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Fuels and fire behavior in chipped and unchipped plots: Implications for land management near the wildland/urban interface

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Abstract

Fire behavior was measured and modeled from eight 1 ha experimental plots located in the Francis Marion National Forest, South Carolina, during prescribed burns on February 12 and February 20, 2003. Four of the plots had been subjected to mechanical chipping during 2002 to remove woody understory growth and to reduce large downed woody debris from the aftermath of Hurricane Hugo in 1989. The remaining four (control) plots were left untreated. The burns were low intensity (mean flame length = 36.2 cm) and slow moving (mean spread rate = 1.18 m min^{-1}). Neither flame length nor rate of spread differed significantly between treatments (ANOVA F's < 0.5, $P > 0.7$, d.f. = 1,4). Post-burn observations provided somewhat more convincing evidence of treatment effects on fire behavior. According to transect data, only slightly more than half the area in the chip plots burned as compared to upwards of 80% in the burn-only plots. BehavePlus and Hough–Albini (HA) fire models correctly predicted the low intensity, slow moving fires given the observed wind and fuel moisture conditions. Accuracy of BehavePlus predictions depended on the value for fuel height entered in the model. Use of mean fuel height for the fuel depth parameter, as is typically recommended, somewhat overestimated fire hazard in the burn-only plots. However, limiting fuel height to the observed litter depth resulted in roughly accurate predictions. HA predictions for untreated fuels were close to correct even without adjusting fuel depth. When provided with two ''high-risk'' fuel and fire weather scenarios both models predicted more extreme fire behavior in the untreated fuels. In contrast, chipping appeared to protect against dangerous wildfires as long as fuel heights remained low. Smoke monitoring data from a companion study carried out in the same plots indicated a 60% reduction in smoke particulate production from chipped areas, roughly consistent with predictions of the fire effects model FOFEM. Mechanical chipping is apparently a useful method for limiting fire-hazard and smoke production in long-unburned fuels. However, questions remain concerning the long-term fate of heavy chip fuels and resultant effects on fire and smoke during severe drought.

Keywords: Fuels; Fire behavior; Mechanical chipping; Wildland/urban interface; Flatwoods; Southeastern coastal plain

1. Introduction

Land managers use prescribed fire to treat 2–3 million ha of forest and agricultural lands in the southern United States each year (Wade et al., 2000), more than any other comparable area in the USA. Prescribed fires are used to reduce hazardous fuel accumulations and to conserve threatened fire dependent ecosystems, particularly those containing longleaf pine (Hermann, 1993). However, the use of prescribed fire as a land management tool in this region is becoming increasingly problematic. The South is experiencing rapid population growth. Large urban centers have grown into historically forested areas. Many people are retiring to communities cut into forested areas. These demographics have created an enormous wildland/urban interface problem for Southern land managers. In addition to the wildfire threat, there is the threat from smoke—either from smoke as a nuisance (Achtemeier, 2001) or from smoke as a threat to air quality (Achtemeier et al., 1998). Though several southern states have passed legislation to try to protect responsible burners, many land managers have curtailed the use of fire or have abandoned fire altogether due to threat of litigation (Mobley, 1989).

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As prescribed burning becomes more difficult, land managers are turning increasingly to mechanical treatments (Outcalt and Wade, 2000; Ottmar et al., 2001). These treatments may be used either as fire substitutes or to complement a prescribed burn program, i.e. to alter fire fuels in such a manner as to produce a safer and less smoky burn. Ecological goals may also be paramount, including reduction of dense mid-story for the benefit of flora and fauna adapted to open, fire maintained conditions. Another goal is to reduce wildfire risk along roads and land boundaries. One recently developed and already popular treatment is ‘‘chipping’’ or ‘‘shredding’’ wherein down fuels and medium-sized and smaller live woody stems are pulverized via flail or fixed blades mounted on a rotating drum (Ottmar et al., 2001). This technique is similar to traditional drum chopping used for site preparation in timber stand regeneration except that the drum is mounted on a hydraulic lift so that it may be raised above the soil surface, thus reducing soil disturbance and disruptions to plant roots.

Though mechanical chipping is now in wide use, its effects on fire behavior, smoke and the ecology have not been carefully evaluated. An opportunity to perform such an evaluation was provided by the Francis Marion National Forest (FMNF) near Charleston, South Carolina. This National Forest sustained major canopy disturbance in September 1989 when Hurricane Hugo felled some one hundred million board feet of timber (Sheffield and Thompson, 1992). Because of the fallen log problem, prescribed burning was halted over large areas of the National Forest. A consequence was the development of dense loblolly pine and hardwood mid-stories in formerly open pine woodlands and savannas. Mechanical chipping is being utilized to reduce fire and smoke hazards and to restore desired ecological and burning conditions. This study was initiated to determine whether the treatments as implemented were in fact meeting the desired fire behavior modification, smoke reduction, and ecological management objectives. Results pertaining to fuels, fire behavior, fire behavior modeling and smoke production modeling are presented herein. Complementary publications deal with smoke measurements and smoke dispersion models (Achtemeier et al., in press; Naeher et al., in press) and effects on plant community structure and composition (Streng et al., in preparation).

2. Materials and methods

2.1. Study site

The study was located in compartment 53 of the Francis Marion NF, in the outer south Atlantic Coastal Plain, approximately 50 km northwest of Charleston, SC (Fig. 1). Climate is mild and temperate with a mean annual temperature of 18.3 °C. Annual precipitation averages around 121.9 cm (Alcock, 1985). The location of the experiment within the FMNF is indicated by the black dot (Fig. 1). The site is located in the northwestern part of the FMNF within the wildland–urban interface zone surrounding the town of Moncks Corner, approximately 7 km distant. There had been no fire on the site since before Hugo. Typical of such sites, vegetation was loblolly pine flatwoods with dense post-Hugo regeneration dominating the mid-canopy and understory strata. In addition to *Pinus taeda* L. itself, dominant tree and shrub species included *Acer rubrum* L., *Clethra alnifolia* L., *Ilex glabra* (L.) Gray, *Liquidambar styraciflua* L., *Quercus nigra* L., *Quercus phellos* L., and *Vaccinium* spp. A few open, grass dominated (*Schizachyrium scoparium* (Michx.) Nash) patches remained, especially on moister micro-sites. Soils are Ultisols of the Wahee series (Clayey, mixed, thermic Aeric Ochraquult). These soils are characterized by sandy loam surface soils and shallow clay subsoils (Long et al., 1980). During wet periods precipitation percolates through the surface sand and ‘‘perches’’ on top of the clay subsoil. Perched water tables can persist during most of the dormant season during typical winters on flat, poorly drained outer Coastal Plain sites (Long et al., 1980). An important consequence of this hydrological pattern for smoke and fire propagation is that lower litter layers and heavy fuels in contact with the soil maintain persistently high moisture levels during much of the prescribed burn season. Traditionally, most prescribed burns in the southeastern USA are carried out in winter through early spring, i.e. January through early March (Robbins and Myers, 1992).

