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EVALUATION OF DORMANT-SEASON HERBICIDE TREATMENT METHODS FOR CHINESE PRIVET AT CONGAREE NATIONAL PARK

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EVALUATION OF DORMANT-SEASON HERBICIDE TREATMENT METHODS FOR CHINESE PRIVET AT CONGAREE NATIONAL PARK

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ABSTRACT

Chinese privet (*Ligustrum sinense* Lour.) is a non-native invasive shrub that has become ubiquitous throughout the southeastern United States. There is a large infestation of privet at Congaree National Park in South Carolina, and the National Park Service is interested in controlling it with dormant-season foliar herbicide treatments. The primary objective of this study was to determine which combination of herbicide and applicator provides the most effective control of privet, while minimizing damage to non-target plants. Another objective was to document impacts of privet invasion on Congaree's plant communities. Seven vegetation plots were installed in each of five large privet populations, and one plot outside of each population in a similar un-invaded area. Herbicide treatments were applied in January of 2012, and consisted of the herbicides glyphosate, metsulfuron, and a combination applied with both backpack sprayers and mistblowers. Measurement plots were set up using the protocols of the Carolina Vegetation Survey.

Chinese privet invasion significantly affected native plant communities at Congaree National Park. Density of canopy tree stems from 1-5cm dbh was lower in invaded than un-invaded plots, suggesting that privet may inhibit canopy regeneration. Invaded areas had a lower density of native shrubs and understory trees and lower cover of sedges. A significant negative correlation was found between privet abundance and species richness, herbaceous cover, and density of canopy tree stems. However, cover of *Microstegium vimineum* was higher in un-invaded plots, suggesting that Chinese privet may also inhibit the establishment of other invasive species.

The efficacy of Chinese privet control did not differ among herbicide types, but it did differ between the two applicators. Mistblowers achieved more effective control of privet, in part due to their greater height of spray. All treatments appeared to be highly effective below the maximum height of spray. The height of some privet stems exceeded the reach of both applicator types.

Tests for non-target impacts showed that for most variables, no treatments differed from control plots. The greatest non-target impacts detected were to sedges and winter-green species from treatments containing glyphosate. The backpack-metsulfuron treatment showed a significant decrease in tree and shrub cover (<50cm height), and the mistblower-glyphosate treatment showed a small decrease in fern cover as compared to the control. Mistblowers showed fewer impacts overall. No treatments significantly impacted species richness.

No single combination of herbicide and applicator met all objectives. However, mistblowers showed a number of advantages for both privet control and non-target impacts. Glyphosate, despite greater impacts to some graminoid species, may be preferred for its soil-binding properties. Height of privet must be considered in planning treatments. Benefits from the removal of privet are expected to outweigh the negative impacts of herbicide application.

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CHAPTER ONE

PROJECT OVERVIEW

Chinese privet (*Ligustrum sinense* Lour.) is a non-native invasive shrub that has become ubiquitous throughout the southeastern United States. Its bird and water-dispersed fruit, rapid growth, and generalist habitat requirements allow it to spread rapidly and form dense thickets (Miller et al. 2010). Chinese privet has been shown to negatively impact native plants in the understory and may inhibit forest canopy regeneration (Greene and Blossey 2012). There is a large and substantial infestation of Chinese privet in Congaree National Park, South Carolina. A central part of the National Park Service (NPS) mission is to protect the native plant and animal communities found within the parks, and it has made the control of invasive plants a management priority (Andrascik et al. 1996).

In controlling extensive populations of invasive plants, there are a number of concerns that must be balanced. Treatments must be efficient and effective in order to keep costs reasonable. However, more efficient broadcast methods run the risk of causing high collateral damage to non-target plants. The NPS is interested in using foliar herbicide sprays to control privet at Congaree, but is concerned about potential impacts to native plants from a large-scale spray operation. One advantageous factor in managing Chinese privet is that it can be effectively controlled with herbicide during the winter when most plants are dormant. However, native evergreen and winter annual plants may still be affected. Some level of non-target damage must be accepted as part of any management action, but it may be possible to reduce impacts by carefully evaluating treatment options. Different applicator types and herbicide formulations have different advantages and disadvantages, and the objective of this study was to evaluate various combinations of herbicide and applicator to determine which one provides the best overall results. The ideal treatment method would reduce Chinese privet abundance to the point where it is no longer a dominant species, while keeping impacts to native plant populations below the level where active restoration would be required.

Backpack sprayers are standard equipment for herbicide application in forested areas. However, mistblowers have also proven to be effective for privet control (Nespeca and Kemp 2006). Mistblowers are backpack-mounted units that spray a fine mist of herbicide. Backpack sprayers have the advantage of being lighter and smaller, but it is harder to maintain constant pressure and their larger droplets are more likely to fall through privet foliage and contact ground-layer plants (Devine et al. 1993). Mistblowers are heavy and require the transport of fuel, and are more likely to cause spray drift. However, they maintain high pressure and allow for the use of lower volumes of herbicides in some situations (Nespeca and Kemp 2006). Their small droplets are more likely to be intercepted by privet foliage (Devine et al. 1993).

Several herbicides have proven effective for privet control. Glyphosate, or N-(phosphonomethyl) glycine, has been the top-rated herbicide in several privet control studies (Harrington and Miller 2005, Miller 2005). It acts by disruption of the shikimic acid pathway used in the production of the amino acids tryptophan, tyrosine, and phenylalanine (Franz et al. 1997). Glyphosate is a widely-used herbicide in forestry and agriculture (Williams et al. 2012). It binds tightly and rapidly to soil particles, which minimizes the chance of leaching or residual impacts to plants (Vereecken 2005). There are glyphosate formulations approved for use near surface waters, which allows for application near riverbanks and reduces concern about rainfall events shortly after treatment. However, it is highly non-selective and will kill or damage most plant types (Franz et al. 1997). Metsulfuron, or Methyl 2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoate, has also been successful in privet-control trials (Miller 2005, Nespeca and Kemp 2006). It acts by inhibiting the acetolactate synthase enzyme, which is involved in production of the amino acids isoleucine, leucine, and valine (Ferenc 2001). A number of species, including many grasses, have some resistance to metsulfuron. However, it does not bind as tightly to the soil, and cannot be used near surface waters (Getsinger et al. 2011). It has some potential to cause residual impacts to non-target species, including canopy trees (Evans et al. 2008).

Different combinations of the abovementioned applicators and herbicides were applied to vegetation plots within privet populations at Congaree. As a supplement to the study of herbicide treatments, plots were set up in areas not yet invaded by privet to allow for investigation of the impacts of privet on native plant communities. The impacts of privet invasion are discussed in Chapter 2. Chapter 3 focuses on the effectiveness of herbicide treatments for privet control, while Chapter 4 focuses on the impacts of herbicide treatments on native plant communities. Chapter 5 is a review of conclusions and management recommendations, drawing on the results from Chapters 2-4. The overall goal of this study is to provide information to assist the National Park Service in the complicated process of invasive plant management at Congaree National Park.

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CHAPTER TWO

IMPACTS OF CHINESE PRIVET INVASION ON PLANT COMMUNITIES AT CONGAREE NATIONAL PARK

Introduction

Chinese privet (*Ligustrum sinense* Lour.) is a non-native, evergreen shrub that has become widespread throughout the southeastern United States. Its range stretches from east Texas to the Atlantic coast, with populations as far north as Massachusetts, and it is present in every county in South Carolina (University of Georgia 2013). Chinese privet is a shrub or small tree up to 9m in height and is a member of the olive family, or Oleaceae (Miller et al. 2010). This species is primarily evergreen in the southeastern US, although cold temperatures can cause it to shed its leaves (Faulkner et al. 1989). *L. sinense* has small (2-4 cm long and 1-3cm wide) ovate to elliptic leaves with a rounded tip, and leaf arrangement is opposite or occasionally whorled (Miller et al. 2010). From April to June it produces abundant panicles of white flowers that are insect pollinated (Grove and Clarkson 2005). They may occasionally have a second period of flowering in the fall (Maddox et al. 2010). Privet can produce fruit from July to March, though most fruit ripens in September and October and persists through the winter (Miller 2005). The fruit is a round to oblong drupe, purple to black when ripe, 5-8mm long, and containing 1 (but up to 4) seeds.

