RESEARCH EFFORTS ON FUELS, FUEL MODELS, AND FIRE BEHAVIOR IN EASTERN HARDWOOD FORESTS

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Abstract.—Although fire was historically important to most eastern hardwood systems, its reintroduction by prescribed burning programs has been slow. As a result, less information is available on these systems to fire managers. Recent research and nationwide programs are beginning to produce usable products to predict fuel accumulation and fire behavior. We introduce some of those tools and examine results from regional studies of hardwood fuel distribution.

INTRODUCTION

A broad array of natural disturbances has contributed to the development of eastern hardwood ecosystems. The role played by natural and anthropogenic fire has not been appreciated until recent years. There is considerable knowledge on the fire-dependent pine ecosystems of the Western United States and the Southeastern Coastal Plain. However the role of fire is not well recognized for the Central Hardwood region, Southeastern Piedmont, and Southern Appalachian Mountains. In these areas, prescribed burning programs and supporting research has lagged behind that of the West and Southeastern Coastal Plain because of the perceived damage to hardwoods, difficulty of controlling high-intensity fires on slopes, and the potential for soil/site damage (Van Lear and Waldrop 1989). Consequently, basic fire-planning information such as fuel models and fire behavior models are missing or poorly calibrated.

Although fire was never entirely missing from the eastern hardwood region, prescribed burning only began to be used in hardwood stands during the 1980's for site preparation (Phillips and Abercrombie 1987) and in the 1990's for restoration of individual species (Waldrop and Brose 1999) or entire ecosystems (Sutherland and Hutchinson 2003). Fire managers use a number of tools to describe fuels and predict fire behavior. Many of these tools were developed for western systems and have not been tested for eastern hardwoods. The purpose of this paper is to examine several existing models of fuels and fire behavior, describe several ongoing projects that will develop new models, and describe fuel characteristics specific to the eastern hardwood region.

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National Projects with Hardwood Fuel Components

Models have been developed for application in numerous ecosystems throughout the United States. Probably the most well known and used in eastern hardwood systems are BEHAVE (Burgan and Rothermel 1984), FARSITE (Finney 1998), and FOFEM (Reinhardt and others 1997). Newer projects include LANDFIRE (http://www.landfire.gov), a photo series for major natural fuel types of the United States (http://www.fs.fed.us/pnw/fera/), and the USDA Forest Service Forest Inventory and Analysis (FIA) National Assessment of Fuel Loadings (Woodall 2003). We present a brief description of each that is intended as an introduction rather than an exhaustive evaluation of all available fuel and fire behavior models.

BEHAVE and BEHAVEPlus

The BEHAVE fire prediction system was developed by Forest Service researchers to predict fire spread and intensity (Burgan and Rothermel 1984; Andrews 1986; Andrews and Chase 1989; Andrews and Bradshaw 1990). Three later versions of this model (BEHAVEPlus v.1, v.2, and v.3) were developed to allow use in a Windows®-based environment and to incorporate updates in fire and modeling technology. This series of programs uses 13 fuel models that describe common fire-prone fuel types like grasslands, chaparral, coniferous forests, and logging slash (Anderson 1982). A set of 40 additional models, described by Scott and

Burgan (2005), was added in the most recent version of BehavePlus (3.0.1) that allow both static and dynamic simulations (that is, simulations that involve seasonally changing fuelbeds). The most commonly used fuel models for eastern hardwood systems are models 6 (hardwood slash), 8 (closed timber litter), and 9 (hardwood litter) (Brose 1997). The system also allows input of local fuel measurements by developing a customized fuel model. These are used for areas where fuel conditions are not adequately described by the standardized fuel models (Burgan and Rothermel 1984). A description of each version of BEHAVE and BEHAVEPlus is found at http://fire.org. Free program downloads are available at this site.