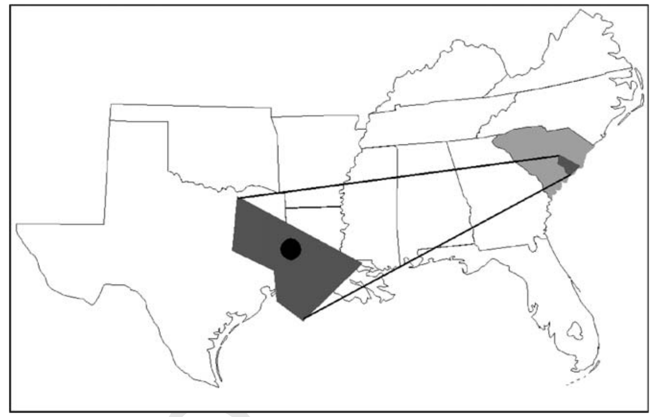

Fig. 1. Location of the experimental burn site (black dot) within the Francis Marion National Forest (highlighted in dark gray) within South Carolina.

2.2. Experimental design

The study encompassed 12 1 ha experimental plots arranged in a randomized block design. There were three experimental treatments: (1) shear, or chip, only (henceforth referred to as ‘‘chip only treatment’’), (2) ‘‘burn only’’ (also referred to as ‘‘control’’), and (3) chip, then burn (henceforth ‘‘chip and burn treatment’’). Only the latter two treatments are of interest in the present context. Plots within blocks were randomly assigned to treatments, with the exception of the two most distant plots. These two plots were selected for smoke monitoring (Naeher et al., in press; Achtemeier et al., in press). Accordingly one of the two plots was assigned a chip and burn treatment while the other was retained as a control (burn only treatment). Chip treatments were carried out in December 2001 as part of an operational scale chipping treatment in the surrounding FMNF compartment.

2.3. Fuels

Fuel data were collected from the eight study plots (four burn-only and four chip + burn) prior to experimental fires. Data on downed woody fuels were collected using Brown's vertical plane method (Brown, 1974; Brown et al., 1982). Fifteen meter long transects were located at eight systematic locations in each plot. One hour (<0.62 cm diameter) and 10 h (0.62–2.5 cm diameter) fuels were recorded along the first 2.07 m, whereas 100 h (2.6–7.6 cm diameter) and 1000 h (>7.6 cm diameter) fuels were recorded across the entire transect length. Equations provided in Brown (1974) and Brown et al. (1982) were used to convert twig intercept data to weight per unit area (Mg ha^{-1}).

Fine fuels, including 1 and 10 h downed woody and live woody stems <50 cm tall, were collected along each transect from a 0.25 m^2 randomly located circular plot. Duff depth was measured from the center of the plot after litter was removed. Harvested fuels were sorted into standing grass-plus-forbs, live woody, standing dead woody, fine litter and the two twig components (in the chip plots this included fragments generated by the chipping operation). The sorted fine fuels were bagged, dried at 60 °C and weighed.

Live woody stems <50 cm tall in the 0.25 m^2 plots were harvested, bagged and weighed as described above. Woody stems greater than 50 cm tall were measured for basal diameter. In addition, subsamples were harvested, dried and weighed. Subsampled individuals were used to estimate biomass for stems that were not harvested. Best-fit polynomial regression equations were developed using a step-wise procedure wherein terms were added only if significant at $P < 0.05$. Separate equations were developed for loblolly pine (Biomass = 51.37355171 × BasalDiameter − 10.4553484, $n = 14$, $R^2 = 0.64$), hardwood trees ($B = 39.0019983 - 102.5407686 \times \text{BD} + 86.61767916 \times \text{BD}^2$, $n = 16$, $R^2 = 0.86$) and shrubs ($B = 12.92613495 - 60.82444975 \times \text{BD} + 107.9232518 \times \text{BD}^2$, $n = 35$, $R^2 = 0.96$).

ANOVA (excluding the block effect, which was not significant $P > 0.05$) and the non-parametric Kruskal–Wallis test (STATISTIX for Windows version 2.1, Analytical Software1998) were used to test for differences in individual fuel components between treatments. Data were then pooled across plots within treatments to provide a single best estimate for each fuel component.

2.4. Fuel moisture

''Grab samples'' of the primary litter components were collected from plots on each burn day prior to lighting fires. Wet weight was determined in the field; samples were then bagged and, subsequently, dried and weighed. Percent moisture was determined based on the difference between wet and dry weight.

The two smoke monitoring plots were burned separately from the other plots (see following Section 2.5). In these two plots samples for fuel moisture determinations were collected near the origin point of each of the eight fuel sampling transects (thus $n = 8$ for each plot). The remaining six plots were burned on a single afternoon and little time was available for pre-burn fuel moisture sampling and processing. Only a single sample was collected from each treatment plot and samples from the same treatment were combined in the field prior to weighing. These data did not afford the opportunity of statistical tests for treatment effects. They did, however, provide reasonable ''ballpark'' fuel moisture parameter estimates for fire behavior modeling (see Section 2.7).

2.5. Firing techniques

The two plots used in the smoke study (Achtemeier et al., in press; Naeher et al., in press) were burned on 12 February 2003. Strong winds, exceeding prescription levels, prevailed throughout the day. Finally, after dark, winds decreased sufficiently to light the fires. The dense vegetation in the burn-only plot and the time of the burn limited available firing procedures and complicated documentation of fire behavior. The procedure at the burn-only plot was to install a broad black-line on the downwind side and then to ignite the upwind side of the plot. Additional strip fires were impossible without compromising safety of the burners. Regardless, the fire moved rapidly across the plot. In contrast, the fire moved at a slow rate through the chipped plot, necessitating numerous strip head-fires in order to ultimately burn the majority of the plot area. Standardization of burn techniques would have been desirable, but was impossible under the circumstances.

The remaining six plots, three chip and three non-chip, were burned 8 days later on February 20, 2003. Burns were lit over an approximately 6 h period, from 1200 to 1800 LST. Plots within blocks were lit at approximately the same time in an effort to control for confounding effects of humidity, wind, and other environmental variables. Firing procedures were carefully controlled to facilitate video documentation. Strip headfires were lit at four predetermined locations in each plot: 10, 30, 60, and 100 m. Fires moved slowly and ''filling in'' was ultimately necessary to complete the fires, but only after fire behavior had been thoroughly documented.

Weather data were collected on site during the February 12 smoke experiment using a Campbell Scientific CR23X Station (Achtemeier et al., in press). This equipment was not available for the February 20 burns. However, wind speed data were obtained from the nearest NWS station in Charleston, SC, approximately 51 km distant. Winds during the February 20 burn period ranged from 9.2 to 23.9 km h^{-1} (2.5–6.5 m s^{-1}). Calmer winds ranging from 9.2 to 14.7 km h^{-1} (2.5–4.1 m s^{-1}) prevailed from 1200 to 1400 followed by a period of stiffer breezes (22–23.9 km h^{-1}, 6.1–6.5 m s^{-1}) later in the afternoon (1500–1800). By the time of the final burn ~1800 LST winds had subsided to speeds in the same range as those observed earlier in the day. NWS wind data are collected at a height of 30 feet (10 m). However, wind speed at mid-flame height is needed for fire behavior modeling. Procedures for estimating mid-flame wind speed from 10 m wind data are reviewed in Section 2.7.

