



Long-term impacts of silvicultural treatments on wildland fuels and modeled fire behavior in the Ridge and Valley Province, Virginia (USA)

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ABSTRACT

Active forest management operations, such as regeneration harvests, can reduce hazardous fuel loads and alter fuel structure, potentially minimizing extreme wildfire conditions while maintaining ecosystem services, such as wildlife habitat and water quality. Regeneration harvests of differing intensities (clearcut, high-retention shelterwood, and low-retention shelterwood) were first applied between 1995 and 1996 to three sites on the George Washington-Jefferson National Forest in the Ridge and Valley Province of Virginia, USA. Over two decades after the clearcut was conducted and 11–12 years after the overwood was removed in the shelterwood stands, woody debris, litter, and duff masses and depths were quantified. One-hour fuel loads were greater in clearcut units than in high-retention shelterwood, low-retention shelterwood, or control units. Ten-hour fuel loads were greater in clearcut and low-retention shelterwood units than in high-retention shelterwood and control units. No significant differences in 100-hour fuels were observed between treatments. Control units contained more rotten and total 1000-hour fuels than all other treatments. The total woody debris load was less in the clearcut and high-retention shelterwood than in the low-retention shelterwood and control. High-retention shelterwood woody fuel depth was greater than clearcut woody fuel depth. Litter and duff loads were less in treated units than in the control units. Total fuel load (woody fuel load + litter load + duff load) was greater in the control than the silvicultural treatments. Litter depth did not differ between treatments, while duff depth was greater in the control than in the treated units. Using the computer modeling software, BehavePlus 6.0.0, these alterations to fuel loads and depths led to increased values in the control units for six fire behavior parameters. Predicted surface flame length in the low-retention shelterwood was the only modeled value that was not less than control values. Overall, these results indicated that harvest intensity and timing may have long-term effects on down and dead woody fuels, forest floor depth, and potential fire behavior. Clearcutting reduced fire behavior most, followed by the high-retention shelterwood system. The potential differences in slash and debris generated by varying shelterwood systems may impact long-term fuel and fire dynamics.

1. Introduction

Since 2013, over 50% of the United States Forest Service's discretionary funding has been allocated for wildfire suppression activities (Congressional Research Service 2018). Current wildfire projections through the year 2100 include increased wildfire size, suppression costs, and resource usage in highly developed areas and longer wildfire seasons (Collins and Knutti 2013, Abatzoglou and Williams 2016).

Specifically, forests of the southeastern United States are projected to experience extended periods of drought, increased wildfire incidence, and narrower windows in which prescribed fire may appropriately be utilized (Mitchell et al. 2014, Kupfer et al. 2020). For this reason, fuel reduction has increasingly been targeted in forest management plans to reduce potential wildfire ignitions, mitigate extreme fire behavior, and reduce subsequent, negative wildfire effects, such as increased soil erosion (Robichaud et al. 2008, Moody and Martin 2009, Robichaud

Abbreviations: ANOVA, Analysis of Variance; CC, clearcut; C, control; DBH, diameter at breast height; HS, high-retention shelterwood; LS, low-retention shelterwood; HSD, Tukey's Honest Significant Difference.

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et al. 2014), air pollution (Goodrick et al. 2012, Liu et al. 2016, Cascio 2018), and residual tree damage or mortality (O'Brien et al. 2010, Varner et al. 2016, Schweitzer et al. 2019, Kreye et al. 2020).

Research investigating fuel reduction treatments in the Ridge and Valley Province and Appalachian Mountains of the United States is needed. Wildfire incidence within this region is predicted to increase through 2060 (Prestemon et al. 2016). Previous fuel reduction studies conducted in this region have generally included prescribed fire, either alone or in conjunction, with mechanical treatments (Waldrop et al. 2016, Vaughan 2020). Applying prescribed fire to forests of the Appalachian Mountains can be limited by short burn windows and a lack of public support and qualified personnel (Ryan et al. 2013), therefore mechanical treatments are often applied to alter potentially hazardous fuel loads and vertical fuel structure. A common mechanical fuel reduction method is the mastication of shrubs and small diameter stems (McIver et al. 2009, Stottlemeyer et al. 2015). This method generally increases fuel loads in the short-term and can be costly to implement (Jernigan et al. 2016, Waldrop et al. 2016).

Few studies in the eastern United States have quantified fuel loads and potential fire behavior following the removal of overstory stems, either following intermediate treatments, such as commercial thinnings (Waldrop et al., 2008; Vander Yacht et al., 2019) or regeneration harvests (Brose 2016). Most previous research studies have compared fuel loads 3–5 years post-treatment (Graham and McCarthy 2006, Stephens et al. 2009, Phillips and Waldrop 2013, Brose 2016). Quantifying long-term effects of timber harvests on fuel loads and potential fire behavior will address a critical knowledge gap for forest managers in the eastern United States and in other locations with similar land management goals around the globe. If commercial timber harvests can reduce fuel loads and generate income, wildfire risk might be mitigated and incentivized on both private and public lands. In a study of pine plantations in northwestern Spain, Arellano-Pérez et al. (2020) found that the likelihood of active crown fires could be reduced with thinning treatments alone. However, fire severity and soil erosion were not greatly reduced with thinning alone. The authors determined that surface fuel treatments were also needed to achieve the desired severity and erosion reductions. In another study of thinning treatments in south Australia, Cruz et al. (2017) determined that a combination of pruning and thinning was most effective for altering fuel vertical structure and reducing fireline intensity.

