FUEL LOADING FOLLOWING FUEL-REDUCTION TREATMENTS AND IMPACTS FROM NATURAL DISTURBANCES

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Abstract—A long-term study of fuel-reduction treatments (mechanical fuel removal, prescribed burning, and the combination of mechanical treatment and burning) was begun in 2000 and 2001 for sites located in the Piedmont of South Carolina and the Southern Appalachian Mountains of North Carolina, respectively. During this time multiple natural disturbances [southern pine beetle (*Dendroctonus frontalis*) infestations and ice storms] occurred that allowed us to observe effects that fuel-reduction treatments had on impacts from these disturbances at these two sites. After 8 years and multiple natural disturbances, the mechanical treatment at the Piedmont site showed little difference in fine fuel and 1,000-hour fuel loadings from the control, whereas the mechanical+burn treatment had significantly less fuel. For the Appalachian site, an ice storm event in 2005 resulted in large inputs of fine fuels in the mechanical treatment and control units. Two years later, fine fuel loadings in those treatments were still significantly higher than that measured in the burn and mechanical+burn treatments; however, units treated with prescribed fire had greater 1,000-hour fuel loadings. Predicted fire behavior following fuel-reduction treatments, ice storms, and/or pine beetle infestations was lowest for the mechanical treatment at the Piedmont site and for the burn and mechanical+burn treatments at the Appalachian site. Changing fuel loadings through fuel-reduction techniques can have important effects on fire behavior by altering fuel structure and may influence the impact of natural disturbances in treated stands.

INTRODUCTION

With frequent occurrences of southern pine beetle (SPB) (*Dendroctonus frontalis*) infestations (8 to 10 years) and ice storms (5 to 20 years) (Abell 1934, Travis and Meentemeyer 1991) for the southeastern Piedmont and Southern Appalachian regions, these types of disturbances can significantly impact forest composition, structure, and fuel loads. Previous work has suggested these disturbances impact forest succession and species composition (Boerner and others 1988, Lafon 2006, Lafon and Kutac 2003) with relatively few studies focused on fuel loadings (Waldrop and others 2007). Given current forest conditions of southeastern forests—increased fuel loadings as a result of fire suppression over the past century—forest managers have incorporated fuel-reduction techniques to reduce the risk of severe fire occurrence and decrease stand density. However, common natural disturbances, e.g., SPB infestations and ice storms, can significantly alter available fuel, vertical fuel structure, and fuel dynamics, but the degree to which some of these disturbances influence fuel loadings may be affected by forest management practices.

Beginning in 2000, the Southeast experienced a significant SPB outbreak which impacted States from Alabama to Virginia. A SPB epidemic that occurred from 2000 to 2002 devastated over 6 million ha in South Carolina, resulting in over $250 million in losses for 2002 alone (U.S. Department of Agriculture Forest Service 2003). In addition to this large-scale disturbance, several small-scale ice storms occurred in these areas from 2000 to 2008. Two major ice events affected the Piedmont of South Carolina (Dec. 4–5, 2002, and Jan. 26–30, 2004), each producing >2.5 cm of frozen precipitation. The 2004 ice storm resulted in >$95 million in timber losses for over 930 000 ha in South Carolina prompting a Presidential declaration of major disaster (South Carolina Forestry Commission 2004). The Southern Appalachian site experienced one major ice event (Dec.14–15, 2005) with ice accumulations of 0.5 cm to >2.0 cm, the largest accretion occurred around Hendersonville, Saluda, and Tryon, NC (National Weather Service 2005).

The objectives for this paper were to identify differences among four different fuel-reduction treatments with respect to fuel loadings and subsequent fire behavior in the context of real world natural disturbances. How did these treatments influence fine fuel loadings? What impacts did SPB and ice storms have on large, 1,000-hour fuels in stands subjected to fuel-reduction treatments? How did changes in fuel structure and composition affect predicted fire behavior for these stands?

