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An evaluation of seven methods for controlling mountain laurel thickets in the mixed-oak forests of the central Appalachian Mountains, USA

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ABSTRACT

In the Appalachian Mountains of eastern North America, mountain laurel (*Kalmia latifolia*) thickets in mixed-oak (*Quercus* spp.) stands can lead to hazardous fuel situations, forest regeneration problems, and possible forest health concerns. Therefore, land managers need techniques to control mountain laurel thickets and limit their deleterious effects. From 2001 to 2009, I compared the effectiveness of seven understory management techniques (two chemical, two fire, two mechanical, and an untreated control) for reducing mountain laurel thickets. All of the methods except the control decreased mountain laurel coverage for at least 2 years and facilitated establishment of oak seedlings and other hardwood reproduction. However by the fifth year, the mountain laurel thickets had nearly redeveloped and the reproduction of several other hardwood species were outgrowing the oak seedlings. Additionally, all of the methods had operational issues that limited their effectiveness. Research into broadcast herbicides that kill the mountain laurel long-term and prevent redevelopment is needed as none of the techniques tested in this study provided effective control beyond a few years.

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1. Introduction

Throughout forests of the northern hemisphere, some species of heath shrubs (Family: Ericaceae) can form persistent understories (Royo and Carson, 2006). In the Appalachian Mountains of eastern North America, mountain laurel (*Kalmia latifolia*) is one such species (Brose, 2016; Chastain and Townsend, 2008; Monk et al., 1985). The shrub grows up to 4 m tall and broad, is evergreen and shade tolerant, and occurs primarily on dry and intermediate sites (Chapman, 1950; Kurmes, 1961). Mountain laurel spreads via layering of the lowermost branches as well as dissemination of thousands of minute seeds (Chapman, 1950; Kurmes, 1961). In the absence of recurring fire, these silvical characteristics lead to dense thickets that can consist of thousands of stems/hectare and cover several hectares (Brose, 2016; Chapman, 1950; Monk et al., 1985).

Mountain laurel thickets can lead to several forest management problems. Because they occur on dry and intermediate sites, mountain laurel thickets often dominate the understories of the ecologically and economically important mixed-oak (*Quercus* spp.) forests. Their evergreen leaves cast perpetual shade and the resulting light level on the forest floor is usually less than 5 percent of full sunlight (Beckage et al., 2000; Clinton et al., 1994; Monk et al., 1985), a level too low for the long-term survival and development of oak seedlings (Brose, 2011a; Miller et al., 2004). Consequently, oak seedlings are usually scarce, small, and suppressed in mountain laurel thickets, making regeneration of this valuable forest type an arduous protracted process. Also, mountain laurel thickets are highly flammable; their leaves have a waxy cuticle and they contain volatile phenolic compounds. Waldrop and Brose (1999) documented flame lengths exceeding 7 m when mountain laurel thickets burned during a spring prescribed fire in northern Georgia. Such fire behavior often results in the damage and/or death of the overstory trees (Waldrop and Brose, 1999; Waldrop et al., 2008) and poses a threat to human life and property as demonstrated by the recent fires in eastern Tennessee (Gabbert, 2016; Wilent, 2017). Finally, mountain laurel is susceptible to *Phytophthora ramorum*, the fungus that causes sudden oak death in California and Oregon, making the shrub a likely host if the disease becomes established in the eastern United States (Tooley and Kyde, 2007; Tooley et al., 2004).

Research on controlling mountain laurel thickets has been sporadic for several decades. The control techniques can be placed into three categories (herbicides, mechanical techniques, and prescribed fire) and these have been tested on a limited basis. Regarding herbicides, researchers have tested both chemicals and their application methods. Sluder (1958) compared two herbicides commonly used at that time, 2,4,5-Trichlorophenoxyactic acid solution (2,4,5-T) and ammonium sulfate (Ammate), and two application methods, basal bark and cut stump, as controls for mountain laurel

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in western North Carolina. The 2,4,5-T applied via a diesel oil solution to the lower stem of the mountain laurel resulted in 70 percent of the shrubs completely killed with virtually no basal sprouting. Similarly, when the 2,4,5-T was applied via the cut stump technique, only 4 percent of the stumps produced sprouts. Conversely, applying Ammate crystals to mountain laurel stumps did not control the shrub as the stumps subsequently averaged 46 sprouts. In Virginia, Picloram pellets (4-Amino-3,5,6trichloro-2-pyridinecarboxylic acid) applied during the summer at 4.5 or 6.0 kg/ha killed 77 –97 percent of the mountain laurel stems by the following year (Neary et al., 1984).

Mechanical control involves crushing, cutting, or otherwise physically damaging the thickets with equipment. This may be done in conjunction with a logging operation or as site preparation for planting seedlings. In North Carolina, Wahlenberg and Doolittle (1950) tested four mechanical means of removing mountain laurel thickets: cutting by hand, cutting and root grubbing by hand, and clearing lanes and spots with a small bulldozer. These techniques were followed by planting of eastern white pine (*Pinus strobus*) seedlings. After 14 years, the mountain laurel thickets had re-established themselves in the cutting and cutting/grubbing treatments and more than 50 percent of the pine seedlings had failed to grow taller than the shrubs. Conversely, clearing the mountain laurel with the small bulldozer resulted in the thickets not reforming as quickly and more than 50 percent of the pine seedlings growing taller than the shrubs in 14 years. More recently, Waldrop et al. (2016) reported the results of chainsaw felling of mountain laurel from the North Carolina replicate of the nationwide Fire and Fire Surrogates (F/FS) Project. They found chainsaw felling initially reduced mountain laurel density from 1433 to 447 stems/ha while cover dropped from 77 to 8 percent. These reductions were temporary; within 5 years mountain laurel density and cover had rebounded to 1210 stems/ha and 22 percent, respectively.

