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A comparison of three foliar-applied herbicides 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 conditions, forest regeneration problems, and possible forest health concerns. Generally, land managers use mechanical means or prescribed fire to control mountain laurel thickets, but these treatments are expensive, dangerous to implement, or have short-term effectiveness. From 2012 to 2016, we compared the effectiveness of three herbicides applied as broadcast foliar treatments at varying rates and in different months for reducing mountain laurel thickets. Triclopyr (ester formulation) top-killed mountain laurel within a few weeks at most month/rate combinations, but subsequent sprouting reduced overall effectiveness by year 3. Conversely, imazapyr provided little initial control of mountain laurel, but by year 3, the herbicide had killed nearly all the treated shrubs with no subsequent sprouting regardless of the month of application or rate. Glyphosate had limited effectiveness; spraying in August at 8 and 12 L/ha killed the mountain laurel over 3 years with little sprouting while all others treatments had little or no impact. From these results, it appears that several month/rate combinations of all three herbicides have potential for controlling mountain laurel thickets and merit further testing to refine application procedures.

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 to 4 m tall and broad, is evergreen and shade tolerant, and occurs primarily on dry and intermediate moisture sites (Chapman, 1950; Kurmes, 1961). Mountain laurel spreads via layering of the lowermost branches as well as through 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 dense shade. 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, 2011; Frey and Ashton, 2018; Miller et al., 2014). 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. Mountain laurel thickets burn with high intensity posing a threat to human life and property as demonstrated by the fall 2016 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 et al., 2004; Tooley and Kyde, 2007).

Presently, forest managers rely on crushing, mowing, and prescribed fire to reduce the size and density of mountain laurel thickets, but these methods have serious limitations. Crushing is a low cost method done by skidders during a timber harvest, but not all mountain laurel thickets occur in stands suitable for a commercial harvest. Mowing costs range from \$500 to \$1000 per hectare (pers. comm. Andrea Hille, Silviculturist, Allegheny National Forest; Rob Beleski,

☆ Mention of a specific herbicide or surfactant in this manuscript does not constitute an endorsement of that product by the USDA Forest Service.

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Silviculture Section Chief, Pennsylvania Bureau of Forestry). Prescribed fires in mountain laurel thickets can produce flame lengths exceeding 7 m resulting in the damage and/or death of the overstory trees (Waldrop and Brose, 1999; Waldrop et al., 2008). Finally, both of these methods control mountain laurel for just a few years; post-treatment sprouting by the shrub re-establishes the thicket in 5–10 years (Brose 2017). Foliar herbicide applications may provide a more effective means of treating mountain laurel thickets than mowing and prescribed fire.

Foliar herbicides applied by mechanized spray equipment or by backpack sprayers have a long history of research and use in Pennsylvania. Horsley (1981) and Horsley and Bjorkbom (1983) pioneered the use of glyphosate as a site preparation technique to control hay-scented fern (*Dennstaedtia punctilobula*), root suckers of American beech (*Fagus grandifolia*), and striped maple (*Acer pensylvanicum*) in northern hardwood forests prior to regeneration harvests. Subsequent research identified sulfometuron methyl as an appropriate herbicide to reduce undesirable grasses and sedges that germinate en masse from stored seed after a timber harvest and prevent fern rhizome fragment development (Horsley 1988, 1990, 1991). More recently, researchers studied the effects of herbicides on non-target vegetation (Ristau 2010, 2017; Ristau et al., 2011). Conversely, foliar herbicide applications for controlling mountain laurel have not been extensively studied and the research used outdated chemicals. For example, Romancier (1971) found that spraying mountain laurel sprouts with 2,4,5-Trichlorophenoxyacetic acid solution (2,4,5-T) controlled them with no resprouting. However, 2,4,5-T was discontinued in the early 1980s.