Published tests of BEHAVE in eastern hardwood systems are rare but have been presented by Brose (1997) for oak-dominated (*Quercus* sp.) shelterwood stands in central Virginia and by Grabner and others (1997) for oak savannas in Missouri. Both studies used the original BEHAVE model. No published tests of the 40 new fuel models are available for eastern hardwood systems. Brose (1997) compared actual flame length (FL) and rate of spread (ROS) measurements from winter, spring, and summer burns to values predicted by BEHAVE using fuel models 6, 8, 9, and a customized fuel model. Of the four, the customized fuel model most accurately predicted both flame length and rate of spread. Model 6 overestimated these measures of fire behavior while models 8 and 9 consistently underestimated them. The custom fuel model provided accurate predictions with r^2 values of 0.88 for flame length and 0.96 for rate of spread. Grabner and others (1997) also compared observed and predicted values for FL and ROS. They tested BEHAVE fuel models 1 (short grass), 2 (timber and grass), 3 (tall grass), 9 (hardwood litter), and a customized fuel model. In this comparison, the customized fuel model and fuel model 2 provided reasonable estimates of ROS but all models poorly estimated FL. In both studies, the authors concluded that BEHAVE was a useful tool for eastern hardwood systems, especially when site-specific fuel measurements can be used as input for a customized fuel model. When those types of measurements are impossible, BEHAVE fuel models can be substituted with a reasonable degree of confidence.

A limitation of BEHAVE is that it was developed to produce information on the intensity and rate of spread of point source fires. It does not take into consideration changes in topography, weather, or the influences of the fire itself on its environment that can affect observed fire behavior. The original 13 models are not dynamic but some of the new models have been designed that way. Currently, BEHAVE is intended to be used by an experienced fire manager who can combine the outputs with experience to develop an expectation of fire behavior.

Fire Area Simulator

The Fire Area Simulator, FARSITE (Finney 1998), is a GIS-based fire growth model originally developed for planning and management of prescribed natural fires. Its use has since expanded to suppression efforts for wildfires, evaluating fuel treatments (Finney 2001; Stephens 1998; Stratton 200;, van Wagtendonk 1996), and reconstructing past fires (Duncan and Schmalzer 2004). Developed in the Western United States, the model has been validated on fires in Yosemite, Sequoia, and Glacier National Parks (Finney 1993; Finney and Ryan 1995). While the use of this model is growing in the Southwest, Midwest, Florida, and in other countries, it has received little attention in the Eastern United States. FARSITE uses the same spread and intensity models as BehavePlus and, therefore, is subject to some of the same limitations. It requires a minimum of five raster layers to generate simulations: elevation, aspect, slope, fuel model, and canopy cover. The landscape data (elevation, slope, and aspect) are used for making adiabatic adjustments for temperature and humidity as well as for computing slope effects on fire spread and solar radiation effects on fuel moisture.

Phillips and others (2005) tested FARSITE on study sites in the Southern Appalachian Mountains that had been treated with mechanical fuel reduction (chainsaw felling of small trees and shrubs) or left untreated. They used measurements from systematically placed temperature sensors during prescribed burns to recreate test fires and compared fire behavior simulated by FARSITE with observed behavior. Initial simulations using default settings resulted in overpredictions for all fire behavior fuel models (FBFM) because the standard fuel models estimate fire behavior during the western fire season when fuel moisture contents are low (Anderson 1982). Actual fuel moisture values collected prior to burning were input into FARSITE, and subsequent simulations underpredicted fire spread for FBFM 9 and FBFM 11 but still overpredicted spread for FBFM 6. After adjustments, the rate of spread, flame length, and fire intensity for FBFM 9 appeared to adequately represent fire behavior in the leaf litter of oak-hickory (*Carya* sp.) forests. FBFM 11 seemed appropriate for modeling the mechanical treatment. For FBFM 6, adjustments allowed realistic rate of spread. However, the other variables of flame length and fire intensity were excessive, with predicted flame lengths of up to 20 m and fire intensities up to 27,000 kW/m, which were not observed during the prescribed burn. The authors suggested that FARSITE should be viewed as an option for fire modeling in the Southern Appalachians, but that work is needed on developing fuel models that better represent existing conditions of fuels in this region. In particular, fuel moisture the and presence of ericaceous shrubs presented difficulties for simulations. New fuel models introduced by Scott and Burgan (2005) were not incorporated into FARSITE at the time of this test.

First Order Fire Effects Model

FOFEM, the First Order Fire Effects Model, has been under development by the USDA Forest Service's Fire Laboratory at Missoula, Montana. It has been used widely by fire and land managers across the United States and has been endorsed by the National Wildfire Coordinating Group. FOFEM synthesizes the results of many fire effects studies into one computer program that can be easily and quickly used by novice or expert resource managers. Currently, FOFEM (v. 5.2) provides quantitative fire effects predictions for tree mortality, fuel consumption, smoke production, and soil heating from prescribed fires and wildfires. Although still under development, FOFEM provides the framework for predicting fire effects in most forest cover types listed by Eyre (1980) in the United States (http://fire.org/index.php?option=com_content&task=view&id=57&Itemid=31).