Historically, recurring fire at a frequency of approximately once a decade was a likely factor limiting the density and size of mountain laurel thickets (Brose et al., 2014; Lafon et al., 2017; Marschall et al., 2016) so researchers have investigated prescribed fire as a control agent. In North Carolina, Hooper (1969) found that a dormant-season burn killed or heavily damaged more than 80 percent of the mountain laurel stems. Nearly all these shrubs sprouted from their bases, but regrowth was slow, less than 15 cm/year, so planted pines were likely to pass the mountain laurel before the thicket reformed. Also in North Carolina, Hagan et al. (2015) reported similar sprouting following a spring wildfire, but a second spring wildfire 7 years later reduced mountain laurel stem densities by more than 2000 stems/ha. In the northeastern United States, Ducey et al. (1996) and Ward (2015) noted that mountain laurel was the most prolific sprouter following prescribed fires of varying seasonality and intensity. In the aforementioned F/FS Project, Waldrop et al. (2016) found that three prescribed dormant-season fires conducted over a decade actually increased mountain laurel stem density although the shrub's cover was decreased by approximately 50 percent.

Fire, herbicides, and mechanical controls have also been tested in combinations to a limited degree. Romancier (1971) used fire to initially top-kill mountain laurel followed 2 years later with various herbicides on the new sprouts. He found 2,4,5-T applied as a basal spray and two foliar sprays also containing 2,4,5-T to provide almost 100 percent control of the shrub. Waldrop et al. (2016) combined chainsaw felling (two applications) and dormant-season prescribed fire (three burns) over a 12-year period in western North Carolina. While each treatment initially reduced mountain laurel density, by the end of the study shrub density was 6.5 times more abundant than before the project began (1596 stems/ha versus 10,169 stems/ha).

Aside from the F/FS Project (Waldrop et al., 2016), a limitation in much of this research is that they were case studies (one replication) of a singular treatment (fire or herbicide or mechanical) compared to an untreated control. Consequently, foresters are left unsure as to how the treatment methods compare to each other. Additionally, much of this research was done decades ago and is no longer relevant (2,4,5-T was discontinued in 1985). To address these limitations, I designed and carried out an 8-year study at three sites across Pennsylvania to compare the effectiveness of seven common methods (two fire, two herbicide, two mechanical, and an untreated control) for regenerating mixed-oak forests with interfering mountain laurel thickets. My hypothesis was that the treatments would form a continuum of effectiveness (most to least): herbicides $\gg$ fire = mechanical $\gg$ control. Understanding how these various treatments compare to one another will help foresters trying to manage mixed-oak forests on sites where mountain laurel thickets are problematic.

2. Methods

2.1. Study sites

This study was conducted from 2001 to 2009 in three upland oak stands located across Pennsylvania (Fig. 1). The westernmost site (4°19′03″N, 79°02′21″W) was on Clear Creek State Forest (CCSF) while the easternmost site (41°18′27″N, 75°05′50″W) was on Delaware State Forest (DESF). The third site was in central Pennsylvania (40°42′59″N, 77°54′03″W) on the Rothrock State Forest (RRSF). Despite being 150–400 km from each other, the three study stands shared a number of characteristics. Each stand was 15- to 20-ha, situated on the upper slopes or summits of hills, had a stony loam soil, and an oak site $index_{50}$ of 16–20 m (Braker, 1981; Taylor, 1969; Zarichansky, 1964). In the upper canopy, chestnut oak (*Quercus montana*) and northern red oak (*Q. rubra*) were the most abundant oak species, but black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), pitch pine (*Pinus rigida*), and white pine were also present. Associated midstory tree species included black birch (*Betula lenta*), blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), sassafras (*Sassafras albidum*), and serviceberry (*Amelanchier arborea*). Canopy cover was not ubiquitous due to past canopy disturbances, but I visually estimated overstory stocking to be more than 70 percent. Mountain laurel dominated the understory plant community with its abundance ranging from individual shrubs to thickets covering a few hectares. Also present were other shrub species such as bear oak (*Q. ilicifolia*), blueberry (*Vaccinium* spp.), huckleberry (*Gaylussacia* spp.), and sweet fern (*Comptonia peregrina*). Herbaceous plant diversity was quite limited; it consisted of small areas of hay-scented fern (*Dennstaedtia punctilobula*) and scattered specimens of beetleweed (*Galax aphylla*), Virginia tephrosia (*Tephrosia virginiana*), trailing arbutus (*Epigaea repens*), and wintergreen (*Gautheria procumbens*). Similarly, hardwood reproduction was infrequent and consisted of small seedlings of the same species as the overstory and midstory trees.

Because these sites were 150–400 km apart, they differed in a number of characteristics. The CCSF site was in the Allegheny Plateau region while the DESF and RRSF sites were in the Pocono Plateau and Ridge/Valley regions, respectively (Schultz, 1999). Their weather varied with CCSF being the coolest and wettest (−9.4 to 25.1 C, 1080 mm rainfall), RRSF being the warmest and driest (−4.4 to 28.0 C, 1030 mm rainfall), and DESF was intermediate (−6.0 to 26.0 C, 1050 mm rainfall) (Braker, 1981; Taylor, 1969; Zarichansky, 1964). The RRSF site was on a north aspect while the other two sites had southeastern aspects. The CCSF site was the highest, approximately 575 m, while DESF and RRSF were