2.6. Fire behavior

SONY digital camcorders were used to videotape the February 20 burns. Metal signs and poles of known size were placed in the plots at 5 m intervals along one side of each plot to provide scale in the videos and facilitate rate of spread determinations. Filming was initiated as each strip was lit and continued until fire either stopped or moved one 5 m interval. Succeeding strips were not lit until filming ended at the previous strip. When analyzing videos it was sometimes difficult to discern markers, especially in dense no-chip plots. In such cases distinctive trees or other natural objects were used as reference objects. Follow-up field checks were made to determine dimensions of these impromptu markers.

The camcorders recorded time in 0.01 s increments directly on the videos. Streaming videos were downloaded to computer using a USB cable and Sony ImageMixer software. Rate of spread was determined by measuring the time taken for fires to move between metal poles. Images with reference objects were ''captured'' using ImageMixer. Able Image Analyzer software ver. 2.1 (Mu-Labs 2000–2004, Slovenia) was then used to calculate flame lengths by comparison with reference objects. Four strip headfires were lit in each plot. Atleast four flame length determinations were made for each of the four strips. The first measurement was taken shortly after the line was lit and two subsequent measurements were taken at 30 s intervals while the original pole was generally still in the field of view. The fourth flame length measurement was recorded as the flame front passed the next 5 m pole. If the opportunity presented, additional measurements were made as the fire passed other poles or other reference objects as described above.

In addition to video analysis, fire behavior differences were inferred from post-fire observations on crown scorch and fine twig diameters of shrubs. This was accomplished using the same vertical plane transects used in pre-fire fuels sampling. To estimate burned areas within plots we determined the percentage of each transect that intersected burned ground. We did not comprehensively resample fuels post-fire; however, spot checks indicated that heavy fuels ($\geq$10 h) along transects were for the most part not consumed in any of the fires.

Temperatures during fires (February 12 and February 20) were measured using THERMAX heat sensitive strips wrapped in aluminum foil (temperature range 38–79 °C). Ten indicators were systematically located along 100 m transects running the length of the plots. Indicators were put out the morning of the fires and collected the same evening. Indicators were placed at the transition point from litter to duff to check for potentially lethal temperatures to plant roots in the duff.

Finally, a survey was made for large (i.e. 1000 h) logs or snags still burning in the plots on the mornings following the experimental fires. ''Residual'' smoke from heavy fuels following fires is perhaps the greatest concern from the standpoint of visibility and traffic.

2.7. Fire behavior modeling

Fire behavior actually observed in this study represented a small subset of possible outcomes given the documented fuel arrays and varying weather conditions. BehavePlus version 3.02 (Andrews et al., 2005) was used to explore other possible fire scenarios. An implementation of Rothermel's (1972) model, BehavePlus represents the current standard approach for fire behavior prediction including assessment of fuel treatment effects (Brose and Wade, 2002). Model predictions have been validated in a variety of North American fuel types (Grabner et al., 2001). On the other hand, fundamental assumptions, including horizontal and vertical homogeneity of fuel structure, are routinely violated in real world situations with consequences for model predictions that are not well understood (Hough and Albini, 1978; Evans et al., 2004). BehavePlus was used in this study to assess the envelope of possibilities rather than as a precise predictor. The Surface Module was used since crown fires are uncommon in mature pine woodlands in southeastern USA.

Accuracy of BehavePlus predictions depends in part on selection of an appropriate fuel model. The term fuel model, in this context, refers to a set of descriptor variables that collectively define fuel structure and fuel loading. BehavePlus provides a set of standard fuel models including those recently developed by Scott and Burgan (2005, henceforth ''SB''). In addition, a user has the option to input a ''custom'' fuel model incorporating data from a particular field site. We selected SB fuel model tu2 (''moderate load, humid climate, timber-shrub'') for the burn-only plots and SB model sb3 (''high load activity fuel or moderate load blowdown'') for the chip and burn plots. We then ''customized'' these models using measured values for live woody, 1, 10, and 100 h dead fuels. The value for 1-h fuels was the sum of standing herbaceous (mostly dead and dry at this season), non-woody litter, and 1-h diameter down twigs. Live woody included all live stems $<$ 2.0 m tall including those harvested in the litter plots and those estimated from biomass equations (see Section 2.3).

The issue of fuel depth is often problematic in fire behavior modeling (Hough and Albini, 1978). Fuel depth in Behave is defined as mean maximum fuel height, i.e. mean height of tallest flammable objects averaged across the surface of the ground. A problem arises because diameter, and height, of fuels consumed in a particular fire are a function of the fire itself. In statistical terms, fuel depth is to some extent a dependent variable rather than an entirely independent predictor of fire behavior. The problem is exacerbated as time since fire and understory height increase. Vertical stratification of fuels tends to develop with larger diameter live fuels forming the upper stratum and dead and smaller live fuels closer to the ground (Peterson et al., 2005). This type of non-homogeneity of fuel structure violates a fundamental assumption of Rothermel (1972). A possible solution occurs when upper fuel strata do not burn, or are not significantly consumed by fire. In this case one can apply the model in a satisfactory manner by limiting analysis to the lower strata. Unfortunately, it may not be evident in advance of the fire which strata will be consumed.

The untreated fuels at our study site were characterized by an essentially continuous understory canopy, ~2.0 m tall, of pine and hardwood saplings and some tall shrub species, e.g. *Myrica cerifera*. Fuel depth as typically estimated for BehavePlus would thus be approximately 2.0 m. However, fires rarely reach into this sapling stratum in coastal SC flatwoods except, perhaps, under exceptionally dry or windy conditions. The next stratum beneath the saplings was a layer of mid-size shrubs, particularly *Clethra alnifolia* and *Ilex glabra*. The height of this stratum, referred to as the ‘‘shrub layer’’, was estimated at 0.5–0.7 m. The lowest fuel layer, termed the ‘‘litter layer’’, included litter, downed woody fuels, short shrubs and sparse dried herbs. We estimated the height of this layer at 0.2–0.3 m. Since we were uncertain which stratum might represent the ‘‘true’’ fuel depth for fires occurring under different drought and wind conditions, we repeated each simulation for three different fuel depths representing the different strata described above.

Fuel depth in the treated plots was better defined since the sapling and shrub strata, as defined above, had been essentially eliminated by the chip operation. Fuel depth in these plots was estimated as 0.05–0.15 m. This low value reflected the highly compacted litter layer produced by chipping as well as the scarcity of grass fuels in these long fire suppressed stands.