Privet exemplifies many of the traits associated with invasiveness in woody plants (Richardson and Rejmanek 2011), including rapid growth (Grove and Clarkson 2005), prolific fruit production (Burrows 1983), bird-dispersed fruit (Miller et al. 2010), ability to reproduce vegetatively (Johnson et al. 2010), and tolerance of a wide range of environmental conditions (Grove and Clarkson 2005, Brown and Pezeshki 2000). Privet is of special concern because it is shade tolerant, surviving in as little as 10-15% of full sunlight (Brown and Pezeshki 2000), which allows it to persist in relatively undisturbed forests with closed canopies.

Once it becomes established, privet appears to have negative impacts on its associated plant communities, and these impacts are generally attributed to the low-light environment under a dense privet canopy (Greene and Blossey 2012). Multiple studies have found decreased abundance and richness of herbaceous and woody plant species in privet-invaded areas (Wilcox and Beck 2007, Loewenstein and Loewenstein 2005, Merriam and Feil 2002). Several transplant studies have shown decreased growth and survival under a privet canopy. Greene and Blossey (2012) found that seedlings of *Acer negundo*, *Boehmeria cylindrica*, *Carex tribuloides*, and *Chasmanthium latifolium* showed reduced growth under a privet canopy, and all but *B. cylindrica* showed reduced survival. Osland et al. (2009) found that clonal expansion and growth in height and diameter of rivercane (*Arundinaria gigantea*) were significantly higher in sites where privet had been removed, although survival did not differ from untreated plots. Privet may also impact plant communities indirectly. It has been shown to alter nutrient cycling through the rapid decomposition of its leaf litter (Mitchell et al. 2011), and it has the potential to alter fire regimes (Faulkner et al. 1989).

One of the greatest concerns over privet invasion is that it will inhibit the regeneration of forest canopies. Invasive, shade-tolerant shrubs like *L. sinense* often display a high degree of phenotypic plasticity and can adapt to a variety of environmental conditions. Morris et al. (2002) compared growth and reproduction between privet and a co-occurring native shrub (*Forestiera ligustrina*). They found that privet had an advantage in both high and low-light environments due to its ability to initiate height growth and to allocate biomass to leaf production. Similarly, the invasive shrub *Lonicera maackii* was demonstrated to outperform the native shrub *Lindera benzoin* in a wide range of light conditions (Luken et al. 1997). Many tree species, especially those with low to intermediate shade tolerance, depend on the opening of canopy gaps to regenerate. Privet has been found to allocate more of its resources to producing aboveground rather than belowground biomass (Pokswinski 2008), which may allow it to initiate rapid canopy spread and thereby dominate forest canopy gaps and inhibit growth of tree seedlings.

The objectives of this study were to investigate whether privet sites at Congaree National Park support the assertion that privet decreases native plant abundance and diversity, whether impacts to tree regeneration are apparent, and whether particular plant species or species groups are most vulnerable to the impacts of privet invasion.

Materials and Methods

Study Area

Congaree National Park (33°47’59”N, 80°47’18”W) is located in the upper coastal plain of South Carolina, about 20 miles southeast of Columbia. Mean monthly temperatures range from 7.7°C in winter to 26.9°C in summer, with significant year to year variation (Doyle 2009). The mean monthly precipitation ranges from 6.0cm in winter to 13.8cm in summer. The park is situated in the floodplain of the Congaree River, and it experiences flooding an average of 10 times per year (Doyle 2009) with an average of 1 flood per year that covers the majority of the park (Patterson et al. 1985). Study sites were located between 40 and 215m of the river, primarily within the natural levee zone of the floodplain, which becomes inundated only during the highest flooding events and usually for only a few days (Doyle 2009).

The forest is characterized by bottomland hardwood vegetation, and common tree species were *Acer negundo, Celtis laevigata, Ulmus* spp., *Liquidambar styraciflua,* and *Asimina triloba*. Common understory species included *Boehmeria cylindrica*, *Carex* spp., *Microstegium vimineum*, and lianas such as *Vitis* spp., *Bignonia capreolata*, and *Toxicodendron radicans*. The Congaree floodplain is a highly productive system, with trees showing high growth rates and reaching very large size (Doyle 2009). Study sites were characterized by floodplain soils; primarily Congaree loam, with a small amount of Toccoa loam (Soil Survey Staff 2013). Much of the area has a history of agriculture and logging, with some salvage logging occurring as recently as 1990 after Hurricane Hugo (M. Kinzer, pers. comm.). Privet distribution was variable within study sites. Some areas had dense privet thickets with a closed canopy and little understory vegetation, while others had with more widely-spaced privet shrubs, allowing for abundant growth of herbaceous species.

Experimental Design

This study was designed as a randomized complete block experiment, with blocks made up of five large privet populations designated as Sites 1-5. Within each site, seven vegetation plots were installed within privet populations (“invaded” plots) and one plot outside of privet populations (“un-invaded” plots) in an area of similar habitat type. Un-invaded plots were supplemental to an experiment comparing herbicide treatments for privet control (see Chapters 3 and 4). A single plot was installed in an area of extremely dense privet to provide a glimpse of the impacts of heavy invasion.

Plot design and data collection were based on the protocols of the Carolina Vegetation Survey (Peet et al. 1998). Invaded plots were surveyed from May-July, 2011. The approximate outer boundary of the main privet population at each of the sites was mapped in a GIS, and this map was used to pre-select plot locations. Un-invaded plots were installed and surveyed in July of 2012, and locations were selected by walking parallel to the river away from privet sites until an un-invaded area of similar habitat type was reached.

Plots were 20 x 20m, and were further divided into four 10 x 10m modules. Corners were permanently marked with steel conduit stakes. All data was recorded on a per-module basis and divided into an herbaceous stratum (0-50cm in height) and a shrub stratum (50cm – maximum height of privet). A visual estimate of canopy cover was made for each species in the herbaceous stratum using the following cover classes: trace, 0-1%, 1-2%, 2-5%, 5-10%, 10-25%, 25-50%, 50-75%, 75-95%, and 95-100%. Cover estimates were also made for shrub-stratum privet and feral hog disturbance. Vines, regardless of total height, were documented by percentage cover of foliage in each stratum due to the difficulty of identifying stems and finding the rooting point; vines with no foliage visible were not included. Woody stems above 50cm in height and rooted in the plot were tallied into size classes by species. Any stem that branched from the main stem below 50cm was considered an individual. Stems below breast height (137cm) were tallied in height classes (50-100cm and 100-137cm) and stems above breast height were tallied into the following classes by dbh (cm): 0-1, 1-2.5, 2.5-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, and 35-40. For trees greater than 40cm in diameter, individual dbh measurements were recorded.

Data Analysis

For percentage cover, data from the four modules were averaged and cover values were based on the midpoint of each cover class. The "trace" class was assigned a value of 0.01%. For stem density variables, plot totals were used due to low stem numbers in some categories. Stem size classes were combined when stem numbers were too low for analysis. Species richness represents the average number of species per module. Diversity was calculated with Simpson's Index ($D=\Sigma p_i^2$ where p_i is the proportion of total cover made up by species i). Simpson's Index represents the probability that two randomly selected individuals will be of the same species, and the reciprocal ($1/D$) was used here so that the index increased with increasing diversity (Magurran 2004). Herbaceous-stratum species were grouped by growth form (annual herbs, perennial herbs, trees and shrubs, vines, ferns, sedges, and native grasses). The abundant non-native grass

Microstegium vimineum was analyzed individually. Canopy tree species were analyzed as a group to investigate impacts on regeneration. This group included the following species: *Acer negundo*[1], *Carya cordiformis*[2], *Celtis laevigata*[1], *Fraxinus pennsylvanica*[2], *Liquidambar styraciflua*[2], *Platanus occidentalis*[2], *Quercus laurifolia*[1], *Quercus pagoda*[2], and *Ulmus* spp[2]. Shade-tolerant species are marked with a [1] and intermediate to intolerant species are marked with a [2] (Burns and Honkala 1990).

Statistical analyses were performed using the JMP software package of the SAS Institute (SAS Institute Inc. 2012). ANOVA tests were used to compare un-invaded plots to pre-treatment data from invaded plots. Site was designated as a random effect and invasion status as a fixed effect. A correlation analysis was used to investigate relationships between privet abundance and the abundance and diversity of non-target plants. Results significant at 0.1 are reported.

