Fuels on disturbed and undisturbed sites in the southern Appalachian Mountains, USA

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Abstract: Fuel distribution in the southern Appalachian Mountain region was measured in over 1000 study plots that were stratified by topographic position (aspect and slope position) and disturbance history. Few fuel differences occurred among topographic positions for undisturbed plots, indicating that fuel accumulation is no greater on highly productive sites than on less productive sites. Litter was slightly higher on undisturbed upper slopes (4.2 t/ha) than on lower slopes (3.7 t/ha) but woody fuels showed no significant differences. Rhododendron (*Rhododendron* spp.) and mountain laurel (*Kalmia latifolia* L.) were less common than expected, occurring on 25% and 42% of sampled plots, respectively. Disturbance history and type played a greater role in determining fuel loads than did topographic position. Disturbances had occurred on 30% of sample plots within the past 10 years and were most common on exposed slopes. Litter was significantly lower in burned plots (3.5 t/ha vs. 4.0 t/ha in undisturbed plots). One-hour fuels (1.0 t/ha) were significantly higher on beetle-killed plots than on undisturbed plots (0.7 t/ha) while larger woody fuels tended to be greater in plots subjected to beetle attack, fire, and wind.

Résumé : La distribution des combustibles dans la région sud des Appalaches a été mesurée dans plus de 1000 places-échantillons stratifiées selon la position topographique (exposition et position sur la pente) et l'historique des perturbations. Il y avait peu de différence entre les combustibles dans différentes positions topographiques dans les parcelles non perturbées, indiquant que l'accumulation de combustibles n'est pas plus forte dans les stations très productives que dans les stations moins productives. Il y avait légèrement plus de litière au sommet (4,2 t/ha) qu'au bas (3,7 t/ha) des pentes non perturbées mais la quantité de combustibles ligneux n'était pas significativement différente. Présent dans respectivement 25 et 42 % des places-échantillons, le rhododendron (*Rhododendron* spp.) et le kalmia à larges feuilles (*Kalmia latifolia* L.) n'étaient pas aussi communs qu'on l'aurait cru. Le type et l'historique des perturbations jouaient un rôle plus important pour déterminer la quantité de combustibles que la position topographique. Des perturbations étaient survenues dans 30 % des places-échantillons au cours des 10 dernières années et elles étaient plus fréquentes sur les pentes exposées. Il y avait significativement moins de litière dans les places-échantillons brûlées (3,5 vs 4,0 t/ha dans les places-échantillons non perturbées). Il y avait significativement plus de combustibles dont le taux d'humidité atteint l'équilibre après une heure (1,0 t/ha) dans les places-échantillons où les arbres avaient été tués par les insectes que dans les places-échantillons non perturbées (0,7 t/ha) tandis que les combustibles ligneux de plus forte dimension avaient tendance à se retrouver en plus grande quantité dans les places-échantillons perturbées par les attaques d'insectes, le feu et le vent.

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Introduction

The southern Appalachian Mountains have long been appreciated for their diversity of plants and plant communities. Many factors combine to establish this diversity including a mosaic of soils, aspects, elevations, weather patterns, and disturbances. However, fire, a key factor for several communities, has been missing for many decades. Lightning- and human-caused fires played a significant role in the evolution of southern Appalachian plants and plant communities (Van Lear and Waldrop 1989). Fire-exclusion policies on public lands likely reduced the diversity of the southern Appalachian Mountains and may have altered fuel loads. The dynamic nature of forest structure resulting from the succession of fire-dependent pine–hardwood communities to hardwood-dominated stands, as well as an abundant ingrowth of flammable understory species such as mountain laurel (*Kalmia latifolia* L.) makes it necessary to measure and update fuel load estimates frequently (Vose et al. 1999; Harrod et al. 2000). Fuel loads are a particular concern in these mountains because the numbers of retirement communities and single homes multiply each year. The major causes of wildfires in the region are debris burning and incendiary fires, which become more common with population growth.

Even prescribed burning had limited use in the southern Appalachian Mountains until the middle to late 1980s. Land managers perceived fire as too dangerous because of the difficulty of controlling fires on steep slopes and the potential for soil erosion and damage to valuable hardwoods (Van Lear and Waldrop 1989). Today burning is limited, and most prescribed fires are for fuel reduction, wildlife habitat, and biotic community restoration. Fire managers of the re-

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gion are gaining skills for prescribed burning, but they lack basic information that is readily available for other regions. Models of fuel loading and photo series have not been developed. Thus, fire managers use limited direct measurements of fuels or best guesses of fuel loading to predict fire behavior and develop fire plans.