STUDY AREA

The study sites are located in the South Carolina Piedmont on the Clemson Experimental Forest (34°40' N, 82°49' W) in Anderson, Oconee, and Pickens Counties and in the Southern Appalachian Mountains of North Carolina on the Green River Game Land (35°17' N, 82°19' W) in Polk County (fig. 1). The Clemson site is dominated by loblolly pine (*Pinus taeda*) and shortleaf pine (*P. echinata*) growing over highly degraded soils. Most of the forest is second- or third-growth timber resulting from reforestation programs in the early 1900s with stand ages ranging from 15 to 120 years. The climate of the region is warm continental with mean monthly temperatures between 5 °C to 26 °C and mean annual precipitation of 1372 mm distributed evenly throughout the year (National Oceanic and Atmospheric Administration 2002b).

The Green River site supports a variety of oaks (*Quercus* spp.) and hickories (*Carya* spp.), red maple (*Acer rubrum*), yellow-poplar (*Liriodendron tulipifera*), sourwood

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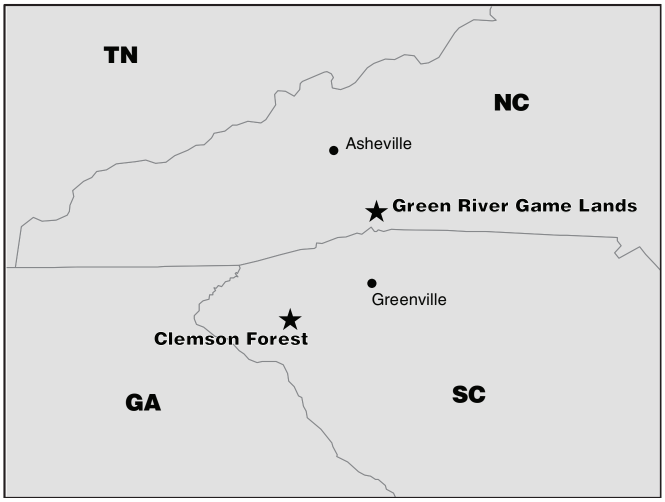

Figure 1—Location for the Piedmont and Southern Appalachian study sites.

(*Oxydendrum arboreum*), pitch pine (*P. rigida*) and a dense layer of ericaceous shrubs—mountain laurel (*Kalmia latifolia*) and rosebay rhododendron (*Rhododendron maximum*), which act as vertical fuels, potentially causing wildfires to reach the tree canopy (Waldrop and Brose 1999). The forests of the study area were 80 to 120 years old, and no indication of past agriculture or recent fire was present, though the historical fire return interval in the area prior to 1940 was approximately 10 years (Harmon 1982). Mean monthly temperatures range between 2 °C and 23 °C; mean annual precipitation averages 1438 mm distributed evenly throughout the year (National Oceanic and Atmospheric Administration 2002a).

METHODS

We used a randomized complete block design with each of 4 treatments present in 3 blocks (12 treatment units per study site). Initial fuel-reduction treatments (mechanical removal of fuel, prescribed burning, a combination of mechanical removal and burning, and a control) were applied from 2000 to 2002 at Clemson and 2001 to 2003 at Green River. We used different techniques for the mechanical treatment for the two sites to address the issues of fuel accumulation. At the Clemson site, we reduced stand density to a residual basal area of 18 m^2/ha using a single entry thinning from below during the winter of 2000 to 2001. Slash created from this treatment was distributed throughout the site. To reduce the vertical buildup of fuels at Green River, contract chainsaw crews felled all tree stems >1.8 m tall and <10.2 cm diameter at breast height (d.b.h.), as well as all shrub stems (predominantly mountain laurel and rhododendron), regardless of size, during the winter of 2001 to 2002. Prescribed burning was conducted on a 3-year cycle with the burn treatment units receiving initial treatment in April 2001 and March 2003 for Clemson and Green River, respectively. The mechanical+burn treatment units were initially burned in 2002 at Clemson and 2003 at Green River. Due to high overstory mortality from SPB in the burn treatment at Clemson, a second set of burn treatment areas was established in 2003 (designated as burn1 for the original and burn2 for the replacements). A second burn was conducted at Clemson in March to April 2004 (burn treatment) and March to May 2005 (mechanical+burn treatment) and at Green River in February to March 2006 (burn and mechanical+burn). Details on prescribed fire behavior are given by Phillips and Waldrop (2008) for the Clemson site and Waldrop and others (2008) for the Green River site.