Between 2012 and 2016, we tested three foliar herbicides commonly used in forestry operations to kill interfering understory vegetation as potential controls for mountain laurel thickets. We evaluated the application of three herbicides in four months and at three spray rates because month of application and spray rate strongly affect herbicide efficacy (Horsley and Bjorkbom, 1983; Horsley, 1988, 1994; Jackson and Finley, 2005). Our hypothesis was that least one herbicide/month/rate combination that would reduce dense mountain laurel cover to less than 20 percent, the threshold at which mountain laurel ceases to interfere with hardwood seedlings (Brose 2016). Knowing which chemical, dosage rate, and month of application provides the most control of mountain laurel will inform foresters challenged by mountain laurel thickets and, possibly, by other ericaceous shrubs.

2. Methods

2.1. Study sites

This study was conducted from 2012 to 2016 in four mixed-oak stands located in northwestern and central Pennsylvania (Fig. 1). The northwestern stands were Edeburn Hill (EBH) on Clear Creek State Forest (41.318 N, 79.039 W) and Hoover-Nelson Road (HNR) on Moshannon State Forest (41.061 N, 78.510 W) while the central stands were Pine Creek Hollow (PCH) on Bald Eagle State Forest (40.971 N, 77.203 W) and Shade Mountain (SHM) on Game Lands 107 (40.672 N, 77.343 W). Despite being 50 to 200 km from each other, the four study stands shared a number of characteristics. Each stand was 15- to 20-ha, had an elevation of approximately 550 m, a southerly aspect, and an oak site index$_{50}$ of 15–18 m (Braker, 1981; Hallowich, 1988; Lipscomb and Farley, 1981; Zarichansky, 1964). The upper canopy trees were 20–25 m tall and consisted primarily of chestnut oak (*Quercus montana*) and northern red oak (*Q. rubra*). Black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), pitch pine (*Pinus rigida*), and eastern white pine (*P. strobus*) were also present. Associated midstory tree species included black birch (*Betula lenta*), blackgum (*Nyssa sylvatica*), red maple (*Acer rubrum*), sassafras (*Sassafras albidium*), and serviceberry (*Amelanchier arborea*). Canopy cover was not ubiquitous due to past disturbances. We visually estimated overstory stocking to be more than 70 percent. Mountain laurel dominated the understory plant community; visual estimates indicated thickets occupied at least 70 percent of each stand and ranged in height from 1 to 2 m. 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 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 50–200 km apart, they differed in a number of characteristics. EBH and HNR were in the Allegheny Plateau region while PCH and SHM were in the Ridge/Valley region (Schultz, 1999). EBH and PCH were situated on midslope benches while HNR and SHM were located at/near hilltops. Local climate varied with EBH and HNR being the coolest and wettest (−10.8 to 25.1 C, 1100 mm precipitation) while PCH and SHM were the warmest and driest (−6.4 to 30.1 C, 950 mm precipitation) (Braker, 1981; Hallowich, 1988; Lipscomb and Farley, 1981; Zarichansky, 1964).

2.2. Study design, installation, and measurements

We designed the study as a 3 × 3 × 4 factorial with the four sites serving as replicates. The factors were three foliar herbicides, three spray rates, and four application times. The herbicides were glyphosate (Rodeo*), imazapyr (Chopper Gen II*), and triclopyr ester (Garlon 4 Ultra*). We chose these herbicides because they are commonly used in forest management to control undesirable understory vegetation (Jackson and Finley, 2005; Kochenderfer et al., 2011). Herbicide product labels approved by the U.S. Environmental Protection Agency (EPA) specify a maximum of 20 L per hectare (l/ha) for glyphosate and triclopyr and 8 l/ha for imazapyr (Senseman, 2007). For glyphosate and triclopyr, we chose spray rates of 4, 8, and 12 l/ha and 2, 4, and 6 l/ha for imazapyr. We chose these rates based on consultation with knowledgeable local foresters. The application times were between the 10th and 20th of April, June, August, and October 2013. We chose these months because mountain laurel is evergreen so April and October spraying may be possible, June is when the shrub is producing new growth that does not yet have a waxy cuticle, and August is the traditional spraying month in Pennsylvania (Horsley and Blorkbom, 1983; Horsley, 1994). For the remainder of this paper, the herbicides are referred to by their chemical names, the application times by their month, and rates by their l/ha amounts.