Results

The number of canopy tree stems below 1cm dbh did not differ between invaded and un-invaded plots (Table 2.1). The 1-2.5 and 2.5-5cm classes had more stems in un-invaded plots, while the 5-10cm class did not differ by invasion status. Total stem count was higher in un-invaded plots. For the shade-tolerant group, size classes below 1cm dbh had very low stem numbers and there was no difference in stem number between invaded and un-invaded plots. The 1-2.5 and 2.5-5cm classes had more stems in un-invaded sites, and the 5-10cm class showed no difference (Table 2.2). For the intermediate to intolerant group, no stems were present in classes <1cm dbh (Table 2.3). Otherwise, intolerant species showed the same pattern as tolerant species, with more stems in un-invaded plots for the 1-2.5 and 2.5-5cm classes, and no difference in the 5-10cm class. Cover of canopy tree species in the herbaceous stratum did not differ between invaded and un-invaded plots (Table 2.4). For non-privet shrubs and understory trees, every size class had more stems in un-invaded plots except for the 5-10cm class, which did not differ (Table 2.5). Invaded plots had higher total woody stem density (including privet) in the 50-100cm, 100-137cm, 0-1cm and 2.5-5cm classes as compared to un-invaded plots (Table 2.6). The 1-2.5cm and 5-10cm classes did not differ. Basal area of trees >15cm dbh did not differ significantly between invaded and un-invaded plots (22m^2/ha vs. 19.75m^2/ha, p=0.6332).

Un-invaded plots had higher cover in the herbaceous stratum (Table 2.4). However, the difference disappeared when the species *Microstegium vimineum* was removed (invaded: 15.21%, un-invaded: 22.32%, p=0.2302), and this species had considerably greater cover in un-invaded plots (Table 2.4). Un-invaded plots also had higher cover of sedges and lower cover of shrub-stratum vines (Table 2.4). No significant difference was found for cover of canopy trees species (<50 cm), total trees and shrubs, perennial and annual herbs, vines (<50cm), ferns, or native grasses (Table 2.4). Diversity (6.20 vs. 3.18, p=0.2147) and species richness (21.08 vs. 23.63, p=0.2330) also did not differ between invaded and un-invaded plots.

Correlation analysis detected significant negative relationships between privet abundance (measured as both basal area and canopy cover) and total herbaceous cover and species richness (Table 2.7). A significant positive relationship was found between privet basal area and diversity, but not between privet cover and diversity (Table 2.7). Density of canopy stems from 1-5cm dbh had a significant negative correlation with privet basal area and cover (Table 2.7). Results from the heavily invaded plot are shown in Table 2.8.

Table 2.1. Number of canopy tree stems in invaded vs. un-invaded plots by size class. Differences significant at α=0.1 are marked with asterisks.

	Stems per 400m^2		
Size Class	Invaded	Un-invaded	P-value
50cm height – 1cm dbh	0.27	0.20	0.8846
1-2.5cm dbh	0.66	3.40	0.0052*
2.5-5cm dbh	1.31	4.80	0.0060*
5-10cm dbh	3.14	3.80	0.5931
Total	5.41	12.20	0.0218*

Table 2.2. Number of shade-tolerant canopy tree stems by size class in invaded vs. un-invaded sites. Differences significant at α=0.1 are marked with asterisks.

	Stems per plot (400m^2)		
Size Class	Invaded	Un-invaded	p-value
50cm height – 1cm dbh	0.27	0.20	0.8846
1-2.5cm dbh	0.54	2.60	0.0084*
2.5-5cm dbh	1.02	3.80	0.0088*
5-10cm dbh	2.72	3.40	0.5626
Total	4.58	10	0.0331*

Table 2.3. Number of intermediate to intolerant canopy tree stems by size class in invaded vs. un-invaded sites. Differences significant at α=0.1 are marked with asterisks.

	Stems per plot (400m^2)		
Size Class	Invaded	Un-invaded	p-value
50cm height – 1cm dbh	0	0	-
1-2.5cm dbh	0.11	0.80	0.0279*
2.5-5cm dbh	0.28	1.00	0.0450
5-10cm dbh	0.43	0.40	0.9264
Total	0.83	2.20	0.0685*

Table 2.4. Percentage cover by plant growth form in invaded vs. un-invaded plots. Differences significant at α=0.1 are marked with asterisks.

	Percentage Cover		
	Invaded	Un-invaded	P-value
Canopy trees	1.78	1.00	0.2565
Trees and shrubs	3.35	2.83	0.5783
Herbaceous cover	18.85	42.20	0.0154*
Perennial herbs	1.01	0.84	0.6044
Annual herbs	0.25	0.13	0.3559
Vines (<50cm)	3.20	1.94	0.3067
Vines (>50cm)	1.78	0.13	0.0631*
Ferns	0.19	0.23	0.7759
Native grasses	0.61	0.73	0.6873
Sedges	6.58	15.60	0.0267*
Microstegium vimineum	3.41	22.20	0.0004*

Table 2.5. Number of non-privet shrub and understory tree stems in invaded vs. un-invaded plots by size class. Differences significant at $\alpha=0.1$ are marked with asterisks.

	Stems per plot (400m^2)		
Size Class	Invaded	Un-invaded	P-value
50-100cm height	17.73	38.80	0.0153*
100-137cm height	6.50	14.80	0.0147*
0-1cm dbh	8.72	20.20	0.0007*
1-2.5cm dbh	9.85	31.40	<0.0001*
2.5-5cm dbh	11.80	23.40	0.0007*
5-10cm dbh	7.39	7.00	0.8569
Total stems	62.04	135.60	0.0005*

Table 2.6. Number of woody stems (including privet) per 400m^2 plot in invaded vs. un-invaded plots. Differences significant at α=0.1 are marked with asterisks.

	Stems per plot (400m^2)		
Size class	Invaded	Un-invaded	P-value
50-100cm height	122.73	45.20	0.0125*
100-137cm height	59.00	15.00	0.0378*
0-1cm dbh	85.86	20.80	0.0001*
1-2.5cm dbh	37.44	35.00	0.6680
2.5-5cm dbh	48.79	28.40	0.0063*
5-10cm dbh	26.13	10.80	0.0004*
Total	380.04	155.20	0.0005*

Table 2.7. Correlation analysis of privet abundance with herbaceous-stratum abundance and diversity measures and canopy tree density. Relationships significant at α=0.1 are marked with asterisks.

	Privet basal area		Privet canopy cover	
	Correlation coefficient	P-value	Correlation coefficient	P-value
Herbaceous cover	-0.4062	0.0093*	-0.3435	0.0300*
Species richness	-0.4030	0.0099*	-0.4766	0.0019*
Diversity (1/D)	0.2864	0.0731*	0.1422	0.3813
Canopy tree density (1-5cm dbh)	-0.3410	0.0313*	-0.4091	0.0088*

Table 2.8. Descriptive statistics from a plot heavily invaded by privet as compared to the average from un-invaded plots. Differences were not analyzed for statistical significance.

	Heavily invaded	Un-invaded
Herbaceous cover	2.61% cover	44.52% cover
Species richness	16.5 species/100m^2	24.6 species/100m^2
Diversity (1/*D*)	6.79	2.56
Privet basal area	4.75m^2/ha	-
Privet cover	92.5%	-

Discussion

Determining the direct impacts of invasive plant species is difficult because data about pre-invasion conditions are usually lacking. Comparing invaded to un-invaded sites is often the only tool available, but studies using this method have been criticized for their inability to account for possible site differences present prior to invasion (Levine et al. 2003). A number of co-varying factors could account for differences between plant communities. Invasive plants tend to be associated with disturbance, and it may be that the initial disturbance is actually the driving force behind reductions in native plants (MacDougall and Turkington 2005). In this study, data was collected in different years, which may also have influenced results. However, control plots showed relatively small differences in herbaceous cover and richness between years (see Chapter 4).

Congaree National Park has been subjected to a number of disturbance types, including historic logging and hurricanes. Canopy basal area did not differ between invaded and un-invaded plots, suggesting that they have experienced a similar history of these types of dramatic disturbances. Soil disturbance caused by feral hogs is a major source of disruption to herbaceous-stratum plant communities (Friebel and Jodice 2009). If hogs preferentially forage in the cover provided by privet thickets, they may be causing greater impact than the privet itself. However, hogs are generalists and forage in most habitat types in the park (Friebel and Jodice 2009). Flooding is also a major source of disturbance at Congaree (Doyle 2009), and small differences in topography and elevation can change the hydroperiod and affect soils and plant communities. Effects of disturbance are complex, and climatic conditions shortly after a disturbance can have a dramatic influence on subsequent patterns of assembly and succession. In a study of post-logging succession in a tract of land that is now part of Congaree National Park, Kupfer et al. (2010) found that an unusually dry period followed shortly by an unusually wet year favored the establishment of disturbance-adapted shrubs and vines.