The objectives of this study were to measure and compare: 1) down and dead woody fuel loads and depths, 2) O Horizon loads and depths, and 3) predicted fire behavior across 3 different silvicultural treatments (clearcut, low-retention shelterwood, high-retention shelterwood) over two decades after their initial implementation in Virginia's Ridge and Valley Province. Hypotheses for this study were: a) 1-hour (0–0.64 cm diameter), 10-hour (0.65–2.54 cm diameter), and 100-hour (2.55–7.62 cm diameter) down and dead woody fuel loads would be greatest following the low-retention shelterwood treatment when compared to other treatments and the control, while 1000-hour (>7.62 cm diameter) fuel loads would be greatest in the high-retention shelterwood treatment; b) total (woody + O Horizon) fuel loads would be greatest in the control followed by the low-retention shelterwood, high-retention shelterwood, and clearcut; c) woody fuel depths would be greater in treated units than in control units and O Horizon depths would be greater in control units than in treated units; d) predicted fire behavior would be greatest in the control.

2. Materials and methods

2.1. Study areas

Three sites were utilized for this study: Blacksburg 1 (BB1), Blacksburg 2 (BB2), and New Castle (NC). All sites are in the Eastern Divide Ranger District of the Jefferson National Forest (Fig. 1; Table 1). The BB1 and BB2 sites are located in Montgomery County, Virginia (BB1:

37.29316°N, 80.45621°W; BB2: 37.30518°N, 80.44048°W) and contain mixed-hardwood stands (approximately 110 years old). Common species present are chestnut oak (*Quercus montana* Willd.), white oak (*Quercus alba* L.), American beech (*Fagus grandifolia* Ehrh.), and red maple (*Acer rubrum* L.). The mean annual temperature range is 2 °C (Winter) to 21 °C (Summer). Annual precipitation is 1030 mm (Hammond 1997, Wender 2000, Sucre 2008, Atwood et al. 2009). Soils at the BB1 and BB2 sites consist mainly of the Jefferson series (Ultisols; Typic Hapludults) (USDA-NRCS 2015a).

The New Castle (NC) site is located in Craig County, Virginia (37.455216°N, 80.382528°W) and contains an approximately 70-year-old mixed-hardwood stand (Atwood et al. 2009). Common species listed for BB1 and BB2 are also present at the NC site. Mean annual temperature range is 2 °C (Winter) to 21 °C (Summer). Annual precipitation is 950 mm (Hammond 1997, Wender 2000, Sucre 2008, Atwood et al. 2009). Soils at the NC site consist mainly of the Oriskany series (Ultisols; Typic Hapludults) (USDA-NRCS 2015b).

2.2. Silvicultural treatments

Four, 2-ha stands were treated at each site (Fig. 1). Silvicultural treatments were as follows (Table 2): a) clearcut (CC; in which all woody stems > 5 cm diameter at breast height (DBH) were felled, regardless of height - merchantable stems were removed and non-merchantable stems were left on-site); b) high-retention shelterwood (HS; in which over-topped and intermediate stems were removed, leaving 12–15 m² ha⁻¹ of dominant or co-dominant stems); c) low-retention shelterwood (LS; in which dominant and co-dominant trees were removed, leaving 4–7 m² ha⁻¹ of trees 5–25 cm DBH); and d) control (C) with no treatment. No more than 10 stems ha⁻¹ of mast, snag, or cull trees were left on-site in the CC unit to maintain wildlife habitat (Hood 2001).

The CC harvests and initial shelterwood cuts at all three locations began in 1995 and were completed in 1996 (Atwood et al. 2009). The overwood removal harvests in the shelterwood stands were completed in 2007 (BB1) and 2008 (BB2, NC) (Howell et al. 2021, in preparation).

2.3. Study design and field measurements

The silvicultural treatments at BB1, BB2, and NC were established in a randomized complete block design with each stand serving as a block (Hammond 1997, Wender 2000, Hood 2001, Sucre 2008, Atwood et al. 2009). Fuels within three replications of the CC, HS, LS, and C were quantified in our June - August 2019 assessment, yielding a total of 12 stands.

Within each of the 12 stands, 16 fuel inventory plots were established on a 30.5 m × 30.5 m grid. Down and dead woody fuels were tallied using a modified version of Brown's Planar Intercept Method (Brown 1974), similar to that implemented by Coates et al. (2019). To summarize, this method used down and dead woody debris tallies along planar transects to approximate woody fuel mass. Down and dead woody fuel particles were distinguished based upon time-lag size classes (Cohen and Deeming 1985): 1-hour (0–0.64 cm), 10-hour (0.65–2.54 cm), 100-hour (2.55–7.62 cm), and 1000-hour (>7.62 cm). Each transect was 15.2 m in length with the first transect oriented at 0°, the second at 120°, and the third at 240° (Fig. 2). Along each transect, 1- and 10-hour fuels were tallied within the first 1.8 m and 100-hour fuels were tallied within the first 3.7 m. One thousand-hour fuels were tallied along the entire 15.2 m transect and were identified as either hardwood or softwood (Fig. 3). Additionally, a decay class (sound or rotten) was assigned to each 1000-hour fuel based upon that fuel's exterior physical properties (Maser et al. 1979, Lutes et al. 2006). If any portion of a 1000-hour fuel's texture appeared soft when kicked, for example, that fuel was classified as rotten. Diameter was measured to the nearest 0.64 cm. Fuel counts were converted to masses using equations developed by Brown (1974) and modified by Coates et al. (2019):