The main goal of modeling was to investigate possible treatment effects under more extreme fire conditions than we could observe directly. Accordingly, we defined two risk scenarios: (A) Fuel moistures were as utilized by Brose and Wade (2002) in their ‘‘drought scenario’’: 1 h = 5%, 10 h = 6%, 100 h = 6%, live woody = 104%. Head wind was 12.5 km h^{-1} (at 10 m height), the prevailing wind during the February 20 fires as determined from NWS data. (B) Fuel moistures were as in the Brose and Wade (2002) drought scenario. Wind speed (10 m) was 111 km h^{-1}, the highest sustained wind observed during February, 1930–1996, in Charleston, SC (NOAA, 1998). Scenario B is similar to conditions documented during known extreme wildfire situations in southeastern Coastal Plain fuels (Brose and Wade, 2002; Omi and Martinson, 2002).

In addition to these two high-risk scenarios, we also simulated the February 20, 2003, experimental fires using the wind (12.5 km h^{-1}) and drought conditions actually observed on those dates. This allowed for a test of the accuracy of model predictions by comparison to actual fire behavior data as determined from the video analysis.

NWS wind data are typically collected at 30 feet (10 m). However, the required parameter to calculate Rothermel's (1972) model is mid-flame wind speed. BehavePlus provides the capability to make the adjustment (the so-called ‘‘wind adjustment factor’’). In dense stands, e.g. the non-treated plots in our study, the adjustment is approximately 0.09. In open stands, e.g. the post-treatment plots, the adjustment depends on fuel depth and structure. The calculated WAF for the chip plots was approximately 0.32.

Parameter values required by BehavePlus, other than those already discussed, were as given in the tu2 and sb3 fuel models (Scott and Burgan, 2005).

Rothermel (1972) model predictions may be imprecise even when one has customized a fuel model. It may be necessary to further ‘‘tweak’’ the model, i.e. adjust the subtler details of the parameterization and implementation as necessary until the predictions fit observed data. Ideally, the altered model is then validated against independent data. Such tweaking was beyond the scope of the current study. However, there already exists a well-known example for southern pine woodlands: the saw palmetto (*Serenoa repens*)–gallberry (*Ilex glabra*) model of Hough and Albini (1978, henceforth ‘‘HA’’). Our study site is north of the range of *Serenoa*. HA predictions for sparse overstory and low palmetto coverage (HA Tables 1 and 2, 19) should, nevertheless, be appropriate for our data set. Predictions for the different treatments and model scenarios discussed above were made by consulting the HA tables and figures for the following combinations of fuel and weather characteristics. (1) Untreated fuels, observed conditions prior to February 20, 2003 fires—age of rough 15 years, fuel height 2.0 m (6 ft), fuel

Table 1
Fuel loadings (Mg ha^{-1}) in burn only and chip plus burn plots

	Burn only	Chip + burn	$P^{t\text{-test}}$	P^{KW}
Downed woody				
1 h[a]	1.66	2.82	0.04	0.02
1 h[b]	0.54	1.86	0.01	0.01
10 h[a]	7.48	24.10	0.04	0.02
10 h[b]	0.85	5.73	0.01	0.02
100 h[a]	3.00	35.15	0.06	0.02
1000 h[a] sound	10.42	111.15	0.03	0.08
1000 h[a] rotten	282.40	16.15	0.04	0.02
Litter 1 h (non-woody)[b]	6.47	5.31	0.02	0.02
Grass/forb standing[b]	0.07	0.18	0.07	0.04
Standing live woody[b]				
Total understory	10.40	0.95	0.01	0.02
<2.0 m tall	2.16	0.95	0.25	0.15
Standing dead woody[a]	0.22	0.07	0.12	0.14
Depth of duff (cm)	4.75	3.34	0.10	0.08

Two independent determinations of 1 and 10 h downed woody fuels are shown, from (a) transect intercepts, and (b) sorted litter samples. Standing live woody biomass was estimated in part from basal diameter data utilizing regression equations developed from data collected on site. Tests of significance are shown for the parametric two-sample *t*-test (treatment $n = 4$, d.f. = 6) and the non-parametric Kruskal–Wallis rank sum test. *P* values are equal to or less than the number shown. Statistics were calculated using STATISTIX ver 2.1 for Windows (1998).

Table 2
Fuel moisture (% wet weight) contents of selected fuel components measured 12 February 2004 and 20 February 2004 before experimental fires on those dates

	Burn only	Chip + burn
(A) February 12th fires		
Downed woody 1 h	14.63	20.72
Downed woody 10 h	33.61	33.15
Litter 1 h non-woody	16.34	19.87
Grass/forb standing	14.57	12.98
(B) February 20th fires		
Downed woody 1 h	17.32	13.22
Downed woody 10 h	29.75	22.07
Litter 1 h non-woody	18.56	12.66
Grass/forb standing	23.62	17.30

moisture 20%, mid-flame wind speed 1.1 km h^{-1} (0.67 miles h^{-1}). (2) Untreated fuels, risk scenario ‘‘A’’—rough age 15 years, fuel depth 2 m, fuel moisture 5%, mid-flame wind speed 1.1 km h^{-1} (0.67 miles h^{-1}). (3) Untreated fuels, risk scenario ‘‘B’’—rough age 15 years, fuel depth 2 m, fuel moisture 5%, mid flame wind speed 9.7 km h^{-1} (6.0 miles h^{-1}). (4) Treated fuels, observed conditions prior to February 20, 2003, fires—age of rough 15 years, fuel height 30 cm (1 ft), fuel moisture 15%, mid-flame wind speed 4 km h^{-1} (2.5 miles h^{-1}). (5) Treated fuels, risk scenario ‘‘A’’—rough age 15 years, fuel depth 30 cm (1 ft), fuel moisture 5%, mid-flame wind-speed 4 km h^{-1} (2.5 miles h^{-1}). (6) Treated fuels, risk scenario ‘‘B’’—rough age 15 years, fuel depth 30 cm (1 ft), fuel moisture 5%, mid-flame wind speed 30.9 km h^{-1} (19.2 miles h^{-1}).

Methods and results for the smoke-monitoring study were reported separately (Achtemeier et al., in press; Naeher et al., in press). Herein we used the model FOFEM (First Order Fire Effects Model) 5.2.1 (Keane et al., 2004) in an attempt to understand the smoke monitoring results in terms of fuel consumption patterns. We also used FOFEM to explore effects of a potential drought scenario on fuel consumption and smoke production. Input to FOFEM was similar to that used in BehavePlus with two exceptions: (1) BehavePlus does not make use of 1000 h fuels given that these largest diameter fuels are mostly irrelevant to fire behavior. FOFEM, in contrast, predicts percentage consumption of 1000 h fuels and incorporates those results in predictions of smoke emissions. Along with inputting total 1000 h fuel loads the user estimates the percentages for ‘‘sound’’ or ‘‘rotten’’. Also one provides the model a determination of skewness, i.e. whether the diameter distribution of the 1000 h fuels is skewed towards small, medium or large logs. (2) Duff loading is not an input variable for BehavePlus. FOFEM calculates duff loads given observed data on depth of duff. It then predicts duff consumption given known or estimated duff moisture levels. Duff consumption is then incorporated into the estimates of smoke production.