However, there is significant evidence supporting the hypothesis that privet directly impacts native plant communities. Observational studies covering large geographic areas and a variety of habitat types have found similar results (Greene and Blossey 2012, Loewenstein and Loewenstein 2005, Merriam 2003). Privet removal experiments have shown increases in cover (Hanula 2009) and growth (Osland et al. 2009) of understory plants, and increases in density of woody stems (Merriam and Feil 2002). Some removal studies also show an increase in herbaceous diversity (Merriam and Feil 2002), although others do not (Vidra et al. 2007, Hanula 2009). While co-varying factors must be considered, the weight of evidence suggests that direct competition with privet is a factor in the reduction of native plant abundance in invaded sites.

One of the most serious concerns about Chinese privet invasion is the possibility that it will inhibit regeneration of the forest canopy, and results suggest that this may be occurring at Congaree. For canopy tree species, cover in the herbaceous stratum and density of stems below 1cm dbh did not differ between invaded and un-invaded plots, suggesting that privet is not affecting germination and early establishment. However, there were fewer stems from 1-5cm dbh in invaded plots than in un-invaded plots, and stem number showed a significant negative relationship with privet basal area and cover.

This suggests that recruitment into larger size classes is limited in privet-invaded areas, and supports previous findings that privet can lower the growth and survival of tree seedlings (Greene and Blossey 2012). Number of stems from 5-10cm dbh did not differ in invaded and un-invaded sites for any variable analyzed. Stems of this size likely have a majority of their foliage above the privet canopy, and these stems may have been present before privet became sufficiently well-established to alter light levels. Both shade-tolerant and intermediate to intolerant stems were similarly affected by the presence of privet, and intolerant stems were uncommon in both invaded and un-invaded plots. Although shade-tolerant species have a better chance of surviving under a privet canopy than intolerant species, both tolerant and intolerant species appear to be more successful at advancing beyond the seedling stage in un-invaded plots.

Privet likely affects regeneration by altering the structure of the habitat. Plots invaded by privet showed an overall greater density of woody stems in the shrub stratum than un-invaded plots. This indicates that privet does not simply replace other species of shrubs or trees, but forms a dense shrub layer that likely would not exist in its absence. The exception was the 1-2.5cm dbh size class, where no difference was detected. Privet may be replacing native species of this size class, which in un-invaded plots was primarily made up of the common understory tree *Asimina triloba,* along with the shrubs *Ilex decidua* and *Lindera benzoin*. Non-privet shrub species had higher density in un-invaded sites across all size classes below 5cm dbh. Most of these species are limited to canopies of similar or lower height than privet and are likely in direct competition for light.

Total herbaceous cover was lower in invaded plots, but this may have been largely due to the greater cover of the invasive grass *Microstegium vimineum* in un-invaded plots (22.20% compared to 3.41%). This species is thought to also negatively impact native plant communities and tree regeneration (Oswalt et al. 2007). Most growth form categories did not differ between invaded and un-invaded plots, but sedges had higher cover in un-invaded plots, indicating that they may be particularly vulnerable to the effects of privet invasion. Shrub-stratum vines had higher cover in invaded plots, which may be related to the support structure provided by privet, which allows vines to expand into the space between trees.

Correlation analysis showed that as privet basal area and cover increased, there was a decrease in total herbaceous cover and species richness, although relationships were relatively weak. Interestingly, privet basal area was positively correlated with diversity. Plots with low privet density were typically heavily dominated by sedges or *Microstegium vimineum*, and dominance by a single species lowers the value of Simpson's Index. In sedge-dominated plots, Simpson's Index was underestimated because cover was usually made up of multiple sedge species. Species richness did not differ between invaded and un-invaded plots, and the only two species found exclusively in un-invaded plots were a single individual of *Botrichium biternatum* and a small clump of *Polystichum acrostichoides*. Considering the substantially lower richness on a site with extremely high privet density (Table 2.8), it may be that many of the invaded plots were below a threshold of privet density at which species richness is affected.

The plot installed in very dense privet offers a glimpse of the potential impacts of heavy privet invasion (Table 2.8). The most striking result was the total herbaceous cover value of only 2.61%. While the species richness value of 16.5 species per module was higher than expected, it was considerably lower than the 24.6 species per module in un-invaded plots. Each species was represented by very few individuals, which would be vulnerable to stochastic events and unlikely to contribute to canopy regeneration.

In conclusion, results from this study support the hypothesis that privet can create a subcanopy layer that decreases abundance of herbaceous-stratum plants. Most notably, canopy tree stem density was lower in invaded than un-invaded plots. Sedges may be particularly vulnerable to privet invasion, but overall herbaceous diversity was not affected. Impacts were smaller than expected, possibly because many of the invaded plots were located in areas of lighter privet density in order to allow for detection of non-target impacts from herbicide treatments (see Chapter 4). The plots established for this study could provide a future opportunity to study whether invaded sites become increasingly similar to un-invaded sites over time after privet is removed, providing further support to the hypothesis that privet is a driving force in reducing native plant abundance and diversity.

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CHAPTER THREE

DORMANT-SEASON FOLIAR HERBICIDE TREATMENTS FOR THE CONTROL OF CHINESE PRIVET

Introduction

Chinese privet (*Ligustrum sinense* Lour.) is a non-native shrub that has become a dominant species in riparian areas and forests of the southeastern Unites States. Originally introduced in the mid-1800's as an ornamental plant (Miller et al. 2010), it has since escaped from cultivation and is now considered a noxious weed. The USDA Plant Protection and Quarantine program rates this species as a "high risk" based on an assessment that includes likelihood of spread, availability of suitable habitat, and potential for economic and environmental damage (U.S. Department of Agriculture 2012). It has been demonstrated to reduce the diversity of herbaceous-layer plant communities (Greene and Blossey 2012) and insect communities (Hanula and Horn 2011a, Hanula and Horn 2011b), alter rates of litter decomposition and nutrient cycling (Mitchell et al. 2011), and compete with commercial timber species (Mixon et al. 2009). Control of Chinese privet is therefore a goal for many land managers in the southeast.

Privet can be controlled using a variety of methods. Although mechanical methods such as burning and mowing can remove aboveground biomass, privet populations can recover quickly through sprouting if herbicides are not used to kill the roots. Cut-stump methods, in which oil-based herbicide mixtures are applied to freshly-cut stumps, have proven to be highly effective with little overspray onto non-target plants (Osland et al. 2009, Ahuja 2003). However, any method that requires treatment of individual stems is labor intensive and may be unfeasible for very large or dense populations.

Foliar herbicide sprays are also highly effective and can achieve nearly 100% control (Miller 2005, Harrington and Miller 2005). While this method is less labor intensive, herbicide is more likely to contact non-target species. Non-target impacts can be reduced by applying herbicides in winter when most species are dormant and leafless, and winter application may actually be more effective for privet control than growing-season application. Privet is capable of year-round photosynthesis (Morris et al. 2002), and herbicide transport generally follows the transport of the carbohydrates, which are being directed towards the roots in winter (Franz et al. 1997). However, uptake and transport of herbicide may be slowed due to low temperatures (Frey et al. 2007).

Glyphosate has been consistently demonstrated as an effective foliar spray for privet control. Harrington and Miller (2005) found that glyphosate foliar treatments at rates ranging from 1.7 – 6.7 kg ae/ha provided up to 100% control in both fall (October and December) and spring (April) treatments. Ahuja (2003) also achieved 100% control with a December application of glyphosate. Summer application was significantly less effective, likely because drought limited the uptake and translocation of herbicide (Harrington and Miller 2005). Miller (2005) tested eight common herbicides, and found glyphosate to be the most effective for growing-season privet control, followed by imazapyr and metsulfuron. The glyphosate treatment remained effective for at least three years, while the other treatments showed some privet regrowth. Metsulfuron is also highly effective for privet control (Miller 2005, Nespeca and Kemp 2006, Evans et al.

