

Fuels and Predicted Fire Behavior in the Southern Appalachian Mountains After Fire and Fire Surrogate Treatments

Thomas Waldrop, Ross A. Phillips, and Dean A. Simon

Abstract: This study tested the success of fuel reduction treatments for mitigating wildfire behavior in an area that has had little previous research on fire, the southern Appalachian Mountains. A secondary objective of treatments was to restore the community to an open woodland condition. Three blocks of four treatments were installed in a mature hardwood forest in western North Carolina. Fuel reduction treatments included chainsaw felling of small trees and shrubs (mechanical treatment), two prescribed fires 3 years apart, a combination of mechanical and burning treatments, and an untreated control. Mechanical treatment eliminated vertical fuels but without prescribed burning; the mechanical treatment added litter (11%) and woody fuels (1 hour 167%; 10 hours 78%) that increased several measures of BehavePlus4-simulated fire behavior (rate of spread, flame length, spread distance, and area burned) for 5 years. Prescribed burning reduced litter mass by 80% and reduced all simulated fire behavior variables for 1 year but had no residual effect by the third year. The combined mechanical and burning treatments had hot prescribed fires (mean temperature of 517°C at 30 cm aboveground) during the first burn that killed some overstory trees, resulting in increased amounts of woody fuels on the forest floor. All active treatments (fire, mechanical, and combined) reduced simulated wildfire behavior, even after a severe ice storm that added fine fuels. Prescribed burning in combination with the mechanical treatment was the most effective in reducing all measures of fire behavior and advancing restoration objectives. Each of the active treatments tested must be repeated to reduce fuels and lower wildfire behavior, but prescribed burning must be repeated frequently. *FOR. SCI.* 56(1):32–45.

Keywords: prescribed fire, fuel reduction, wildfire, restoration, open woodland condition, mechanical, thinning

EXCESSIVE FUEL LOADING has become a concern in most forest types throughout the United States, particularly where wildfires were historically frequent. Contemporary ecosystems are highly altered from their historical conditions because of fire exclusion over the past century (Stanturf et al. 2002). As a result, forests with continuous canopies and subcanopies developed over previously open grasslands, savannas, and woodlands (Buckner 1983, Dobyns 1983, Denevan 1992, MacCleery 1993, 1995, Pyne 1997). Reintroduction of fire to these landscapes may reduce fuels and damage from wildfire, but prescribed burning is not always practical. Other treatments, such as thinning or other mechanical treatments, may act as surrogates to fire, but their impacts on most ecosystem variables are often unknown. Although thinning and prescribed burning are often used to reduce the risks of wildfire (Agee and Skinner 2006) and some insect outbreaks (Fettig et al. 2007), the ecological consequences of these management practices have not been studied, particularly at an operational scale (Allen et al. 2002).

In 2000, a team of federal, state, university, and private scientists and land managers designed the Fire and Fire Surrogate (FFS) study, an integrated national network of

studies of fuel reduction techniques (Youngblood et al. 2005). The network included 12 sites with similar experimental designs to facilitate comparisons of treatment effects on a broad array of variables (see McIver and Weatherspoon [2009] for a description of the national study).

Fuel reduction treatments at each site of the FFS study may be successful for reaching a secondary objective, restoring ecosystems to historic conditions. Restoration goals vary among FFS sites, but all involve changing stand structure to reduce fuel loads. Changes in stand structure can alter many ecosystem components such as vegetative diversity (Dickinson 2006), fire behavior and return interval (Phillips et al. 2006), soil processes (Boerner et al. 2008), and habitat for birds (Annand and Thompson 1997, Baker and Lacki 1997), reptiles and amphibians (Greenberg and Waldrop 2008), mammals (Sullivan 1979, Loeb 1999), and invertebrates (Whitehead 2003, Campbell et al. 2007). FFS study sites represent a wide array of ecosystems, extending from the Cascades in Washington to southern Florida. Most are dominated by conifer forests, but two are located in the eastern hardwood region, one in the central Appalachian region of southern Ohio, and another in the southern Appalachian Mountains of western North Carolina.

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Acknowledgments: This is Contribution 89 of the National Fire and Fire Surrogate Project, funded by the US Joint Fire Science Program and by the US Forest Service through the National Fire Plan. We greatly appreciate the assistance of the North Carolina Wildlife Resources Commission for use of the Green River Game Land, conducting prescribed burning, oversight of mechanical felling contracts, and numerous other chores associated with the large number of researchers who used this site. Field data collection was the responsibility of many employees of the US Forest Service including Gregg Chapman, Chuck Flint, Mitch Smith, Helen Mohr, Lucy Brudnak, and a large group of summer interns.

Manuscript received June 10, 2008, accepted September 5, 2009

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Fuel reduction in the southern Appalachian Mountains is challenging because of steep slopes, heavy fuels in some areas created by a lack of fire, and dense ericaceous shrubs (Waldrop et al. 2007). Lightning- and human-caused fires once played a significant role in determining the species composition and structure of southern Appalachian forests (Delcourt and Delcourt 1997). However, federal and state fire exclusion policies, which began in the early 20th century, probably reduced plant and community diversity and may have altered fuels (Brose et al. 2002). Before fire exclusion, hardwood ecosystems of the region had open canopies, few shrubs, and rich forest floor vegetation (Van Lear and Waldrop 1989); oak species (*Quercus* spp.) were more common in regeneration than other tree species because of frequent fire (Brose and Van Lear 1998). In the absence of fire, the increase in forest density and structure resulting from succession of pine-hardwood woodlands to hardwood-dominated forests, with concomitant ingrowth of flammable understory species such as mountain laurel (*Kalmia latifolia* L.) and rhododendron (*Rhododendron* spp.) cause increased concern for danger to wildfire risk and potential damage from severe fires. Wildfires are a particular concern in the southern Appalachian Mountains because of an ongoing increase in the number of houses and retirement communities (Southern Appalachian Man and Biosphere Cooperative 1996). Therefore, it is important to have current information and inventory of fuel load estimates to monitor and manage risk to wildfires (Vose et al. 1999, Harrod et al. 2000).

Although fire was never entirely missing from the southern Appalachian Mountains, prescribed burning was generally not used there until the 1980s, when it was introduced for site preparation of pine-hardwood mixtures (Phillips and Abercrombie 1987). In the 1990s, it was tested for restoration of individual tree species (Waldrop and Brose 1999). Fire managers in the southern Appalachians are gaining skills for prescribed burning, but they lack basic tools, such as fuel models or photo series that are readily available in other regions and information from studies of the effects of different fuel reduction techniques on fuel loading and fire behavior. Few studies on fuels exist, and most provide broad generalizations or are specific to some fuel types but not others (e.g., Deeming et al. 1972, Johansen et al. 1976, Anderson 1982). Often, these resources assume a homogeneous fuel complex and do not account for large and/or live ericaceous fuels. Graham and McCarthy (2006) examined fuel loading after prescribed burning, with and without thinning, in mixed-oak forests of southeastern Ohio. They found few differences in loading among treatments over time (3 years), which they hypothesized to be caused by a balance between fuel inputs and decomposition. Waldrop et al. (2007) provided descriptions of fuels over a four-state area of the southern Appalachian Mountains that were stratified by topographic position (aspect and slope position) and disturbance history. However, fuel reduction treatments and wildfire behavior were not a part of that study.