Prediction of fuel loading in the southern Appalachian Mountains can be as complex as the mountains themselves, because fuels may be closely associated with site quality and forest cover type. Studies by Iverson et al. (2003), Kolaks et al. (2004), and Waldrop et al. (2004) suggest that fuel loads are controlled by the varying inputs associated with different species and productivity levels across the landscape while Abbott and Crossley (1982) discussed the impacts of varying decomposition rates at different site types. At any given time since disturbance, loading of fuels is a function of inputs from dying or broken vegetation minus losses from decay. Waldrop et al. (2004) also showed that fuels can be distributed across the landscape by gravity.

A few researchers have studied fuel loading across different landscape positions. Waldrop (1996) used a gap model (Shugart 1984) to predict fuel loads on undisturbed sites on the Cumberland Plateau of eastern Tennessee. Fuel inputs were approximately 65% greater on mesic sites than on xeric sites based on predicted tree growth and mortality. However, fuel accumulation was nearly identical on both sites because of higher decomposition rates on mesic sites (8% vs. 6%). Kolaks et al. (2003) collected fuels data in the southeastern Missouri Ozarks to determine if aspect had an effect on fuel loading in previously undisturbed stands. Aspect ranges included exposed slopes (135°–315°), ridges with no aspect, and protected slopes (315°–135°). They found no difference in loading of 1, 10, and 100 h fuels or vertical structure of fuels across aspects, suggesting that the different input and decomposition rates across the landscape balance the loading of these fuels. However, the authors found significantly higher loading of 1000 h fuels on protected slopes, possibly because of logging and (or) redistribution by gravity. Stottlemyer et al. (2006) found that some fuels were closely associated with landscape ecosystem classification (LEC) unit in the mountains of northeastern South Carolina. The LEC system was developed by Jones (1991), Hutto et al. (1999), and Carter et al. (2000) to describe similar ecological units on the basis of topography and plant community assemblages. Stottlemyer et al. (2006) found that cover of *Vaccinium* spp. was greater on dry LEC units, whereas large-diameter fuels and rhododendron (*Rhododendron* spp.) were more common on moist units. Large-diameter fuels were suggested to be from recent windthrow that had not decomposed.

Although some data exist, there is limited documentation of fuels across the diverse topography of the region. In addition, past work has not covered the range of inherent variability. Thus our specific objective was to determine fuel loading by type across a range of combinations of aspect, slope position, and disturbance types in the southern Appalachian Mountains.