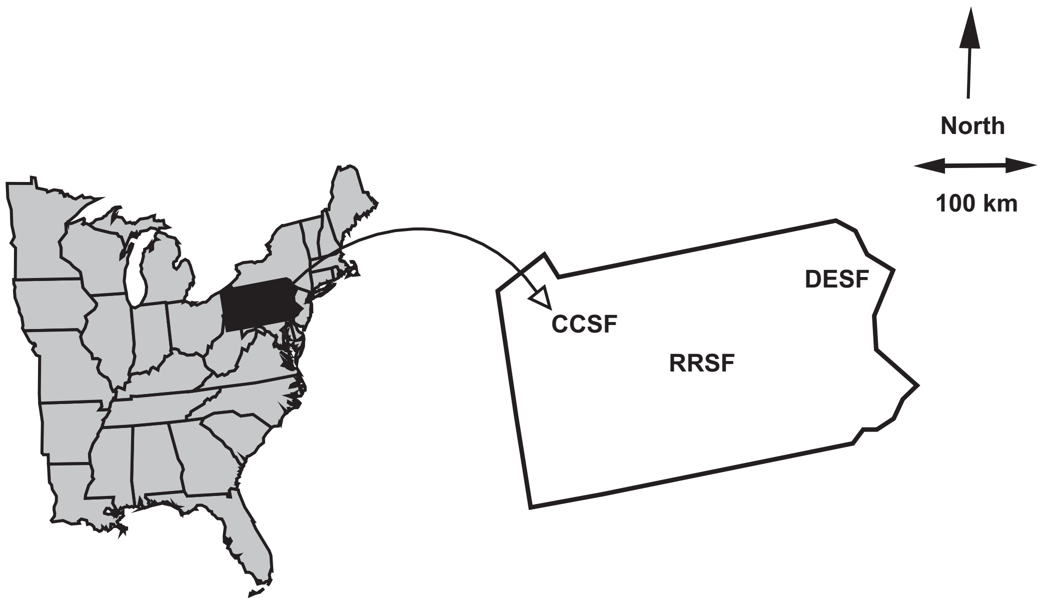

Fig. 1. Location of Pennsylvania in the eastern United States and the locations of the three study sites (CCSF, DESF, and RRSF) within Pennsylvania.

between 450 and 500 m. Their histories differed too; RRSF probably had been subjected to short-rotation timber harvesting for several decades due to its proximity to charcoal iron furnaces while the other two sites likely experienced just one or two timber harvests in the early 1900s (DeCoster, 1995; Eggert, 1994).

2.2. Study implementation and measurements

In 2001, I divided each site into seven 2- to 3-ha treatment areas and each area was randomly assigned to one of the following treatments; (1) cutting, (2) prescribed burning, (3) cutting followed by burning, (4) crushing, (5) basal herbicide application, (6) cut stump herbicide application, and (7) an untreated control. Cutting consisted of felling the mountain laurel and saplings using brush saws and lopping them into several pieces. The prescribed fires were dormant-season burns ignited in a strip head-fire pattern using drip torches. The cut/burn treatment was the same as #1 and #2 with two years passing between the cutting and the burning. Crushing involved felling the overstory trees with chainsaws and dragging the logs through the thickets with skidders. Loggers and skidder operators were given instructions to maximize damage to the mountain laurel thicket. The basal herbicide treatment was a mid-July application of triclopyr in an oil carrier (~25 percent AI) to the bottom 30 cm of each mountain laurel that was more than 1 m tall. The cut stump herbicide treatment was a mid-July application of a 50-percent solution of glyphosate in water (~25 percent AI) applied within an hour of cutting to each mountain laurel stump more than 2.54 cm in diameter. Treatments were applied between 2002 and 2004 inclusive by forest technicians of the U.S. Forest Service, Northern Research Station and personnel of the Pennsylvania Bureau of Forestry. During or immediately after implementing the treatments, each site was fenced with a 2.4 m tall woven wire fence to exclude whitetail deer (*Odocoileus virginianus*).

Within each treatment area, I systematically established twelve to fifteen 200-m^2 (8.0 m radius) circular plots to uniformly cover the area and inventory the mountain laurel. In each of these plots, I visually estimated the cover of mountain laurel to the nearest 5 percent. Additionally, I established a 15-m transect that extended from the center of each seedling plot in a random direction. At the 5, 10, and 15 m points of this transect, I measured the height of the tallest mountain laurel to the nearest 0.01 m.

At the center of each mountain laurel plot, I established a 10-m^2 (1.8 m radius) circular plot to inventory the hardwood seedlings. In these plots, I tallied the most common hardwood reproduction between 0.05 and 3.00 m tall by species (blackgum, sassafras, and serviceberry) or species group (birch, maple, and oak) and by 0.15 m height classes. Birch was almost entirely black birch, but did include an occasional paper birch (*Betula papyrifera*) or yellow birch (*B. alleghaniensis*). Similarly, maple was almost entirely red maple as well as the occasional striped maple (*Acer pensylvanicum*) and sugar maple (*A. saccharum*). Oak included the five upland oak species, but chestnut oak and northern red oak seedlings predominated. Additionally, the height of the tallest seedling in each species/species group was measured to the nearest 0.01 m.

All plots at all sites were initially inventoried in 2001 or 2002 (prior to applying the treatments). They were re-inventoried twice, at 2 and 5 years post-treatment.

2.3. Data analysis

I analyzed the cover of mountain laurel, increase in the number of new hardwood seedlings, and the heights of the tallest seedlings using a randomized complete block with repeated measures via Proc MIXED (SAS Institute, 2009). The seven treatments were the fixed effects in the model while site was the random effect and inventory year (first, second, or fifth) was the repeated measure. I calculated the increase in new seedlings of each species/species group by subtracting their pretreatment counts from their second year inventories. I used the Student-Newman-Keuls mean separation test to compare among the fixed effects and least square means to compare among the treatment∗inventory interactions for each of the dependent variables. Residuals were examined to ensure that model assumptions were met. All comparisons were evaluated at alpha equal to 0.05.

I used the results of the analyses to rank the seven treatments as to their effectiveness for regenerating oak forests with interfering mountain laurel thickets. I developed a 5-point scale (−2 to +2) based on existing mountain laurel research and regional oak regeneration guidelines (Brose et al., 2008; Brose, 2016). Each treatment was scored on this scale at year 5 for (1) mountain laurel cover, (2)

Table 1
Criteria for rating the effectiveness of the seven mountain laurel control treatments for enhancing oak reproduction after 5 years. Criteria are based on mountain laurel and oak regeneration guidelines for the Mid-Atlantic region (Brose et al., 2008; Brose, 2016). Negative number of seedlings indicate that the density of seedlings decreased during the course of the study.