More work has been done in the southern Appalachian Mountains on the secondary objective of the FFS study, fuel reduction for restoration. Most studies dealt with short-term impacts of a single fire or fuel reduction treatment on oak

regeneration (Abrams 1992, Loftis and McGee 1993, Brose and Van Lear 1998, Adams and Rieske 2001) and changes to the herbaceous layer (Elliott et al. 1999, Hutchinson 2006, Phillips et al. 2007). Restoration objectives at the Southern Appalachian Mountains FFS site were to increase oak regeneration and to improve wildlife habitat by creating early-successional habitat, particularly cover of grasses and forbs. It may be possible to attain each of these goals by restoring this community to the open woodland habitat once common in these regions (described in syntheses by Stan-turf et al. 2002, Van Lear and Waldrop, 1989).

Some restoration goals were achieved by fuel reduction treatments at the Southern Appalachian Mountains FFS site. Two prescribed fires, 3 years apart, opened dense stands by killing midstory and some overstory trees (Waldrop et al. 2008) and increased breeding bird abundance (Greenberg et al. 2007). Mechanical fuel reduction changed stand structure by removing the midstory, but other components of the ecosystem were unaffected. The combination of prescribed fire and mechanical fuel reduction was the only treatment that would open the canopy sufficiently to create early-successional habitat, increase oak regeneration density, and increase cover of grasses and forbs. Some wildlife species responded to the increase in light and change in stand structural diversity with the combination of prescribed fire and mechanical fuel reduction. This treatment had a positive effect on white-footed mice (*Peromyscus leucopus*) (Greenberg et al. 2006), a negative effect on shrews (Matthews et al. 2009), no effect on amphibians, and a positive effect on reptiles (Greenberg and Waldrop 2008). Breeding bird abundance was generally increased by open stands, but some species that prefer dense canopies or shrubs declined (Greenberg et al. 2007). Changes to soils, including bulk density, pH, organic carbon, soil nitrogen, and microbial activity were minor and/or ephemeral, suggesting that multiple treatments would not damage soils (Boerner et al. 2008, Coates et al. 2008). Waldrop et al. (2008) emphasized the need for frequently repeated treatments during the restoration phase to obtain the desired open woodland condition.

Studies by Stephens and Moghaddas (2005), Agee and Lolley (2006), Graham and McCarthy (2006), and Stephens et al. (2009) examined the success of FFS study treatments (thinning, prescribed fire, and thinning plus fire) for their primary purpose, fuel reduction and mitigation of wildfire behavior. The positive effects of fuel reduction treatments toward restoration goals in the southern Appalachian Mountains must be obtained while reducing wildfire risk at the same time. This article presents treatment impacts on fuel loads and simulated behavior of wildfires at the southern Appalachian Mountain site of the national FFS study. Results will allow managers to evaluate the wildfire risk associated with each fuel reduction/restoration treatment.

Methods

Study Site

The Southern Appalachian Mountains site of the FFS study is located in Polk County, North Carolina, on the



Figure 1. Location of the Green River Game Management Land.

Green River Game Land (Figure 1), which is managed for wildlife habitat, timber, and other resources by the North Carolina Wildlife Resources Commission. Elevations range from 366 to 793 m. The climate of the region is warm continental with mean annual precipitation of 1,638 mm distributed evenly throughout the year and mean annual temperature of 17.6°C (Keenan 1998). The forests of the study area were 80 to 120 years old, and showed no indication of past agriculture or recent fire. However, fire history research by Harmon (1982) in the nearby Great Smoky Mountains National Park, Tennessee, indicated that fire occurred at an interval of approximately 10 years before 1940. Forest composition is mixed-oak with pitch pine (*Pinus rigida* Mill.) and Table Mountain pine (*Pinus pungens* Lamb.) on xeric ridges and eastern white pine (*Pinus strobus* L.) in moist coves. Chestnut oak (*Quercus prinus* L.), scarlet oak (*Quercus coccinea* Muenchh.), white oak (*Quercus alba* L.), northern red oak (*Quercus rubra* L.), and black oak (*Quercus velutina* Lam.) predominate in all sites, with other common species including sourwood (*Oxydendrum arboreum* [L.] DC.), red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), mockernut hickory (*Carya tomentosa* [Poir.] Nutt.), and blackgum (*Nyssa sylvatica* Marsh.).

A dense layer of ericaceous shrubs—mountain laurel, rhododendron (*Rhododendron maximum* L. and *Rhododendron minus* Michx.), flame azalea (*Rhododendron calendulaceum* [Michx.] Torr.), and blueberry (*Vaccinium* spp. L.)—is found throughout. Although these species are native to the region, today they are more abundant and dense than they were before fire exclusion policies of the early 20th century (Harrod et al. 2000, Brose et al. 2002), covering as much as 35% of the mountain landscape (Waldrop et al. 2007). Dense thickets of ericaceous shrubs create a barrier to regeneration of many vegetative species (Waterman et al. 1995, Turrill et al. 1996) and act as vertical fuels, potentially increasing wildfire intensity and risk of fire damage to the crown (Waldrop and Brose 1999).

Soils at the study site are primarily Evard series (fine-loamy, oxidic, mesic Typic Hapludults) with portions of two replications (blocks 1 and 2) of the Clifffield series

(loamy-skeletal, mixed, mesic Typic Hapludults). These are moderately deep, well-drained, mountain upland soils (Keenan 1998).

Experimental Design

The experiment was designed as a randomized complete block with three replicate blocks composed of four factorial treatment units. Blocks 1 and 2 (35°17'N, 82°17'W) were adjacent but separated by Pulliam Creek. Block 3 (35°16'N, 82°18'W) was approximately 2.9 km southeast of blocks 1 and 2, across the Green River. Individual treatment units were 10 to 12 ha in size. All treatment units were surrounded by buffer zones of approximately 4 to 10 ha, and both the treatment unit and its corresponding buffer received the experimental treatment. Buffers were 20 m wide to approximate the height of dominant trees. These treatment units were designed to include all prevailing combinations of elevation, aspect, and slope. However, these conditions varied within experimental units (treatment areas) and could not be separated for analysis. A 50 × 50-m grid was established in each treatment unit to measure fuels, with 36 grid points marked with metal rods. Ten sample plots of 0.10 ha were established at randomly selected grid intersections within each treatment unit to measure vegetation. The position of each grid point and sample plot was permanently marked and geo-referenced.

Treatments were selected to alter stand structure in a manner to reduce fuels, improve density of oak regeneration, and improve habitat for some wildlife species by reducing shrub cover and increasing herbaceous density. Factorial treatments were randomly allocated among treatment units within a site, and all treatment units were sampled through the pretreatment year (2001). Treatments consisted of prescribed burning (B), mechanical fuel reduction (M), the combination of mechanical treatment and prescribed burning (MB), and an untreated control (C). M involved creating a vertical fuelbreak by chainsaw felling all tree stems >1.8 m tall and <10.2 cm dbh as well as all stems of ericaceous shrubs, regardless of size. All slash was left on site. This treatment was accomplished between December 2001 and February 2002. Prescribed fires were applied in B and MB units during March 2003 and again in March 2006.