2008), although it has been less extensively tested as a dormant-season treatment. Both of these herbicides have low volatility and are considered relatively non-toxic to wildlife and humans (Williams et al. 2012, Ferenc 2001).

Foliar herbicides can be applied using a variety of equipment types. Backpack sprayers are commonly used in forest settings, but backpack-mounted mistblowers may be able to provide similar control using a lower volume of herbicide (Nespeca and Kemp 2006). Mistblowers produce small droplets that are better able to penetrate a dense canopy and be intercepted by leaves (Devine et al. 1993). The Nature Conservancy installed demonstration plots in South Carolina to test glyphosate, metsulfuron, a combination of glyphosate and metsulfuron, and krenite using both mistblowers and backpack sprayers (Nespeca and Kemp 2006). They found that mistblowers achieved higher levels of control using about 1/5 the volume of herbicide and half the amount of time for application. The glyphosate, metsulfuron, and combination treatments were all highly successful (>80% control), while the krenite had low (or possibly delayed) success.

The National Park Service is interested in using dormant-season foliar herbicide treatments to control a large privet infestation at Congaree National Park. The objective of this study was to determine which combination of applicator and herbicides provides the most effective privet control while minimizing damage to native plant communities. This chapter focuses on the findings related to privet control.

Materials and Methods

Study Area

Congaree National Park (33°47’59”N, 80°47’18”W) is located in the upper coastal plain of South Carolina, about 20 miles southeast of Columbia. Mean monthly temperatures range from 7.7°C in winter to 26.9°C in summer, with significant year to year variation (Doyle 2009). The mean monthly precipitation ranges from 6.0cm in winter to 13.8cm in summer. The park is situated in the floodplain of the Congaree River, and it experiences flooding an average of 10 times per year (Doyle 2009) with an average of 1 flood per year that covers the majority of the park (Patterson et al. 1985). Study sites are located between 40 and 215m of the river, primarily within the natural levee zone of the floodplain, which becomes inundated only during the highest flooding events and usually for only a few days (Doyle 2009).

The forest is characterized by bottomland hardwood vegetation, and common tree species were *Acer negundo*, *Celtis laevigata*, *Ulmus* spp., *Liquidambar styraciflua*, and *Asimina triloba*. The Congaree floodplain is a highly productive system, with trees showing high growth rates and reaching very large size (Doyle 2009). Study sites were characterized by floodplain soils; primarily Congaree loam, with a small amount of Toccoa loam (Soil Survey Staff 2013). Much of the area has a history of agriculture and logging, with some salvage logging occurring as recently as 1990 after Hurricane Hugo (M. Kinzer, pers. comm.). Privet distribution was variable within study sites. Some areas had dense privet thickets with a closed canopy and little understory vegetation, while others had with more widely-spaced privet shrubs, allowing for abundant growth of herbaceous species.

Experimental Design

This study used a randomized complete block design. Blocks consisted of five large privet populations (designated as Sites 1-5) located in similar habitat types. Within each site, seven plots were installed to correspond with six herbicide treatments plus an untreated control (Table 3.1).

Plot design and data collection were based on the protocols of the Carolina Vegetation Survey (Peet et al. 1998). Plot locations were preselected on a GIS map, but were sometimes relocated in the field to avoid areas with extensive soil disturbance or privet so dense that few other plant species were present. Plot corners were permanently marked with steel conduit stakes. Plots were 20 x 20m, and were further divided into four 10 x 10m modules. Data was recorded on a per-module basis.

Woody stems above 50cm in height and rooted in the plot were tallied into size classes by species. Any stem that branched from the main stem below 50cm was considered an individual. Stems below breast height (137cm) were tallied in height classes (50-100cm and 100-137cm) and stems above breast height were tallied into the following classes by dbh (cm): 0-1, 1-2.5, 2.5-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, and 35-40. For trees greater than 40cm in diameter, individual dbh measurements were recorded. For plants in the herbaceous stratum (0-50cm height), an estimate of canopy cover was made for each species. An estimate of canopy cover was also made for shrub-stratum privet (>50cm height). Pre-treatment data was collected from May to July, 2011.

Table 3.1. Herbicide treatments applied to plots. Each treatment type was applied once in each of five study sites for a total of 35 treatments.

Applicator	Herbicide	Rate
Mistblower	Glyphosate	6.5oz/gal (49.53g/L)
	Metsulfuron	0.0625oz/gal (0.47g/L)
	Combination	6.5oz glyph. + 0.0625oz met./gal
Backpack sprayer	Glyphosate	6.5oz/gal (49.53g/L)
	Metsulfuron	0.0625oz/gal (0.47g/L)
	Combination	6.5oz glyph. + 0.0625oz met./gal
Control		NA

Treatments

Herbicide treatments were applied on January 11, 2012 by an experienced contract crew. Mistblowers were Stihl brand SR model 450, which is a backpack-mounted unit with a 3.7 gallon capacity. Their specified range is 14.5 horizontal meters and 13.0 vertical meters, with a droplet size generally ranging from 60-130μm (Jessop and Bateman 2007). Backpack sprayers used were SP Systems brand Yard Tender model 101 with a 5.3 gallon capacity, which is pressurized by a hand-pump. Spray range and droplet size vary according to pressure.

Glyphosate was mixed in a 5% solution containing 6.5oz/gal (49.53g/L) of Rodeo® liquid concentrate (53.8% a.i.). The metsulfuron solution contained 0.0625oz/gal (0.47g/L) of AmTide MSM 60DF® powder concentrate (60% a.i.). The combination treatment contained 6.5oz glyphosate and 0.0625oz metsulfuron per gallon. The water conditioner Choice (Loveland Industries, Inc., ¼% by volume), and the surfactant Rebound (Red River Specialties, Inc., ½% by volume) were added to all spray mixes. The volume of spray applied to each plot varied depending on the density of privet. Spray volumes ranged from 1.5 – 2.5 gallons (5.68-9.46L) per 400m^2 plot, or approximately 15 – 25 gal/acre (142-236 L/ha). Privet was sprayed to wetness, and privet-free gaps within plots were not sprayed.

Post-treatment data collection

Plots were re-surveyed from May-July of 2012, 4-6 months after treatment, using the same protocols. Foliated stems were considered alive, and stems with less than 1% of full foliage were considered dead. However, a cut was made in the bark of defoliated stems to see whether green, live cambium was still present. Green stems were recorded separately using the same size classes. After noting that taller privet stems were sometimes missed by sprayers, we began collecting height data, including height of tallest privet stem and maximum spray height. A single measurement was taken for each height using a 7.6m steel tape measure, and the tallest stems sometimes exceeded this height.

Data Analysis

Statistical analyses were performed using the JMP software package of the SAS Institute (SAS Institute Inc. 2012). Two-way ANOVA tests were used to analyze treatment effectiveness based on a factorial model with site, applicator, herbicide, and herbicide x applicator interaction as model effects. Control plots were not included; it is well established that herbicide causes high privet mortality (Harrington and Miller 2005, Miller 2005), and comparisons between treatment plots and control plots would not be informative. Data from control plots were analyzed by comparing pre and post-treatment data using t-tests. All results significant at 0.1 are reported.

Treatment effectiveness was quantified as percentage control to account for differences in pre-treatment privet densities. ANOVA tests were run for percentage control of privet basal area, canopy cover, and stem density of small (50-137cm height), medium (0-5cm dbh), and large stems (5-15cm dbh). Basal areas were calculated using the midpoint diameter of each size class, and stems below breast height were excluded.

Because privet cover was low in the herbaceous stratum (average of 0.85%), control was calculated as direct change in cover rather than percentage control to avoid giving undue weight to small changes. Green privet stems were analyzed as percentage of pre-treatment basal area that remained green after treatment. The observations from each of the 100m^2 modules were averaged to calculate plot values. A total of nine modules and one whole plot were rejected from all analyses due to treatment irregularities.