Criteria	Score				
	−2	−1	0	+1	+2
Mountain laurel cover	>80%	60–80%	41–59%	20–40%	<20%
Number of oak seedlings					
Per 10 m^2 plot	>−25	−5 to −25	−4 to +4	+5 to +25	>+25
Number of non-oak seedlings					
Per 10 m^2 plot	>+12	+6 to +12	−5 to +5	−6 to −12	>−12
Height relationship of	ML > Oak	ML > Oak	ML & Oak	Oak > ML	Oak > ML
Oak to mountain laurel	By >1 m	By 0.5–1 m	Within 0.5 m	By 0.5–1 m	By >1 m
Height relationship of	NON > Oak	NON > Oak	NON & Oak	Oak > NON	Oak > ML
Oak to non-oaks	By >1 m	By 0.5–1 m	Within 0.5 m	By 0.5–1 m	By >1 m

increase in oak seedling density, (3) increase in competitive reproduction density, (4) the height ratio between oak seedlings and mountain laurel, and (5) the height ratio between oak seedlings and non-oak reproduction. Each treatment's five scores were summed to produce a total score between −10 and +10. Negative scores indicated that the oak regeneration potential was impaired, positive scores indicated that the oak regeneration potential was improved and zero represented no effect (see Table 1).

3. Results

At the start of the study, conditions were similar among the treatment areas (Table 2). Mean mountain laurel cover ranged from 45 to 54 percent and mean height of the tallest shrub was from 1.7 to 2.0 m with no differences detected among the seven treatments ($p > 0.05$). Across all treatment areas, total seedling densities ranged from 12 to 15 seedlings per 10 m^2. Red maple was the most common species at 7–10 seedlings per 10 m^2 with no differences detected among the treatments ($p > 0.05$). Similarly, seedling densities of the other hardwood species were uniform among the treatment areas ($p > 0.05$). Among the seedling species, red maple densities were greater ($p < 0.05$) than those of the oaks, 2–4 stems per 10 m^2, and oak densities were usually greater ($p < 0.05$) than those of birch, blackgum, sassafras, and serviceberry which ranged from 0.1 to 1.7 seedlings per 10 m^2. Finally, mean heights of tallest seedlings ranged from 0.12 to 0.24 m with no differences detected among the species or treatments ($p > 0.05$) although all seedlings were shorter than the mountain laurel ($p < 0.001$).

Two years after implementing the treatments, mountain laurel cover was less than 20 percent, a critical threshold for identifying interference (Brose, 2016), in all treatments except the control (Fig. 2). In that treatment mean mountain laurel cover was ≈50 percent, unchanged from the pre-treatment mean ($p > 0.05$). The crushing treatment had the next most mountain laurel, 20 percent, followed by the five remaining treatments (4–9 percent). All six of these mean mountain laurel covers were less than their respective pre-treatment covers ($p < 0.01$). Five years after implementation, mountain laurel cover had increased in all treatments relative to their 2-year levels and it exceeded 20 percent in five of the seven treatments. Of those five treatments, the control and cut treatments had the most mountain laurel, approximately 46 percent, followed by the basal bark herbicide, crush, and prescribed fire treatments (28–37 percent). The least cover of mountain laurel was found in the cut stump herbicide and cut/prescribed fire treatments, ≈19 percent ($p < 0.05$).

Total seedling densities increased two- to threefold in all of the treatments during the 2 years following the treatments and this increase varied by species (Fig. 3). The control and basal bark herbicide treatment had increases of approximately 11 oak seedlings per 10 m^2 ($p < 0.05$) coupled with virtually no change in the densities of the other species ($p > 0.05$). Similarly, the cut stump herbicide treatment had a significant increase in oak seedling density as well as an increase in the density of blackgum seedlings ($p < 0.05$). The crushing and cutting treatments had

Table 2
Pre-treatment abundance and height of mountain laurel (percent cover/200 m^2 plot ± 1 se, m ± 1 se) and hardwood seedlings (stems/10 m^2 plot ± 1 se, m ± 1 se) by method. Means followed by different uppercase letters are different within that row while different lowercase letters signify differences among means within that treatment. Alpha = 0.05 for all comparisons.