The objectives of prescribed burning were to remove vertical fuels and create a few snags for avian habitat. All fires were burned with a spot-fire technique with ignition by helicopter in 2003 and by drip torch in 2006. Fire temperatures varied within and among treatment areas but were generally moderate (temperatures 300–600°C) to high (temperatures 600–900°C) (Table 1). During the first fire, flame lengths of 1–2 m occurred throughout all burn units, but in one block (block 1, MB), flame lengths reached up to 5 m where topography or intersecting flame fronts contributed to erratic fire behavior. The second fire was less intense with flame lengths generally less than 1.5 m. Temperatures measured with thermocouples placed 30 cm aboveground at each grid point averaged 312°C during 2003 and 158°C during 2006 in B sites. MB sites had mean temperatures of

Table 1. Percentage of each experimental unit burned (prescribed burn and mechanical understory + burn treatments) in 2003 and 2006 at different temperature categories and mean maximum temperature in the Green River Game Land, Polk County, North Carolina

Block no.	0–300°C	301–600°C	601–900°C	Mean (°C)
Burn 1—2003				
Block 1				
Burn only	45.3	32.8	21.9	396.4
Mechanical + burn	18.4	35.4	46.2	568.8
Block 2				
Burn only	44.1	50.0	5.9	333.5
Mechanical + burn	26.4	51.5	22.1	426.3
Block 3				
Burn only	70.6	23.5	5.9	232.7
Mechanical + burn	20.6	30.9	48.5	556.1
Burn 2—2006				
Block 1				
Burn only	72.2	25.0	0.3	239.9
Mechanical + burn	66.7	30.6	0.3	261.2
Block 2				
Burn only	94.9	5.1	0	135.7
Mechanical + burn	91.7	5.6	0.3	197.8
Block 3				
Burn only	95.0	2.5	2.5	97.8
Mechanical + burn	82.6	15.1	0.3	210.2

517°C in 2003 and 223°C in 2006. Additional details of fire behavior are given by Phillips et al. (2006).

Sampling and Analysis

Vegetation and fuels data were collected before treatment (2001) and at various years after treatment, depending on the date the treatment was completed. B plots were measured in 2003 (1 year after burning), 2005 (3 years after burning), and 2006 (1 year after the second burn). M plots were measured in 2002 (1 year after felling), 2004 (3 years after felling), and 2006 (5 years after felling). MB plots were measured in 2002 (1 year after felling), 2003 (1 year after burning), 2005 (3 years after burning), and 2006 (1 year after the second burn). C plots were measured every year from 2001 through 2006.

Vegetation data were collected on the 0.1-ha sample plots established before treatment. Each plot was 50 × 20 m in size and divided into 10 subplots, each 10 × 10 m in size. All trees 10 cm dbh or larger were measured in five subplots. For each tree, the tree number, species, dbh, and status (i.e., standing live or dead) were recorded. Status included standing live or standing dead during pretreatment and posttreatment samples. After treatment, trees were also recorded as dead and down or cut, but those trees were not measured for dbh. Overstory mortality was computed as the total basal area of trees whose status changed from live to dead during each sample year in all 0.1-ha vegetation plots ($n = 30$ plots per treatment). Shrubs >1 m tall were measured on five 10 × 10-m subplots using ocular estimates of the percentage of area covered by the crowns of each shrub species.

Litter and duff depth and mass were determined by destructively sampling the forest floor. Samples were randomly selected in areas that represented the full range of forest floor depth on each treatment area. A pilot study was

conducted in one treatment area before treatment to determine the sample size needed for the remaining areas. Two forest floor samples were collected from each grid point and processed in the laboratory. Based on the dry weight of litter (L layer) and duff (fermentation (F) and humus (H) layers combined) samples, the sample size equation (Schaeffer et al. 1979) predicted that 25 samples per treatment area would estimate the true population mean to within 2%. To be conservative, one litter and one duff sample were collected at each of the 36 grid points in the remaining treatment areas as well as one set of samples from each 0.1-ha vegetation sample plot, giving a total of 46 samples per treatment area.

A 0.1-m-square wooden frame was used along with a cutter to collect each sample by layer (L and F/H), and each layer was bagged separately. After careful removal of the frame, each layer was measured on each side of the sampled area. Each sample was then washed to remove soil and rocks and dried in an oven set at 85°C to a constant weight. Litter and duff samples were then weighed in the laboratory to develop regression equations for depth and weight. Resulting equations were used to calculate litter and duff weight on an area basis.

The down, dead-woody fuels were measured before and after treatment using the planar intercept method described by Brown (1974). Three 15.3-m transects were established approximately 2 m from each grid point in a randomly selected direction. This method produced a total of almost 22,000 m of fuel transects. Fuels were classified by size class: 1-hour fuels (0–0.635 cm in diameter), 10-hour fuels (0.636–2.54 cm), 100-hour fuels (2.51–7.6 cm), and 1,000-hour fuels (>7.6 cm) (Brown 1974). 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 along the entire transect. Litter and duff depth were measured at three points along each

transect. Fuel counts were converted to mean weights per treatment area with equations given by Brown (1974).

Analysis of treatment effects on vegetation and fuels was completed with repeated-measures analysis of variance, with treatment and year modeled as fixed effects and block as a random effect. To account for differences among years, we interpreted significant treatment and (or) treatment $\times$ year interactions ($\alpha = 0.05$), as evidence of treatment effects and made post hoc comparisons using linear contrasts. Because much of the 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.

Simulated Fire Behavior

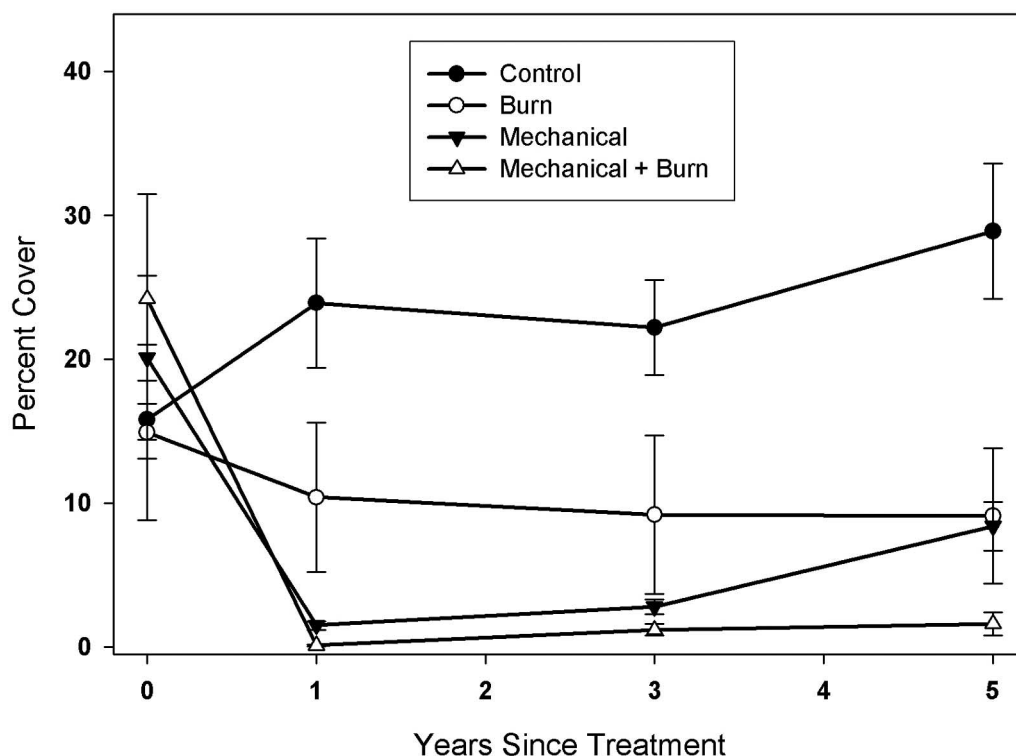
The BehavePlus4 fire modeling system (Andrews 2008) was used to test the effectiveness of each fuel reduction treatment for controlling wildfire behavior during extreme weather conditions that might occur in the area during the fire season. Means for the pretreatment year and for the

first, third, and fifth years after treatment were used to develop custom fuel models. Following FFS study protocols, 80th percentile weather conditions were calculated from observations at the Asheville-Hendersonville Airport, approximately 25 km from the study site (elevation 670 m). These values included a high temperature of 13°C, low relative humidity of 42%, and peak 5-minute wind speed of 9.4 m/s (National Climatic Data Center) during the wildfire season for the North Carolina Mountains (February–April). We used fuel moisture scenarios representative of conditions in this region given the above-described weather parameters: 1-hour fuel moisture content was 6%; 10-hour moisture content was 7%; and 100-hour moisture content was 8%. BehavePlus4 provided estimates of flame length, rate of spread, spread distance, and area burned.