Approximately 120 fuel transects were established in each treatment unit and were measured using the planar intercept method (Brown 1974) every year or every other year depending on treatment schedule. Fuels were classified by size class: 1-hour fuels (0 to 0.6 cm), 10-hour fuels (0.6 to 2.5 cm), 100-hour fuels (2.5 to 7.6 cm) and 1,000-hour fuels (7.7+ cm). Along the transect, 1- and 10-hour fuel intercepts were counted along the first 2 m and 100-hour fuels were counted along the first 4 m. Fuels in the 1,000-hour class were recorded by species, diameter, and decay class (sound or rotten) along the entire transect (15.2 m). Litter and duff depths were measured at three points along each transect. Fuel counts were converted to mean weights per treatment area with equations given by Brown (1974).

We used repeated measures analysis of variance (SAS Institute Inc. 2002) to identify differences in fine fuel loadings (litter, 1-, 10-, and 100-hour fuels) and large fuel loadings (1,000-hour fuels) and made post-hoc comparisons using linear contrasts for each site separately. We interpreted significant treatment and/or treatment × year interactions ($\alpha = 0.05$) as evidence of treatment effects. As much of these data did not meet the assumption of normality, it was necessary to use data transformations to normalize the distributions. Logarithmic and square root transformations were used in these analyses; however, all reported means were calculated using the nontransformed data.

Custom fuel models were developed for each treatment and fire behavior predictions (based on 80th-percentile weather during the wildfire season for each study site) were made using BehavePlus 4.0 (Andrews and others 2008). Eightieth-percentile weather conditions from February to early April calculated from observations from the Greenville/Spartanburg airport (approximately 72 km from the Clemson study site) included a high temperature of 22 °C, low relative humidity of 34 percent, and peak 5-minute wind speed of 13 m/second. For the Green River study site, values calculated from observations at the Asheville Regional airport (approximately 25 km from the study site) included a high temperature of 13 °C, minimum relative humidity of 42 percent, and peak 5-minute wind speed of 9.4 m/second. We used fuel moisture scenarios representative of conditions in these regions given the above described weather parameters: 1-hour fuel moisture content was 6 percent; 10-hour moisture content was 7 percent; and 100-hour moisture content was 8 percent. BehavePlus 4.0 provided estimates of flame length, rate of spread, spread distance, area burned, and scorch height.

RESULTS AND DISCUSSION

Southeastern Piedmont

Immediately following fuel-reduction treatments at the Clemson site, fine fuel loadings (litter, 1-, 10-, and 100-hour fuels) decreased across all treatments (fig. 2A). The decrease in fine fuels for the mechanical treatment is misleading because 1-, 10-, and 100-hour fuels actually increased after treatment (0.12 Mg/ha, 0.46 Mg/ha, and 2.02 Mg/ha, respectively), but litter decreased 2.92 Mg/ha—a result of less input and the manipulation of the existing forest floor (Waldrop and others 2004). Eight years after treatment and multiple natural disturbances, fine woody fuels were greatest in the mechanical treatment (27.8 Mg/ha) and the control (26.4 Mg/ha) with the mechanical+burn treatment containing significantly less fuel (22.0 Mg/ha) than all other treatments (*P*-values ≤ 0.019).

Large woody fuels (1,000-hour fuels) increased immediately following mechanical treatment (mechanical and mechanical+burn), whereas the burn treatment decreased and the control showed little change (fig. 2B). Large increases in 1,000-hour fuels were observed 2 to 3 years