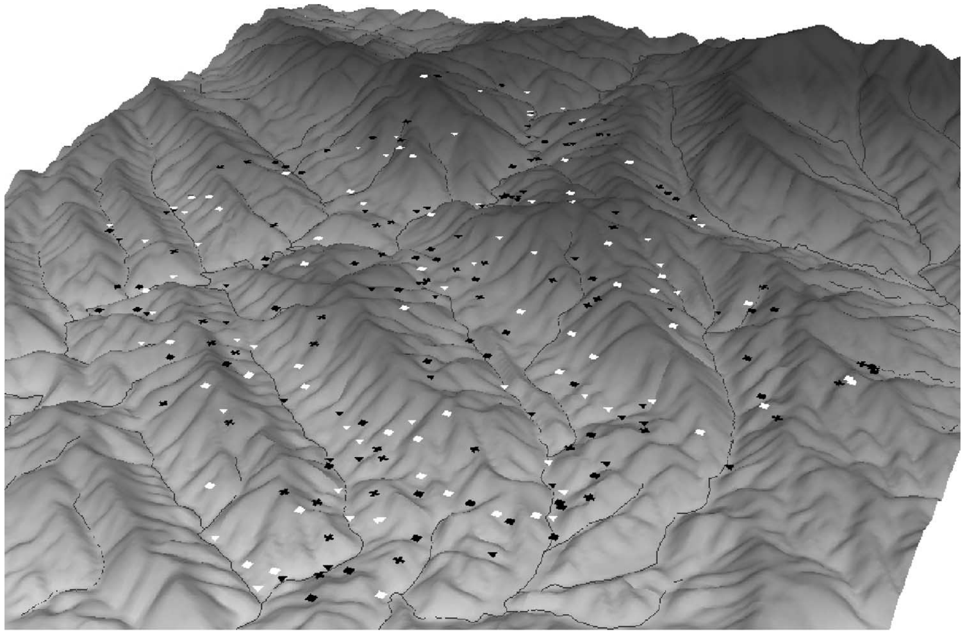
Methods

We designed this study to provide an exhaustive data set of fuel loading in the southern Appalachian Mountains because of the limited documentation of these fuels, the diverse topography of the region, and our perception that variability would be high among combinations of aspect and slope position. Therefore, we selected study sites in four states representing much of the range in elevation and topography of the region. We sampled one study area of 26 km^2 in each state: South Carolina, Georgia, North Carolina, and Tennessee. Study sites included: the Sumter National Forest in northwestern South Carolina, the Chattahoochee National Forest in northeastern Georgia, the Nantahala National Forest in western North Carolina, and the Great Smoky Mountains National Park in southeastern Tennessee. The study area in South Carolina is bisected by the Chauga River and has short, steep slopes trending southwest to northeast with the Brevard Fault Zone, a narrow band of low-grade metamorphic rock. Elevations range from 300 to 600 m. The Chattahoochee National Forest study area is characterized by short, steep slopes, with elevations ranging from 250 to 600 m. The Nantahala National Forest lies in an area described as the high rainfall belt of the southern Appalachian Mountains, receiving an average of about 200 cm of rainfall annually (Carter et al. 2000). Slopes in this study area are steep, and elevations range from 600 to 1400 m. The Great Smoky Mountains National Park also lies in the high rainfall belt of the southern Appalachian Mountains; elevations range from 350 to 900 m, with topography characterized by long ridges, steep slopes, and deep ravines. Specific study areas for each forest or park were selected that would provide the full range of topographic positions and where there was an active burning program so that managers would benefit from the fuels data being collected.

Plot locations were generated randomly within each 26 km^2 study area and were stratified by slope position and aspect using ArcView® GIS (Geographic Information System) software. We defined topographic position as a combination of slope position and aspect and assumed that tree productivity and, thus, fuel loading would be greater on more productive sites. Fifty plots each were located on middle slopes and lower slopes on northeast (325°–125°) and southwest (145°–305°) aspects (Fig. 1). Lower slope positions and northeast sites were considered to be more productive than were middle slope and southwest sites, because they are more shaded and have greater soil moisture. An additional 50 plots were located on ridgetops, the driest of all sites, for a total of 250 plots in each of the four study areas (1000 total). A global positioning system receiver was used to locate plots in the field. Additional plots were included when necessary to give adequate representation of all slope position–aspect combinations. The resulting data set had measurements from 1008 plots. Field measurements over this large area and for this large sample required nearly 3 years to complete (August 2002 through April 2005).

Dead and down woody fuels were surveyed using Brown's (1974) planar intersect method along three 15.2 m transects arranged with a common starting point and with the outer two transects 45° apart. Orientation of the middle transect in each set was determined randomly. Fuel transect measurement began on the end away from the common point for the outer transects and at the common point for

Fig. 1. Example plot locations within a 26 km^2 study area. Plots were selected randomly and stratified by topographic position using ArcView® GIS software. This study area lies within the Great Smoky Mountains National Park.



the middle transect. We recorded numbers of 1 h and 10 h fuels (0–0.64 cm diameter and 0.64–2.54 cm diameter, respectively) crossing the transect plane along the first 1.8 m of each transect. Along the first 3.7 m of each transect, we recorded the number of 100 h fuels (2.54–7.62 cm diameter) crossing the transect plane. All fuels greater than 7.62 cm in diameter, at the point where they crossed the transect plane, were classified as 1000 h fuels and were counted along the entire length of each transect. The 1000 h fuels were recorded by diameter, type (hardwood or softwood), and decay class (solid or rotten). These counts were converted to masses using Brown's (1974) equations and specific gravity estimates for southern species by decay class developed by Anderson (1982). At the 3.7, 7.6, and 12.2 m marks along each of the three transects, we measured litter depth (Oi and Oe layers) and height of dead and down woody fuel. Litter depth was converted to mass using equations for pine and hardwood litter developed by Waldrop et al. (2004) and Phillips et al. (2006).