Results

Fuels

At the beginning of the study, mean shrub cover ranged from 15 to 24% among treatments, but differences were not significant (Figure 2). Species comprised mountain laurel



All shrubs (% cover)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	15.8a	0.0992	23.9c	0.7669	22.2c	0.0017	28.9c
Burn Only	14.9a	0.2367	10.4b	0.6447	9.2b	0.7753	9.1b
Mech Only	20.1a	0.0001	1.5ab	0.1981	2.8b	0.0024	8.4b
Mech + Burn	24.2a	0.0002	0.1a	0.3020	1.2a	0.6955	1.6a

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

Figure 2. Shrub cover (%) for 5 years after fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.

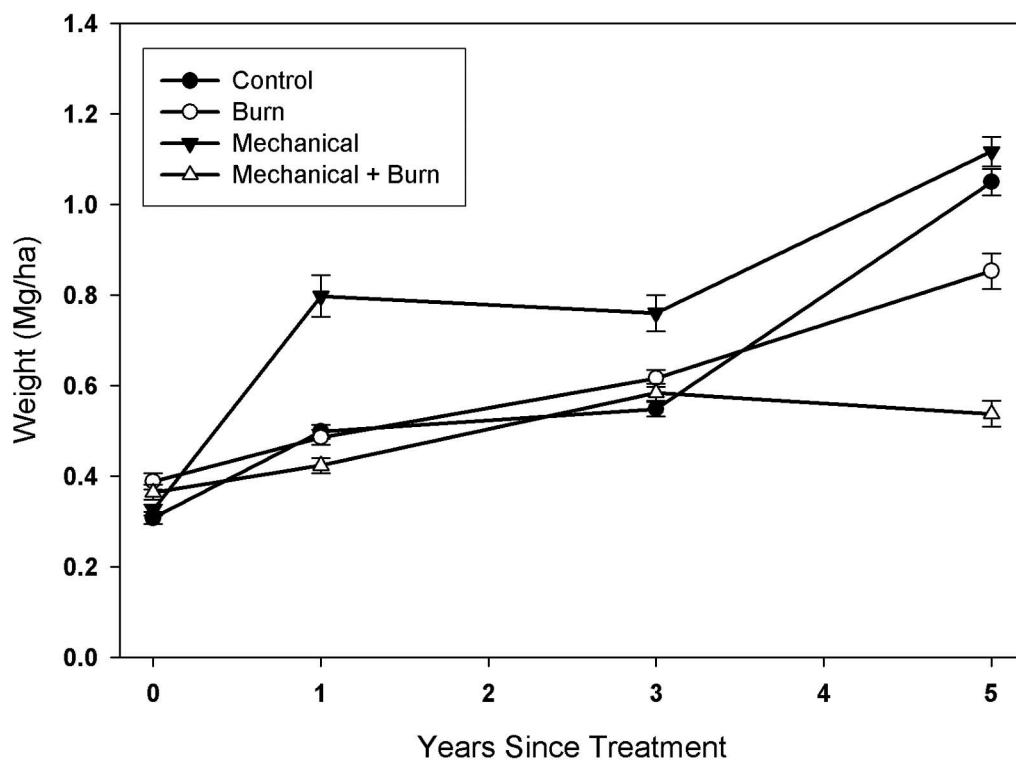
almost entirely with some rhododendron (see Waldrop et al. 2008 for a complete description of vegetation). At the end of the first growing season after treatment implementation, shrub cover had increased in C from 16 to 24%, although the difference between years was not significant. B had significantly less shrub cover (10%) than did C whereas M (1.5%) and MB (0.1%) had almost no shrub cover. Shrub cover did not change significantly between the first and third years after treatment so the relative abundance among treatments did not change. Cover increased significantly between years 3 and 5 in C and M. However, the second prescribed fire had been completed before year 5 so similar increases were not measured in B and MB. At the end of 5 years, shrub cover had been significantly reduced by all active treatments and was lowest in MB.

One-hour fuels increased significantly in C, B, and M between the pretreatment year and the end of the first growing season after treatment (Figure 3). During year 1, loading of 1-hour fuels was significantly higher in M than in all other treatment areas. Loading of 1-hour fuels did not change in C and M between year 1 and year 3, but it

increased significantly in the treatment areas that were burned because of continued tree mortality after burning.

One-hour fuel loading increased significantly in all treatment areas between the time measurements were taken in years 3 and 5 because of a heavy ice storm that occurred in December 2005 (Figure 3). Year 5 measurements were completed during the summer of 2006, after the ice storm occurred and after the second burn was completed. It is impossible to determine the exact amount of fuel that was added to study plots by the ice storm, but 1-hour fuel loads doubled in C between years 3 and 5. During the fifth year, 1-hour fuel loads were significantly lower in B than in C and M. MB had significantly lower 1-hour fuel loads than did all other treatment areas.

Loading of 10-hour fuels increased slightly in C between the pretreatment measurement and the end of year 1 but almost doubled in M areas (Figure 4). Prescribed burning did not have an impact on the amounts of these fuels. In B, fuels lost by consumption were replaced by new fuels resulting from top-kill of saplings and shrubs. In MB, loading of 10-hour fuels was increased by chainsaw felling but

