference between the observed and predicted FL and ROS for each FM (Smith and Rose 1995, Sneeuwjagt and Frandsen 1977). This metric quantifies how much an overestimation or underestimation differs from the observed on a percent scale. It is calculated by subtracting the predicted FL or ROS from the observed FL or ROS, dividing that difference by the observed FL or ROS, then multiplying that quotient by 100.

RESULTS

The nine burn units were quite similar to each other (Table 2). Each had a complete covering of leaf litter that contributed 2.1-3.3 tons per acre to the total fuel loading. The summer burn units had leaf litter loadings that were approximately 25 percent lower than those of the winter and spring burn units. Each burn unit had 80-85 percent of its woody fuels in the 100-hour size class. Total fuel loadings for the nine burn units were 9.9-16.0 tons per acre. Fuel moisture content varied among the nine burn units from 5-20 percent.

The fuels data from the nine burn units were combined to calculate the mean fuel loadings and fuel-bed depth for an oak shelterwood, and those means were compared to fuel characteristic values of the five FMs (Table 3). The oak shelterwood had a fuel-bed depth of 0.9 feet. This was shallower than that of FM 6 (2.5 feet), deeper than that of FMs 8 and 9 (0.2 feet for each), and the same as that of FMs 10 and 11 (1.0 foot each). The oak shelterwood contained 10.84 tons per acre of litter and woody fuels. The fuel loading was concentrated in the 100-hour and 1-hour size classes, which averaged 6.74 and 2.98 tons per acre, respectively. The balance, 1.12 tons per acre, was in the 10-hour size class. In the 1-hour size class, FMs 9 (2.92 tons per acre) and 10 (3.01 tons per acre) did not differ from the oak shelterwood mean of 2.98 tons per acre; the other three FMs had considerably lighter loadings at 1.50 tons per acre for each. In the 10-hour size class, FM 9 had lower loading (0.41 tons per acre) and FMs 6, 10, and 11 had higher loading (2 to 4.51 tons per acre) than oak shelterwood mean of 1.12 tons per acre. FM 8, at 1 ton per acre, did not differ from the oak shelterwood. In the 100-hour size class, all FMs had loadings that were lower than the 6.74 tons per acre calculated for the oak shelterwood, but only those of FMs 6, 8, and 9 were statistically different.

Table 2.—Fuel loadings and moistures of the nine oak shelterwood burn units in central Virginia

Fuel or site attribute	Prescription fire 1	Prescription fire 2	Prescription fire 3
Litter cover (%)	100	100	100
Leaf litter (tons/acre)	3.3 ± 0.3	3.3 ± 0.3	3.1 ± 0.3
1-hour fuels (tons/acre)	0.3 ± 0.1	0.4 ± 0.1	0.4 ± 0.1
10-hour fuels (tons/acre)	0.6 ± 0.1	1.7 ± 0.2	0.8 ± 0.2
100-hour fuels (tons/acre)	4.7 ± 0.8	7.7 ± 1.3	5.2 ± 1.0
Total fuels (tons/acre)	9.9	14.1	10.5
1-hour fuel moisture (%)	6	12	12
10-hour fuel moisture (%)	10	15	15
100-hour fuel moisture (%)	18	20	20
	Prescription fire 4	Prescription fire 5	Prescription fire 6
Litter cover (%)	100	100	100
Leaf litter (tons/acre)	3.1 ± 0.3	3.3 ± 0.3	3 ± 0.3
1-hour fuels (tons/acre)	0.4 ± 0.1	0.6 ± 0.1	0.5 ± 0.1
10-hour fuels (tons/acre)	0.7 ± 0.1	1.7 ± 0.2	0.8 ± 0.2
100-hour fuels (tons/acre)	5.2 ± 0.8	9.4 ± 1.3	6 ± 1
Total fuels (tons/acre)	10.4	16	11.3
1-hour fuel moisture (%)	9	5	7
10-hour fuel moisture (%)	10	10	10
100-hour fuel moisture (%)	12	12	12
	Prescription fire 7	Prescription fire 8	Prescription fire 9
Litter cover (%)	100	100	100
Leaf litter (tons/acre)	2.4 ± 0.3	2.6 ± 0.3	2.1 ± 0.3
1-hour fuels (tons/acre)	0.4 ± 0.1	0.2 ± 0.1	0.4 ± 0.1
10-hour fuels (tons/acre)	0.7 ± 0.1	2.2 ± 0.2	0.9 ± 0.2
100-hour fuels (tons/acre)	6.4 ± 0.8	9.3 ± 1.3	6.8 ± 1
Total fuels (tons/acre)	9.9	14.3	10.2
1-hour fuel moisture (%)	11	9	9
10-hour fuel moisture (%)	10	15	15
100-hour fuel moisture (%)	14	14	14

Table 3.—Fuel-bed characteristics of oak shelterwoods (mean ± 1 standard error) in central Virginia, along with potentially suitable hardwood fuel models. Fuel model values marked by an asterisk (*) are different from the corresponding oak shelterwood mean at the 0.05 level.