Tests of FOFEM for eastern hardwood systems have not been published, though independent use of the program suggests that mortality and litter consumption are highly overpredicted and that duff consumption is underpredicted. Although the scope of FOFEM is intended to be national, most of the models within FOFEM currently are based on western conifer forests. Mortality predictions are fitted to bark thickness and percent crown scorch relationships described by Ryan and Reinhardt (1988) for western conifers. Studies in the Southeast indicate that crown scorch is a poor predictor of mortality of southern pines (Wade and Johansen 1986; Waldrop and Lloyd 1988) and is not relevant to mortality prediction for dormant-season burns in eastern hardwoods (Yaussy and others 2004; Waldrop and Mohr 2005). Litter consumption is assumed to be 100 percent in FOFEM; this does not reflect the patchy nature of burns in eastern hardwood systems (Waldrop and others 2004). FOFEM uses models of duff consumption developed by Hough (1978) for southern pine communities but no models are available for eastern hardwoods. The Joint Fire Science Program recently funded a proposal to modify FOFEM for use in the Southeastern Coastal Plain (unpublished). However, calibration for use in eastern hardwoods has not been scheduled.

The Landscape Fire and Resource Management Planning Tools Project

The Landscape Fire and Resource Management Planning Tools Project, or LANDFIRE Project, was initiated by federal land agencies that asked principal investigators to develop maps needed to prioritize areas for hazardous fuel reduction. The objective of the project is to provide the spatial data and predictive models needed by land and fire managers to prioritize, evaluate, plan, complete, and monitor fuel treatment and restoration projects essential to achieving the goals targeted in the National Fire Plan. This project will generate consistent, comprehensive maps and data describing vegetation, fire, and fuel characteristics across the United States. The consistency of LANDFIRE methods ensures that data will be nationally relevant, while a 30-m grid resolution assures that data can be locally applicable. LANDFIRE is a multiagency project among the USDA, USDI, and The Nature Conservancy. The principal investigators are located at the Rocky Mountain Research Station's Fire Sciences Laboratory (MFSL) and the USGS National

Center for Earth Resources Observation and Science (EROS), in Sioux Falls, South Dakota) (http://www.landfire.gov/index.html).

The first step began with the selection of two prototype areas with which to develop the best methods for mapping the rest of the country (Schmidt and others 2002). Selected areas included the central Rockies of Utah and the Central Rockies of Montana, and north-central Idaho. Protocols for producing comprehensive digital maps of current vegetation composition and condition, wildland fuel, historical fire regimes, and fire-regime condition class were developed using the Utah study area as a test case. Lessons learned during this process were applied to the study area in Montana and Idaho and completed in May 2005 (Keane and others 2002). The Wildland Fire Leadership Council chartered national implementation of LANDFIRE in October 2003. A national organizational structure was developed in addition to a project plan and associated schedule. The LANDFIRE technical teams at MFSL, EROS, and The Nature Conservancy have developed strategies and procedures for building on the approaches used in the LANDFIRE Prototype. National delivery of LANDFIRE products will occur incrementally over the next 5 years as follows: Western United States in 2006; Eastern United States in 2008; and Alaska/Hawaii in 2009 (http://www.landfire.gov/ABOUT_Milestones3.html).

LANDFIRE includes a national Rapid Assessment component which will deliver a "first pass," coarse- to midscale assessment of fire regime conditions that is moderately accurate but quickly delivered. The Rapid Assessment will map and model potential natural vegetation, historical fire regimes, and fire regime condition class via existing datasets and expert opinion. The Rapid Assessment completed 12 workshops to create succession models and mapping rules for potential natural vegetation groups across the country. Participants included land managers and scientists from numerous organizations. Succession models were developed in the workshops for numerous biophysical settings defined as communities of vegetation that persist for long periods at landscape scales under natural disturbance regimes. Vegetation models currently are undergoing scientific and technical review (http://www.landfire.gov/ABOUT_Milestones2.html).