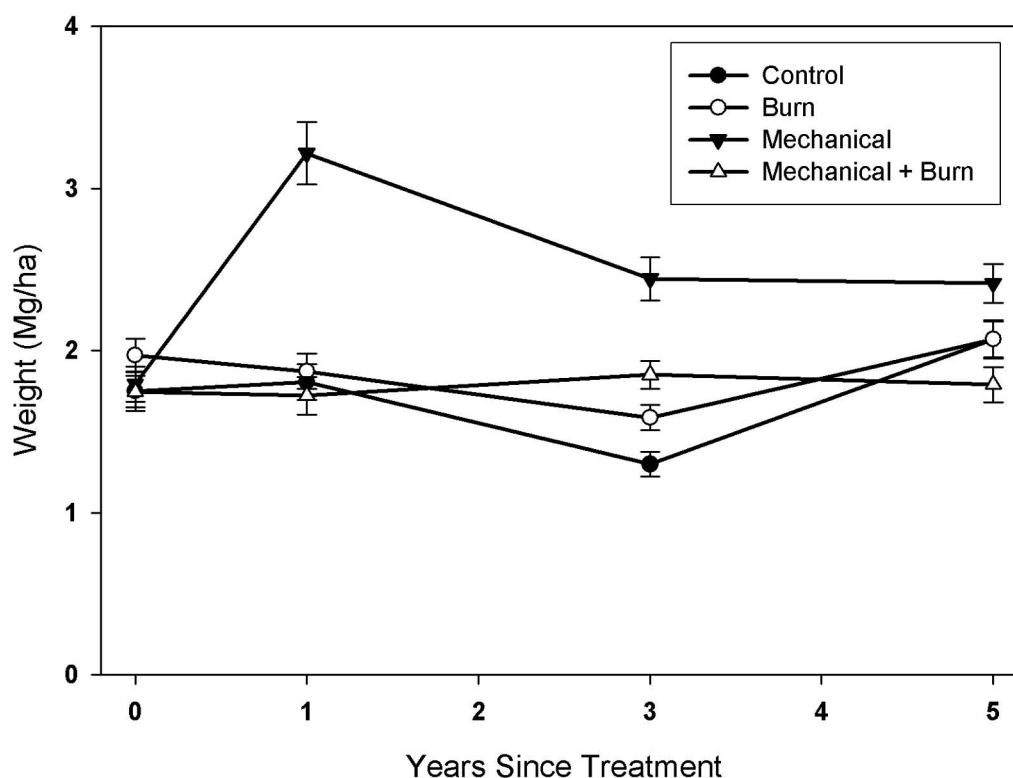


One-hour fuels (Mg/ha)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	0.3a	0.0001	0.5a	0.8960	0.5a	0.0101	1.0c
Burn Only	0.4b	0.0001	0.5a	0.0001	0.6b	0.0001	0.9b
Mech Only	0.3ab	0.0001	0.8b	0.3953	0.8c	0.0001	1.1c
Mech + Burn	0.4b	0.0111	0.4a	0.0001	0.6b	0.0074	0.5a

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

Figure 3. Loading of 1-hour fuels (Mg/ha) for 5 years after fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.



Ten-hour fuels (Mg/ha)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	1.7a	0.0001	1.8b	0.0001	1.3a	0.0002	2.1b
Burn Only	2.0a	0.3518	1.9c	0.0840	1.6b	0.0014	2.1b
Mech Only	1.8a	0.0001	3.2d	0.0001	2.4c	0.8521	2.4c
Mech + Burn	1.7a	0.3766	1.7a	0.0537	1.8b	0.2816	1.8a

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

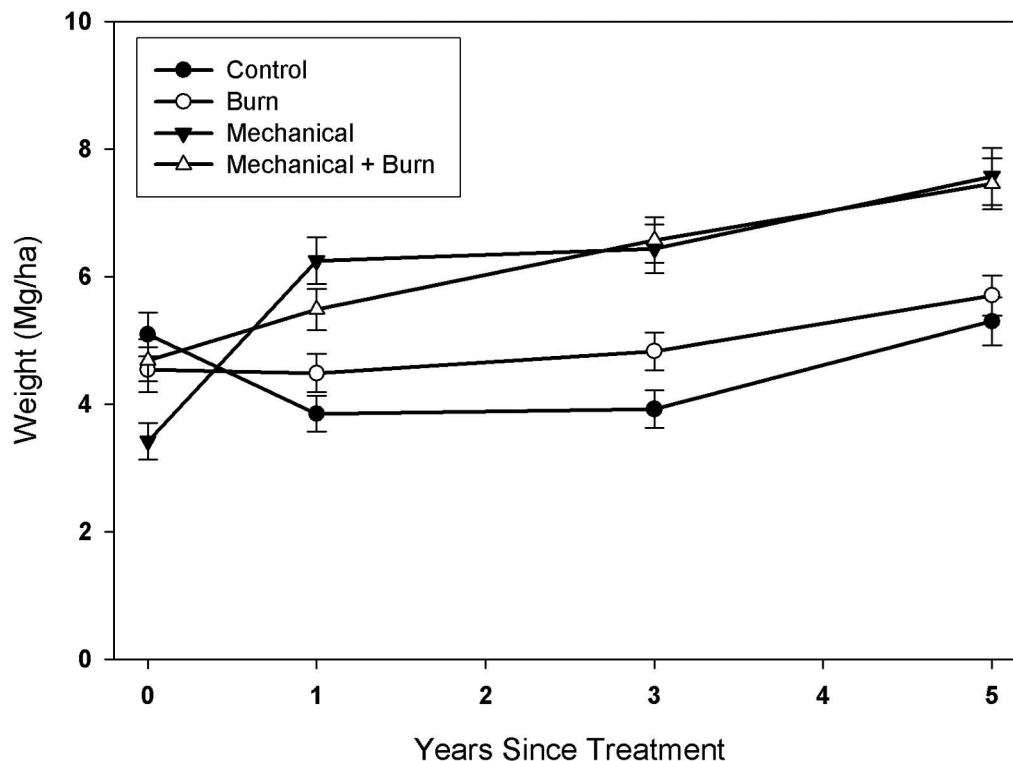
Figure 4. Loading of 10-hour fuels (Mg/ha) for 5 years after fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.

reduced to pretreatment levels by intense fires. Although the differences were significant, loading of 10-hour fuels was similar in all treatment areas 1 year after treatment with the exception of very high loading in M. These fuels were beginning to decompose as evidenced by a significant reduction in loading of M during year 3. During that year, M had significantly greater loading of 10-hour fuels than in all other treatment areas, but the absolute difference between means was smaller. The impact of the December 2005 ice storm was less obvious with these larger fuels, but the significant increase of these fuels in C between years 3 and 5 is probably due to that storm. At the end of year 5, MB had the lowest loading of 10-hour fuels and M had the greatest.

Loading of 100-hour fuels was significantly lower in M before treatment than in all other treatment areas but was significantly higher than in C or B 1 year after treatment (Figure 5). These fuels changed little between sample years 1 and 3, although there was a significant increase in MB, probably because of dead trees falling into the sample areas. Loading increased in all treatment areas between sample

years 3 and 5, although the difference was not significant in C. Fuels of this size class were small enough to be added to sample areas by the mechanical treatment but large enough that they were not consumed by prescribed fires. Combined impacts of the second fire, decomposition, overstory mortality, and the ice storm make it difficult to understand the dynamics of these fuels.

Fuels in the 1,000-hour size category were not directly affected by the M treatment at any time during the study because they were too large to be cut by the contract crew, and there were no significant differences before treatment. These fuels were significantly higher in MB during sample year 1 because fires were intense in these areas, overstory trees died rapidly and fell, or standing trees dropped limbs (Figure 6). Overstory mortality was delayed in B so increases in this size class of fuels were not observed until sample year 3. Prescribed burning before sample year 5 increased overstory mortality somewhat, resulting in the heaviest loading of 1,000-hour fuels in B and MB. At the end of the study, loading of these fuels ranged from 14.8 Mg/ha in C to 25.2 Mg/ha in MB.



Hundred-hour fuels (Mg/ha)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	5.1b	0.0005	3.8a	0.4670	3.9ac	0.3572	5.3a
Burn Only	4.5b	0.0001	4.5a	0.1182	4.8b	0.0107	5.7a
Mech Only	3.4a	0.0001	6.3b	0.7182	6.4c	0.0289	7.6b
Mech + Burn	4.7b	0.0093	5.5b	0.0094	6.6c	0.0500	7.5b

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

Figure 5. Loading of 100-hour fuels (Mg/ha) for 5 years after fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.