	Fuel loading in tons/acre				
Fuel model	1-hour	10-hour	100-hour	Total	Fuel-bed depth (feet)
Oak shelterwood	2.98 ± 0.32	1.12 ± 0.19	6.74 ± 1.58	10.84 ± 0.77	0.9 ± 0.2
6 (dormant brush)	1.50*	2.50*	2.00*	6.00*	2.5*
8 (compact litter)	1.50*	1.00	2.50*	5.00*	0.2*
9 (loose litter)	2.92	0.41*	0.15*	3.48*	0.2*
10 (timber and litter)	3.01	2.00*	5.01	10.02	1.0
11 (light slash)	1.50*	4.51*	5.51	11.52	1.0

Table 4.—Linear equations and associated r^2 values created by regressing the BehavePlus-generated flame length (FL) and rate of spread (ROS) predictions for the five hardwood fuel models on the measured fire behavior during the nine prescribed fires. Over/under refers to BehavePlus's overprediction (+) or underprediction (–) of the FL and ROS relative to the measured fire behavior during the prescribed fires.

Fuel model number and description	FL equation	FL r^2	Over/under	ROS equation	ROS r^2	Over/under
06 (hardwood slash)	1.151 + 0.823x	0.791	+32%	1.857 + 1.378x	0.695	+50%
08 (compacted litter)	0.141 + 0.188x	0.799	–281%	0.206 + 0.123x	0.757	–420%
09 (loose litter)	0.706 + 0.271x	0.737	–52%	0.346 + 0.453x	0.917	–72%
10 (litter and timber)	1.611 + 0.711x	0.405	+34%	1.100 + 0.707x	0.430	–22%
11 (light slash)	0.625 + 0.851x	0.745	+15%	0.200 + 0.839x	0.892	–18%