Photo Series for Major Natural Fuel Types of the United States

Most managers have little available fuels data of the extent, detail, or resolution needed for fire behavior and effects prediction. A sequence of photos called a "photo series" provides a quick, easy means for quantifying and describing existing fuel properties for selected sites across a landscape. To measure fuels in the field, the user matches observed field conditions to the fuels shown in one of the photographs. Measurements of fuels given for each photograph can be used as a reasonable estimate for that area. Photo series are available for western systems but few exist for the East (Wade and others 1993; Scholl and Waldrop 1999). Only two have been completed for the eastern hardwood region (Wilcox and others 1982; Sanders and Van Lear 1988). The Fire and Environmental Research Applications (FERA) team from the Pacific Northwest Research Station initiated a nationwide effort to produce photo series in major natural fuel types in 1995. The work was conducted in three phases. Phase I was commissioned by the USDI and covered 18 fuelbed types that were published in six volumes. Represented fuelbeds were western types with the exception of longleaf pine (*Pinus palustris* Mill.), pocosin, and marshgrass types in the Southeast. Phase II was funded by the Joint Fire Science Program in 1998. Eastern types included sand hill pines, hardwood/conifer mixtures, marshgrass, and pine/palmetto. Hardwood/conifer sites were measured in north Georgia and oak/hickory sites were measured in Kentucky and Ohio. Phase III was funded by the Joint Fire Science Program and the National Fire Plan. Work began in 2001. Eastern types included mixed hardwoods, cutover mixed hardwoods, pitch pine, and additional sand hill pines. Publications and additional information are available on the FERA website: http://www.fs.fed.us/pnw/fera/.

An interesting development in newer photo series is the digital photo series. The Natural Fuels Photo Series is designed for field use and is a source of high quality fuels data for a variety of forest and range ecosystems throughout the United States. These data were developed for on-the-ground assessments and are not fully utilized in the planning environment. Technological advances since the inception of the original Photo Series projects coupled with development of new fire- and natural resource-based software applications highlight the need to bring the Photo Series concept into the electronic age. The Digital Photo Series will be a software application that will include a fuels database with a user-friendly interface that will leverage the already high value of the Photo Series data. The Digital Photo Series is nearing completion (http://www.fs.fed.us/pnw/fera/).

FIA National Assessment

The Forest Inventory and Analysis program (FIA) of the Forest Service has been monitoring forest resources for 75 years and represents the most comprehensive, consistent, and current assessment of U.S. forests available. FIA added measurements of fuel loading to a subset of its permanent inventory plots in 2001. The inventory, known as the Down Woody Materials (DWM) Indicator, has been implemented in 38 states to provide a regional-scale estimation of fuel complexes. The process measures 1-, 10-, 100-, and 1,000-hr fuels annually using planar intercepts, fixed radius sampling, and point sampling. The goal of the project is to provide a seamless link to fire and fuel models and to serve as a robust source of fuels data for national and regional fire scientists and managers (Woodall 2003). Fuel profiles are available for Minnesota, South Carolina, and the North Central States at http://www.ncrs.fs.fed.us/4801/national-programs/indicators/dwm/.

Chojnacky and others (2004) examined data on DWM collected in 2001 by FIA on plots in several states. DWM data from 778 plots were used to compute biomass for coarse woody material, fine woody material, litter, duff, and shrub/herb cover. Regression equations were used to predict DWM components for extension to FIA's more intensive plot network. Seven regression equations were applied to the FIA data to create maps of DWM biomass. General trends showed that woody fuels and duff were most heavily loaded in the northern states and decreased from north to south. The litter layer and the shrub and herb layer followed an opposite pattern with heavy abundance in the south and decreasing to the north. The authors suggested the patterns were due to differences in climate and decomposition and that these patterns could be used to assess regional fire-fuels conditions.