Species	Control	BB Herb.	CS Herb.	Crushing	Cutting	Presc. Fire	Cut/Fire
Abundance							
Mtn. laurel	46.8 ± 3.2A	45.4 ± 3.2A	54.4 ± 3.1A	47.1 ± 3.0A	51.1 ± 3.3A	52.5 ± 3.0A	46.4 ± 3.3A
Birch	0.6 ± 0.6Ac	0.4 ± 0.6Ac	0.3 ± 0.5Ac	0.2 ± 0.5Ad	0.4 ± 0.6Ad	0.5 ± 0.6Ac	0.2 ± 0.7Ad
Blackgum	0.3 ± 0.7Ac	0.7 ± 0.7Ac	0.5 ± 0.7Ac	0.2 ± 0.7Ad	0.3 ± 0.7Ad	0.5 ± 0.6Ac	0.4 ± 0.7Ad
Maple	10.0 ± 0.8Aa	8.3 ± 0.7Aa	7.1 ± 0.5Aa	7.0 ± 0.5Aa	8.7 ± 0.9Aa	8.4 ± 0.6Aa	9.0 ± 0.5Aa
Oak	3.2 ± 0.8Ab	2.0 ± 0.8Ab	3.0 ± 0.7Ab	3.7 ± 0.6Ab	3.1 ± 0.9Ab	2.5 ± 0.7Ab	4.0 ± 0.5Ab
Sassafras	0.1 ± 0.1Ac	0.3 ± 0.2Ac	0.1 ± 0.1Ac	0.3 ± 0.1Ad	0.2 ± 0.2Ad	0.3 ± 0.2Ac	0.3 ± 0.2Ad
Serviceberry	1.1 ± 0.4Ac	1.5 ± 0.4Ab	0.9 ± 0.4Ac	1.7 ± 0.4Ac	1.7 ± 0.4Ac	0.9 ± 0.4Ac	1.5 ± 0.4Ac
Heights (m)							
Mtn. laurel	1.70 ± 0.25Aa	1.80 ± 0.25Aa	1.71 ± 0.24Aa	2.00 ± 0.25Aa	1.75 ± 0.26Aa	1.83 ± 0.23Aa	1.83 ± 0.26Aa
Birch	0.13 ± 0.05Ab	0.11 ± 0.04Ab	0.15 ± 0.02Ab	0.17 ± 0.03Ab	0.15 ± 0.02Ab	0.14 ± 0.01Ab	0.06 ± 0.03Ab
Blackgum	0.16 ± 0.07Ab	0.16 ± 0.06Ab	0.16 ± 0.07Ab	0.18 ± 0.06Ab	0.18 ± 0.07Ab	0.16 ± 0.06Ab	0.17 ± 0.07Ab
Maple	0.14 ± 0.02Ab	0.16 ± 0.02Ab	0.14 ± 0.02Ab	0.16 ± 0.02Ab	0.14 ± 0.02Ab	0.14 ± 0.02Ab	0.13 ± 0.02Ab
Oak	0.13 ± 0.02Ab	0.12 ± 0.02Ab	0.18 ± 0.03Ab	0.13 ± 0.02Ab	0.13 ± 0.02Ab	0.12 ± 0.03Ab	0.12 ± 0.02Ab
Sassafras	0.15 ± 0.01Ab	0.20 ± 0.02Ab	0.20 ± 0.01Ab	0.19 ± 0.02Ab	0.26 ± 0.03Ab	0.20 ± 0.02Ab	0.22 ± 0.02Ab
Serviceberry	0.15 ± 0.04Ab	0.21 ± 0.03Ab	0.21 ± 0.03Ab	0.24 ± 0.40Ab	0.22 ± 0.02Ab	0.20 ± 0.04Ab	0.16 ± 0.03Ab

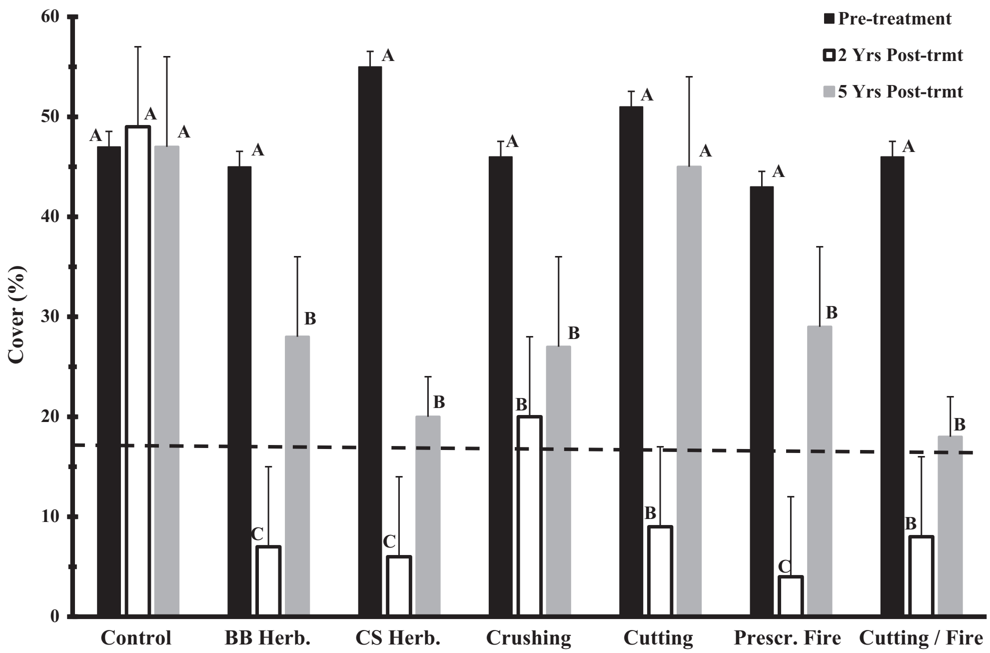

Fig. 2. Overall mean percent cover of mountain laurel for the three study sites by inventory (pre-treatment, 2 years post-treatment, and 5 years post-treatment) and by method (control, basal bark herbicide, cut stump herbicide, crushing, cutting prescribed fire, and cut/fire combination). The dashed line at 20 percent marks the threshold when cover of mountain laurel becomes a serious interfering problem for hardwood seedlings. Vertical bars represent one standard error and different letters signify statistical differences among inventories for that method.

increases of 10 oak seedlings/10 m^2 ($p < 0.05$) and increases of 4–5 seedlings/10 m^2 for birch, blackgum, and sassafras seedlings ($p < 0.05$). The prescribed fire treatment saw a 27 stems/10 m^2 increase in the density of sassafras seedlings ($p < 0.001$), but no significant increases in the densities of any other species ($p > 0.05$). The cut/fire combination also had a large increase in sassafras seedlings (21 stems/10 m^2, $p < 0.001$), an increase of 12 oak seedlings/10 m^2 ($p < 0.05$), and little change in the densities of the other species ($p > 0.05$).