The center transect became the midline of a 15.2 m × 13.4 m vegetation plot with each side of the plot extending 6.7 m from it. All trees taller than 1.37 m were recorded within the entire plot, identified by species, and assigned to a 5 cm diameter class. Live fuels were difficult to measure in this study, because sampling was required during all seasons. However, Vose et al. (1999) and Waldrop and Brose (1999) showed that ericaceous shrubs contributed to fire behavior more than do other live fuels; these shrubs could be measured all year. On one-half of each plot, we visually estimated percent cover of ericaceous shrubs, primarily rhododendron (*Rhododendron maximum* L.), mountain laurel, lowbush blueberry (*Vaccinium pallidum* Ait.), and highbush blueberry (*Vaccinium constablaei* Gray, *Vaccinium corymbosum* L., *Vaccinium fuscatum* Ait., and *Vaccinium stamineum* L.).

We visually estimated recent disturbance and assigned one of five disturbance categories to each plot: none, fire, logging, kill by southern pine beetle (*Dendroctonus frontalis* Zimm.), or windthrow. To corroborate field observations, we obtained disturbance records for each site from offices of the appropriate jurisdiction, for example, Great Smoky Mountains National Park Headquarters. A plot was considered undisturbed if records confirmed that no disturbance had occurred during the past 10 years.

Disturbed and undisturbed plots were analyzed separately by analysis of variance using topographic position as the independent variable. Dependent variables included masses of litter, 1, 10, 100, and 1000 h fuels plus cover of live fuels, predominantly mountain laurel and rhododendron. Mean separation was by linear contrast. All differences were considered significant at $\alpha = 0.05$.

Results

Of the 1008 plots measured in this study, 70% (705) showed no signs of recent disturbance, whereas 30% (303) had visual evidence of disturbance. Among undisturbed and disturbed plots, composition of major species groups was similar across topographic positions (Table 1). Total basal area averaged 29.1 m^2/ha across all undisturbed plots and 27.2 m^2/ha on disturbed plots; it was greatest on lower slopes and decreased toward the ridges. On undisturbed and disturbed sites, oak (*Quercus* spp.) was the dominant species group followed by pines (*Pinus* spp.). The most common oak species included chestnut oak (*Quercus prinus* L.), scarlet oak (*Quercus coccinea* Muenchh.), and northern red oak

Table 1. Basal area (BA; m^2/ha) by major species or species groups and topographic position on undisturbed (n = 705) and disturbed (n = 303) study plots in the southern Appalachian Mountains of South Carolina, Georgia, North Carolina, and Tennessee, USA.

Species or group	Northeastern lower	Northeastern upper	Ridge	Southwestern upper	Southwestern lower	All plots
Undisturbed						
Maples	3.4 (11)	2.7 (9)	3.8 (14)	2.4 (9)	2.5 (8)	3.0 (10)
Hickories	0.9 (3)	0.8 (3)	1.1 (4)	1.7 (6)	1.0 (3)	1.1 (4)
Yellow-poplar	1.5 (5)	2.5 (9)	3.8 (14)	3.1 (11)	2.4 (8)	2.7 (9)
Pines	6.8 (22)	7.4 (26)	3.5 (13)	4.5 (16)	8.2 (27)	6.0 (21)
Oaks	10.3 (34)	10.0 (34)	7.5 (27)	8.0 (28)	9.7 (32)	9.0 (31)
Hemlock	1.7 (6)	0.8 (3)	2.3 (9)	1.7 (6)	0.8 (3)	1.5 (5)
Understory	3.4 (11)	2.1 (7)	2.9 (11)	4.3 (15)	2.6 (8)	3.1 (10)
Other overstory	2.7 (9)	2.8 (10)	2.5 (9)	2.6 (9)	3.4 (11)	2.8 (10)
Total BA	30.7 (100)	29.1 (100)	27.4 (100)	28.3 (100)	30.5 (100)	29.1 (100)
Disturbed						
Maples	2.6 (10)	2.2 (8)	3.8 (13)	2.6 (10)	2.5 (9)	2.7 (10)
Hickories	0.8 (3)	1.2 (4)	1.0 (3)	1.4 (5)	0.8 (3)	1.1 (4)
Yellow-poplar	1.9 (7)	1.4 (5)	2.7 (9)	3.3 (12)	1.5 (5)	2.1 (8)
Pines	6.3 (24)	6.1 (23)	5.6 (20)	4.4 (16)	8.5 (32)	6.2 (23)
Oaks	10.7 (40)	11.1 (42)	9.2 (32)	7.5 (28)	10.7 (40)	9.8 (36)
Hemlock	1.2 (4)	1.2 (5)	2.0 (7)	1.8 (7)	0.5 (2)	1.3 (5)
Understory	0.9 (4)	2.1 (8)	1.5 (5)	2.6 (10)	1.0 (4)	1.6 (6)
Other overstory	2.3 (9)	1.9 (7)	2.7 (9)	3.3 (12)	1.5 (5)	2.3 (8)
Total BA	26.7 (100)	27.2 (100)	28.4 (100)	26.9 (100)	27.0 (100)	27.2 (100)