Regional Projects with Hardwood Fuel Components

Hardwood fuels have been measured in numerous individual studies conducted for various purposes throughout many eastern hardwood systems. Examples include low-quality hardwood stands on the Cumberland Plateau (Muncy 1981; Waldrop 1996), pine-hardwood mixtures in the Southern Appalachians (Phillips and Abercrombie 1987), white pine-hardwood mixtures in North Carolina (Clinton and others 1998), central hardwoods in the Missouri Ozarks (Hartman 2004; Kolaks and others 2003; Kolaks and others 2004; Shang and others 2004), and mixed-oak stands in Central Ohio (Riccardi 2002; Sutherland and Hutchinson 2003). Hardwood fuels were described for studies of stand-replacement prescribed burning in the Southern Appalachians by Swift and others (1993), Waldrop and Brose (1999), and Welch and others (2000). A photo series was developed for Southern Appalachian pine-hardwood clearcuts by Sanders and Van Lear (1987). The National Fire and Fire Surrogate Study (NFFSS) (Youngblood and others 2005) has three sites in eastern hardwoods: the Ohio Hill Country, Southern Appalachians, and the Southeastern Piedmont. Fuel characteristics for these sites were described by Iverson and others (2003), Phillips and others (2005), and Waldrop and others (2004), respectively. The Great Smoky Mountains National Park is conducting a parkwide vegetation mapping project using photogrammetric and GIS techniques to support an all-taxa biodiversity inventory. As a component of this project, fuels are being mapped using the 13 fuel categories described by Anderson (1982). A fuel module was developed by He and others (2004) for the LANDIS forest landscape model (Mladenoff and He 1999) and used by Shang and others (2004) to simulate fuel dynamics in the Missouri Ozarks.

Each of these studies provides valuable information about localized fuel loads and response to one or more variables. However, there remains a lack of understanding of how hardwood fuels are distributed across the landscape, an important and beneficial concept for fire management planning. Studies by Iverson and others (2003), Kolaks and others (2004), and Waldrop and others (2004) suggest that loading of dead and down fuels is controlled by the varying inputs associated with different species and productivity levels across the landscape and varying decomposition rates at different sites. At any time since disturbance, fuel loads are a function of the amount input from dying vegetation minus the amount lost from decay. Waldrop and others (2004) also showed that fuels can be distributed across the landscape by gravity or by cultural treatments. Several studies of fuel and landscape interaction are described here.

LANDIS

He and others (2004) developed the LANDIS fuel module to simulate fuel dynamics for the Missouri Ozarks. The model simulates fuel inputs and decomposition for each of 24 land and cover types over a 200-year simulation. Species input data were from extensive inventories measured on the Mark Twain National Forest in the Missouri Highlands. Decomposition rates were those reported by Trofymow and others (2002) for Canadian forests. In a test of the model, Shang and others (2004) described fuel buildup and wildfire frequency that would occur under three fuel management treatments. A valuable product of the work is a GIS map of fuel accumulation across the study area over time. This map will allow fire managers to better predict where fuel amelioration is needed. LANDIS has been applied and tested successfully in a number of forest types in Missouri, Wisconsin, California, Canada, and China. A current effort by researchers from Texas A&M University and the Forest Service is the parameterization of LANDIS for ridgetop pine-hardwood communities in the Southern Appalachians. Although untested, local site-specific input and decomposition rates may be necessary to simulate the diverse topography of those mountains.

FORCAT

Another model designed to study dynamics of fuel loading was reported by Waldrop (1996). He used the FORCAT model (Waldrop and others 1986) to simulate inputs and decomposition of coarse fuels for xeric and mesic forest types on the Cumberland Plateau of East Tennessee. FORCAT is a gap model of forest succession that is a member of the family of models produced by Botkin and others (1972) and Shugart (1984). The simulation was set to examine fuel loads after a major disturbance; in this case, clearcutting was used. A uniform decomposition rate of 6 percent was used for both sites as suggested by Harmon (1982).

The estimated fuel load immediately after clearcutting was 49 Mg/ha on the xeric site and 69 Mg/ha on the mesic site (Fig. 1). On both sites, these levels were higher than at any other time during the 200-year simulation period. Fuels decompose rapidly in clearcuts at a period when inputs are small. In this simulation, decomposition exceeded inputs through year 32. Between years 30 and 75 there was a rapid increase in fuels for both simulated sites. FORCAT predicted decreases in stand basal area during this period as crown closure occurred and several large trees began to die. The period of rapid accumulation on the xeric site lasted until the stand was about 70 years old. Fuels continued to accumulate but at a slower rate, to a maximum at year 91. For the remainder of the 200-year simulation period, decomposition slightly exceeded inputs and fuel loads decreased gradually. Tree growth on the simulated mesic site exceeded that on the xeric site, producing a more rapid rate of accumulation (Fig. 1). On this site, fuels accumulated rapidly from years 30 through 89. Between years 90 and 200, fuel loading decreased much