In 2012, we installed the study in each stand by locating and inventorying two hundred 40-m^2 (3.6 m radius) circular plots arranged in 40 rows of 5 plots each. The rows were at least 15 m apart and the plots within a row were 10–15 m apart based on each plot having at least 50 percent cover of mountain laurel. The center of each plot was marked with a 1-m fiberglass rod and the plot boundary was delineated with flagging. Each plot was inventoried for the percent cover of mountain laurel using established guidelines (Brose et al., 2008) and the height of the tallest mountain laurel was measured to the nearest 15 cm. After the pre-treatment inventory was completed in each stand, we randomly assigned each row of plots to one of the 36 herbicide/rate/month combinations with four rows serving as untreated controls.

In 2013, we prepared the herbicide solutions shortly before each spraying under controlled conditions at the Forestry Sciences Laboratory in Irvine, Pennsylvania. A non-ionic surfactant (Cide-Kick*) was used in all solutions at a rate of 2 l/ha to improve herbicide penetration through the waxy cuticle. Pennsylvania Bureau of Forestry foresters used backpack sprayers to apply the foliar herbicides during April, June, August, and October on the randomly assigned rows of plots. Each backpack sprayer was assigned to and only used with one herbicide to avoid cross contamination. Additionally, each backpack sprayer was thoroughly rinsed when switching from one spray rate to another to ensure the rates remained consistent.

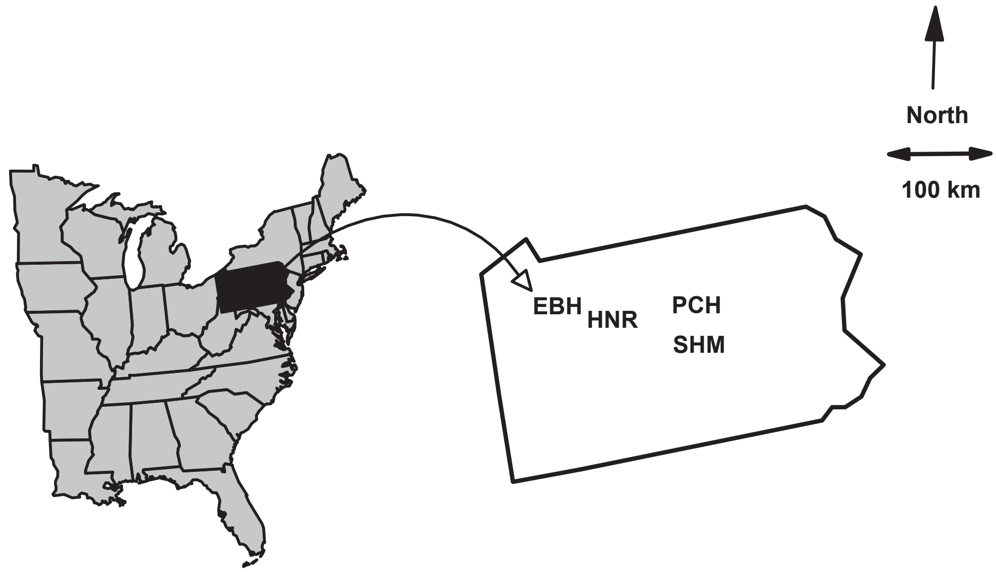

Fig. 1. The location of Pennsylvania in the eastern United States and the location of the four study sites (EBH, HNR, PCH, and SHM) within Pennsylvania.

We re-inventoried each plot for cover of mountain laurel at the end of the first, second, and third growing season post-treatment. For the April and June sprayings, these inventories were in October 2013, 2014, and 2015; for the August and October sprayings these were one year later. Also, we noted if any hardwood seedlings within the plots or overstory trees near the plots displayed signs of herbicide injury.