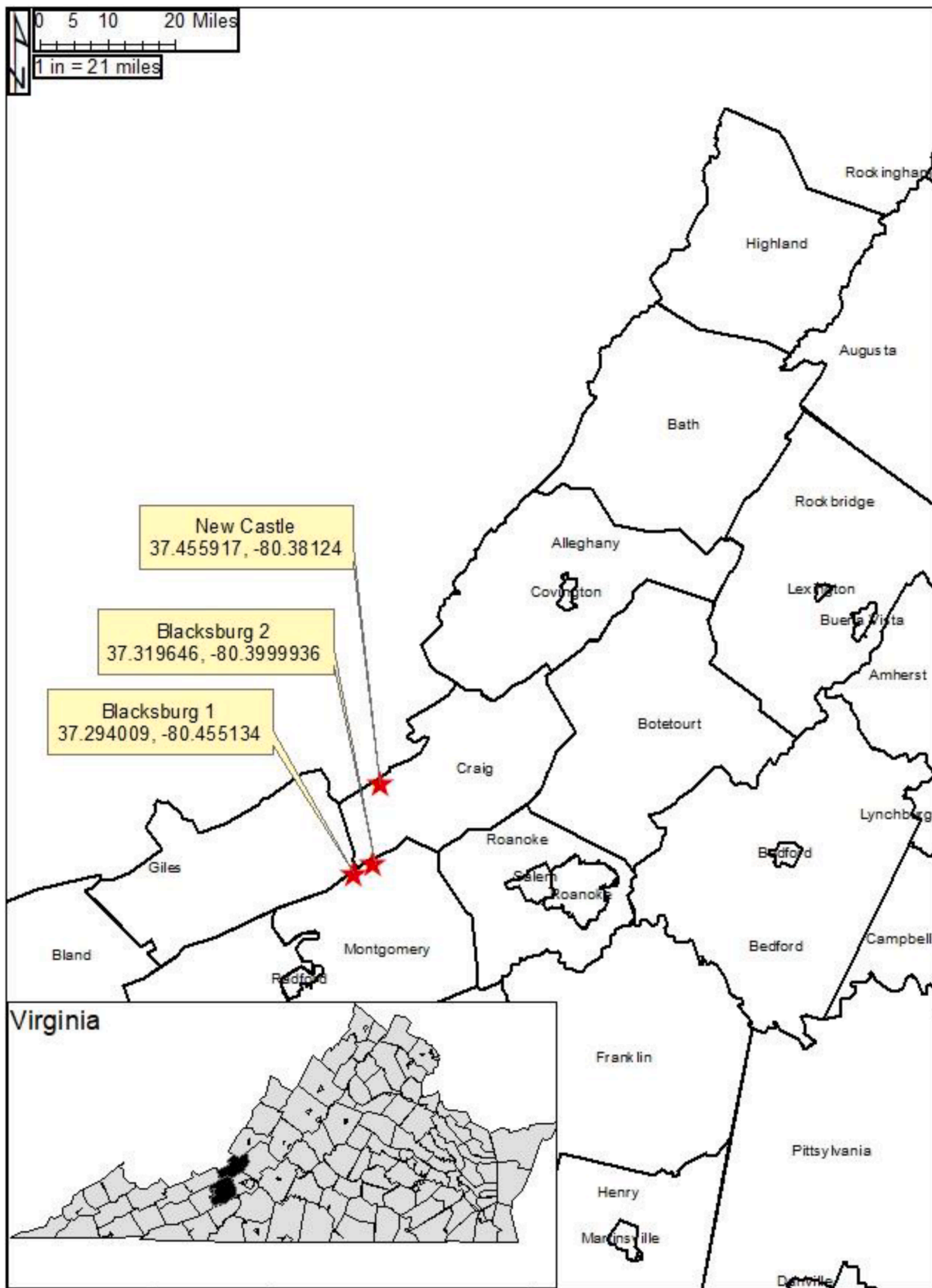


Fig. 1. Study location for the long-term silvicultural study, Ridge and Valley Province, Virginia, USA.

Table 1
Site descriptions for the Blacksburg 1, Blacksburg 2, and New Castle sites.

Site	Predominant Soil Series*	Cover Type [†]	Average Slope	Aspect	Initial Harvest Year ^{††}	Overwood Removal Year ^{†††}
Blacksburg 1	Jefferson	Chestnut Oak	11%	Southeast	1995	2007
Blacksburg 2	Jefferson	Chestnut Oak	16%	Southeast	1996	2008
New Castle	Oriskany	Chestnut Oak	7%	Southeast	1996	2008

* USDA-NRCS, Web Soil Survey, Montgomery (2015a) and Craig County, VA (2015b).

[†] Eyre (1980).

^{††} Hood (2001).

^{†††} Howell et al. (2021), in preparation.

Table 2
Post-treatment basal area ($\text{m}^2 \text{ha}^{-1}$) for each site following the 1995 and 1996 harvests (Howell et al. 2021, in preparation).