By the fifth year post-treatment, mean heights of the tallest mountain laurel and the tallest hardwood seedlings varied among and within the seven treatments (Fig. 4). In the control, mountain laurel was the tallest species at 1.8 m followed by blackgum and sassafras at ~1.0 m tall ($p < 0.05$). Serviceberry was somewhat shorter (~0.7 m) and birch, maple, and oak were the shortest at 0.3–0.4 m ($p < 0.05$). In the two herbicide treatments, blackgum was the tallest species at ~1.6 m followed by birch, mountain laurel, sassafras and serviceberry at 0.6–1.0 m tall. Maple and oak

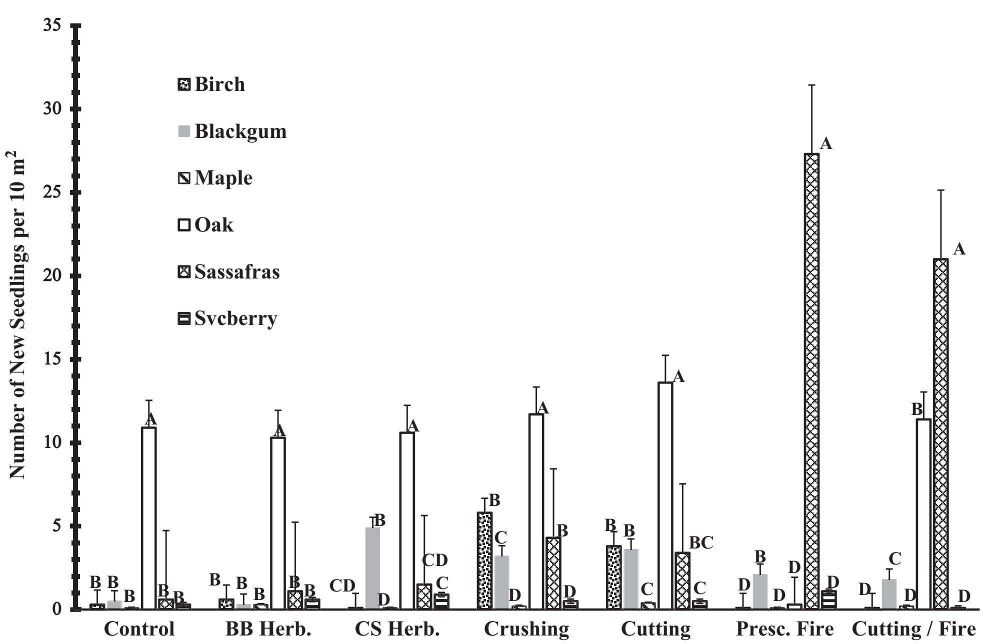

Fig. 3. Mean number of new seedlings established per 10 m^2 plot during the first 2 years after treatment by species or species group (birch, blackgum, maple, oak, sassafras, and serviceberry) and by method (control, basal bark herbicide, cut stump herbicide, crushing, cutting prescribed fire, and cut/fire combination). Vertical bars represent one standard error and different letters signify statistical differences among species for that method.

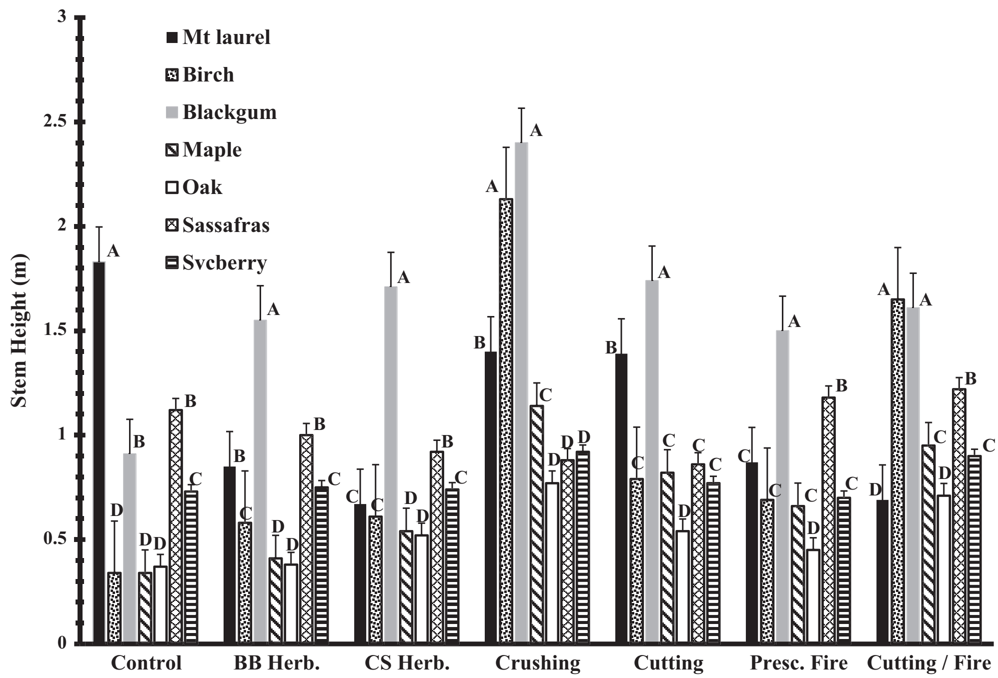

Fig. 4. Mean height (m) of the tallest seedlings at 5 years post-treatment by species or species group (birch, blackgum, maple, oak, sassafras, and serviceberry) and by method (control, basal bark herbicide, cut stump herbicide, crushing, cutting prescribed fire, and cut/fire combination). Vertical bars represent one standard error and different letters signify statistical differences among species for that method.

Table 3
Comparison of the relative effectiveness of the seven understory treatments for improving the oak regeneration potential of mixed-oak forests with mountain laurel thickets after 5 years. A positive score indicates that the treatment enhanced the competitive position of the oak seedlings while a negative score indicates the opposite and a zero suggests no appreciable change.