2.3. Data analysis

We analyzed the mountain laurel cover data as a randomized factorial with repeated measures via Proc GLMMIX (SAS Institute, 2009). The herbicides, spray rates, months of application, and their associated interactions were the fixed effects in the model while site was the random effect. Time since application (Yr0 (pre-treatment), Yr1, Yr2, and Yr3) was the repeated measure. To measure the correlation between inventories, we used an autoregressive order 1 covariance structure. Because the response variable was a percentage with many large and small values, we used a beta distribution, logit link function, and the Kenward-Rogers denominator degrees of freedom method. We used the Tukey-Kramer least squares mean separation test and an alpha of 0.05 for all multiple comparisons. Residuals were examined to ensure that model assumptions were met.

Finally, we assessed the 36 herbicide/rate/month combinations using two metrics. First, we compared mean annual mountain laurel cover to the 20-percent cover threshold considered to be problematic for hardwood seedlings (Brose, 2016). Second, we compared each combination's mean annual mountain laurel cover to that of its previous year to determine if cover was decreasing, stable, or increasing. Fully successful combinations had mean mountain laurel covers less than 20 percent and those covers were stable or decreasing relative to the previous year. Partly successful combinations had mean mountain laurel covers equivalent to 20 percent or their covers were increasing relative to the previous year. Failed combinations had mean mountain laurel covers greater than 20 percent.

Table 1
Results of the Type III tests of fixed fffects from the PROC GLMMIX procedure. Probability values less than 0.05 indicate there are significant differences among the factors of that effect or interaction.

Effect	Num DF	Den DF	F Value	Prob > F
Herbicide	2	10.28	10.34	0.0035
Month	3	10.67	19.26	0.0001
Herbicide*Month	6	10.76	5.88	0.0061
Rate	2	102.50	81.00	<.0001
Herbicide*Rate	4	102.50	8.41	<.0001
Month*Rate	6	102.50	4.16	0.0009
Herb*Month*Rate	12	102.50	2.37	0.0099
Year	3	147.90	107.97	<.0001
Herbicide*Year	6	166.30	61.69	<.0001
Month*Year	9	176.90	2.18	0.0468
Herb*Month*Year	18	191.20	2.83	0.0013
Rate*Year	6	166.30	1.62	0.1705
Herb*Rate*Year	12	183.60	0.95	0.4779
Month*Rate*Year	18	191.20	1.29	0.2273
Herb*M*R*Y	36	197.10	0.91	0.5924