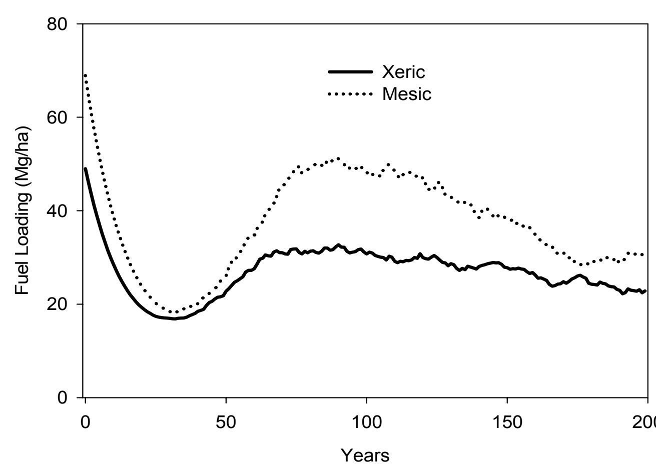

Figure 1.—Fuel dynamics after clearcutting xeric and mesic sites (predicted by FORCAT using a 6 percent decomposition rate for both sites).

more rapidly than on the xeric site. Species on the mesic site were longer lived than those on the xeric site and the trees continued to grow. Mortality was higher on the xeric site during this period due to moisture stress. Therefore, inputs were less on the mesic site than the xeric site. Loads of coarse woody fuel projected by FORCAT were similar to those reported by Muller and Liu (1991) for old-growth stands on the Cumberland Plateau.

The work of Abbott and Crossley (1982) indicates that decomposition rates are higher on moist sites. By assuming a decomposition rate of 8 percent on the mesic site and 6 percent on the xeric site, the difference in simulated fuel loads between sites was greatly reduced (Fig. 2). Even though loading was much higher on the mesic site in year 1, it decomposed to a smaller amount than the xeric site by year 32. By year 75, fuel loading again was greater on the mesic site, but beyond that point the lines converged. During the last 50 years of the simulation, fuel loads on the two simulated sites were nearly identical. This comparison (Fig. 2) illustrates the observation of Abbott and Crossley (1982) that differences in decomposition rates between sites can be more important than differences in sizes or input of woody debris. Although the mesic site produced far more biomass than the xeric site, the relatively small difference in decomposition rates (8 vs. 6 percent) produced similar fuel loading throughout the 200-year simulation. This study is limited in scope, but suggests that fuel loads may be somewhat uniform across site types.

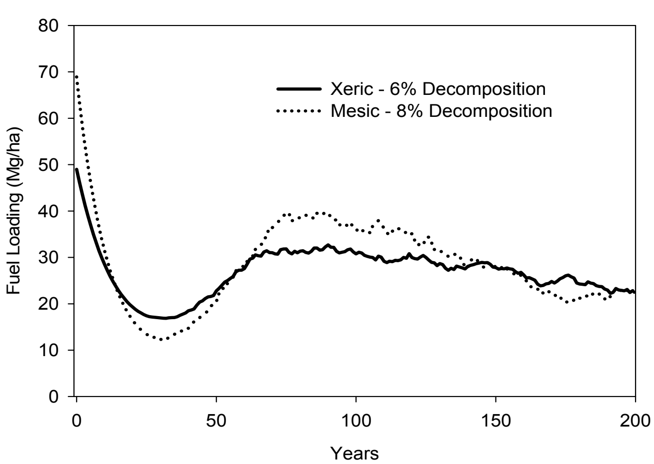

Figure 2.—*FORCAT predictions of fuel loads by site type and decomposition rate.*

Field Measures in the Missouri Ozarks

Kolaks and others (2003) collected fuels data in the Southeast Missouri Ozarks to determine whether aspect had an effect on fuel loading in previously undisturbed stands. Aspect ranges included exposed slopes (135 to 315 degrees), ridges with no aspect, and protected slopes (315 to 135 degrees). Fuel measurements were made at 15 points within each of 12 experimental units. They found no difference in loading of 1-, 10-, and 100-hour fuels or vertical structure of fuels across aspects, suggesting that the different input and decomposition rates across the landscape balance the loading of these fuels. However, the authors found significantly higher loading of 1,000-hr fuels on protected slopes. They attributed this to lower decomposition rates on moist sites, but we suggest (from experience gained from the study described below) that this is an anomaly due to the limited size of the study. The study was continued to determine whether aspect affects fuel loading after thinning and prescribed burning (Kolaks and others 2004). Both thinning and burning increased fuel loads across all aspects, though the increase followed the pattern of protected > ridge > exposed. This result agrees with the general pattern that moist sites produce greater quantities of fuel. Burns consumed fine fuels more than those more than 3 inches in diameter. Total consumption did not differ among aspects but the data suggest that a greater proportion of fine fuels was consumed on exposed slopes, likely due to differences in fuel moisture.