Results

Herbicide and herbicide x applicator interaction were not significant for any tests unless otherwise stated. Percentage control of privet basal area showed a significant effect of applicator type, with mistblowers achieving greater control than backpack sprayers (Table 3.2, Figure 3.1). Density of small stems (50-137cm height) showed only a significant applicator x herbicide interaction in which the mistblower-combination treatment was significantly more effective than the mistblower-metsulfuron or the backpack sprayer-combination treatments (Table 3.2). For medium (0-5cm dbh) and large (5-15cm dbh) stems, there was a significant effect of applicator, with mistblowers outperforming backpack sprayers (Table 3.2, Figure 3.2). Percentage control of privet canopy cover showed a significant applicator effect, with mistblowers outperforming backpack sprayers (Table 3.2). Herbaceous-stratum privet showed no significant effects of applicator, herbicide, or applicator x herbicide interaction for change in cover (Figure 3.3). Green stems showed a significant applicator effect, with a lower percentage of green stems in mistblower plots than in backpack sprayer plots (Table 3.2).

Mistblowers achieved greater height of spray than backpack sprayers (6.1m vs. 5.4m, p=0.072, Figure 3.4). If it was assumed that spray height was a mechanical rather than a chemical effect and herbicide and interaction were omitted from the model, applicator was significant with a p-value of 0.047. For height missed (height of tallest privet stem – maximum spray height), applicator was also significant (p=0.0641) with mistblowers showing 0.7m of missed canopy height and backpacks showing 1.4m of missed height. There was no significant difference in maximum privet height (sprayed or unsprayed) between backpack and mistblower plots (6.63m vs. 6.83m, p=0.4619, Figure 3.4). Control plots showed no change or a slight increase in privet density, indicating that the decrease found in treatment plots was directly related to herbicide application.

Table 3.2. Factorial analysis of various measures of percentage control of privet. Differences significant at α=0.1 are marked with asterisks.

	P-value			% control	
	Applicator	Herbicide	Interaction	Backpack	Mistblower
Basal area	0.0108*	0.1640	0.5443	65.71	89.18
Stems per 100m^2					
50-137cm ht	0.1551	0.8198	0.0254*	90.84	94.54
0-5cm dbh	0.0213*	0.4009	0.7394	84.62	92.51
5-15cm dbh	0.0105*	0.1542	0.4975	63.38	89.08
Canopy cover	0.0321*	0.6329	0.5105	90.32	98.00
Green stems	0.0425*	0.2092	0.3381	48.87[1]	32.07[1]

[1] Values represent percentage of pre-treatment basal area that was defoliated but still had live stem tissue following herbicide application. A higher value may indicate a greater chance of privet recovery.

Figure 3.1. Percentage control of privet expressed as basal area by treatment (+1 SE). Mistblowers showed greater control than backpack sprayers.

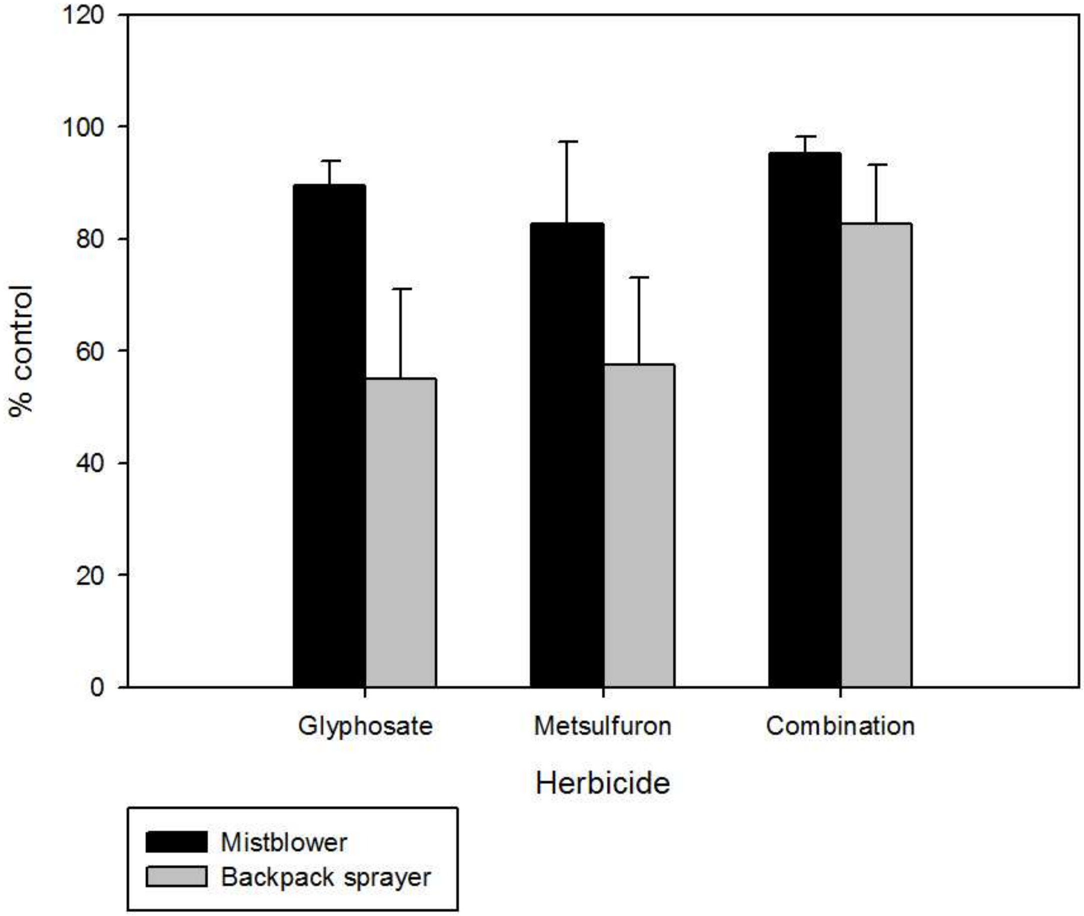


Figure 3.2. Percentage control of privet expressed as density by size class and applicator type (+1 SE). Mistblowers showed significantly greater control of medium and large stems than backpack sprayers.

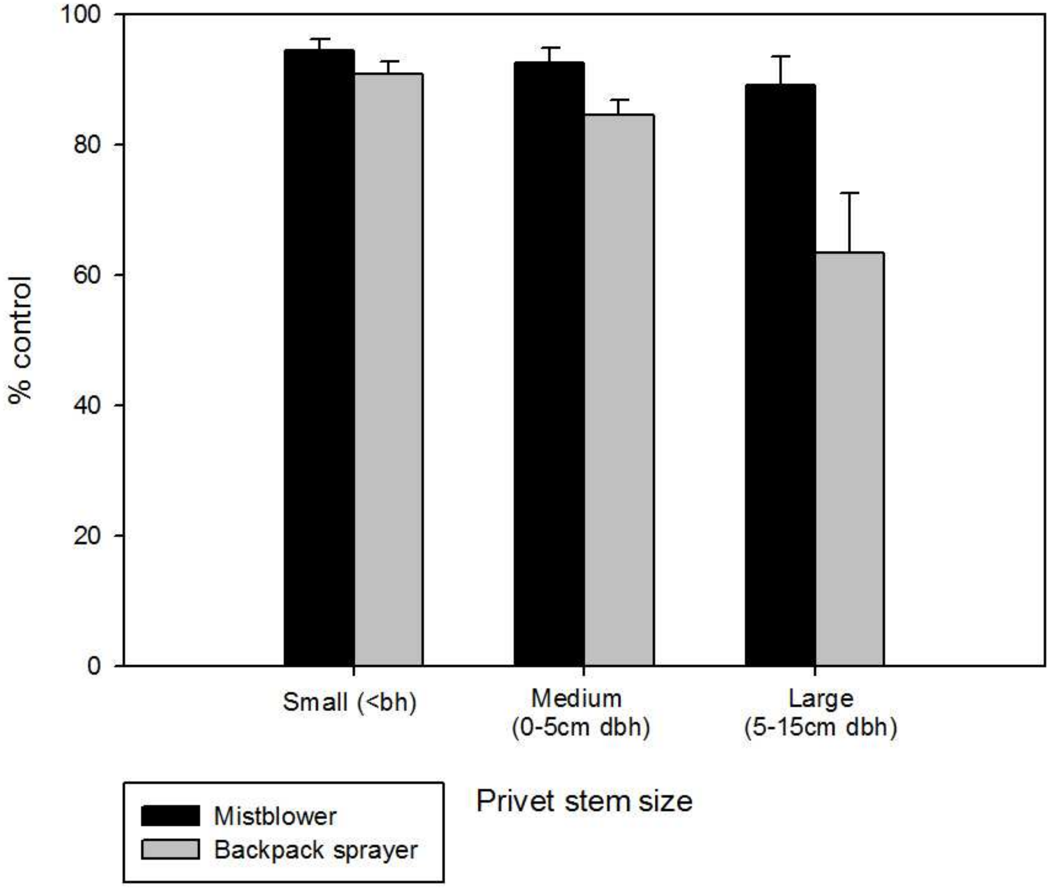


Figure 3.3. Change in percentage cover of herbaceous-stratum privet (<50cm in height) following herbicide treatment (+1 SE). There were no significant effects of applicator, herbicide, or applicator x herbicide interaction.