Site	Clearcut	High-retention Shelterwood	Low-retention Shelterwood	Control
Blacksburg 1	0.89	14.33	7.78	36.97
Blacksburg 2	2.78	17.66	5.40	35.24
New Castle	0.57	7.53	0.00	36.92

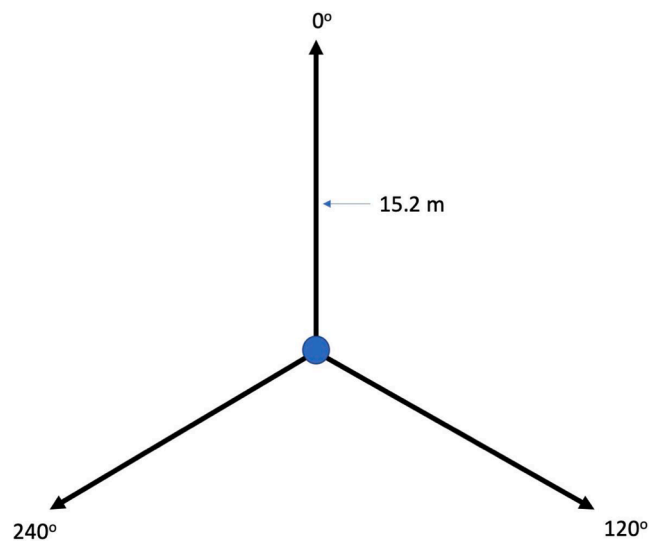


Fig. 2. Fuel transect configuration utilized in this study. Three, 15.2 m transects were established at 0°, 120°, and 240° around plot center.

For material with diameter ≤ 7.62 cm: W

$$= 2.24[(11.64)(n * d^2 * s * a * c) / (N * L)]$$

For material with diameter > 7.62 cm: W

$$= 2.24[(11.64)(\sum d^2 * s * a * c) / (N * L)]$$

where:

2.24 = conversion factor of tons acre⁻¹ to tonnes ha⁻¹

11.64 = conversion factor of volume to tons acre⁻¹

n = the number of woody fuels tallied per timelag-size class

d = quadratic-mean-diameter of particles (in)

s = specific gravity of fuels ($s = 0.70, 0.58, 0.58,$ and 0.30 for 1- and 10-hour, 100-hour, 1000-hour sound, and 1000-hour rotten material, respectively) (Anderson, 1982)

a = non-horizontal angle factor correction factor

c = slope correction factor

N = number of transects at each plot ($N = 3$)

L = length (ft) of sampling plane ($L = 6$ for 1- and 10-hour fuels; $L =$

12 for 100-hour fuels; and $L = 50$ for 1000-hour fuels)

Non-horizontal angle correction factor values from Brown (1974) were used in these equations. Slope percent is factored into this equation; therefore, slope was measured using a Suunto clinometer (percent scale) along each transect.

Litter (Oi Horizon), duff (Oe + Oa Horizons), and woody fuel depth (defined as the length from the top of the Oi horizon to the top of a down and dead woody fuel particle lying along a planar transect) were measured at 3.7, 7.6, and 12 m along each linear transect. Additionally, litter and duff were destructively sampled within a 0.09 m² PVC plastic frame to determine the O Horizon load (Coates et al. 2020). Along each transect, one sample was collected at the end of the 120° and 240° transects and one sample was collected within 1.5 m of the origin for the 0° transect. This yielded three destructive samples of litter and duff per plot. Litter and duff samples were oven-dried for at least 72 h at 65 °C, then mass was recorded to the nearest 0.1 g.

2.4. Fuel data analysis

The fuels data failed to meet the equal variance assumption for one-way analysis of variance (ANOVA). Therefore, a square root transformation was applied to all woody fuel masses except sound and rotten 1000-hour fuels which were transformed by square and cube root transformations, respectively. Additionally, a $\log(x + 1)$ transformation was applied to the litter and duff masses, depths, and dead woody fuel depth.

An ANOVA was conducted for the following fuel load and depth variables: duff mass; litter mass; duff + litter mass; down and dead woody fuel time-lag size class loads (1-hour, 10-hour, 100-hour, 1000-hour sound, 1000-hour rotten, and total 1000-hour); total woody fuel load (all down and dead woody fuels); total fuel load (O Horizon load + total woody fuel load); duff depth; litter depth; duff + litter depth; woody fuel depth.

If differences were detected between treatments, a Tukey's Honest Significant Difference (HSD) test was conducted to determine specific differences between treatments. All analyses were conducted using JMP Pro 15 (SAS Institute Inc., Cary, NC, USA). Differences were declared significant at $\alpha = 0.05$.

2.5. Fire behavior modeling

Fuels data were entered in BehavePlus 6.0.0 (Andrews 2013) for the following variables: a) 1-hour fuel load (1-hour woody fuel load + litter load, b) 10-hour fuel load, c) 100-hour fuel load, and d) fuel bed depth (litter depth + woody fuel depth). All other variables remained constant for modeling each silvicultural treatment (Fig. 4). Fire behavior estimates were obtained for the following parameters: a) Surface Fire Rate of Spread (m min^{-1}), b) Surface Fireline Intensity (kW m^{-1}), c) Surface Fire Flame Length (m), d) Surface Fire Spread Distance (m), e) Surface Fire Area (ha), f) Surface Fire Perimeter (m).