Field Measures in the Southern Appalachian Mountains

A large-scale study was funded by the Joint Fire Science Program in 2001 to develop hyperspectral image maps of fuel loads for study sites in Tennessee, North Carolina, Georgia, and South Carolina (http://jfsp.nifc.gov/JFSP_Project_Info_4.htm). The remote sensing component of the study will be completed by summer 2006. The field component is complete and has similarities to the studies by Waldrop (1996) and Kolaks and others (2003). Preliminary analyses were reported by Brudnak and Waldrop (2005) and Stottlemyer and others (2005). Additional analyses are presented here.

Table 1.—Fuel characteristics by slope position and aspect in the Southern Appalachian Mountains of TN, NC, GA, and SC

Slope/Aspect	Litter	1 hr	10 hr	100 hr	1,000 hr	Fuel Ht	Kalmia	Rhododendron
	--------------------------t/acre				--------------------------	Inches	Percent	Percent
Northeast								
Lower	1.68 a[1]	0.32	0.91	3.8	24.0	4.3	10.6 a	37.0 c
Upper	1.82 b	0.30	0.91	3.5	18.0	4.6	13.6 a	19.7 b
Ridge	1.83 b	0.29	1.04	4.2	16.2	4.6	13.1 a	6.1 a
Southwest								
Upper	1.75 ab	0.30	0.97	3.7	17.3	4.3	21.0 b	6.8 a
Lower	1.70 a	0.29	0.92	3.4	18.3	4.1	15.6 a	15.4 b

[1]Means followed by the same letter within a column are not significantly different at the 0.05 level.

Fuels data were collected at 250 randomly selected plots in each of four study areas (10 square miles in size). Study areas are on the Chattahoochee National Forest in northeastern Georgia, Nantahala National Forest in western North Carolina, Sumter National Forest in northwestern South Carolina, and Great Smoky Mountains National Park in southeastern Tennessee. Plot locations were generated randomly within each 10-square-mile study area using ArcView® GIS software and were stratified by slope position and aspect. Fifty plots each were located on middle and lower slopes on northeast (325 to 125 degrees) or southwest (145 to 305 degrees) aspects. An additional 50 plots were on ridgetops for a total of 250 plots in each of the four study areas. A GPS receiver was used to locate the plots in the field. Additional plots were included when necessary to provide adequate representation of all slope position/aspect combinations. Methods for measuring dead and live fuels followed standard protocols and were described by Brudnak and others (2005). The resulting dataset had measurements from 1,008 plots.

Downed woody fuels showed few differences in fuel loading across aspect/slope position plots (Table 1). Differences were observed only in the litter layer. The litter on the 1,008 sample plots tended to be heaviest along the ridges and decreased going downhill on both southwest and northeast slopes, suggesting that decomposition exceeded leaf litter inputs on the wetter sites. Although this difference among site types was significant, the relative differences were small. There was approximately 8 percent less litter on northeast lower slopes (1.68 t/acre) than on ridges (1.83 t/acre). There were no significant differences among slope/aspect combinations for loading of 1-, 10-, 100-, and 1,000-hr fuels or average fuel bed depth. These are preliminary data because analyses of impacts such as disturbance or cover type are not yet complete. However, these findings closely agree with those of Kolaks and others (2003), indicating that down woody fuels tend to be uniformly distributed across slopes and aspects.

Another component of fuels in eastern hardwood systems that must be considered is live fuel cover, particularly from ericaceous shrubs. Waldrop and Brose (1999) and Phillips and others (2005) reported a strong relationship of fire intensity to cover of mountain laurel (*Kalmia latifolia*). Van Lear and others (2002) discussed the importance of rhododendron (*Rhododendron* sp.) on the ecology of the Southern Appalachians. Although generally moist-site species, they occasionally ignite and can act as vertical fuels. In this study, both mountain laurel and rhododendron were missing from most measured plots but occurred in thick clumps where they were found. Mountain laurel was found at all aspect/slope position combinations but was significantly more abundant on southwest upper slopes (Table 1). Wildfires that might occur could reach dangerous intensities if they burned uphill on dry southwest slopes and ran into thickets of mountain laurel. Rhododendron also was present at all slope/aspect combinations but was more common at lower slope and northeast-facing plots.