Like BehavePlus, FOFEM provides default estimates for fuel and fuel moisture parameters that are then subject to user modification. We collected most of the data required by FOFEM as part of our fuels sampling as described above. Selections for the other variables were as follows: (1) region = southeast; (2) moisture condition = wet for observed data, dry for drought scenario; (3) season (of fire) = winter; (4) cover classification = SAF/SRM; (5) cover type = SAF 81 (loblolly pine-coastal), rough age 15 years for untreated fuels, 1 year for treated fuels; (6) fuel category = natural fuels. We could have selected a different fuel category option for chip fuels but neither pile fuel nor slash fuel seemed appropriate. Regardless, the fuel category option is used mainly for specifying default options for fuel loads and we inputted our own data.

3. Results

3.1. Fuels

Calculated fuel loads for the treated and untreated plots are shown in Table 1. The chip treatments achieved the objective of greatly reducing 1000 h fuels. However, the large majority of 1000 h fuels in the untreated plots were classified as rotten. Most of these logs were badly decomposed and appeared unlikely to burn except in very dry conditions. Considering sound wood alone, a different pattern was apparent. As a consequence of incomplete pulverization of larger woody stems, chip treatments substantially increased 1000 h sound fuels as compared to background levels in the untreated plots. Likewise, loadings for 100 h and 10 h downed woody fuels were also much greater following chip treatments. One hour non-woody fuels, primarily pine needles, were lower in the chip plots, presumably reflecting lesser needle deposition following elimination of the pine mid-canopy.

Grass/forb standing fuel weights were low in both treatments as might be expected following a long period without fire and consequent declines in understory herbs. (Compare to results of Glitzenstein et al. (2003) from edaphically similar sites with a history of frequent prescribed fire). Furthermore, fuels were collected during the dormant season when some herb species would not be present above ground. Grass/forb weights were, however, significantly higher in the chip plots, suggesting some tendency towards ground layer rehabilitation.

Weight of standing live woody fuels (defined as live tree stems less than 2.0 m tall and shrubs regardless of height) was significantly greater in the non-chipped plots. The magnitude of this difference was not as great as might have been expected, probably because smaller woody stems in the non-chipped plots had already thinned out considerably beneath the dense mid-canopy. Furthermore, most hardwood stems re-sprouted post-treatment and consequently contributed to potential standing live fuels.

Fuel moisture data collected prior to fires on February 12 and 20 are presented in Table 2. Fuels in all plots were quite moist, i.e. percent water contents exceeding even the ‘‘high moisture’’ scenario of the standard southern rough fire behavior parameter set provided by the BehavePlus fire modeling program (Andrews et al., 2005). High fuel moisture values reflected perched water tables and saturated soils—soil moistures determined using a neutron probe on February 12 were essentially at field capacity in both plots.

3.2. Fire behavior

Fire behavior was not precisely documented in the two smoke plots. However, field observations suggested a rather substantial treatment effect. The fire front moved rapidly across the no-chip plot, covering the 80 m or so distance between backline and blackline in less than 10 min, i.e. an estimated rate of spread of approximately 7.8 m min^{-1}. Flame lengths appeared to be mostly less than 1 m, but with occasional flare-ups up to 3.0 m as pyrogenic shrubs, e.g. *M. cerifera*, were combusted. In contrast, the fire moved slowly through the chipped plot. Flame lengths were also much lower, averaging approximately 25 cm according to field observations. Reduced wind-speeds during the chip plot burn (Achtemeier et al., in press) may have contributed to these differences in fire behavior. Also the chip plot may have been slightly lower and

Table 3
Mean fire behavior measurements in the February 20, 2003, burn plots as determined from video analysis

Plot	Treatment	Time of burn (LST)	Wind speed (km h^{-1})	Rate of spread (m min^{-1})	Flame length (cm)
3	Chip–burn	1400	10.8	0.52	20.95
5	Burn only	1200	12.6	0.53	27.56
7	Burn only	1600	23.4	1.50	42.37
9	Chip–burn	1600	23.4	0.46	39.76
10	Burn only	1700	21.6	0.99	42.56
11	Chip–burn	1800	12.6	3.09	44.06
Median	Burn only		21.6	0.99	42.37
Median	Chip–burn		12.6	0.52	39.76
Mean	Burn only		19.2	1.01	37.50
Mean	Chip–burn		15.6	1.36	34.92

Times of burns, and wind speed data from the National Weather Service station in Charleston, SC, are also presented.

moister, though fuel moisture differences were comparable between the two plots (Table 2).

Fire behavior in the February 20 burn plots was more carefully documented using video analysis (Table 3). These burns were low intensity (mean flame length = 36.2 cm) and slow moving (mean spread rate = 1.18 m min^{-1}). Neither flame length nor rate of spread differed significantly between treatments (ANOVA F's < 0.5, $P > 0.7$, d.f. = 1,4), although flame lengths averaged slightly higher in the no chip plots (37 cm versus 34 cm). The most important influence on these two variables appeared to be time of burning, a probable indicator of changed burning conditions. Flame lengths increased significantly ($r = 0.84$, $n = 6$, $P = 0.03$) during the course of the day and a similar tendency was evident with regards to rate of spread ($r = 0.63$, $P = 0.13$). The plot with the highest mean rate of spread (3.10 m min^{-1}), a chipped, plot, was the last to be burned, and fuels had no doubt by this time dried considerably, especially after two consecutive hours of strong winds (Table 3). This plot was also somewhat atypical in that the intensity of chipping was least and some large patches of untreated fuel remained. The remaining two chipped plots had among the lowest spread rates (Table 3), similar to the chipped plot burned earlier as part of the smoke experiment.

Post-burn observations (including the smoke plots) provided somewhat more convincing evidence of treatment effects on fire behavior (Fig. 2). Perhaps most telling was the determination of percentage of burned area (Fig. 2a). According to the transect data, only slightly more than half the area in the chip plots burned as compared to upwards of 80% in the burn-only plots. This difference was statistically significant ($t = 2.68$, $P = 0.04$). Another marginally significant ($t = 1.32$, $P = 0.23$, Kruskal–Wallis $F = 4.5$, $P = 0.07$) difference was a somewhat higher mean scorch height in the burn-only plots (247 cm versus 126 cm in the chip plots, Fig. 2c). Other measured variables reinforced the conclusion that the fires in general were low intensity with low fuel consumption. Post-fire twig diameters on live shrubs averaged approximately 0.8 mm and did not differ significantly between treatments ($t = 0.34$, $P = 0.75$, Fig. 2b). None of the temperature indicators changed color, indicating that the lower litter layers and duff did not burn or contribute to smoke production.

A summary of large 1000 h fuels flaming and/or smoking on the mornings after fires is presented in Table 4. Both numbers and basal area of large smoking objects were significantly ($P < 0.05$) greater in the burn-only plots.