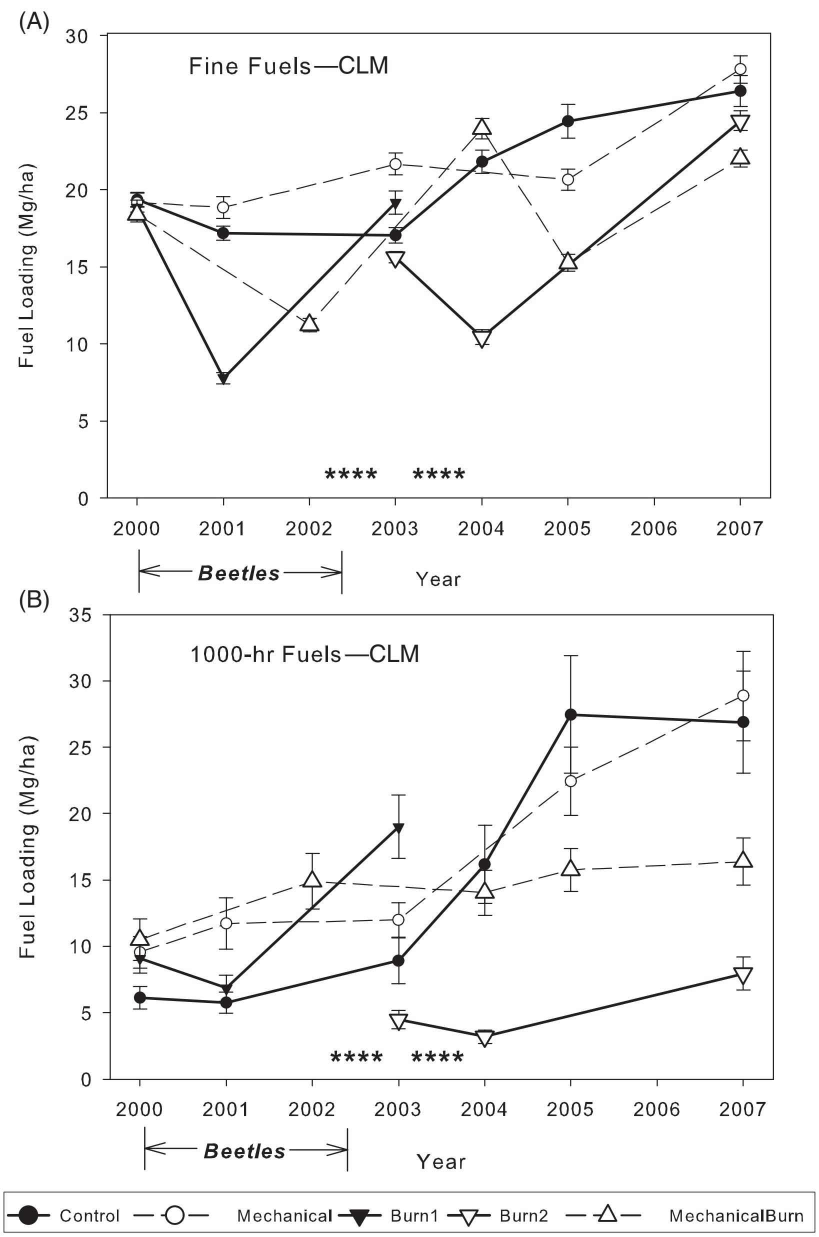

Figure 2—Loadings (Mg/ha) for (A) fine fuels (litter, 1-hour, 10-hour, and 100-hour) and (B) 1,000-hour fuel in stands affected by fuel reduction treatments and natural disturbances in the Piedmont of South Carolina. Southern pine beetle infestations lasted from September 2000 to October 2002. Two ice storm events (****) affected these stands in December 2002 and January 2004. Fuel reduction treatments were applied during 2000 to 2002 and 2004 to 2005.

after SPB infestations for the mechanical treatment and the control resulting in significantly more 1,000-hour fuels in these treatment areas as compared to the other treatments (P-values ≤ 0.0010). By year 8, large fuel loadings for all treatments were (in decreasing order) mechanical (28.9 t/ha), control (26.9 t/ha), mechanical+burn (16.4 t/ha), and burn2 (7.9 t/ha). However, the burn2 treatment had only been subjected to a single prescribed fire and was 3 years behind schedule compared to the other treatments.