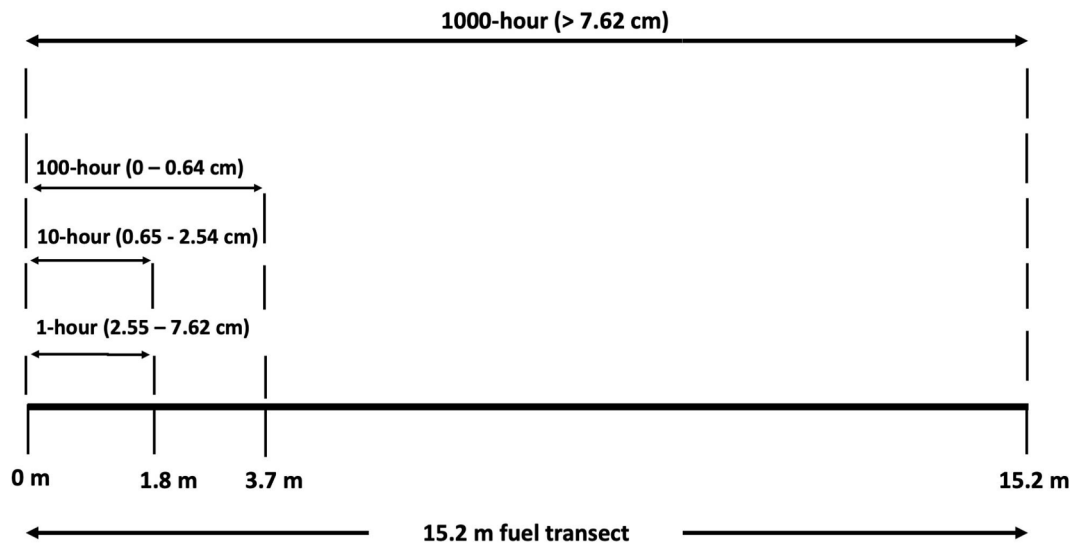


Fig. 3. Sampling lengths utilized along each fuel transect to tally 1-, 10-, 100-, and 1000-hour fuels (Coates et al. 2019).

3. Results

3.1. Fuel loads

Significant differences in litter and duff loads were present between treatments ($p < 0.0001$) (Table 3). Litter and duff loads were highest in the C, but these values did not differ from the CC. Litter loads for the HS treatment were only 76% of the C values and only 49% of the duff values. The total O Horizon load was significantly greater in the C than all other treatments ($p < 0.0001$). The silvicultural O Horizon loads represented the following percentages of the C loads: CC – 75%, HS – 65%, LS – 74%.

Significant differences in down and dead woody fuel loads between treatments were found in all time-lag size classes except for 100-hour ($p = 0.4679$) and 1000-hour sound ($p = 0.3492$) (Table 3). The CC had the highest 1-hour fuel loads ($p = 0.0044$). However, the range of the mean 1-hour loads was only 0.09 tonnes ha^{-1} . Ten-hour fuel loads were highest in the CC and LS treatments ($p < 0.0001$). The HS and C 10-hour fuel loads represented approximately 60–62% of the CC and LS 10-hour fuel loads. Rotten 1000-hour fuel loads were greatest in the C ($p = 0.0002$) treatment. The value of the rotten 1000-hour fuel loads in the C treatment was approximately 3.6 times greater than the CC treatment value, nearly double the value of the HS treatment, and 1.6 times greater than the LS treatment value. Total 1000-hour fuel loads were greatest in the C when compared to all other treatments ($p < 0.0001$), more than double the HS and LS values, and nearly quadruple the CC value. Total woody fuel load was greatest in the C ($p = 0.0018$), but was only significantly different from the CC and HS. The CC and HS treatments contained 30% less woody fuels than the C.

The sum of the O Horizon load and the down and dead woody fuel load was greatest in the C treatment ($p < 0.0001$). The silvicultural treatments contained only 65% (HS), 64% (LS), and 75% (CC) of the C total fuel load.

3.2. Fuel depths

Duff depth was 51–73% greater in the C than the silvicultural treatments, resulting in a statistically significant difference between treatments ($p < 0.0001$) (Table 4). Litter depth, however, was not significantly different between treatments ($p = 0.2115$). The total O Horizon depth was greater ($p < 0.0001$) in the C than the treated units. Down and dead woody fuel depth was greater in the C and HS than CC ($p = 0.0081$). No difference was found in woody fuel depth between the

LS and the other treatments.

3.3. Fire behavior estimation

Fuels data entered in BehavePlus 6.0.0 are listed in Table 5. Values for the 6 estimated fire behavior parameters were greatest for C, with the exception of surface fire flame length (Table 6). This value did not differ between the LS and C. Values for all parameters were lowest for the CC and were between 46.0 and 87.3% lower than C estimates. The HS had the second highest reductions for each parameter, between 7.7 and 25.2% less than the C. Values for LS were most closely aligned with C values (0 – 16.4% reductions).

4. Discussion

4.1. Fuel properties and predicted fire behavior

Woody fuel, litter, and duff loads in our study (Table 3) were notably lower than others reported in the southern Appalachian Mountains (Vander Yacht et al. 2019, Coates et al. 2019), however, our fuel loads were comparable to those reported by Brose (2009) in Pennsylvania. These differences emphasize the spatial and temporal variability that may be present for fuel loads between similar ecosystems and ecoregions (Keane et al. 2013). Accounting for potential site-specific differences in these properties currently represents knowledge that is lacking in this region.