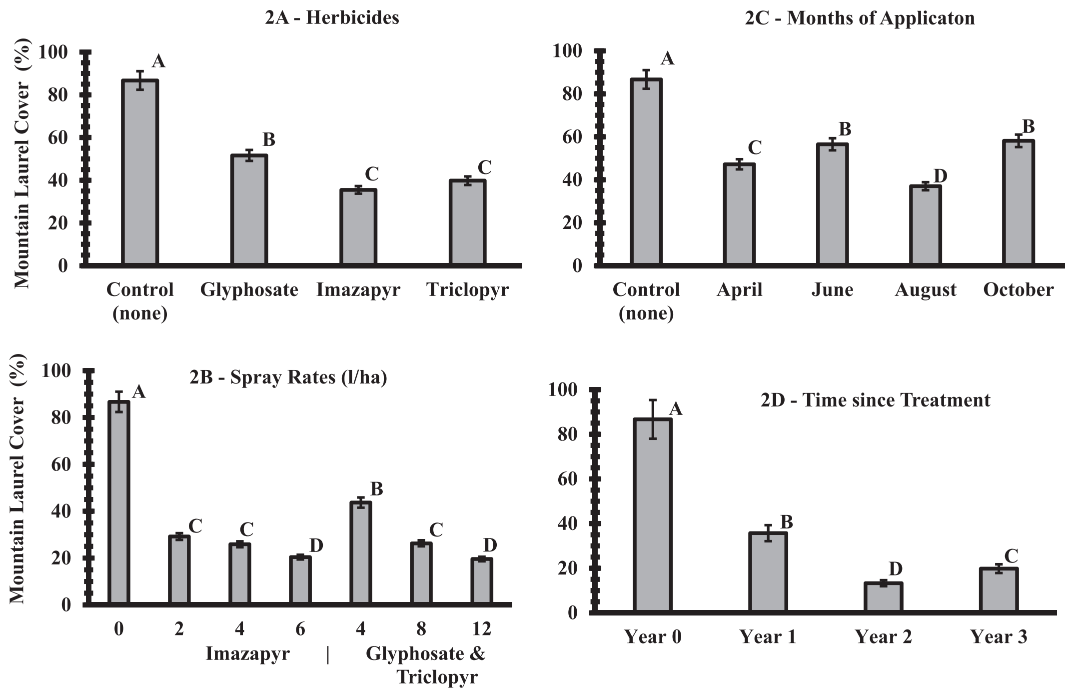

Fig. 2. The effects of the three foliar-applied herbicides, their months of application and spray rates, and time since treatment on the cover of mountain laurel. Bars with different letters are statistically different at the 0.05 level. Year 0 equals pre-treatment.

3. Results

At the start of the study, mountain laurel cover was high at all sites, means ranged from 79 to 93 percent, and differed among sites ($p < 0.001$) with PCH having the most, 90.3 percent, followed by EBH at 84.9 percent. SHM at and HNR had the least cover of mountain laurel at 81.8 and 80.5 percent, respectively. Mean maximum heights of mountain laurel also varied among the sites ($p < 0.001$) with HNR, PCH, and SHM being equivalent at 130–140 cm and EBH being shorter at 112 cm.

Analysis discovered significant differences in mountain laurel cover among the herbicides ($p = 0.0035$), among the rates ($p < 0.0001$), among the months ($p = 0.0001$), and among years ($p < 0.0001$) (Table 1). Five 2-way interactions were significant (p values ranged from < 0.0001 to 0.0468) as well as two 3-way interactions; herbicide * month * rate ($p = 0.0099$) and herbicide * month * year ($p = 0.0013$) indicating a dose response for each herbicide that varied by month of application and time since application.

Comparing just the herbicides over the three years of the study, mountain laurel cover was less in the herbicide-treated plots (35–52 percent) than it was in the unsprayed control (87 percent) and that cover varied among the three herbicides (Fig. 2a). Triclopyr ester and imazapyr were the most effective herbicides, resulting in 35 and 38 percent cover of the mountain laurel, respectively, followed by glyphosate at 52 percent. Among the rates over the three years of the study, mountain laurel cover decreased as the spray rate increased (Fig. 2b). Cover was the highest in the unsprayed control plots (87 percent), followed by plots treated with the lowest rate of glyphosate and triclopyr (44 percent at 4 l/ha). Mountain laurel cover was the least after herbicide application at the highest rates (20 percent at 6 l/ha imazapyr and 12 l/ha glyphosate and triclopyr). The remaining rates, 2 and 4 l/ha of imazapyr and 8 l/ha of glyphosate and triclopyr, resulted in mountain laurel cover of 26–29 percent. Among the months of application over the three years of the study, all resulted in less mountain laurel cover (37–57 percent) than not spraying (87 percent) with significant differences detected among the months (Fig. 2c). The plots sprayed in August had the least mountain laurel cover, 37 percent, while those sprayed in April had 48 percent cover. The June and October sprayings resulted in 57 percent mountain laurel cover. Regarding time since treatment, the percent cover of mountain laurel differed each year (Fig. 2d). It was the most in year 0 (pre-spraying) when it was 87 percent. That number dropped to 36 percent after 1 year and declined again to 13 percent after year 2. However, mountain laurel cover increased in the third year of the study to 20 percent.