Over the duration of this study, fuels increased approximately 100 percent in the mechanical and control, roughly 60 percent in burn2, almost 40 percent for burn1, and 33 percent for mechanical+burn treatments which could have significant consequences on fire behavior. Based on fuel models created for the Clemson site, potential fire behavior 8 years after initial treatment was lowest for the mechanical treatment (table 1) even though the mechanical+burn treatment had significantly lower fuel loadings for all fine fuels. These results indicate the sensitivity of BehavePlus to fuel depth as this variable was the only factor lower in the mechanical (12.4 cm) vs. the mechanical+burn (15.4 cm) for that sample period. The burn and mechanical+ burn treatments showed reduced potential fire behavior the first few years following prescribed burning but increased time between burn intervals results in rapid fuel accumulation for these forests (Wade and others 2000).

The SPB infestations affected stands with higher basal areas, i.e., mechanical treatment and control, with little damage observed in the mechanical+burn treatment (Phillips and Waldrop 2008). Effects from the SPB would have lessened the amount of fine fuel input typically expected from ice storms since needles from affected trees had already dropped, leaving less surface area for ice deposition. Shepard (1978) showed that a thinning from below, similar to the mechanical treatment used for this study, would reduce susceptibility of loblolly pine stands to damage from ice storms by removing high-risk trees and encouraging vigorous growth, but timing of the thinning with respect to ice storm occurrence is an important factor. The mechanical treatment applied for this study occurred 2 years prior to the first ice event; therefore, the remaining trees should have had sufficient time to recover and the stands should have been less vulnerable to ice damage (Bragg and others 2003). However, differences between effects from the beetles, ice storms, and/or mortality from treatment on fuel input could

Table 1—Fire behavior predictions (BehavePlus 4.0) for stands affected by southern pine beetles, ice storm damage, and fuel-reduction treatments in the Piedmont of South Carolina

Sample year	Treatment	Rate of spread	Flame length	Spread distance	Area	Scorch height
		km/ha	-------------------- *m* --------------------		*ha*	*m*
2000	C	1.1	2.4	9.0	890.8	2.4
	M	2.1	3.8	17.1	2778.9	7.9
	B	1.0	2.2	7.8	691.9	1.8
	MB	2.5	4.3	20.1	3847.8	11.0
2001	C	0.7	1.8	6.0	452.8	1.2
	M	1.8	3.2	14.0	1875.9	5.2
	B	0.2	0.8	1.7	58.0	0.3
	MB	N/A	N/A	N/A	N/A	N/A
2005	C	3.0	5.0	23.6	5324.9	15.9
	M	2.4	4.1	19.2	3516.3	9.8
	B	N/A	N/A	N/A	N/A	N/A
	MB	0.6	1.6	4.9	338.5	0.9
2007	C	2.7	4.6	21.2	4264.3	12.8
	M	2.0	3.5	15.6	2327.1	6.7
	B	2.5	4.4	19.9	3740.4	11.6
	MB	2.9	4.8	23.1	5084.1	14.3

C = control; M = mechanical; B = burn; MB = mechanical+burn; N/A = not applicable.

Note: Model parameters included 80th-percentile weather conditions for the typical fire season (February to April) and a fire duration period of 8 hours.

not be determined based on the fuel measurements recorded. But examining the interactions between multiple disturbances and understanding their relative influences on fuel loadings, rather than focusing on a single event, (e.g., Lundquist 2007) could provide valuable information for land managers, e.g., fire risk assessment and hazard fuel reduction.

Southern Appalachian Mountains

Following initial treatment at the Green River site, fuel-reduction treatments increased fine fuel loadings in the mechanical treatment, but burning decreased fine fuel loadings by almost half (fig. 3A), most of which included removal of leaf litter—the primary fuel in surface fires for these forests. Damage from the 2005 ice event caused significant increases in fine fuel loadings for the mechanical treatment and control (P-values ≤ 0.0001), which were significantly greater than the burn and mechanical+burn treatments (P-values ≤ 0.0001). After 8 years, the mechanical treatment had the greatest fine fuel loadings (23.0 t/ha), whereas the burn (18.8 Mg/ha) and mechanical+burn (18.6 t/ha) treatments had significantly less fuel (P-values ≤ 0.0068). However, the burned areas experienced high overstory mortality following the 2003 prescribed burns (Waldrop and others 2008), which led to increased 1,000-hour fuel loadings