Note: Values in parentheses are percentages of total BA.

Table 2. Fuel characteristics of undisturbed plots by topographic position (n = 705) in the southern Appalachian Mountains of South Carolina, Georgia, North Carolina, and Tennessee, USA.

Slope and aspect	Litter (t/ha)	1 h (t/ha)	10 h (t/ha)	100 h (t/ha)	1000 h (t/ha)	Fuel height (cm)	Laurel (%)	Rhododendron (%)
Northeast lower	3.8a	0.7b	2.0	7.8	44.4	10.7	12.0a	36.0c
Northeast upper	4.3b	0.7b	2.0	8.1	32.3	11.2	10.5a	16.6b
Ridge	4.2b	0.6a	2.1	8.3	32.7	10.9	15.8a	12.1ab
Southwest upper	4.0ab	0.7b	2.0	7.6	38.5	10.7	25.1b	8.4a
Southwest lower	3.7a	0.7b	1.9	7.2	30.5	10.2	14.8a	16.0b

Note: Means followed by the same letter within a column are not significantly different at the 0.05 level.

(*Quercus rubra* L.). Chestnut oak and scarlet oak were most common on dry sites, and northern red oak was most common on moist sites. White pine (*Pinus strobus* L.) was the most common pine throughout all study sites and was more common on northeastern slopes than on southwestern slopes.

Downed woody fuels showed few differences in loading in undisturbed plots across topographic positions (Table 2). No significant differences were found for 10, 100, and 1000 h fuels and for fuel height. Ten hour fuels averaged approximately 2.0 t/ha at all topographic positions, and 100 h fuels weighed approximately 7.6 t/ha. Fuels in the 1000 h class weighed approximately 35 t/ha except on northeastern lower slopes, where they measured 44 t/ha. One hour fuels were significantly lower on ridge plots than at all other topographic positions. The litter on these 705 sample plots tended to be heaviest along the ridges and decreased downhill on both southwestern and northeastern slopes, suggesting that decomposition exceeded leaf litter inputs on the wetter sites. Even though this difference among site types was significant, the relative differences were small. There was 12% less litter on northeast lower slopes (3.8 t/ha) than on ridges (4.2 t/ha).

Both mountain laurel and rhododendron were missing from the majority of measured plots (mountain laurel was absent on 58% of plots, and rhododendron was absent from 75% of plots) but occurred in thick clumps where they were found. Mountain laurel was found at all aspect–slope position combinations but was significantly more abundant on southwest upper slopes (Table 2), where fire danger is high. Rhododendron was also present at all slope–aspect combinations, but it was more common on moist lower slope and northeast plots. Cover from lowbush and highbush blueberries was negligible on our study plots.

Evidence of disturbance was present in all four study areas, occurring on 30% of sampled plots. The most common form of disturbance was fire, impacting 35% of disturbed plots (12% of all plots). Wind was the second most frequent disturbance; it impacted 25% of disturbed plots and 8% of all plots. Study plots showing signs of disturbance were much more common on ridges and southwest slopes than

Table 3. Numbers of study plots by disturbance type and topographic position in the southern Appalachian Mountains of South Carolina, Georgia, North Carolina, and Tennessee, USA.

Disturbance type	Northeast upper	Northeast lower	Ridge	Southwest upper	Southwest lower
None	135	128	159	130	152
SPB*	2	2	16	12	8
Harvest	4	6	16	18	5
Fire	12	18	50	35	22
Wind	18	11	19	14	14

*Southern pine beetle (*Dendroctonus frontalis* Zimm.).