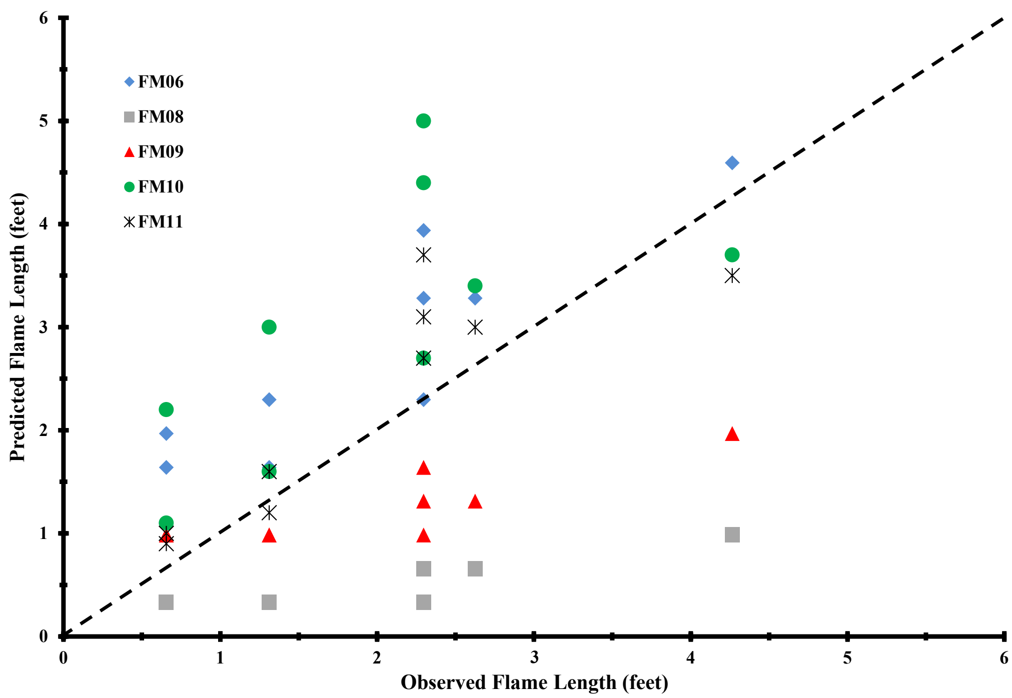

Figure 1.—The predicted flame lengths of fuel models 6, 8, 9, 10, and 11 regressed onto the flame lengths observed in nine prescribed fires conducted in oak shelterwood stands in central Virginia. The black diagonal line marks perfect agreement of the observed and predicted flame lengths. Fuel model predictions of flame length above and below this line are overestimations and underestimations, respectively.

Of the five FMs, FM 10 was the most similar to the oak shelterwood. It differed only in the 10-hour fuel loading; 2.0 tons per acre compared to 1.12 tons per acre for the oak shelterwood. FM 11 was also quite similar to the oak shelterwood; it differed in the 1-hour size class at 1.50 versus 2.98 tons per acre, and in the 10-hour size class at 4.51 versus 1.12 tons per acre. FM 6 was the most dissimilar fuel model relative to the oak shelterwood. It differed in loading in all fuel size classes, in total fuel loading, and in fuel-bed depth. FM 8 agreed with the oak shelterwood only in terms of 10-hour fuel loading; FM 9 agreed only in terms of the 1-hour fuel loading.

Regressing the BehavePlus-generated FL prediction derived from each FM onto the mean observed FL of each prescribed fire showed that BehavePlus outputs for FM 11 most closely match those of the oak shelterwood (Fig. 1, Table 4). For FM 11, BehavePlus overestimated FL by an average of 15 percent. Furthermore, the FL predictions consistently tracked changes in observed FL as evidenced by an r^2 value of 0.745. BehavePlus also overestimated FL when

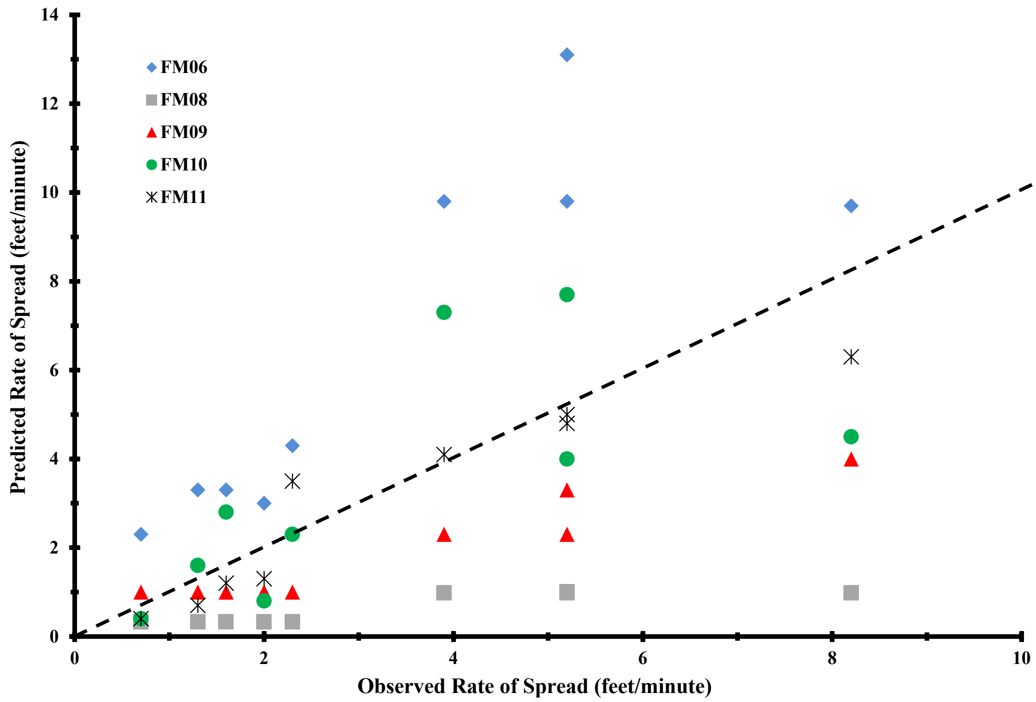

Figure 2.—The predicted rates of spread of fuel models 6, 8, 9, 10, and 11 regressed onto the rates of spread observed in nine prescribed fires conducted in oak shelterwood stands in central Virginia. The black diagonal line marks perfect agreement of the observed and predicted rates of spread. Fuel model predictions of rate of spread above and below this line are overestimations and underestimations, respectively.