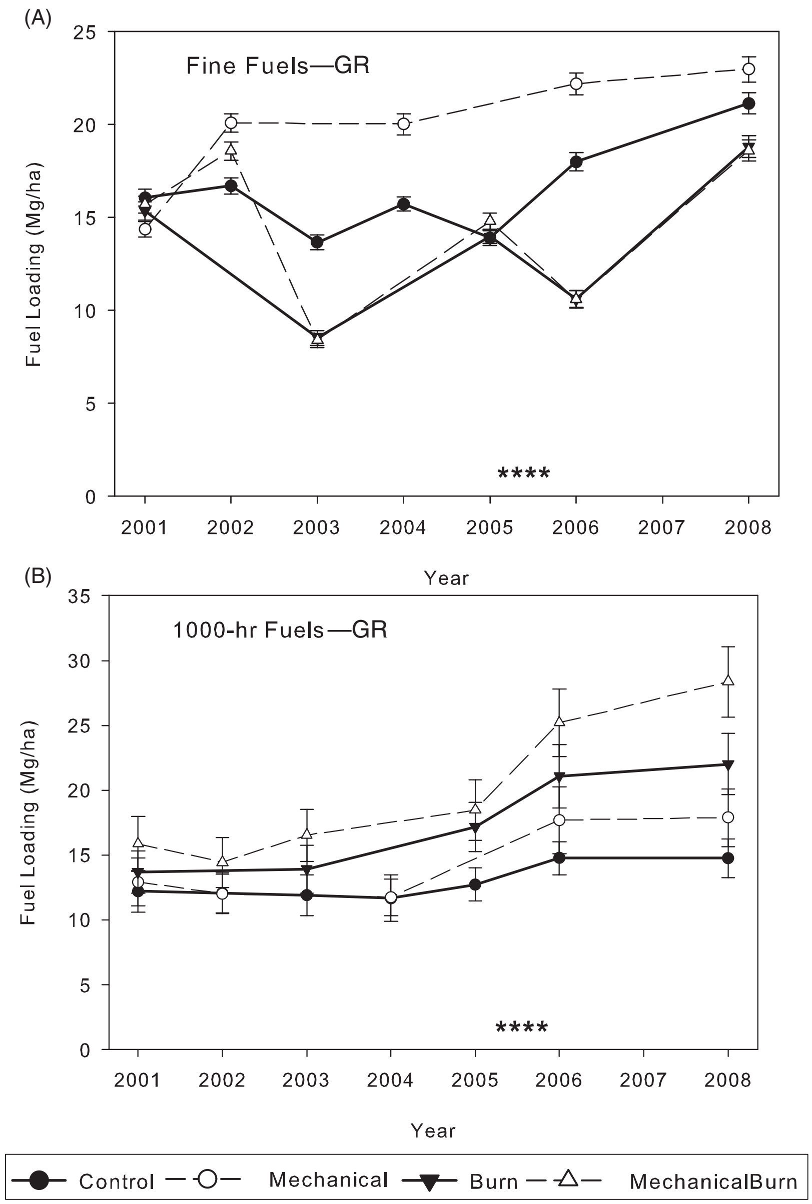

Figure 3—Loadings (Mg/ha) for (A) fine fuels (litter, 1-hour, 10-hour, and 100-hour) and (B) 1,000-hour fuel in stands affected by fuel reduction treatments and natural disturbances in the Southern Appalachians of North Carolina. An ice storm event (****) affected these stands in December 2005. Fuel reduction treatments were applied during 2001 to 2003 and 2006.

2 to 5 years after treatment (fig. 3B). This delayed mortality coincided with the ice storm causing substantial increases in large woody fuels. All treated areas and the control showed significant increases in 1,000-hour fuels following the ice event (P-values ≤ 0.0058) with large fuel loadings continuing to increase 2 years later for the mechanical+burn treatment. After 8 years, the mechanical+burn treatment had significantly greater 1,000-hour fuels than the mechanical treatment (P-value = 0.0002) and the control (P-value ≤ 0.0001). But it was not significantly different from the burn treatment (P-value = 0.1427).