Table 4. Fuel characteristics of all disturbed plots by topographic position (n = 303) in the southern Appalachian Mountains of South Carolina, Georgia, North Carolina, and Tennessee, USA.

Aspect and slope	Litter (t/ha)	1 h (t/ha)	10 h (t/ha)	100 h (t/ha)	1000 h (t/ha)	Fuel height (cm)	Laurel (%)	Rhododendron (%)
Northeast lower	3.9	0.6	2.3	11.2	95.0b	13.0	4.2a	27.3c
Northeast upper	3.5	0.7	2.2	8.1	65.4ab	11.7	8.2ab	17.0b
Ridge	3.9	0.8	2.8	11.7	48.6a	14.7	6.6ab	1.9a
Southwest upper	3.9	0.8	2.5	9.4	54.0	13.2	10.9ab	3.8a
Southwest lower	4.2	0.8	2.5	9.2	69.7ab	13.2	16.0b	13.5b

Note: Means followed by the same letter within a column are not significantly different at the 0.05 level.

Table 5. Fuel characteristics of plots on all topographic positions by disturbance type (n = 1008) in the southern Appalachian Mountains of South Carolina, Georgia, North Carolina, and Tennessee, USA.

Disturbance	Litter (t/ha)	1 h (t/ha)	10 h (t/ha)	100 h (t/ha)	1000 h (t/ha)	Fuel height (cm)	Laurel (%)	Rhododendron (%)
None	4.0b	0.7a	2.0a	7.6a	36.3a	10.7a	15.8c	21.4b
SPB*	4.1b	1.0b	3.0c	11.7b	64.1b	15.5c	14.8bc	9.5ab
Harvest	4.3b	0.7a	2.8c	7.6a	29.6a	11.4ab	3.1a	0.5a
Fire	3.5a	0.7a	2.4b	10.5b	45.7ab	13.7bc	11.6bc	7.7a
Wind	3.9ab	0.7a	2.2ab	10.8b	96.8c	13.0bc	6.2ab	16.7b

Note: Means followed by the same letter within a column are not significantly different at the 0.05 level.
*Southern pine beetle attack.

on northeast slopes (Table 3). Plots disturbed by southern pine beetle, harvesting, or fire were three to five times more numerous on these exposed sites than on the more protected northeastern slopes. Windthrow was observed on approximately equal numbers of plots across all topographic positions. We expected more windthrow on exposed slopes. However, this result may be misleading, because windthrow may have been the secondary effect after another disturbance, such as root disease. Our methods did not allow us to make that distinction.

Patterns of fuel loading on disturbed plots were similar to those on undisturbed plots with few differences in loading across slope and aspect positions (Table 4). Masses of litter, 1, 10, and 100 h fuels did not vary significantly and averaged 3.9, 0.7, 2.5, and 9.9 t/ha, respectively. Cover of mountain laurel and rhododendron varied by topographic position but followed predictable patterns similar to those of undisturbed plots. However, loading of 1000 h fuels followed a different pattern on disturbed sites, with higher loading at lower topographic positions. Northeastern lower slopes had the highest loading of these large woody fuels. Masses of 1000 h fuels on disturbed plots (Table 4) were almost twice as high as those on undisturbed plots (Table 2). The mean mass of these fuels was 66.6 t/ha on disturbed plots but was only 36.5 t/ha on undisturbed plots.

Fuel loads varied significantly among plots impacted by different types of disturbance in the four 26 km^2 study areas. Litter accumulation was significantly lower on burned plots than on plots that had not been disturbed, but there were no differences in plots impacted by southern pine beetle, harvesting, or wind (Table 5). One hour and 10 h fuels tended to be greater on disturbed plots than on undisturbed plots with those increases being significant after beetle attacks in 1 h fuels and beetle attacks, harvesting, and fire for 10 h fuels. Masses of 100 h and 1000 h fuels were not significantly higher in harvested plots, probably because these fuels were removed from the site. Other disturbances leave dead trees in place and may be the cause of significant increases in the loading of larger woody fuels. Fuel heights were significantly increased in plots impacted by all disturbances with the exception of harvesting. Cover of mountain laurel was significantly lower in plots with a history of harvesting and wind. Rhododendron cover was significantly lower in plots that were harvested or burned.