The long-term impact of the CC, HS, and LS treatments on fuel loads and depths in the Ridge and Valley Province of Virginia was intricate. These treatments did not universally reduce all fuel properties (Tables 3 and 4), as one might assume. One-hour and 10-hour woody fuel loads were not highest in the C (Table 3). One hundred-hour and 1000-hour sound woody fuel loads did not differ between treatments (Table 3), nor did litter or woody fuel depth (Table 4). A similar lack of differences in 100-hour fuel loads was found by Brose (2016) in a study of shelterwood harvests in the Virginia Piedmont and litter depth has been noted to reaccumulate to pre-harvest levels within 3–4 years post-harvest (Graham and McCarthy 2006). This is particularly noteworthy given results suggesting litter is a primary or secondary driver of surface fire behavior in most forest types (Andreu et al. 2012). Duff and litter loads (when measured separately) and the total down and dead woody fuel load were highest in the C, but did not differ statistically with at least one other treatment (Table 3). When these values were taken into account for the BehavePlus entries, only the 1-hour + litter value was



Inputs: SURFACE, SIZE

Description

Fuel/Vegetation, Surface/Understory

		Initialize from a Fuel Model
Fuel Model Number		256
Fuel Model Code		9
Fuel Load Transfer Portion	%	0
Fuel Model Type		S
1-h Fuel Load	tonne/ha	3.743643
10-h Fuel Load	tonne/ha	1.681277
100-h Fuel Load	tonne/ha	3.855728
Live Herbaceous Fuel Load	tonne/ha	0.
Live Woody Fuel Load	tonne/ha	0.
1-h Fuel SA/V	m ² /m ³	8202.099738
Live Herbaceous Fuel SA/V	m ² /m ³	4921.259843
Live Woody Fuel SA/V	m ² /m ³	4921.259843
Fuel Bed Depth	m	0.079248
Dead Fuel Moisture of Extinction	%	25
Dead Fuel Heat Content	kJ/kg	18622.359102
Live Fuel Heat Content	kJ/kg	18622.359102

Fuel Moisture

Moisture Scenario d211

Weather

Midflame Wind Speed (upslope) km/h 24.14

Terrain

Slope Steepness % 5

Fire

Elapsed Time h 3

Fig. 4. BehavePlus 6.0.0 input for the control treatment. The same values were entered for all variables to compare the fire behavior output for each silvicultural treatment except for: a) 1-hour fuel load, b) 10-hour fuel load, c) 100-hour fuel load, and d) fuel bed depth.

highest in the C (Table 5). Nevertheless, every approximated fire behavior parameter was highest for the C, with the exception of surface fire flame length in the LS treatment (Table 6). This would suggest that wildfire ignitions occurring at the same time under similar weather conditions in the C would generate more intense fires that spread more rapidly and require more resources to extinguish. In this regard, it appeared that active forest management, planned and implemented by way of regeneration harvests, reduced the values of the specific, fire behavior parameters that were modeled using a subset of the properties measured during this field study. This is helpful information for forest

managers within this region seeking to alter fuel loading and structure, particularly in situations where prescribed fire might be desirable, but a multitude of constraints may limit its use.

Clearcutting resulted in the greatest reductions of approximate fire behavior when compared to the C, despite having the second highest fuel load entered into BehavePlus 6.0.0 (Table 6). The CC treatment did have the lowest fuel bed depth entry (Table 5), therefore it seems logical that the greatest reduction in the fire behavior parameters was most related to a lower fuel bed depth value. O Horizon depth was similar between the silvicultural treatments and differed from the C, but woody

Table 3

Mean litter, duff, and woody fuel load (tonnes ha⁻¹) (\pm standard error of the mean) comparisons between treatments. Different letters following mean loads (\pm standard error of the mean) are associated with significant differences within each row ($\alpha = 0.05$).

Fuel Size Class	Fuel Loads (tonnes ha ⁻¹)				p-value
	Clearcut n = 48	High-retention Shelterwood n = 48	Low-retention Shelterwood n = 48	Control n = 48	
O Horizon					
Duff Load (Oe + Oa Horizons)	4.86 \pm (0.37)A	3.24 \pm (0.23)B	3.57 \pm (0.26)B	6.63 \pm (0.61)A	<0.0001
Litter Load (Oi Horizon)	3.23 \pm (0.13)AB	2.63 \pm (0.09)C	3.00 \pm (0.13)BC	3.47 \pm (0.15)A	<0.0001
Duff + Litter Load (Total O Horizon)	8.09 \pm (0.41)B	5.87 \pm (0.26)C	6.57 \pm (0.34)C	10.10 \pm (0.62)A	<0.0001
Down and Dead Woody Fuels					
1-hour Fuel Load	0.36 \pm (0.02)A	0.31 \pm (0.03)B	0.29 \pm (0.01)B	0.27 \pm (0.02)B	0.0044
10-hour Fuel Load	2.79 \pm (0.18)A	1.68 \pm (0.14)B	2.70 \pm (0.18)A	1.69 \pm (0.19)B	<0.0001
100-hour Fuel Load	3.89 \pm (0.36)	3.50 \pm (0.39)	4.45 \pm (0.45)	3.85 \pm (0.36)	0.4679
1000-hour Rotten Fuel Load	1.14 \pm (0.23)B	2.18 \pm (0.35)B	2.58 \pm (0.60)B	4.16 \pm (0.49)A	0.0002
1000-hour Solid Fuel Load	0.54 \pm (0.48)	1.02 \pm (0.64)	0.14 \pm (0.9)	2.47 \pm (0.72)	0.3492
Total 1000-hour Fuel Load	1.68 \pm (0.57)B	3.20 \pm (0.75)B	2.72 \pm (0.61)B	6.63 \pm (0.86)A	<0.0001
Total Down and Dead Woody Fuel Load (1-,10-,100-,1000-hour)	8.72 \pm (0.69)B	8.69 \pm (0.98)B	10.16 \pm (0.82)AB	12.44 \pm (1.05)A	0.0018
Total Fuel Load					
Total Fuel Load (O Horizon + Down and Dead Woody Fuels)	16.81 \pm (0.85)B	14.56 \pm (1.00)B	16.73 \pm (0.86)B	22.54 \pm (1.29)A	<0.0001