using FMs 6 and 10, by averages of 32 percent and 34 percent, respectively. Of these two FMs, FL estimates based on FM 6 were more consistent than those of FM 10 (r^2 of 0.791 and 0.405, respectively). Conversely, BehavePlus underestimated FL by an average of 52 percent when using FM 9 and by approximately 280 percent when using FM 8. The predictions became especially erroneous for both when the actual FL exceeded 2 feet. The consistency of the BehavePlus FL predictions using FMs 8 and 9 was quite strong with respective r^2 values of 0.737 and 0.799.

Like FL, BehavePlus estimates of ROS from FM 11 most closely matched those measured in the oak shelterwood burn units (Fig. 2, Table 4). ROS predictions derived from FM 11 were, on average, underestimated by 18 percent. These predictions were also strongly consistent with an r^2 value of 0.892. BehavePlus produced underestimates of ROS when using FM 8 and 9; those of FM 9 were more accurate than those of FM 8 at -72 percent versus -420 percent, respectively. Both sets of predictions were strongly consistent, however, with an r^2 of 0.757 for FM 8 and 0.917 for FM 9. When using FM 6, BehavePlus consistently overestimated ROS by 2-8 feet per minute relative to those measured in the oak shelterwood burn units. This resulted in an average overestimation of 50 percent and an r^2 of 0.695. BehavePlus estimates of ROS were inconsistent when using FM 10. Three times BehavePlus estimates of ROS were well matched to those of the oak shelterwood, but three times it overestimated ROS and three times it underestimated ROS. Consequently, the underestimation was only 22 percent, but the r^2 value was 0.43.

DISCUSSION

Of the 13 standard FMs, five (FMs 6, 8, 9, 10, and 11) have attributes that make them potentially suitable for modeling fire behavior in oak shelterwoods on productive upland sites. Of these five, FM 11 (light slash) appears to best represent the fuel conditions that occur in an oak shelterwood based on fuel-bed characteristics and agreement between BehavePlus estimates of FL and ROS and measured fire behavior. FM 11's 100-hour fuel loading, total fuel loading, and fuel-bed depth were quite similar to those found in an oak shelterwood. The oak shelterwood had more 1-hour fuel loading and less 10-hour fuel loading than FM 11. These are likely due to the combining the leaf litter loading with the 1-hour fuel loading and the fact that the oak shelterwoods were 2-4 years old and some of the small branches of the logging slash would have decayed. The agreement of the observed and predicted FLs and ROSs further indicate the appropriateness of FM 11 as a representation of an oak shelterwood. On average, FL was overestimated by 15 percent and ROS was underestimated by 18 percent. The r^2 values for both parameters (0.745 for FL and 0.892 for ROS) indicate that the predictions were quite consistent. The FM 11 predictions closely matched the measurements in the fire behavior plots.

FM 6 represents dormant shrubs but is also used for hardwood slash (Anderson 1982). In this regard it is a potential FM for oak shelterwoods. In 17 of 18 comparisons, BehavePlus overestimated FL by 32 percent and ROS by 50 percent when using FM 6, even though it has only about half the total FL of the oak shelterwoods (6.00 tons per acre versus 10.84 tons per acre). For FL, these overestimations were fairly consistent across all nine prescribed fires (r^2 = 0.791), and the differences between observed ROS and predicted ROS tended to increase as observed ROS increased (r^2 = 0.695). These results are likely due to the differences in fuel-bed depth and orientation between FM 6 and the oak shelterwoods. FM 6 has a vertically oriented 2.5-foot deep fuel bed (Anderson 1982); an oak shelterwood has a horizontally oriented < 1-foot deep fuel bed. Fires burn hotter and move faster through vertically oriented fuel beds than through horizontally oriented fuel beds (Pyne et al. 1996). Consequently, BehavePlus produced overestimations for both fire behavior parameters when using FM 6.