The weight of the litter layer was not significantly different among areas before treatment, but it was significantly lower in B and MB than in C during all subsequent sample years (Figure 7). Litter increased to near pretreatment levels in B and MB between the first burn and year 3 but was consumed by the second fire before the year 5 sample.

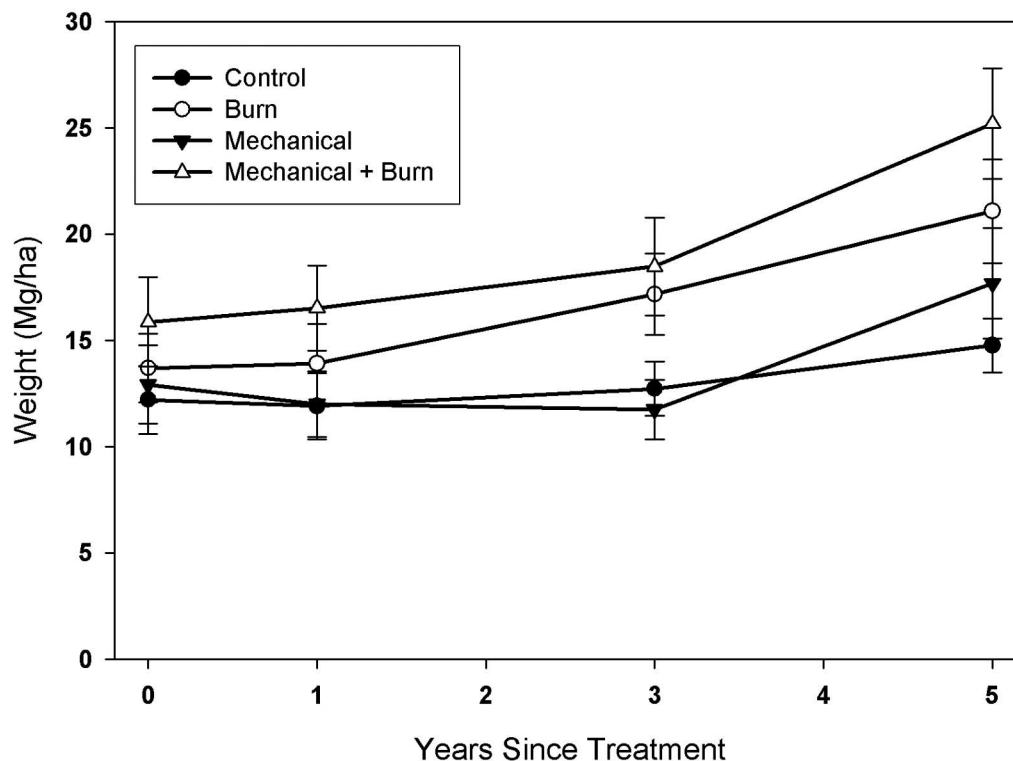
Mass of the duff layer was significantly lower in MB and significantly higher in M during sample year 1 than in C or B (Figure 8). Duff mass decreased in all treatment areas between sample years 1 and 3 and again between sample years 3 and 5. These differences were significant for all treatments except for the MB treatment between sample years 1 and 3. After mechanical treatment and two prescribed burns, MB had only 8.9 Mg/ha of duff compared with more than twice that amount in C and M. Prescribed burning alone reduced duff mass significantly but by a smaller amount than that for the more intense fires in MB.

Simulated Fire Behavior

Fire behavior predicted by the BehavePlus4 fire modeling system (Andrews 2008) was similar for each area under

80th percentile weather conditions before fuel reduction treatments (Table 2). In each area, a wildfire would have flame lengths >2.5 m, spread at a rate of $>1,000$ m/h, cover a distance of approximately 9 km, and burn an area of approximately 1,000 ha. During the first year after treatment, wildfires would be easier to control in areas previously subjected to the B or MB treatments. However, the felled shrubs and trees in the M treatment areas would contribute to very hot fires (flame length 7.3 m) that spread rapidly (>5 km/h), and cover large areas. Actual prescribed fires conducted in MB were less intense fires with flame lengths of 5 m. However, those fires were conducted in controlled conditions with less severe weather conditions than those of the simulated wildfire.

Three years after fuels treatments, simulated fire behavior was similar in all treatment areas as fine fuels had accumulated for 2 years in the burned treatment areas and begun to decompose in M. By the fifth year, all active fuel treatments provided at least some reduction of fire behavior. Predicted behavior was lowest in B and MB after the second prescribed fire had been completed. Fire behavior increased in C and M from year 3 to year 5 because fuels were heavier



Thousand-hour fuels (Mg/ha)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	12.2a	0.3785	11.9a	0.8358	12.7a	0.0261	14.8a
Burn Only	13.7a	0.7129	13.9a	0.0136	17.2b	0.0047	21.1ab
Mech Only	12.9a	0.4432	12.0a	0.6768	11.8a	0.0085	17.7a
Mech + Burn	15.9a	0.2288	16.5b	0.8372	18.5b	0.0001	25.2b

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

Figure 6. Loading of 1,000-hour fuels (Mg/ha) for 5 years following fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.

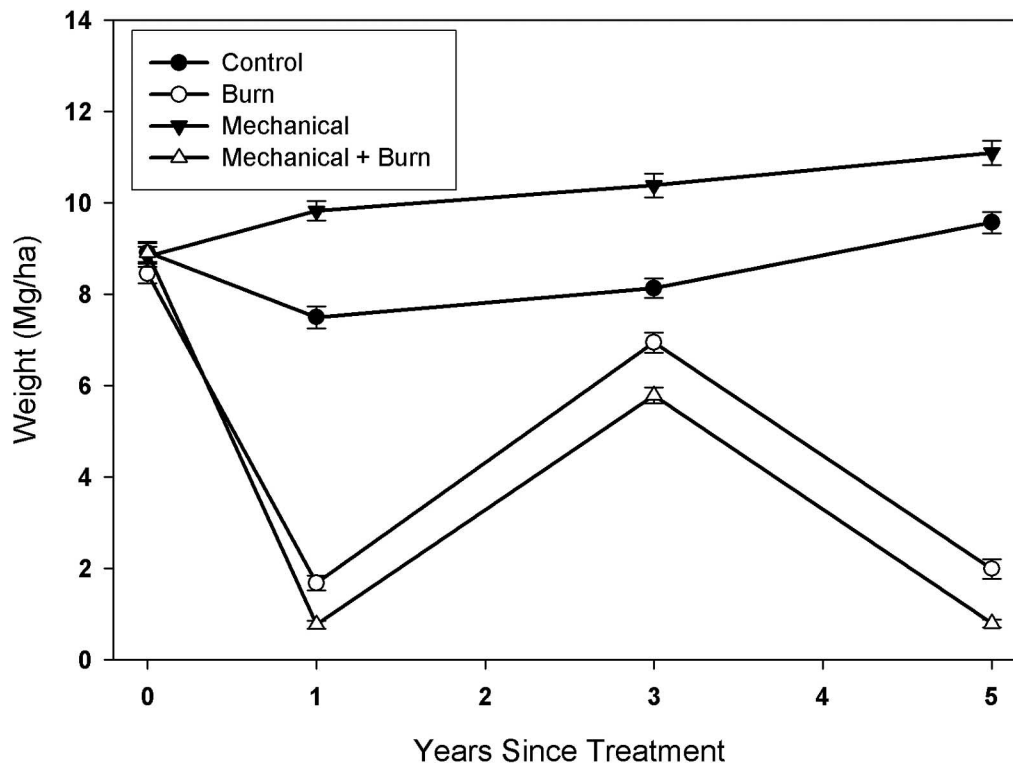
after the ice storm. However, each variable was slightly lower for M than for C, indicating that the impact of the heavy fuel loads created by the M treatment on fire behavior was decreasing.