A nested arrangement of an analysis of variance was used to test for interactions in the patterns of fuel loads among topographic positions and disturbance types. Topographic position was the main effect with disturbance nested within topographic position. Significant interactions occurred for litter, 1, 100, and 1000 h fuels, indicating that loading of

Table 6. Fuel characteristics of plots by topographic position and disturbance type (n = 1008) in the southern Appalachian Mountains of South Carolina, Georgia, North Carolina, and Tennessee, USA.

Disturbance	Litter (t/ha)	1 h (t/ha)	10 h (t/ha)	100 h (t/ha)	1000 h (t/ha)	Fuel height (cm)	Laurel (%)	Rhododendron (%)
Lower northeastern slopes								
None	3.8	0.7	2.0	7.8	44.4b	10.7	12.0	36.0
SPB	3.1	0.7	2.2	2.5	6.1a	12.2	3.3	27.0
Harvest	4.3	0.7	2.8	9.0	20.8a	13.5	4.6	39.1
Fire	3.2	0.7	1.7	10.8	19.3a	9.4	10.6	23.8
Wind	4.2	0.5	2.3	11.7	155.5c	14.2	1.1	32.4
Upper northeastern slopes								
None	4.3bc	0.7	2.0b	8.1	32.3	11.2	10.5	16.6
SPB	6.4d	1.3	2.6b	13.4	50.6	19.6	11.1	13.8
Harvest	5.0cd	0.5	3.0b	6.3	56.7	10.9	3.9	6.7
Fire	2.4a	0.6	2.4b	9.4	67.9	11.2	9.6	19.6
Wind	3.5b	0.6	1.0a	3.8	50.6	11.4	13.9	36.7
Ridges								
None	4.2	0.6a	2.1a	8.3a	32.7a	10.9a	15.8	12.1
SPB	3.7	1.1c	3.2b	11.9ab	71.5b	14.7b	11.3	3.6
Harvest	4.0	0.9bc	3.1b	9.6ab	11.7a	12.2ab	0.1	2.1
Fire	3.9	0.7ab	2.7b	12.1b	37.9a	15.7b	7.3	0.2
Wind	3.8	0.7ab	2.3ab	13.4b	83.6b	13.7ab	8.2	8.1
Upper southwestern slopes								
None	4.0b	0.7a	2.0	7.6a	38.5a	10.7a	25.1	8.4
SPB	4.4b	1.0b	3.0	13.7b	60.5ab	18.0b	23.0	10.7
Harvest	4.2b	0.7a	2.4	7.2a	34.1a	11.2a	3.0	2.9
Fire	3.2a	0.7a	2.2	9.2ab	46.2a	12.7a	21.0	4.7
Wind	4.0ab	0.8ab	2.6	12.1ab	83.4b	13.5ab	10.9	8.5
Lower southwestern slopes								
None	3.7	0.7a	1.9	7.2	30.5a	10.2	14.8	16.0
SPB	4.3	0.7a	2.9	7.2	75.3b	13.5	15.1	13.3
Harvest	4.3	0.6a	3.1	4.3	38.8ab	8.4	6.1	10.2
Fire	3.7	0.6a	2.3	9.9	63.0b	13.7	21.3	20.7
Wind	3.9	0.9b	2.0	8.5	77.5b	12.4	10.3	11.1

Note: Means followed by the same letter within a topographic position and column are not significantly different at the 0.05 level.

these fuels did not follow the same pattern among disturbance types for each topographic position. Few differences were seen among disturbance types on northeastern slopes because of the relatively small number of disturbed plots at this aspect (Table 6). On lower northeastern slopes, 1000 h fuels were higher in plots subjected to windthrow but lower in plots impacted by all other forms of disturbance. Litter on upper northeastern plots was significantly lower in burned plots but higher in plots after beetle attacks. Ten hour fuels on upper northeastern slopes were significantly lower in windthrow plots, a pattern which we cannot explain. Fuel patterns on ridges and upper southwestern plots closely followed those described for all plots (Table 5) with the exception that litter masses did not vary by disturbance type on ridges and 10 h fuels did not vary on upper southwestern slopes. Few differences occurred on southwestern lower slope positions, which is probably a result of small sample size because disturbances are less common on protected sites. In addition, mountain laurel and rhododendron cover did not vary among disturbance types at any topographic position. These species vary more among than within topographic positions and disturbances reduced the number of sample size of plots with these species present.