The significant 2-way and 3-way interactions indicate that some herbicide/rate/month combinations had reduced mountain laurel cover more than others (Table 2). By the end of the first post-treatment growing season, 4 combinations containing triclopyr and 1 combination containing glyphosate were considered fully successful as they resulted in 2–14 percent mountain laurel cover. Additionally, there were 7 combinations (5 triclopyr and 2 glyphosate) that were partly successful; they reduced mountain laurel cover to near the 20 percent threshold. These partly and fully successful combinations occurred in all months and nearly all were at the higher application rates. None of the imazapyr combinations were deemed partly or fully successful in Year 1, but it was observed that mountain laurel sprayed with this herbicide looked unhealthy even though it was still alive.

By the end of the second year, there were 19 fully successful and 6 partly successful combinations. All of the combinations that were partly or fully successful in Year 1 were fully successful in Year 2 and they were joined by 13 more combinations. Of these 13, eleven were imazapyr, one was triclopyr, and one was glyphosate. Fully successful combinations occurred in all months, but were concentrated in August, and occurred at all rates. Also, we observed some basal sprouting of mountain laurel in plots sprayed with triclopyr at the lowest rate.

At the end of the study (Year 3), there were 17 fully successful combinations (Table 2). Imazapyr accounted for 12 of these 17 combinations while triclopyr and glyphosate had 3 and 2 combinations, respectively. Imazapyr controlled mountain laurel in all months and at all rates. Triclopyr controlled mountain laurel at the 8 and 12 l/ha rates in April and August and glyphosate was only successful at these same rates in August. There were also 7 partly successful combinations (5 triclopyr and 2 glyphosate). Six of these seven combinations had been fully successful the previous year, but mountain laurel was sprouting in

Table 2
Percent cover of mountain laurel (mean ± 1 se) for each of the 36 herbicide/month/rate combinations and the untreated controls for the 4 years of the study. Yr0 are the pre-treatment covers. Combinations with bold means were judged to be partly successful and those marked with an asterisk (*) were judged to be fully successful.

Month	Herbicide	Rate (l/ha)	Yr0	Yr1	Yr2	Yr3
April	None	N/A	84±3	83±2	82±2	86±3
April	Glyphosate	4	90±3	70±5	76±4	77±4
April	Glyphosate	8	79±2	41±6	33±5	37±5
April	Glyphosate	12	86±3	37±6	31±4	34±5
April	Imazapyr	2	87±3	59±3	**15±3***	**8±2***
April	Imazapyr	4	80±4	53±5	**11±4***	**5±2***
April	Imazapyr	6	79±4	49±5	**6±3***	**2±1***
April	Triclopyr	4	81±3	38±6	35±6	37±5
April	Triclopyr	8	86±3	**20±5**	**7±3***	**21±4**
April	Triclopyr	12	90±2	**6±2***	**3±1***	**7±2***
June	None	N/A	90±2	89±2	87±2	91±2
June	Glyphosate	4	85±3	61±7	47±8	53±8
June	Glyphosate	8	83±3	39±7	**29±6**	38±6
June	Glyphosate	12	82±2	**28±5**	**23±6**	**26±6**
June	Imazapyr	2	86±2	75±3	33±4	**15±2***
June	Imazapyr	4	82±4	66±4	**21±3**	**5±1***
June	Imazapyr	6	86±2	67±4	**24±4**	**5±1***
June	Triclopyr	4	85±3	**26±5**	**7±2***	34±5
June	Triclopyr	8	87±3	**25±5**	**4±2***	**29±6**
June	Triclopyr	12	86±4	**6±2***	**2±1***	**26±4**
August	None	N/A	91±2	91±2	90±2	87±6
August	Glyphosate	4	87±3	30±4	29±2	28±3
August	Glyphosate	8	86±2	**14±1***	**4±1***	**11±2***
August	Glyphosate	12	86±3	**19±7**	**3±1***	**6±2***
August	Imazapyr	2	79±3	43±4	**10±1***	**3±3***
August	Imazapyr	4	85±3	46±6	**6±2***	**2±0***
August	Imazapyr	6	89±2	38±6	**3±1***	**1±0***
August	Triclopyr	4	89±3	**18±4**	**5±2***	**24±4**
August	Triclopyr	8	86±2	**8±3***	**2±1***	**10±3***
August	Triclopyr	12	79±3	**2±1***	**2±1***	**10±3***
October	None	N/A	89±2	89±2	87±2	84±3
October	Glyphosate	4	93±2	65±7	72±5	83±2
October	Glyphosate	8	87±3	73±2	57±5	68±4
October	Glyphosate	12	83±3	61±4	32±5	48±6
October	Imazapyr	2	81±4	58±5	**21±4**	**15±2***
October	Imazapyr	4	86±3	64±6	**15±5**	**13±3***
October	Imazapyr	6	85±2	33±6	**11±4***	**7±2***
October	Triclopyr	4	85±3	40±8	47±5	66±5
October	Triclopyr	8	84±3	40±6	**7±2***	**24±5**
October	Triclopyr	12	82±2	**28±9**	**6±2***	**13±7**