Fuel-reduction treatments were intended to remove the vertical fuel component of these stands, primarily ericaceous shrubs, which should considerably affect fire behavior. Predicted fire behavior after 8 years was lower for all treated areas as compared to the control, although differences between the mechanical treatment and the control were small (table 2). Relatively few differences between the burn and mechanical+burn treatment were evident, but considering the presence of ericaceous shrubs (Waldrop and others 2008) and fewer 1,000-hour fuels, we would expect increased fire behavior within the burn treatment with respect to that in the mechanical+burn treatment.

Previous studies have reported inputs from ice damage of 5.1 m^3/ha for old-growth oak-hickory forests in Missouri (Rebertus and others 1997); 19.4 m^3/ha for mesic forests in Wisconsin (Bruderle and Stearns 1985); and 33.6 m^3/ha for old-growth hardwood forests in Quebec (Hooper and others 2001). For this study, the average volume of biomass input following ice damage was approximately 13 m^3/ha for woody fuels, which falls on the lower end of this range. However, this additional amount of fuel can appreciably affect fire behavior as mentioned above and should be accounted for when considering hazard fuel reduction. While the mechanical treatment successfully reduced the vertical fuels, it probably had no effect on ice deposition and resulting damage within the stands. Burning reduced overstory basal area which could influence future impacts from storm damage. The ecological impacts of these disturbances and their interactions with other factors are not well understood. Couple that lack of knowledge with changing land management practices, in addition to climate change, and it is evident that continued

Table 2—Fire behavior predictions (BehavePlus 4.0) for stands affected by ice storm damage and fuel-reduction treatments in the Southern Appalachians of North Carolina

Sample year	Treatment	Rate of spread	Flame length	Spread distance	Area	Scorch height
		km/ha	------------------- *m*	--------------------	*ha*	*m*
2001	C	1.1	2.5	8.8	958.2	3.7
	M	1.2	2.7	9.6	1151.5	4.3
	B	1.1	2.6	9.2	1047.8	4.0
	MB	1.2	2.7	9.5	1124.1	4.3
2003	C	0.9	2.2	7.5	701.6	2.4
	M	N/A	N/A	N/A	N/A	N/A
	B	0.1	0.5	0.7	13.0	0.0
	MB	0.1	0.4	0.5	8.4	0.0
2006	C	3.2	5.5	25.2	7898.6	23.5
	M	3.0	5.5	24.1	7213.3	24.1
	B	0.7	1.6	6.0	548.2	0.9
	MB	0.2	0.7	1.6	56.8	0.3
2008	C	1.9	4.0	15.2	2850.6	11.0
	M	1.8	3.8	14.3	2519.1	10.1
	B	1.4	3.0	10.9	1459.7	5.5
	MB	1.4	3.0	11.4	1598.7	5.8

C = control; M = mechanical; B = burn; MB = mechanical+burn; N/A = not applicable.

Note: Model parameters included 80th-percentile weather conditions for the typical fire season (February to April) and a fire duration period of 8 hours.

research is necessary to provide complete recommendations for land management.

CONCLUSIONS

Application of fuel-reduction treatments, including mechanical removal of fuel, prescribed fire, and the combination of mechanical removal and fire, appear to affect impacts from natural disturbances on fuel loadings in the Piedmont and Southern Appalachians. The combination of multiple disturbances at the Piedmont site made it difficult to separate impacts, but the stands experiencing SPB (control, mechanical, and burn1 treatments) had significantly greater fuel loadings. In the Southern Appalachians, fuel loadings within areas that were burned on a 3-year cycle contained less fine fuels but greater amounts of large fuels than other treatments. Surprisingly at the Piedmont site, predicted fire behavior was actually greatest for stands with the least amount of fine fuel loadings (mechanical+burn), demonstrating the sensitivity of BehavePlus to relatively small changes in fuel height. Altering stand structure and fuel complexes can have significant impacts on a variety of ecosystem components; therefore, different treatments may be appropriate depending on management objectives.

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