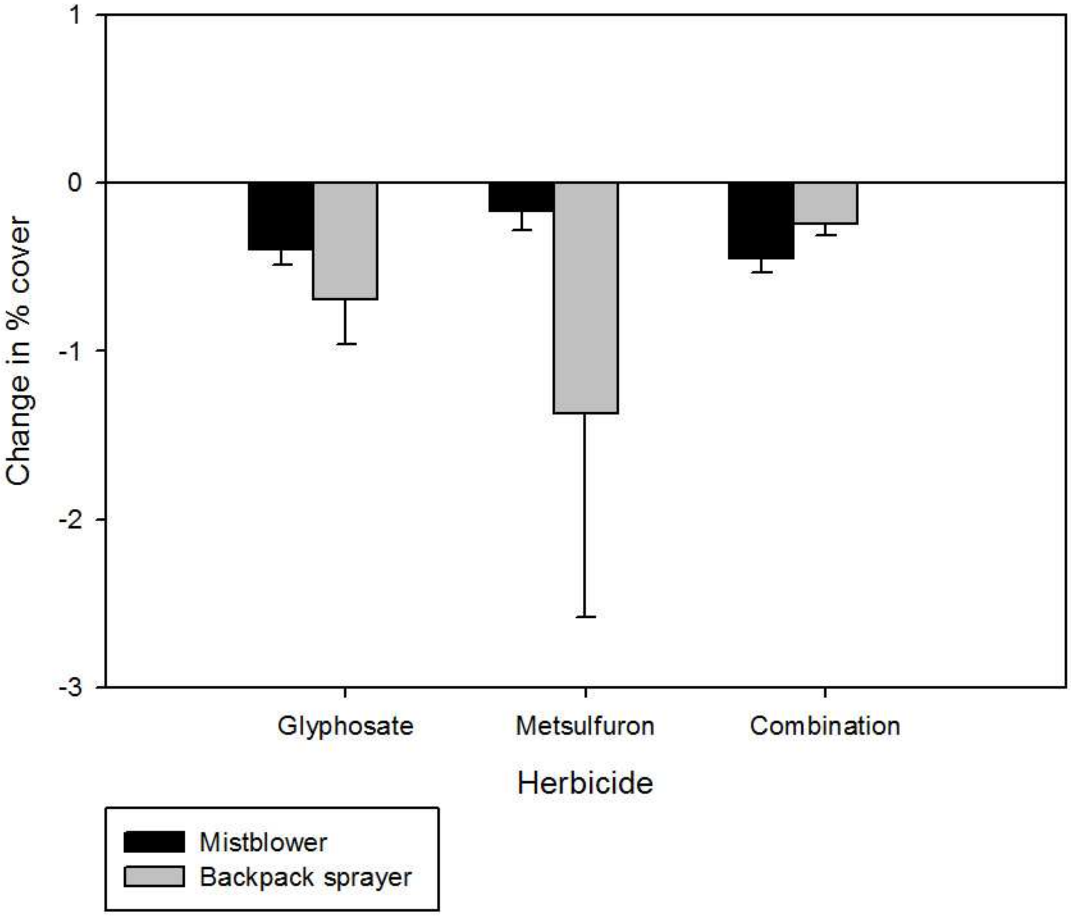
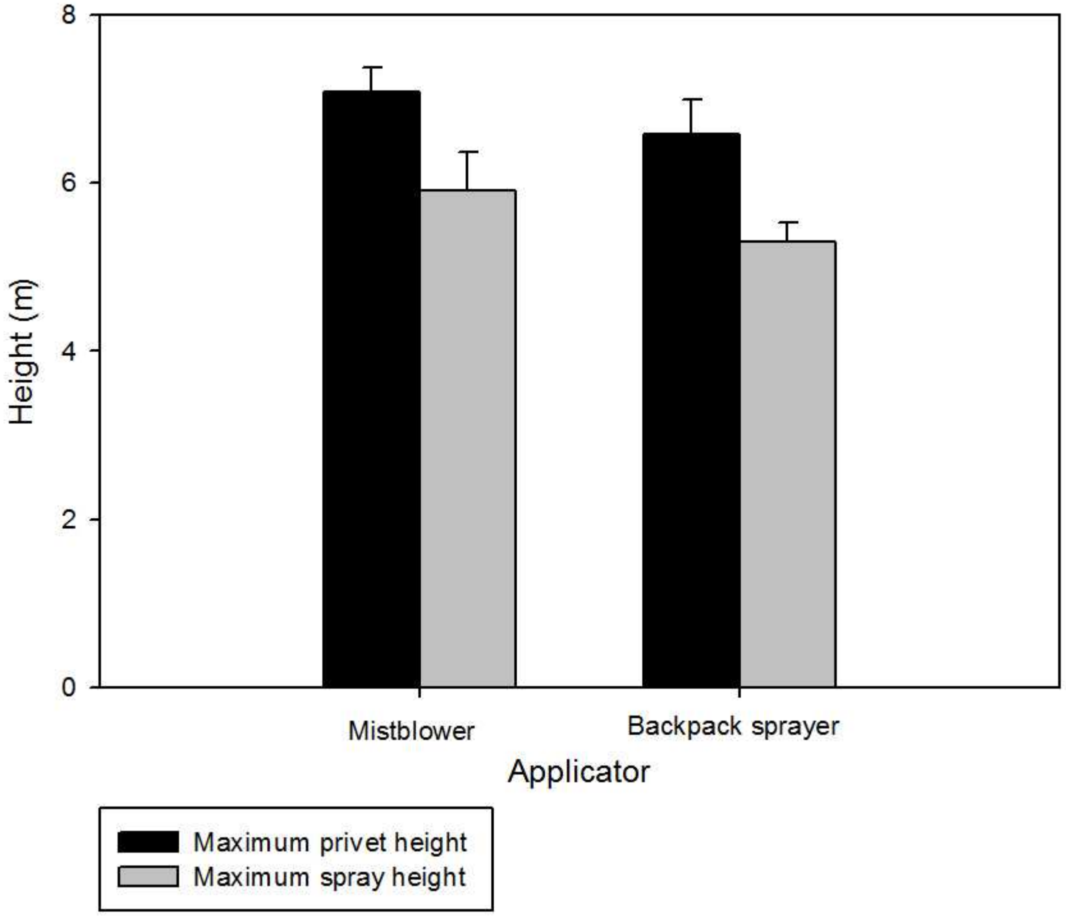


Figure 3.4. Maximum height of privet (up to 7.6m) and maximum spray height by applicator type. Mistblowers sprayed significantly higher than backpack sprayers, but maximum privet height did not differ.



Discussion

Mistblowers provided more complete control of Chinese privet than did backpack sprayers. They achieved higher percentage control of shrub-stratum privet measured as density, basal area, and cover. Mistblower plots also had a lower percentage of stems remaining green after treatment, indicating that herbicides acted more quickly and thoroughly. Green stems were recorded as an indication of plants likely to re-sprout (S. Enloe, pers. comm.), although some of these stems may show delayed mortality. Nespeca and Kemp (2006) found that mistblowers could treat the same area using a lower volume of herbicide as compared to backpack sprayers. However, the height of the privet at Congaree precluded the possibility of reducing the volume applied (S. Frock, pers. comm.). Treatments did not differ in control of herbaceous-stratum privet (<50cm), although all treatments showed a decrease in cover. Pre-treatment cover of herbaceous-stratum privet was low, and herbicide sprays were primarily directed at the larger privet.