all of them. Sprouting was especially pronounced in the triclopyr-treated plots that had been sprayed in June and October.

Observations of herbicide damage to hardwood seedlings within the plots or overstory trees near the plots revealed some interesting trends. Overall, hardwood seedlings were scarce at all locations. When we did observe them, they were in glyphosate plots that had been sprayed in April or October. Otherwise, hardwood seedlings were absent. Crown dieback in nearby overstory trees was also scarce. When we did observe what we thought was herbicide-related injury, it was usually red maple in conjunction with imazapyr-sprayed plots. Finally, we observed an interesting phenomenon; mortality of the mountain laurel was limited to just the sprayed plots; adjacent, untreated shrubs were not killed (Fig. 3). The same phenomenon was also noted within plots when an individual mountain laurel shrub was accidentally skipped during the spraying.

4. Discussion

The goal of any herbicide prescription in forest management is to use the minimum amount of product at the correct time of year that will adequately control the target vegetation. This criteria will likely yield the most economically and environmentally sound prescription. To develop such a prescription for controlling mountain laurel entails answering some basic questions, three of which are (1) what chemical do I use?, (2) when do I apply the chemical?, and (3) how much of the chemical do I apply? The results of this study indicate that several herbicide/rate/month combinations exhibit promise in controlling mountain laurel thickets.

Based on the third-year results, the following herbicide/rate/month combinations successfully controlled mountain laurel: imazapyr at all rates and months we tested, triclopyr at 8 and 12 l/ha in April and August and glyphosate at 8 and 12 l/ha in August. The abundance of

Fig. 3. One of the herbicide-treated plots 2 years after the spraying. Note that the mortality occurred just within the plot and did not extend beyond the boundary. Photo by Patrick Brose.

imazapyr combinations relative to triclopyr combinations was surprising as triclopyr is recommended and used for controlling mountain laurel and similar shrubs (Oppenheimer et al., 1989; Jackson and Finley, 2005; Kochenderfer et al., 2011). This difference may be due to when the herbicide's effectiveness was assessed. In the first year of this study, triclopyr was markedly superior to imazapyr in controlling mountain laurel as the former quickly top-killed the shrub while the latter discolored the foliage. But, mountain laurel started basal sprouting in the triclopyr-sprayed plots in the second year and this sprouting became more widespread in the third year resulting in increases in mountain laurel cover. Conversely, the discolored mountain laurel in the imazapyr-treated plots died in the second and third years and no basal sprouting was observed. The effectiveness of glyphosate at the 8 and 12 l/ha rates in August is consistent with the broadcast herbicide prescription commonly used in hardwood forests in the central Appalachian Mountains (Horsley, 1994; Jackson and Finley, 2005; Brose et al., 2008).