Table 4

Mean duff, litter, and woody fuel depth (\pm standard error of the mean) comparisons between treatments. Different letters following mean depths (\pm standard error of the mean) are associated with significant differences within each row ($\alpha = 0.05$).

Fuel Property	Clearcut n = 48	High-retention Shelterwood n = 48	Low-retention Shelterwood n = 48	Control n = 48	p-value
O Horizon					
Duff Depth (Oe + Oa Horizons) (cm)	2.29 \pm (0.14)B	2.00 \pm (0.15)B	2.05 \pm (0.14)B	3.45 \pm (0.18)A	<0.0001
Litter Depth (Oi Horizon) (cm)	2.80 \pm (0.10)	3.02 \pm (0.17)	2.85 \pm (0.13)	3.16 \pm (0.12)	0.2115
Duff + Litter Depth (Total O Horizon) (cm)	5.09 \pm (0.22)B	5.02 \pm (0.24)B	4.90 \pm (0.22)B	6.61 \pm (0.22)A	<0.0001
Down and Dead Woody Fuels					
Woody Fuel Depth (cm)	3.39 \pm (0.30)B	5.15 \pm (0.39)A	4.79 \pm (0.51)AB	4.83 \pm (0.32)A	0.0081

Table 5

Fuel property inputs for BehavePlus 6.0.0, derived from information listed in Tables 3 and 4.

Fuel Property	Clearcut	High-retention Shelterwood	Low-retention Shelterwood	Control
1-hour + Litter Fuel Load (tonnes ha ⁻¹)	3.59	2.94	3.29	3.74
10-hour Fuel Load (tonnes ha ⁻¹)	2.79	1.68	2.70	1.69
100-hour Fuel Load (tonnes ha ⁻¹)	3.89	3.50	4.45	3.85
Fuel Bed Depth (litter depth + woody fuel depth) (m)	0.062	0.082	0.076	0.080

fuel depth was significantly less for the CC than both the C and HS (Table 4). The LS had the highest fuel load entered (Table 5) and produced fire behavior estimates closest to the C values (Table 6). Each fuel load variable entered into BehavePlus was higher for the LS than the HS, even though the 100-hour fuel load was the only variable entered for LS that was highest between all treatments (Table 5). Despite similar timing of the initial harvests and overwood removals, the intensity with which the shelterwood system was implemented impacted approximate fire behavior. Larger, overstory stems were targeted in the LS initial harvest.

Table 6

Fire behavior estimates generated by BehavePlus 6.0.0. Control estimates for each parameter were equal to or greater than estimates for the silvicultural treatments, therefore percentages in each silvicultural treatment cell represent percent reductions of control estimates for that parameter.

Fire Behavior Parameter	Clearcut	High-retention Shelterwood	Low-retention Shelterwood	Control
Surface Fire Rate of Spread (m min ⁻¹)	3.4 (69.4%)	9.2 (17.1%)	10.1 (9.0%)	11.1
Surface Fireline Intensity (kW m ⁻¹)	102 (79.3%)	369 (25.2%)	465 (5.7%)	493
Surface Fire Flame Length (m)	0.7 (46.2%)	1.2 (7.7%)	1.3 (0%)	1.3
Surface Fire Spread Distance (m)	608.7 (69.4%)	1654.1 (15.4%)	1819.6 (8.6%)	1990.7
Surface Fire Area (ha)	8.5 (87.3%)	50.1 (25.2%)	56.0 (16.4%)	67.0
Surface Fire Perimeter (m)	1351 (68.2%)	3559 (16.2%)	3881 (8.6%)	4246

One might hypothesize that the felling and skidding of larger stems in the LS without any preceding harvest operations may have caused more branch breakage in adjacent stems, therefore down and dead woody fuels ≤ 7.62 cm diameter would be greater in the LS treatment than the HS treatment. This logic did not follow suit for Clatterbuck (2006). In that study, damaged trees increased in harvesting operations with higher retention. This may be a consideration for managers evaluating potential regeneration harvests and their impacts on fuel properties, flammability, and probability of ignition for both wildfires and prescribed fires: differences in initial retention may lead to long-term fire behavior differences.