Treatment	Mountain laurel Cover (%)	Increase in oak seedlings per 10 m^2	Increase in non-oaks per 10 m^2	Oak: ML Heights (m)	Oak: Non-oak Heights (m)	Score
Cutting/Prescribed Fire	18, +2	11,+1	23, −2	0.71: 0.69, 0	0.71: 1.65, −1	0
Basal Bark Herbicide	28, +1	10, +1	3, 0	0.38: 0.85, 0	0.38: 1.55, −2	0
Cut Stump Herbicide	20, +1	11, +1	7, −1	0.52: 0.67, 0	0.52: 1.71, −2	−1
Control (no mgmt.)	47, 0	11, +1	2, 0	0.37: 1.83, −2	0.37: 1.12, −1	−2
Crushing	27, +1	12, +1	14, −2	0.77: 1.40, −1	0.77: 2.40, −2	−3
Cutting	45, 0	14, +1	12, −1	0.54: 1.40, −2	0.54: 1.74, −2	−4
Prescribed Fire	29, +1	0, 0	30, −2	0.45: 0.87, −1	0.45: 1.50, −2	−5

were the shortest species, 0.4–0.5 m tall ($p < 0.05$). The crushing treatment had the tallest seedlings, birch and blackgum at > 2 m tall ($p < 0.05$). These were followed by mountain laurel, maple, and sassafras at 1.2–1.4 m. Oak and serviceberry were the two shortest species, < 1.0 m tall ($p < 0.05$). Heights of the species in the cut treatment were quite similar to those of the two herbicide treatments in that blackgum was the tallest at 1.7 m, birch, maple, sassafras, and serviceberry were equivalent to each other at ~0.8 m, and oak seedlings were the shortest at ~0.6 m. The only difference between the two herbicide treatments and the cutting treatment was in the height of the mountain laurel; it was approximately 0.8 m tall in the former, but 1.4 m tall in the latter. Blackgum was the tallest species in the prescribed fire treatment, 1.5 m ($p < 0.05$) and blackgum and birch were the tallest in the cut/fire combination ~1.5 m ($p < 0.05$). Oak was the shortest species in the prescribed fire treatment, 0.5 m ($p < 0.05$) and it and mountain laurel were the shortest in the cut/fire combination ~0.7 m ($p < 0.05$). In both of these treatments, maple, sassafras, and serviceberry were intermediate in height with sassafras being the tallest of these three species.

Ranking the treatments at Year 5 as to their potential for regenerating oak forests with interfering mountain laurel thickets showed that the treatments formed a continuum of effectiveness (Table 3). The combined cutting/prescribed fire and the basal bark treatments both scored 0 indicating that these two treatments neither benefitted nor hindered the oak regeneration process. All other treatments had negative scores ranging from −1 (cut stump herbicide) to −5 (prescribed fire), indicating that they actually hindered the oak regeneration process.

4. Discussion

Mountain laurel thickets present a challenge to foresters as they are a regeneration obstacle (Beckage et al., 2000; Brose, 2016; Chapman, 1950; Monk et al., 1985), a hazardous fuel (Waldrop and Brose, 1999; Waldrop et al., 2010), and a potential host for the fungus that causes sudden oak death (Tooley and Kyde, 2007; Tooley et al., 2004). Mitigating their deleterious effects on forest regeneration requires reducing the thicket's density and size many years before a planned overstory harvest so that the desirable seedlings can become established and grow past the maximum height of the mountain laurel before the thicket reforms. To do this, foresters use a variety of herbicide, mechanical, and prescribed fire methods. To compare the effectiveness of these methods, one must consider the responses of the mountain laurel, oak reproduction, and other hardwood seedlings. In this study, I hypothesized that the herbicide techniques would be the most effective followed by mechanical and prescribed fire approaches and no management would be the least effective. While the results somewhat support this ranking, what stood out from this project was the lack of long-term effectiveness of any of the treatments. By the second year post-treatment inventory, all of the methods other than the control had reduced the mountain laurel cover to the point that forest regeneration had begun, but 3 years later mountain laurel thickets had substantially redeveloped in the basal bark, crush, cut, and prescribed fire treatments, and were vigorously reforming in the cut stump and cut/burn treatments. Additionally, mountain laurel and non-oak seedlings were overtopping the oak seedlings in all treatments. Consequently, their composite effectiveness scores ranged from 0 (no benefit or harm) to −5 (moderate impairment). Why had the methods performed so poorly?

The basic problem with all of these methods was that none of them killed the mountain laurel roots which allowed the shrubs to sprout. While this outcome was expected following the mechanical and prescribed fire treatments, mountain laurel is a vigorous sprouter (Ducey et al., 1996; Waldrop et al., 2016), the sprouting after the herbicide applications was a surprise. I had anticipated widespread root grafting among the many hundreds of mountain laurel stems that comprised the thicket. Glyphosate readily moves through root grafts (Kochenderfer et al., 2004, 2006) so spraying just the larger stumps should have killed many of the nearby untreated shrubs. That clearly never happened. The herbicide did prevent the treated shrubs from sprouting from their bases, but did nothing to stop the neighboring untreated mountain laurel stumps from sprouting even though the treated and untreated stumps were often only a few centimeters apart. Apparently mountain laurel thickets are not clonal nor does root grafting occur. Rather, it appears that the thickets are composed of thousands of independent shrubs.

The redevelopment of mountain laurel cover after the basal bark herbicide treatment appears to have arisen from some application issues. In this treatment, the mountain laurel stems less than 1 m tall were not sprayed because to do so would have been extremely expensive, tedious, and time consuming. Consequently, these small, untreated shrubs responded to the killing of the nearby larger mountain laurel with increased growth and simply replaced their neighbors in a few years. Second, the larger mountain laurel often had crooked twisted stems that made complete spraying of their bases difficult. Incomplete spraying resulted in some shrubs surviving the herbicide.

Two related factors contributing to the short-term effectiveness of the crush, cut, and prescribed fire methods are the time since the last forest-floor disturbance and the relatively low impact of the treatments. Mountain laurel thickets develop through decades of a lack of substantial forest floor disturbance (Brose et al., 2002; Brose and Waldrop, 2010). In fact, the few disturbances that had occurred in these stands (Brose, 2016) were events such as gypsy moth (*Lymantria dispar*) defoliations that impacted the main canopy and likely enhanced the size and vigor of the mountain laurel thickets (Chastain and Townsend, 2008; Clinton et al., 1994). The cutting treatment was low impact. It was done with brush saws, not large mowers, so there was no damage to the forest floor and the mountain laurel roots. Similarly, the prescribed fires occurred during the dormant season and were low- to moderate-intensity burns (flame lengths < 1 m) that did not consume much, if any, of the duff layer. Consequently, virtually all the mountain laurel roots sprouted after these two treatments.