The superiority of August as the best month for controlling mountain laurel (all three herbicides were effective) is consistent with existing forest-herbicide research and guidelines (Horsley and Bjorkbom, 1983; Horsley, 1994; Kochenderfer et al., 2011). By this time in the summer, translocation of photosynthates is well underway (Kramer and Kozlowski, 1960; Kozlowski, 1971; Kozlowski and Pallardy, 1997) so herbicide active ingrediants are readily moved from the foliage to the roots. April's and October's successful control of mountain laurel by imazapyr and the highest rate of triclopyr was likely due to the shrub's evergreen leaves already being photosynthetically active (insolation in April is equivalent to that of August) and the strong foliage-to-root translocation that occurs in perennial plants at the end of the growing season (Kramer and Kozlowski, 1960; Kozlowski, 1971; Kozlowski and Pallardy, 1997). The poor control of mountain laurel in June, only imazapyr was effective, was likely due to foliage-to-root translocation having not yet started in June. The finding that April and October are viable months for spraying gives foresters a broad window of 6 months for scheduling and conducting herbicide operations.

The finding that the lowest rate for imazapyr (2 l/ha) and middle rate for glyphosate and triclopyr 8 l/ha) controlled mountain laurel is important because it means foresters do not have to use the maximum rates of these herbicides to control this problematic species. Applying lesser amounts of herbicides saves money and reduces the likelihood of unintended environmental impacts and non-target damage. For example, imazapyr is mobile in the soil and can enter into the roots of some tree species, causing injury or mortality (Jackson and Finley, 2005; Senseman, 2007; Kochenderfer et al., 2011). Applying as lower rates of imazapyr as possible may help avoid this negative consequence.

Our observations on hardwood seedling survival, injury to overstory trees, and spread of mountain laurel mortality beyond the plots are consistent with existing forest-herbicide knowledge. When we observed hardwood seedlings, they were in glyphosate plots sprayed in April and October. In these months, the seedlings would have no foliage and glyphosate must enter through foliage (Jackson and Finley, 2005; Senseman, 2007; Kochenderfer et al., 2011). Conversely, imazapyr has soil activity and can enter through the roots while triclopyr ester can enter through stem/bark; thereby killing dormant seedlings (Jackson and Finley, 2005; Senseman, 2007; Kochenderfer et al., 2011). When we observed herbicide injury to overstory trees, it was always in conjunction with imazapyr plots and was usually red maple. Imazapyr is soil mobile and red maple is a species quite sensitive to this herbicide (Kochenderfer et al., 2001; Lewis and McCarthy, 2008). The observation that only sprayed mountain laurel died and adjacent untreated mountain laurel was unharmed supports an earlier finding that mountain laurel thickets are not clonal nor is there any root grafting (Brose, 2017). Had the mountain laurel thickets been clonal or had there been root grafts, the herbicide effects would have extended beyond the boundaries of the plots.

This study has several limitations. First, the spraying was done on plots using backpack sprayers, not on a larger area using commercial broadcast spray equipment. We could take the time and pay close attention to thoroughly wetting all the mountain laurel in a plot. Such attention to detail may not be feasible on a larger scale. Second, we did not test surfactants. We used just one variety because testing more would have added another layer of complexity to the study and made it even more cumbersome. Finally, we did not quantify injury to nearby overstory trees and loss of hardwood seedlings. Both are important considerations in any herbicide prescription and our observations support that importance, but time constraints and other obligations did not allow us to delve into these points in greater detail.

5. Management implications

Broadcast herbicide application may be a viable alternative to mechanical control methods or prescribed fire for forest managers challenged by mountain laurel thickets. Imazapyr herbicides are quite effective anytime between April and October at rates from 2 to 6 l/ha. Drawbacks to imazapyr herbicides are that they kill mountain laurel slowly (2–3 years for full results) and there is the danger of accidentally killing overstory trees that are sensitive to imazapyr. Triclopyr ester herbicides are also a possibility within the April to October period at rates of 8–12 l/ha. These herbicides kill mountain laurel quickly, but subsequent sprouting could be a problem. Finally, glyphosate herbicides applied in August at 8–12 l/ha will also control mountain laurel.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2018.09.034.

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