Discussion

Treatment impacts on fuel loads and fire severity have varied across the FFS network, depending on site location and how the B, M, and MB treatments have been applied. Three of five western FFS sites had an increase in 1- 10- and 100-hour fuels after the M treatment (Stephens et al. 2009). There, the M treatment was thinning with logging techniques that left fuels on the treatment unit. Simulated fire severity was reduced by M, B, and MB where whole-tree harvesting was used as the M treatment. Agee and Lolley (2006) reported increases in 10-hour fuels from M in Washington but less 1- and 10-hour fuels from B. These changes did not have an impact on simulated fire behavior. Fuel loads at the only other hardwood-dominated FFS site, Ohio Hills, were increased by M, B, and MB the first year after

treatment (Graham and McCarthy 2006). However, all fuels smaller than the 1,000-hour size recovered to pretreatment levels by the third year after treatment owing to rapid decomposition typical of eastern sites. Essentially all measured fuels increased at the Southern Appalachian Mountains site the first year after B, M, and MB and the first year after the second burn in B and MB. The amount of change was influenced by cover of ericaceous shrubs, overstory mortality, and an ice storm that occurred near the end of the study.

The Southern Appalachian Mountains site is unique among FFS sites because of its heavy cover of ericaceous shrubs. Although these shrubs were not continuous throughout study areas, they were dense where they occurred (Waldrop et al. 2008). Mountain laurel is highly flammable and, when dense, it can serve as a vertical fuel creating a crown fire (Waldrop and Brose 1999). The M treatment at the Southern Appalachian Mountains site was unique among FFS sites because the strategy was to break this vertical fuel layer by chainsaw felling small trees and all shrubs. Although this strategy opened the midstory layer, it greatly



Litter weight (Mg/ha)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	8.9a	0.0001	7.5c	0.4571	8.1c	0.0001	9.6c
Burn Only	8.5a	0.0001	1.7b	0.0001	6.9b	0.0001	2.0b
Mech Only	8.8a	0.0001	9.8c	0.0199	10.4d	0.0029	11.1d
Mech + Burn	8.9a	0.0001	0.8a	0.0001	5.8b	0.0001	0.8a

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

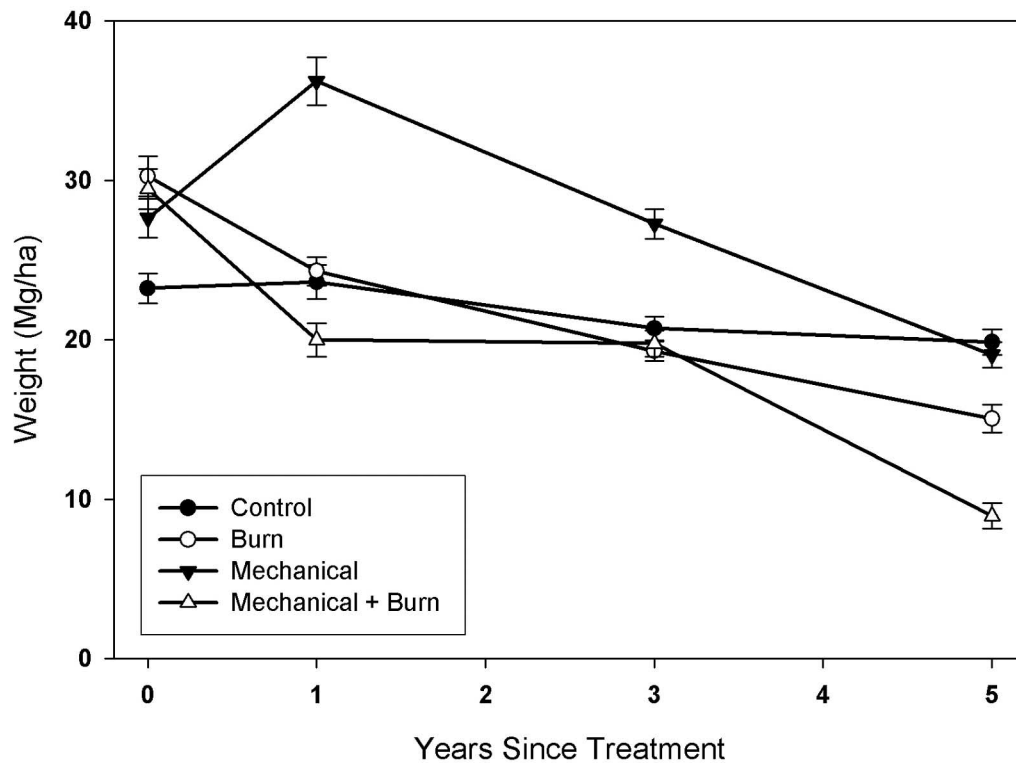
Figure 7. Litter mass (Mg/ha) for 5 years after fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.

increased loading of all fuels smaller than the 1,000-hour category, which exceeded the limits of the felling contract. Litter mass remained high throughout the 5-year sample period in M because the treatment killed the entire standing crop of leaves at once. Otherwise, leaves of mountain laurel fall throughout the year, and only 47% of the standing crop of leaves fall annually (Monk et al. 1985).

Few restoration benefits were realized during the study period by felling ericaceous shrubs without burning. Stand structure was closer to that of the targeted open woodlands, but cut shrubs sprouted and were growing back, indicating the need for additional treatment (Waldrop et al. 2008). Fire behavior predicted in these treatment areas was extreme the first year after treatment but was reduced to slightly less than that of C by year 5. Use of M represents a serious gamble for severe wildfire behavior for several years, but after 5 years, decomposition is progressing and some restoration benefits may be obtained by repeated treatment.

Mortality of overstory trees was an objective for the goal of restoration to open the canopy for establishment of grasses and forbs. B alone killed a few overstory trees and

many understory saplings (Waldrop et al. 2008), which added woody fuels to the forest floor. This treatment did not decrease the loading of 1-, 10-, 100-, and 1,000-hour fuels after two fires, and some fuels continued to increase as overstory trees continued to die. When prescribed burning followed M, prescribed fires were hot, and heavy overstory mortality occurred the first year after burning. Waldrop et al. (2008) reported mortality of 31% of the basal area of overstory trees. These burns were conducted 1 year after M was completed, which probably caused the fires to be more intense than if they had been conducted earlier when felled trees and shrubs were green. Although standing dead trees added some fuels to treatment areas as limbs fell, the addition of snags was considered an advantage by managers who maintain this area for game and nongame species. Many falling limbs and dead trees were large enough to be considered coarse woody debris (>10 cm) and are an important component of habitat for some wildlife species (Loeb 1999). None of the fuel reduction treatments decreased the abundance of this component of ecosystem structure. Heavy overstory mortality associated with MB



Duff weight (Mg/ha)

Treatment	Pretreatment	Years Since Treatment					
		<i>P</i>	Year 1	<i>P</i>	Year 3	<i>P</i>	Year 5
Control	23.2a	0.0001	23.6b	0.0001	20.7b	0.0003	19.8c
Burn Only	30.2b	0.0001	24.3b	0.0001	19.3a	0.0001	15.0b
Mech Only	27.6b	0.0001	36.2c	0.0001	27.3c	0.0001	19.0c
Mech + Burn	29.4b	0.0001	20.0a	0.5027	19.8a	0.0001	8.9a

Means followed by the same letter within a column are not significantly different at the 0.05 level. *P* values indicate differences between means in successive years within a treatment.