3.3. Fire behavior modeling

Given observed conditions of wind and fuel moisture, BehavePlus and HA accurately predicted the slow moving, low

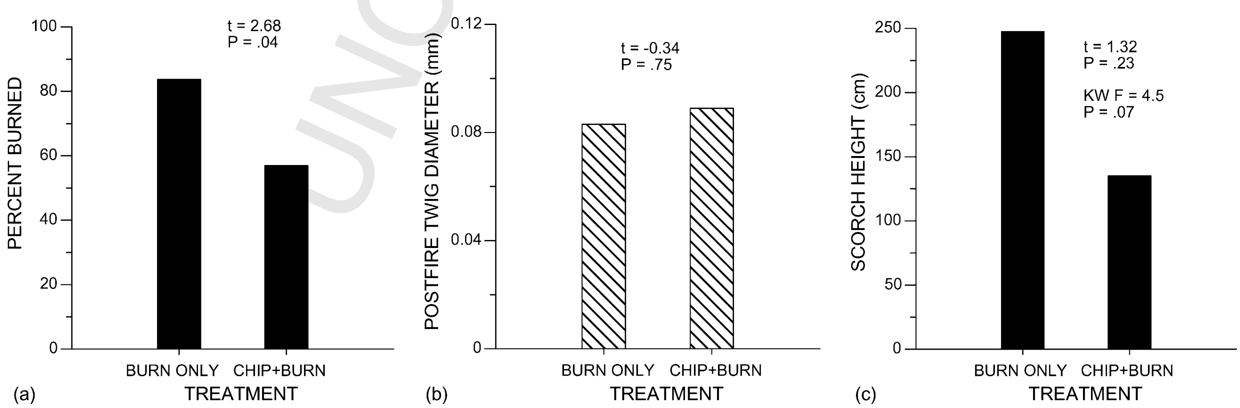

Fig. 2. Field measurements relevant to fire behavior collected after the February 12, 1993, and February 20, 1993, fires.

Table 4
Summary of residual smoke observations in plots the mornings after experimental fires on February 12 and February 20, 2003

Treatment	Plot	Number of objects	Basal area of objects (cm^2)
Burn only	1	5	3311.79
Burn only	5	2	1068.57
Burn only	7	4	2289.57
Burn only	10	2	1276.79
Total		13	7946.72
Mean		3.25	1986.68
Chip + burn	6	4	2277.00
Chip + burn	3	0	0.0
Chip + burn	9	3	2632.14
Chip + burn	11	1	707.14
Total		8	5616.28
Mean		2	1404.07

Smoking objects include any form of 1000 h fuels including logs, stumps, snags, and upturned root mounds.

intensity February 20, 2003, fires (Figs. 3–5 and Table 5). BehavePlus predictions for the untreated fuels were most accurate when fuel depth was assumed equal to the height of the litter-small shrub stratum. When a fuel depth of 2 m was used, i.e. total understory height, BehavePlus to some extent overestimated fire hazard (Figs. 3–5). Using the same 2 m estimate for fuel depth HA erred slightly on the low side (Table 5).

BehavePlus and HA predictions for the treated fuels also depended on assumptions about fuel depth (Figs. 3–5 and Table 5). Predictions ranged from essentially no fire at the low end of the range of fuel depth input values (5 cm) to flame length and rate of spread estimates similar to those observed in the fire videos (for inputted fuel depth of 30 cm). This range of predictions encompassed the range of fire behavior observed in the field bearing in mind that large sections of the treated plots did not burn.

Practically speaking, all the fire behavior predictions based on observed February 20 conditions as input values were close enough to measured values to satisfy a prescribed burner or wild land firefighter. We therefore felt justified in using BehavePlus and HA to explore riskier fire scenarios. We hoped to answer the question of whether chip treatments would protect against dangerous wildfire conditions. The answer appeared to be a qualified ‘‘yes’’. Over the range of estimated fuel depths (5–15 cm), BehavePlus predicted no fire or low intensity, slow moving fire in the 1-year post-chip fuels for both high risk scenarios (Figs. 3–5). This contrasted with predictions of tall flames and fast moving fires in the non-treated fuels (Figs. 3–5 and Table 5). The worst-case scenario for untreated fuels occurred with the combination of high wind, dry fuel (scenario B) and maximum (i.e. 2 m) estimated fuel depth. This scenario resulted in a simulated fire of catastrophic proportions. Such a fire would be essentially uncontrollable.

It should be emphasized that, according to model simulations, much of the benefit of chipping, like other fuel reduction methods, derived simply from reductions in fuel height. If, for example, we underestimated fuel depths in the chip plots and the correct fuel depth was in fact closer to 30 cm (1 ft), the predicted fire behavior would be quite different. HA in particular indicated the potential for dangerous fire behavior in

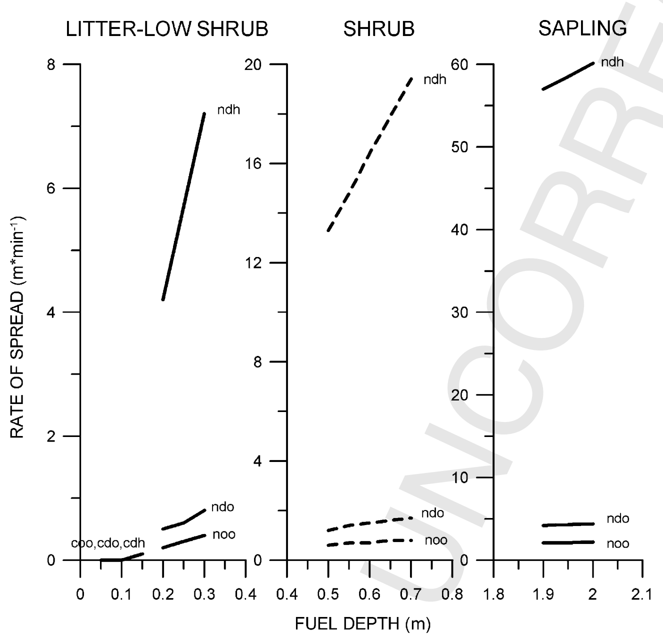

Fig. 3. BehavePlus simulations of fuel treatment and moisture scenario effects on rate of fire spread. Predictions are shown for each of three fuel height strata. Three letter codes next to lines may be interpreted as follows: first letter (n, non-chipped; c, chipped), second letter (o, fuel moisture as observed on February 20, 1993 prior to experimental fires; d, drought scenario), third letter (o, 12.5 km h^{-1} winds as observed at 10 m by NWS on February 20, 1993, the day of the experimental fires; h, the high wind scenario, i.e. 111 km h^{-1} at 10 m).