FM 10 (litter and timber) represents a broad range of forest conditions (insect- or disease-ridden stands, windthrown stands, overmature stands with deadfall, and aged partial harvests) that have accumulated 100-hour and larger fuels in their understories (Anderson 1982). This FM appears to be a good representation of oak shelterwoods because the published fuel-bed characteristics are quite similar to those measured in the oak shelterwoods. For example, FM 10 has 3 tons per acre of 1-hour fuels, 5 tons per acre of 100-hour fuels, 10 tons per acre of total fuels, and a fuel-bed depth of 1 foot. The oak shelterwoods averaged 2.98, 6.74, 10.84, and 0.90 feet, respectively, for these same fuel-bed attributes. BEHAVE-generated predictions of FLs and ROSs for FM 10, however, did not match up well with observed fire behavior in the oak shelterwoods. In four of the nine comparisons, BehavePlus substantially overestimated FLs when using FM 10, and its ROS predictions had no discernible trend (three overestimations, three underestimations, and three close matches). These inconsistencies are apparent in the r^2 values: 0.405 for FL and 0.430 for ROS. The disagreement between FM 10 and the oak shelterwoods in terms of FL may result from their differences in the 10-hour fuel loading; 2.00 tons per acre for FM 10 and 1.12 tons per acre for the shelterwood. Similarly, the differences in ROS between the two may be due to FM 10 containing a live fuel component of 2 tons per acre (Anderson 1982). No such live fuel component was present in the oak shelterwoods.

FMs 8 and 9 represent litter-dominated fuel beds (Anderson 1982). Generally, FM 8 is associated with forest types such as northern hardwoods whose leaves form a compact mat on the forest floor. FM 9 refers to mixed-oak forests whose leaves create and maintain a loose litter bed. This difference in litter composition and arrangement is manifested in their 1-hour fuel loadings: FM 8 has 1.50 tons per acre and FM 9 has 2.92 tons per acre. Also in play is how well they compare to the observed fire behavior in the oak shelterwoods. When using either fuel model, BehavePlus underestimated FL and ROS relative to what was measured, but its predictions based on FM 8 were closely accurate at only the lowest FLs and ROSs (< 1 foot and < 1 foot per min, respectively). As FL and ROS increased, BehavePlus predictions based on FM 8 became increasingly inaccurate resulting in mean relative differences of -281 percent and -420 percent. When using FM 9, BehavePlus estimated FLs and ROSs that were consistently lower than what was measured (-52 percent and -72 percent), but not to the degree of FM 8. These estimations are low because these two FMs lack the woody fuel component in the 10-hour and 100-hour size classes, and the fuel-bed depth is less than 25 percent of what was measured.

Forest managers who intend to use the shelterwood-burn technique in mixed-oak stands should use FM 11 to represent fuel-bed conditions. Of the five FMs examined in this study, BehavePlus most closely predicted FLs and ROSs when using FM 11 and did so consistently in all nine prescribed fires. Conversely, FM 8 should not be used. It is a poor match for an oak shelterwood as evidenced by the model's chronic and increasing underestimation of FL and ROS as both of these fire behavior parameters increased. Similarly, FM 10 should be avoided when modeling anticipated fire behavior in oak shelterwoods. The FL and ROS estimations generated by BehavePlus when using FM 10 are either too high (FL) or too inconsistent (ROS) to be usable.

FM 6 and 9 can be used in preparing for prescribed fires in oak shelterwoods if they are used together. BehavePlus consistently predicted high FLs and ROSs when using FM 6 and low FLs and ROSs when using FM 9. But, if used in tandem, they create an upper and lower bound of probable fire behavior. Some forest managers may find that knowing the minimum and maximum expected fire behaviors is more valuable in prescribed fire planning than knowing the average estimated fire behavior generated by FM 11.

This study has several limitations. The results are most usable in oak shelterwood stands similar to the ones used in this study with upland sandy loam soils, oak site index$_{50}$ of 70-80 feet, 50-percent basal area reduction 2-4 years earlier, and comparable weather and site conditions. They may be applicable outside these conditions, but with caution. The reported FL and ROS data from the prescribed fires were coarse because of the simplistic methodologies for obtaining them. Similarly, the sample size was small, with only nine prescribed fires, and the average observed FL and ROS of each prescribed fire were based on only five observations per fire. Consequently, the ranges of observed FLs and ROSs were limited to less than 4 feet for FL and 8 feet per minute for ROS, and the fire behavior prediction trends of FMs 6, 9, and 11 may not be as accurate at higher FLs and faster ROSs. Repeating and enlarging this study, employing more precise fire-behavior-measuring methodologies, and broadening the sites and conditions would address these limitations and refine the conclusions of this paper.

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