Discussion and conclusions

An objective of this study was to determine if fuel loading varied by topographic position. We assumed that different species composition and productivity levels associated with slope position and aspect would create different fuel loads. For many fuel variables, there was no difference in loading across topographic positions if the plots showed no signs of recent disturbance. Masses of litter and 1 h fuels varied significantly among slope–aspect positions, but masses of 10, 100, and 1000 h fuels and fuel height did not vary. This result was surprising because of the large sample size used for analysis (705 undisturbed plots). The result gives support to the conclusions of Kolaks et al. (2003) and Waldrop (1996), who described the dynamics of fuel inputs and outputs of southern Appalachian ecosystems. Both studies suggested that the differences in fuel inputs associated with site quality at different topographic positions were balanced by differing decomposition rates. Productive sites tend to have higher decomposition rates (Abbott and Crossley 1982), thus removing the higher fuel inputs sooner. The balance between inputs and decomposition deserves additional study in the southern Appalachian region.

Fuels that did vary by topographic position in undisturbed plots included the ericaceous shrubs. Mountain laurel was most common on dry southwestern slopes, whereas rhododendron was most common on moist northeastern lower slopes. Although these patterns are well documented in other literature, the extent of cover had not been measured. We were surprised by the absence of these species on the majority of study plots. Only 25% of plots had any rhododendron present, and only 42% had mountain laurel. However, these shrubs grow in dense thickets where present and act as vertical fuels that contribute to an increased probability of crown fires (Vose et al. 1999; Waldrop and Brose 1999; Phillips et al. 2006). Van Lear et al. (2002) discussed the importance of fire and rhododendron species on the ecology of the southern Appalachian Mountains. Even though these are generally moist-site species, they occasionally ignite and can act as vertical fuels. However, this problem was not widespread through our study sites and may only become a concern where it exists along the wildland–urban interface.

Fuel loads were altered where there was disturbance; however, a direct cause and effect relationship cannot be established in this study, because we did not measure fuels on our plots before they were disturbed. Disturbance was present throughout the four study areas, and these plots had fuel loads that were significantly lower or higher than undisturbed plots. Some form of disturbance occurred on 30% of randomly sampled plots and at all topographic positions. Disturbance was most common on ridges and upper southwest slopes. Fire and windfall were the most common forms of disturbance. The most dramatic impact of disturbance on fuels was the loading of 1000 h fuels, which had significantly higher loadings in disturbed plots. This difference is likely caused by a large influx of woody fuels that have not completely decomposed after the disturbance. Our results suggest that lower slope positions receive greater loading of large woody fuels than do higher slope positions, possibly because of gravitational repositioning and higher productivity. However, if these sites remain undisturbed long enough for fuels to decompose, loads there should be similar to those found at other slope positions.

Fuel loads varied by the type of disturbance. Masses of 1, 10, 100 h, and 1000 h fuels and fuel height were higher in plots after outbreaks of southern pine beetle. Plots that had been harvested had higher 10 h fuel loads and lower cover of mountain laurel and rhododendron. Burned plots had lower cover of mountain laurel and rhododendron but higher loads of 10 h and 100 h fuels. An increase in woody fuels after fire may be unexpected. However, most fires kill, or at least topkill, small trees and shrubs and eventually increase loading of small woody fuels (Scholl and Waldrop 1999; Waldrop et al. 2004). Windfall was present at all topographic positions. These plots had lower cover of mountain laurel and higher loading of 100 h and 1000 h fuels.

This study provided an exhaustive collection of data and the first widespread description of fuels in the southern Appalachian Mountains. Results are useful to fire managers in a number of ways. Numbers provided for fuel loading on undisturbed plots can be used directly for fire planning or fire behavior modeling with a fair degree of accuracy because of our large sample size, the low degree of variability among sample plots, and the widespread (four states) sampling design. If additional fuel measurements are desired, this study provides guidance for where those plots should be placed. Fuels were highly variable where sites had been disturbed or dense cover of ericaceous shrubs was present. These sites should be easily identifiable through remote sensing or stand management records. The study also provides insight to the degree, type, and topographic position of disturbances that occur in the region.

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