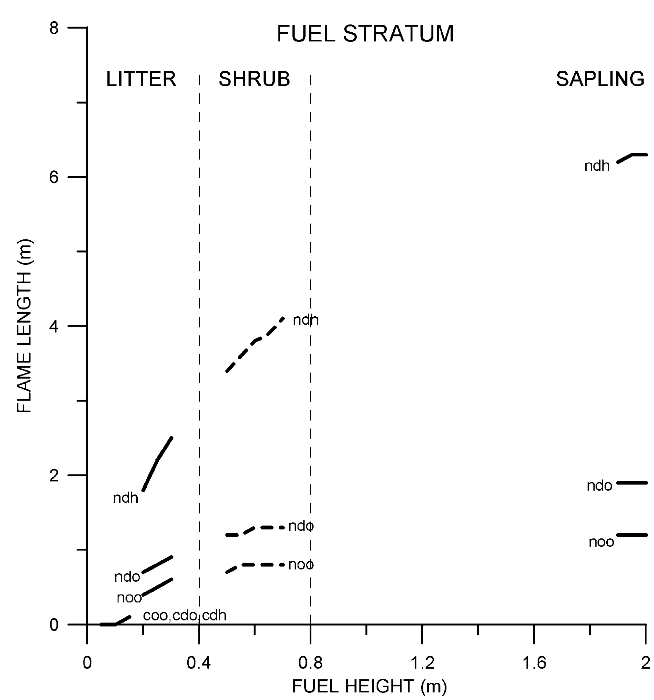

Fig. 4. BehavePlus simulations of fuel treatment and moisture scenario effects on fire flame length. Predictions are shown for each of three fuel height strata. Codes are as in legend of Fig. 3.

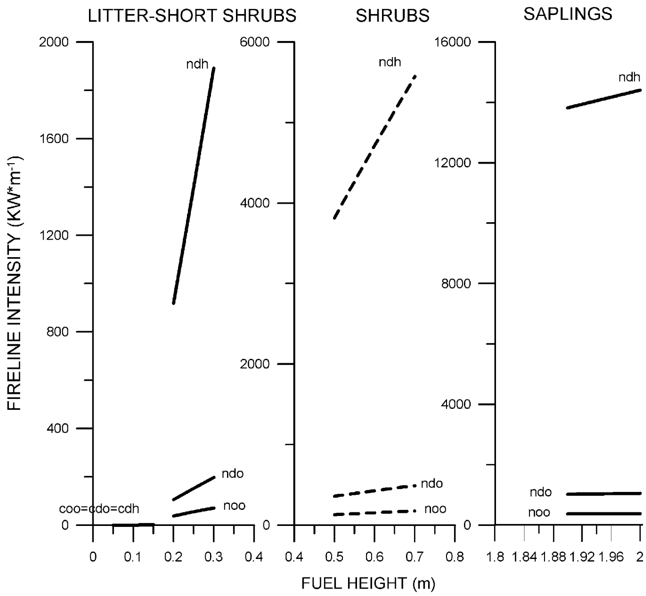

Fig. 5. BehavePlus simulations of fuel treatment and moisture scenario effects on fireline intensity. Predictions are shown separately for each of three fuel height strata. Codes are as in legend of Fig. 3.

1 ft rough given 15 years of fuel accumulations (Table 5). BehavePlus predictions were more conservative but still indicated potentially troublesome 2 m tall flame lengths and spread rates approaching 10 m min^{-1} under scenario B conditions (Table 5).

Table 5
Measured and modeled fire behavior in Francis Marion NF experimental plots

	Flame length (cm)	Rate of spread (m min^{-1})
Burn only		
Observed median	42.37	0.99
Observed mean	37.50	1.01
HA observed	30.21	0.31
BehavePlus observed	120.00	2.20
HA high risk scenario A	96.31	1.10
BehavePlus high risk A	190.00	4.40
HA high risk scenario B	304.64	13.71
BehavePlus high risk B	630.00	60.10
Chip and burn		
Observed median	39.76	0.52
Observed mean	34.92	1.36
HA observed	86.33	1.67
BehavePlus observed	40.00	0.40
HA high risk scenario A	110.00	2.31
BehavePlus high risk A	60.00	0.60
HA high risk scenario B	387.75	59.25
BehavePlus high risk B	190.00	9.00

HA is Rothermel's (1972) model as adjusted by Hough and Albini (1978) for palmetto–gallberry fuel complex with sparse canopy and sparse palmetto. The BehavePlus implementation of Rothermel's (1972) model is for Burgan's (2005) tu2 (used for non-chip) and sb3 (used for chip) fuel complexes. "HA observed" is the HA prediction for fuel moisture and wind as observed on February 20, 2003, the date of the experimental fires. "BehavePlus observed" is likewise the BehavePlus prediction for moisture and wind values observed on February 20, 2003. Fuel depth is 2.0 m for HA and Behave in the burn only fuels and 30 cm in the chip fuels. HA predictions are for 15-year rough. High risk scenarios A and B are discussed in the text.

Table 6
Fuel consumption and smoke (PM2.05) emissions predicted by FOFEM 5.21 for observed conditions and drought scenario

	Burn only		Chip and burn	
	Observed	Drought	Observed	Drought
Fuel consumption percentages				
1 h[a]	100.0	100.0	100.0	100.0
10 h[a]	100.0	100.0	100.0	100.0
100 h[a]	100.0	100.0	100.0	100.0
1000 h[a] sound	64.6	71.4	82.7	93.3
1000 h[a] rotten	76.7	91.6	89.6	97.3
Litter 1 h (non-woody)[b]	100.0	100.0	100.0	100.0
Grass/forb live standing[b]	100.0	100.0	100.0	100.0
Live woody (<2 m): shrubs	67.2	100.0	100.0	100.0
Duff	0.0	16.2	0.0	7.5
Fuel consumed (Mg ha^{-1})	319.6	380.2	307.1	339.4
Smoke produced (kg ha^{-1})	7010.9	5486.6	4484.5	2381.8

Fuel inputs as given in Table 1 except for duff loads, which are calculated by the model from field duff depth measurements.

We used FOFEM to simulate treatment effects on fuel consumption and smoke production for observed conditions and a potential high-risk (drought) scenario. Given observed conditions on February 20, 2003 FOFEM predicted complete consumption of 1, 10 and 100 h-fuels as well as substantial consumption of 1000 h-fuels (Table 6). These predictions were at variance with post-fire field observations indicating little or no consumption of heavier fuels. Given this obvious discrepancy, the validity of FOFEM predictions is questionable. In any case, FOFEM simulations of smoke production were consistent, atleast qualitatively, with empirical results from the smoke study (Achtemeier et al., in press; Naeher et al., in press). For observed fuel moisture data, FOFEM predicted approximately 53% higher smoke production in the non-chipped fuels (Table 6). With lower fuel moisture (i.e. the drought scenario) FOFEM predicted less smoke. Relative smoke production for the two treatments was not altered by drought (Table 6).

4. Discussion

Mechanical chipping is now widely used by southern USA land managers, atleast in part to modify fire behavior. Like other mechanical fuels treatments (Outcalt and Wade, 2000; Brose and Wade, 2002) a goal of chipping is to reduce the likelihood of catastrophic wildfire and increase the ease and safety of prescribed burning. Results of our fire behavior modeling suggested that chipping does indeed reduce the risk of catastrophic fire, atleast in the short term. Results from the field study were also consistent with this conclusion, particularly the observation of large unburned areas following fires in chipped plots.

An important question concerns increase in potential fire hazard in chipped fuels following vegetation re-growth and time after chipping. Unlike burning, which consumes fuels, chipping rearranges but does not decrease fuel loading. As vegetation recovers and fuel height increases, BehavePlus and

HA each predict a rapid return to hazardous fire conditions in the chipped fuels (see also Outcalt and Wade, 2000; Brose and Wade, 2002).