One thousand-hour woody fuel and duff loads were not accounted for in our BehavePlus models. Their exclusion reduced the total fuel loads by the following percentages per treatment: CC – 39%, HS – 44%, LS – 38%, C – 59% (Table 3). While not generally consumed during prescribed fire operations in the eastern US, these fuels may be at least partially or completely consumed during wildfire ignitions in this region (Smith and Hagan 2020). Significant duff consumption resulting from wildfires in long-unburned conditions may significantly influence fire behavior and secondary fire effects, such as soil erosion, overstory mortality, and nutrient loss (Fowler 2004, Johnston et al. 2004, Hiers et al. 2005, Ottmar and Andreu 2007, Chojnkaky et al. 2009). As noted previously, duff and total 1000-hour woody fuel loads were highest in the C (Table 3), therefore, one could hypothesize that approximate fire behavior and long-term fire effects would increase if these fuel parameters were factored into BehavePlus predictions. Additionally, no true assessments of canopy openness or light reaching the surface of the ground were recorded in the field. Fuel loading as a stand-alone metric is not entirely adequate for predicting wildland fire behavior. Fuel spatial arrangement, vertical and horizontal continuity, composition, and moisture content also greatly influence wildland fire behavior (Ottmar et al. 2007, Mohr et al. 2010, Thomas et al., 2010, Keane 2015, Rowell et al. 2016, Cruz et al. 2017, Arellano-Pérez et al. 2020). The addition of fuel arrangement and structural assessments in the field and their inclusion in BehavePlus may have impacted the predicted, fire behavior values, likely increasing the values of the C predicted fire behavior parameters due to increased horizontal continuity of the fuel bed.

4.2. Additional treatments

No additional treatments, such as prescribed fire or herbicides, were combined with harvesting at these locations. Research investigating the efficacy of prescribed fire combined with mechanical treatments has shown promising results for fuel reduction in the Appalachian Mountains. Waldrop et al. (2010) found significant decreases in 1- and 10-hour fuel loads up to 5 years post-treatment in a southern Appalachian hardwood stand. Additionally, modeled fire behavior was lower for each parameter (i.e. rate of spread, flame length, area burned, and spread distance). Furthermore, Graham and McCarthy (2006) observed a decrease in litter and duff following thinning and prescribed fire in Ohio. Reduction in fine fuels was transient, however, as vegetation regenerated and litter re-accumulated. Repeated prescribed fire combined with periodic mechanical treatments may enhance potential reductions of 1-, 10- and 100-hour down and dead woody fuels. However, combination treatments may enhance the shrub layer and potentially increase fire behavior (Waldrop et al. 2010, Phillips and Waldrop 2013, Waldrop et al. 2016). To remedy this, post-fire chemical application or fuel mastication may reduce shrub re-sprouting potential (Romancier 1971, Zedaker et al. 2010). With these studies in mind, it should be understood that other treatments are often utilized alongside harvesting to accomplish multiple site objectives, including fuels management.

4.3. Ecological considerations

While our study was focused on fuel loads and predicted fire behavior responses to silvicultural treatments, it is important to consider

the implications of harvest operations on other site properties, such as nutrient cycling, water quality, and wildlife. Research suggests that the removal of overstory stems has minimal negative impacts on the above-mentioned properties. Twenty years following a clearcut operation at Coweeta Hydrologic Laboratory in North Carolina, Swank et al. (2001) reported that impacts on water yield and nutrient cycling returned to pre-harvest levels within 4 years. Sediment levels, however, were elevated relative to pre-harvest measurements 15 years post-harvest. Benthic community abundance increased in early post-harvest sampling most likely due to changes in stream chemistry and physical properties. Changing site conditions following fuel reduction treatments may affect terrestrial wildlife population dynamics, as well (Gandhi et al. 2008, King et al. 2011). Studies documenting long-term effects of fuel reduction treatments on wildlife populations indicate that different treatments may support different species (Mahoney et al. 2016, Vander Yacht et al. 2016, Greenberg et al. 2017, Greenberg et al. 2018). Management targeted for avian, herpetofaunal, or mammalian species may require adjustments for specific life cycle requirements (Owens et al. 2008). Thus, regeneration harvests to reduce fuels may present an added opportunity to target habitat requirements for specific wildlife species.

While not directly measured, it could logically be inferred that some of the differing fuel loads within the treated units at BB1, BB2, or NC would provide diverse habitat for a host of wildlife species. Therefore, the long-term total fuel load, O Horizon depth, and fire behavior reductions accomplished by the CC, HS, and LS treatments appeared to be holistically feasible and viable within the Ridge and Valley Province of Virginia.

5. Conclusions

Long-term reduction of total fuel loading and O Horizon depth was achieved through the use of silvicultural harvests of varying intensities in the Ridge and Valley Province of Virginia. Predicted fire behavior was reduced by way of these treatments when compared to the untreated control and the reductions followed this order: clearcut > high-retention shelterwood > low-retention shelterwood. The removal of mostly overstory stems for the initial cut of the low-retention shelterwood may have increased 10-hour fuel loads within this treatment. The impacts of commonly applied silvicultural treatments on secondary site properties should be considered in conjunction with potential fuel reduction when natural resource management decisions are made. The use of these silvicultural techniques may reduce potential wildfire behavior and effects in areas where prescribed fire is not able to be applied due to the multitude of constraints that often impair its broadcast use.

CRediT authorship contribution statement

George E. Hahn: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **T. Adam Coates:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Visualization. **W. Michael Aust:** Conceptualization, Methodology, Writing - review & editing. **M. Chad Bolding:** Writing - review & editing. **Melissa A. Thomas-Van Gundy:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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