The crushing treatment administered via a timber harvest should have controlled the mountain laurel more than the cutting or prescribed fire treatments because of more forest floor disturbance (Wahlenberg and Doolittle, 1950), but that was not the case. That contradiction was likely caused by the gentle harvesting of the CCSF site (a communication misunderstanding resulted in the logger not inflicting maximize damage to the mountain laurel thicket and the mistake could not be corrected). Had the CCSF site been harvested in the same manner as the other two sites, the crushing treatment would have likely resulted in more and longer-term control of the mountain laurel thicket.

Conducting a prescribed fire a couple of years after cutting the mountain laurel showed some promise as an effective method, corroborating early results from Waldrop et al., 2016). At 5 years post-treatment, the thicket was slowly reforming and the mountain laurel and oak reproduction were the same height. The order and sequence of events in this combined treatment are probably key in this limited success in that they exploited a weakness of mountain laurel while being highly compatible with the silvics of oak seedlings. Mountain laurel has small root systems (Chapman, 1950; Kurmes, 1961) so the cutting that occurred during the growing season happened when root carbohydrate reserves were low for the shrub. Consequently, mountain laurel growth was probably somewhat impaired. The prescribed fires occurred 2 years later in the fall or early spring. Because mountain laurel is evergreen, it may have already been physiologically active for these dormant-season burns resulting again in reduced growth.

Another part of the evaluating method effectiveness is "What happened to the oak seedlings?" All of the methods, except the prescribed fire, showed an increase in the number of oak seedlings by the second inventory. This is not due to the treatments, but rather to a bumper acorn crop that occurred throughout northern Pennsylvania in 2001 and coincided with the implementation of the treatments (Brose, 2011b; Miller et al., 2017). Had one or more of the methods promoted oak seedling establishment, then differences in the number of new oak seedlings would have been apparent among the treatments. But, oak seedling establishment averaged approximately 11 new seedlings per 10 m^2 with no differences among treatments indicating that none of them significantly enhanced establishment. The prescribed fire treatment also had an increased density of oak seedlings immediately following the acorn crop, but the prescribed fires killed these recent germinants resulting in no net increase in the second inventory. The susceptibility of new oak seedlings to fire concurs with Miller et al. (2017) that reported an 80 percent loss of small oak seedlings due to spring fires. Additionally, that susceptibility is apparent when comparing the prescribed fire treatment to the cut/burn treatment. The latter method had no loss of oak seedlings due to the 2 years of increased understory light allowing the seedlings to develop their root systems and, hence, their post-fire sprouting ability.

However, some of the methods did promote the establishment of other hardwood species. Blackgum increased in the cut stump herbicide treatment because blackgum saplings were cut but not sprayed and blackgum does produce root suckers after severing the main stem (McGee and Outcalt, 1990). Blackgum increased in density in the crushing and cutting treatments for the same reason. These two treatments also increased the densities of birch and sassafras with the former likely arising from wind-blown seed (Lamson, 1990) and the latter from root sprouts and seed stored in the forest floor (Griggs, 1990). Root sprouts and stored seed were the likely sources for the large increase in sassafras seedling density after the prescribed burns and this result is consistent with previous prescribed fire studies in the region (Hutchinson et al., 2005; Waldrop et al., 2008). The basal bark herbicide and untreated control did not prompt regeneration of any of the hardwood species.

All of the methods did cause stark differences in height growth by the end of the study. In the control, all species had at least doubled their height with blackgum, sassafras, and serviceberry growing the most, especially where there were small gaps. This is likely due to excluding deer from the treatment as all the species are moderately preferred browse species (Bressette et al., 2012; Horsley et al., 2003). However, mountain laurel still dominated the control treatment. In the other treatments, blackgum or birch and blackgum were the tallest species, followed by various combinations of maple, sassafras, and serviceberry. Oak was the shortest. This gradation of height was expected because birch and blackgum are known for rapid height growth (Lamson, 1990; McGee and Outcalt, 1990; Miller et al., 2014) while oak seedlings emphasize root development in lieu of height growth (Brose, 2011a; Miller et al., 2004). Generally, the crushing treatment had the tallest seedlings, regardless of species, due to full sunlight reaching the forest floor with birch and blackgum being the tallest.

5. Management implications

Given that none of these treatments showed substantial promise after 5 years, what should oak forest managers do when they have to contend with mountain laurel thickets? If there is an adequate stocking of oak seedlings (a rare situation), a complete harvest that crushes the mountain laurel is probably the best approach, but the forester needs to communicate clearly with the logger to ensure the thicket is thoroughly disturbed. Unfortunately, most oak forests with mountain laurel thickets lack an adequate stocking of oak seedlings. In that case, leaving the thicket undisturbed and waiting for an acorn crop is a wise course of action as mountain laurel thickets develop and spread slowly. However, if the forester wants to begin preparing for a future acorn crop, then cutting of the mountain laurel followed in a few years by one or more prescribed fires will reduce the hazardous fuel situation as well as create a hospitable seedbed. The cutting and burning need to occur in the growing season when the carbohydrate reserves of the mountain laurels' roots will be low as this should decrease sprouting and growth. Regrettably, this approach will regenerate birch, blackgum, and sassafras which will become competitors to the desired oak seedlings.

What is needed is research into broadcast herbicides like those used in northern hardwood stands to control interfering understory vegetation (Horsley, 1990, 1994; Horsley and Bjorkbom, 1983). Broadcast herbicide prescriptions would provide long-term control of mountain laurel and allow oak seedlings to become established and develop. Unfortunately, that research is in its infancy and tested prescriptions are still a few years away (Miller et al., 2016).

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