There is reason to be somewhat skeptical about this conclusion. Uncertainties derive from the aforementioned limitations of Rothermel (1972) and its' kin (including BehavePlus, HA and FOFEM) in dealing with vertically heterogeneous fuel structures. As Evans et al. (2004, p. 3) point out, ''the basic model regards all of the fuel to cover the land surface as if it were painted on''. Fuel beds can be ''inhomogeneous'' with respect to fuel elements and sizes, but there is no vertical structure in how these elements are arranged. The various fuel types defined by Scott and Burgan (2005) and others help in part to specify appropriate fuel combinations but do not deal with the basic issue of vertical heterogeneity.

Consider the post-chip fuel matrix consisting of a dense compact layer of wood fragments and other debris subtending a layer of vegetation re-growth. Rothermel (1972) does not distinguish these zones but instead models the chip debris as uniformly intermingled with the vegetation. As fuel depth increases the heavy chip fuels consequently become more completely aerated and more likely to burn. The model does not recognize, and therefore fails to account for the possibility, that fire may simply burn across the top of the dense compacted layer without consuming it. A new generation of fire models now under development may ultimately allow more sophisticated and accurate methods for predicting fire behavior in vertically stratified fuels (Evans et al., 2004).

In addition to wildfire hazard reduction, a second issue related to chipping in the WUI concerns prescribed fire. Much time and expense currently being invested in mechanical chipping is predicated on the assumption that this pre-treatment is necessary before safely resuming prescribed burning in long-unburned fuels. Our results suggest this assumption is invalid, atleast for the Francis Marion NF and vicinity. Despite many years of fuel accumulations, tall understory vegetation, and steady winds, our prescribed burns were for the most part slow moving and with low flame lengths. This was true for non-chipped plots (with the apparent exception of the February 12 control plot) as well as chipped ones. Fire models BehavePlus and HA likewise predicted that prescribed fires can be carried out safely and even conservatively in 14 year rough in FMNF pine flatwoods if burn conditions are carefully selected. Indeed, given high water tables and persistently high fuel moistures during much of the winter prescribed burn season, it is often difficult to produce an adequate let alone an uncontrollable prescribed burn. Ferguson et al. (2002) reached similar conclusions with respect to west FL longleaf pine stands. Their results on fire behavior and duff consumption, or lack thereof, from ''wet'' and ''moist'' fuels are similar to our own results from the burn-only plots.

Ferguson et al. (2002) also showed that, at low moisture levels, consumption of duff and lower litter layers in long-unburned stands could pose significant forestry and ecological hazards, including, potentially, damage to old longleaf pine trees utilized as nest trees by the endangered red-cockaded woodpecker. Our results indicate that chipping (or mulching as it is sometimes referred to) greatly increases down woody fuels, much of which may be rapidly transformed into duff. Chipping also essentially eliminates the understory, thereby increasing wind movement and drying out of duff and litter. It is plausible that during drought periods a history of chipping may exacerbate problems of duff consumption and tree root mortality.

On the other hand there were indications in our data that, over a period of several years, chipping might actually reduce duff accumulation. By eliminating the understory, chipping removes the source of much pine and oak leaf litter that contribute to duff buildup (Miyanishi, 2001; Hille and den Ouden, 2005). Also chipping tended to reduce pre-existing duff by churning it upwards and mixing it into the litter. Finally, the more open canopy conditions should lead to more rapid duff decomposition rates (Miyanishi, 2001).

Long-term duff and litter dynamics post-chipping should be studied further. In the interim, managers attempting to burn chipped stands should endeavor to avoid dangerously dry conditions, e.g. as indicated by the Keetch–Byram Drought Index (KBDI, Keetch and Byram, 1968).

Results pertaining to the smoke monitoring part of this study are published elsewhere (Achtemeier et al., in press; Naeher et al., in press) but are summarized briefly as follows. PM2.5 particulate measurements were taken at nine locations along the perimeter of each smoke-monitoring plot and at four pole-mounted locations in the interior of each plot. The 12 h average perimeter smoke concentration at the mechanically chipped plot was roughly half that found for the control (burn only) site. The average PM2.5 concentration for the four interior instruments was approximately 60% lower at the chipped plot.

Consistent with these findings, the model FOFEM predicted substantially higher rates of smoke production in the non-treated plots. However, the basis for this prediction was doubtful given that FOFEM incorrectly predicted consumption patterns of downed woody fuels. The primary basis for FOFEM's smoke prediction, higher total consumption of 1000 h fuels in the burn-only plots, may have been valid. Of likely greater importance, however, was the direct negative effect of chipping on fire propagation. It was probably not coincidental that the observed percentage decrease in smoke production due to chipping was approximately the same as the percentage of unburned area in the chip plots. By burning within the first year post-chip, managers can apply Ottmar et al.'s (2001) recommendation to reduce smoke emissions through use of a ''mosaic'' or ''patchy'' burn. It may, however, be worthwhile to repeat their caveat that ''programs to reduce the area burned must not ultimately result in just a delay in the release of emissions either through prescribed burning at a later date or as the result of a wild fire. Reducing the area burned should be accomplished by methods that truly result in reduced emissions over time rather than a deferral of emissions to a later date''. It is not yet clear whether chipping passes this test.

When provided with the drought scenario FOFEM rather surprisingly predicted less smoke released from both treatments although a greater percentage of fuels were combusted.

Apparently the lower efficiency of combustion in the moister fuels leads to enhanced output of smoke particles (Ottmar et al., 2001). We accept that combustion efficiency is lower in moist fuels but tend to doubt the prediction of higher overall smoke production. This likely erroneous result is once again a function of FOFEM's evident tendency to overestimate rates of large diameter woody fuel consumption in moist SC Coastal Plain environments. We suspect the more likely result of burning under dry conditions in these fuels would be much greater total litter and duff consumption and enhanced smoke production. We also would not discount entirely the ''smoking mat'' hypothesis (Ottmar et al., 2001; Achtemeier et al., in press) of prolonged smoldering of heavy chip fuels resulting in much higher smoke production on treated sites. Again, managers might wish to apply considerable caution before burning such sites under dry conditions. Also FOFEM predictions should perhaps be viewed skeptically by SC Coastal Plain managers until the model can be altered to reflect the particular environments and the peculiar fuel structures produced by chipping.

5. Conclusions

We conclude that chipping of forested areas near sensitive wildland/urban interface zones may reduce the threat of hard to control wildfires and smoke (see also Achtemeier et al., in press; Naeher et al., in press). Assuming that BEHAVE results can be accepted as authoritative, this conclusion holds for low fuel moisture and high winds typical of wildfire-producing conditions.

In addition to reducing wildfire hazard, mechanical chipping is also being used as a pretreatment prior to reinitiating prescribed burning. From a fire safety standpoint there appears to be little validity to this practice in Atlantic Coastal Plain flatwoods. As long as burn conditions are carefully selected, it is possible to prescribe burn these habitats even in long-unburned rough with little fear of losing control of the fire or generating unacceptable levels of crown scorch and tree mortality.

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