Fire Behavior in Eastern Hardwoods

Prediction of fire behavior in eastern hardwood systems is complex and includes too many variables to describe in this paper. Factors such as fuel moisture, temperature, relative humidity, windspeed, wind direction, slope, and aspect contribute to this complexity in ways that are similar to other ecosystems across North America. Eastern hardwoods have several differences because most trees are deciduous. After leaffall, abundant sunlight reaches the forest floor changing the microclimate there differently than would be the case under a protective canopy of conifers. Hardwood leaves generally are flat and can be difficult to ignite once decomposition is underway. However, leaves of oaks typically curl more than do those of maple (*Acer* sp.), beech (*Fagus* sp.), and birch (*Betula* sp.), making hardwood fuelbeds more complex than those of conifers. Fires that occur in dry weather soon after leaffall often have a high rate of spread but are of low severity due to a moist duff layer.

Data and other research discussed in this paper indicate that dead woody fuels have a fairly uniform distribution across different slope positions and aspects. Although the reason for this is unknown, it is suggested that the heavy fuel production that occurs on productive sites is balanced by rapid decomposition on those same sites. Regardless, managers should be more concerned with live fuels, such as ericaceous shrubs, jackpots (localized heavy loads due to a limb or tree falling), and past disturbances rather than the overall loading of downed woody fuels. Waldrop and Brose (1999) and Waldrop and others (2005) compared fires of several intensities for successful stand replacement of Table Mountain pine (*Pinus pungens* Lamb.). They found that fires that did not burn into jackpots or mountain laurel remained relatively cool throughout a 900-acre burn. Where flames reached a jackpot, lower limbs were scorched and some tree mortality occurred. If mountain laurel cover was over 40 percent, flames climbed into the crowns of trees and consumed all of the leaves. In areas where cover of mountain laurel was more than 85 percent, flame heights were twice that of overstory trees and carried from one crown to the next.

Additional work is necessary to better understand the relationships of hardwood fuels to fire behavior. Ongoing studies include the NFFSS sites in Ohio, North Carolina, and South Carolina. Numerous temperature sensors are scattered throughout the sites to monitor fire behavior. Both groups of scientists are beginning to use sensors located at different heights above ground to produce a three-dimension view of test fires.

Studies funded by the National Fire Plan and Joint Fire Science Program are being conducted in Ohio to examine landscape-scale fire behavior. The studies entail: 1) predicting the spatial and temporal variability in key drivers of fire behavior, particularly fuel moisture and loading, and 2) monitoring fires using both airborne remote sensing and in-fire monitoring technologies. The first part of the work will provide a better understanding of fuel characteristics and better predictive capabilities as to when and how fuels will burn (that is, their frontal intensity, rate of spread, residence time, fuel consumption, and extinction). The monitoring data will be used to test and calibrate fire behavior models, including BEHAVE and a coupled fire-atmosphere model (http://www.fs.fed.us/ne/delaware/4153/4153.html).

SUMMARY

Although research on fire in eastern hardwoods has lagged behind that of other U.S. regions, there are numerous ongoing studies and several prediction products already available. The BEHAVE system tested well in two hardwood systems for predicting rate of spread, especially when customized fuel models were available. FARSITE has not been used extensively in the region but shows promise as local fuel measurements become available. FOFEM includes the computer code to allow prediction of fire effects in eastern hardwoods. However, it has not been calibrated for the region. LANDFIRE is an aggressive nationwide effort to provide fuel and vegetation maps of the entire country. Products for eastern systems should be available in 3 years. Phase III of the Photo Series for Major Natural Fuel Types of the United States is nearing completion and should include fuel models for eastern hardwoods. And the Forest Service FIA is measuring fuels across the United States and providing valuable information about regional fuel patterns.

In addition to nationwide programs, numerous local studies have been completed that describe local fuel types. Three independent studies compared hardwood fuel loads for different slope positions and aspects. All found few differences and suggested that higher productivity on moist sites was balanced by higher decomposition on those same sites. Major sources of fuel, and thus areas of concern for fire managers, were localized jackpots and presence of mountain laurel and rhododendron. Additional work is needed to better predict fuel loads throughout the eastern hardwood region and to model fire behavior within complex interactions of weather, fuel, and topography.

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