Figure 8. Duff mass (Mg/ha) for 5 years after fuel-reduction treatments on the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina.

Table 2. Fire behavior predicted by the BehavePlus4 fire modeling system (Andrews 2008) for each treatment area and sampling year under 80th percentile weather conditions during the fire season at the Southern Appalachian Mountains site of the National Fire and Fire Surrogate Study, Polk County, North Carolina

Variable and treatment	Pretreatment	Year 1	Year 3	Year 5
Rate of Spread (m/h)				
Control	1,098	939	1,603	5,065
Burn only	1,149	89	1,957	744
Mechanical only	1,205	5,190	2,354	4,836
Mechanical and burn	1,191	66	1,362	195
Flame length (m)				
Control	2.5	2.2	3.3	5.6
Burn only	2.6	0.5	3.7	1.6
Mechanical only	2.7	7.3	4.6	5.5
Mechanical and burn	2.7	0.4	2.8	0.7
Spread distance (km)				
Control	8.8	7.5	12.8	25.2
Burn only	9.2	0.7	15.7	5.9
Mechanical only	9.6	41.5	18.8	24.1
Mechanical and burn	9.5	0.5	10.9	1.6
Area burned (ha)				
Control	959	702	2,043	7,902
Burn only	1,048	13	3,045	548
Mechanical only	1,152	21,412	4,403	7,216
Mechanical and burn	1,124	8	1,473	57

produced the closest conditions to the preferred open woodland condition and provided the greatest positive response of most variables measured for the restoration objective.

Although the study was not designed to measure the impact of the 2005 ice storm, it is a real-world problem for managers of Appalachian forests and reduction of those fuels is an added advantage to these treatments. Reductions in overstory density created by B and MB may reduce wildfire severity because fewer standing trees are left to shed limbs during an ice storm. This effect was impossible to measure because the second prescribed fire was conducted after the ice storm and before the next fuel measurement. Litter and small woody fuels (1- and 10-hour) were lower in B and MB after the second fire because the fire consumed much of the fuel that had accumulated from natural litter fall and the 2005 ice storm. Repeated prescribed fires are needed to control fuel loading in these dynamic systems.

One variable, duff mass, is of critical concern because a duff layer is necessary to protect steep mountain sites from erosion that might occur after wildfires. Boerner et al. (2008) suggested that frequent repeated burning was necessary to restore soils to a point of low available inorganic nitrogen and high recalcitrant organic matter that were once associated with historical cover types in the Appalachian mountains. This process would gradually reduce litter and duff mass, possibly to the point of exposing mineral soil. The end point for restoring soils is unknown, but the need for a compromise between restoration goals and preventing erosion is obvious. None of the fuel reduction treatments eliminated the duff layer at any time during this study. M had duff mass similar to that of C throughout the study, which may be caused by the increase in litter, but the exact relationship is unknown. Burned areas lost some duff over time, particularly those of MB. The B treatment may prove superior to the MB treatment because of this concern alone. High-intensity prescribed fires associated with the heavy fuel loads in MB reduced duff mass to levels much lower than those for other treatments. Future prescribed burns in these areas should be conducted when the duff is moist, thus allowing some duff to remain in place.

After 5 years, fuel-reduction treatments using two prescribed fires, with and without mechanical treatment, provided a high degree of protection from an intense wildfire with low rates of spread, flame lengths, spread distances, and areas burned. Predicted wildfire behavior in B was reduced during the first year after each burn, but it was equal to that of C by sample year 3. This pattern emphasizes the need for prescribed burning more than once and on a short rotation to prevent fuel accumulation. For example, managers of the North Carolina Wildlife Resources Commission selected a 3-year rotation, which is a compromise between the need to burn frequently and the limitations of logistical and budget constraints. B offers the advantage of low cost but the disadvantage of requiring multiple treatments. MB provided the most protection from severe wildfire. Predicted fire behavior during sample years 1 and 5 was very light even after a severe ice storm. As with B, the need for repeated prescribed burning is indicated by the predicted fire behavior in year 3, which is much greater than

that in years 1 and 5 because of the accumulation of litter. This treatment was the most expensive and required the most entries into the stand. M was beginning to show a slight degree of protection. Fire behavior predicted in these treatment areas was extreme the first year after treatment but reduced to slightly less than that of C by year 5. This treatment is expensive but requires fewer entries than does prescribed burning. A second application of the mechanical treatment will be required at some point.

Conclusions

This article provides insight into the dynamics of fuels and wildfire behavior after fuel reduction treatments in the southern Appalachian Mountains, a region for which little other information is available. Waldrop et al. (2007) provided a broad description of fuels in the southern Appalachian region, but no studies have focused on fuel reduction treatments and how well they mitigate wildfire behavior. A large body of work has focused on restoration objectives that might be achieved by prescribed burning and mechanical fuel reduction techniques (Whitehead 2003, Dickinson 2006, Phillips et al. 2006, Campbell et al. 2007, Boerner et al. 2008, Greenberg and Waldrop 2008, Waldrop et al. 2008), but any advantages that may be obtained toward restoration must not interfere with the primary objectives to control wildfires.

In this study, fuel reduction treatments included chainsaw felling of small trees and shrubs, two prescribed fires 3 years apart, and a combination of the mechanical treatment followed by two prescribed fires. These treatments were designed to reduce forest floor fuels, down woody fuels, and vertical fuels. Each treatment reduced one or more of these types of fuel even after a heavy ice storm near the end of the study. Mechanical treatment alone eliminated the vertical fuel component, but the additional litter and woody fuels on the ground caused wildfires predicted by BehavePlus4 to be more intense than those in untreated areas for up to 5 years. Prescribed burning alone or in combination with the mechanical treatment consumed the litter layer, thus reducing predicted fire behavior. However, this effect lasted less than 3 years, emphasizing the need for frequent burning to maintain protection from wildfire. Fine woody fuels were increased by all treatments, particularly the mechanical treatment, but they may have been reduced by decomposition over the 5-year study if the ice storm had not occurred. Prescribed burning 1 year after the mechanical treatment resulted in intense fires that caused some increase in fuel loading from mortality of overstory trees. The additional snags and coarse woody debris created by this mortality helped to advance wildlife management goals for the managers of the Green River Game Land. Duff mass was reduced by all active treatments, which may be beneficial for restoration goals but must be monitored through future treatments to ensure that soils are protected from erosion.

This study provides a variety of options for fuel reduction depending on management objectives and available resources. Wildfire mitigation and restoration objectives were advanced, to some degree, by each of the active treatments. However, none of these treatments should be

considered complete. Fuels increased rapidly with each year's litter fall and with mortality of trees and shrubs of all size classes after prescribed burning. The mechanical treatment removed the vertical fuel component, but those trees and shrubs quickly sprouted and will eventually grow back to pretreatment levels. Additional treatments, particularly prescribed burning, may be necessary as often as every 2–3 years. Managers should consider the advantages and disadvantages shown for each of these treatments when trying to meet management goals.

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