Height of spray appears to be a major factor in the superior performance of mistblowers. Backpack sprayer data was heavily impacted by a few plots with very low control due to a layer of live canopy above the height of spray; one plot showed only 0.6% control. Both applicator types showed a wide range of spray heights (backpack: 4.5-6.5m, mistblower: 3.9-7.6m). They often failed reach all of the highest stems, and consistently sprayed below their demonstrated potential heights. It is possible that there were differences in performance between the sprayer units of each type or between operators. The backpack sprayers used were pressurized with a hand pump, so pressure could not be standardized and likely affected the height of spray. Dense vegetation made it difficult to maneuver within some plots, and the foliage on the tallest stems may not have been easily visible.

The height measurements taken provide an incomplete representation of spray patterns because they record only the difference between the single highest stem (up to 7.6m) and the highest point of defoliation. They do not account for the volume of canopy that was missed. Some privet shrubs were missed entirely, particularly in the corners of the plots, due to insufficient visibility of plot boundary markers. Although these missed stems have a large impact on basal area and density, both applicators achieved a high level of control when expressed as canopy cover (Table 3.2).

Logistical issues, such as weight and maneuverability of equipment, complications related to use of motorized equipment in a wilderness, and public opinion could influence decisions about applicator type. The difference in spray height between mistblowers and backpack sprayers could potentially be overcome by using higher pressures or extension wands with the backpack sprayers. However, any advantage gained by the more complete canopy penetration of mistblowers would be lost, and higher pressures would increase the volume of herbicide used.

Herbicide type was not found to be a significant factor in this study. Glyphosate and metsulfuron were both effective, as seen in previous studies (Harrington and Miller 2005, Miller 2005). Nespeca and Kemp (2006) found a slight increase in control using a combination of these herbicides over using them individually. This study found a numerical increase in control from combination treatments, but it was not significant. According to field observations, all treatments were highly effective at defoliating privet wherever they were thoroughly applied. Sections of the privet canopy were generally either completely defoliated or appeared completely healthy with no signs of herbicide damage. Damage from both glyphosate and metsulfuron can appear as yellow or brown spots on leaves, leaf or vein discoloration (Obrigawitch et al. 1998), or unusual branching patterns (WSSA 2007). The lack of visible damage or deformity suggests that remaining live stems were not contacted by herbicide spray, and that differences between treatments were primarily a reflection of the spray coverage.

In the absence of significant differences in effectiveness between herbicides, glyphosate is most likely the best choice of herbicide at Congaree because it adsorbs tightly soils, which causes it to deactivate and limits the chance of off-site transport (Vereeken 2005). Metsulfuron, on the other hand, is both foliar and soil-active. Although it has shown decreased impacts to sedges (see Chapter 4) and rivercane (Nespeca and Kemp 2006), it has a greater chance of causing impacts to canopy trees. While this may not be an issue when trees are dormant, warm winters could cause trees to break dormancy sooner than expected. The use of glyphosate minimizes these risks with no reduction in treatment effectiveness.

This study reflects only the short-term effects of treatments. There may be further mortality of treated stems, and the well-developed root systems of these large plants are likely to produce new sprouts. It is expected that follow-up treatments will be required for any herbicide operation (Miller et al. 2010). Very few privet seedlings were observed following treatments, but more seedling establishment may occur in years of greater flooding . It is unlikely that plots were flooded during the period of the study. Park-wide flooding occurs when the river level reaches 15ft at gauge 02169625 on the Congaree River (T. Hogan, pers. comm.), and it remained below 12ft between January and May of 2012 (U.S. Geological Survey 2013). Root sprouts may be a more important source of privet regeneration than seedlings, as indicated by privet's low fruit to rhizome ratio (Pokswinski et al. 2008).

Results from this study highlight the need to ensure proper treatment of the tallest privet stems. It may be necessary to apply cut-stump or basal spray treatments to the tallest plants before foliar sprays are applied. This would eliminate the possibility of wasting foliar spray on stems that would then need re-treatment. Basal treatments would significantly increase labor costs, and it may be worthwhile to monitor whether plants with only a few live stems in the upper canopy survive over time. Further monitoring of plots would also indicate whether green stems are a reliable indicator of ability to re-sprout, and would help determine the optimal treatment interval.

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CHAPTER FOUR

NON-TARGET IMPACTS OF HERBICIDE TREATMENTS FOR CHINESE PRIVET CONTROL

Introduction

Non-native invasive plants are increasing in abundance in National Parks throughout the United States, and the National Park Service (NPS) has made invasive plant control a management priority (Andrascik et al. 1996). Congaree National Park in South Carolina has a large infestation of the invasive shrub Chinese privet (*Ligustrum sinense* Lour.). The NPS is interested in using foliar herbicide sprays to control this species, but is concerned about potential impacts to native plants. Privet can reach 9m in height (Miller et al. 2010), and foliar spray application for such tall plants allows only a limited ability to avoid contacting non-target species. A primary motivation for control of invasive species is to prevent a loss of biodiversity caused by the displacement of native species, but there are documented cases where efforts to control non-native species have inadvertently caused long-term reductions in native plant populations (Rinella et al. 2009). Therefore, it is important to weigh the potential consequences and benefits of any management action.

Impacts to non-target plants can be decreased by spraying during the winter when most plant species are leafless and dormant. Privet is an evergreen shrub, and herbicide applications throughout the fall and winter have been demonstrated to be highly effective at controlling this species (Harrington and Miller 2005). However, any species with foliage at the time of treatment, including evergreen perennials and winter annuals, may be impacted. There is also evidence that some deciduous species may be affected by herbicides even in the winter (Willoughby 1996).

Studies of dormant-season treatments for control of privet and other invasive species have demonstrated low impacts to non-target plants. For example, The Nature Conservancy installed demonstration plots to test different dormant-season foliar treatments for control of Chinese privet (Nespeca and Kemp 2006), and they observed no visible damage to hardwood species and an influx of grasses and forbs following treatments. Rivercane (*Arundinaria gigantea*) appeared to be damaged by glyphosate but not by metsulfuron. However, native plant impacts were not quantified in their preliminary study. Several studies document the impacts of dormant-season herbicide treatments for control of garlic mustard (*Alliaria petiolata*) in the Midwest. Hochstedler et al. (2007) applied winter glyphosate treatments annually for five years, and found that species richness and diversity did not differ between sprayed and unsprayed plots. Spring perennials and graminoids (grasses and grass-like plants) had higher cover in sprayed plots in some years, attributed to a release from competitive effects of garlic mustard. Annual and winter-green species had lower cover in sprayed plots in some years, attributed to direct impacts of herbicide. Changes were relatively minor except for a large decrease of another non-native winter-green species, *Stellaria media*. Frey (2007) similarly found that plots given a winter glyphosate treatment had higher non-target plant density than untreated plots, although the difference was no longer significant two growing seasons after herbicide application. Nuzzo (1996) found that 1-2% glyphosate applications had no effect on herbaceous cover or woody cover, although some individual species, including *Geum canadense* and *Galium aparine*, were more sensitive to glyphosate and declined after treatment. However, a 0.5% glyphosate treatment led to a significant decline in sedge cover, and it is not clear why the lower rate would have an effect not seen in the higher rate. They also tested an herbicide with a long residence time in the soil (acifluorfen, 1.12 kg/ha), and it lowered species richness and greatly reduced cover of native forbs. Willoughby (1996) studied the effects of dormant-season glyphosate applications on conifer and hardwood tree seedlings in England. He found no significant effects on growth or survival for most species when using glyphosate at 1.5 L/ha. However, ash (*Fraxinus excelsior*) and willow (*Salix spp.*) showed a decrease in height increment and leaf deformation the following spring, and willows showed decreased survival. Johnson et al. (2010) found some damage to persimmon (*Diospyros virginiana*) following a winter aerial application of glyphosate.

Ideally, the sensitivity of each species to different types and application rates of herbicide would be studied and determined in order to design a control scheme that would minimize impacts to non-target species. However, species-specific studies of herbicide sensitivity are typically performed on agricultural weeds or other commercially important species (Obrigawitch et al. 1998). Studies of native species often use herbicide rates that simulate spray drift on sites adjacent to agricultural fields (Olszyk et al. 2004, Marrs et al. 1989). However, non-target plants in invasive species control operations are interspersed with the target species and are likely to receive the full dose of herbicide. Also, such edge sites contain a plant community that may differ considerably from that of interior, undisturbed habitats. In a review of herbicide impacts to non-target plants, Olszyk et al. (2004) refer to a notable lack of studies dealing with native plants, and report no studies of dormant season treatments.

Responses to herbicide can be highly individualistic and vary greatly among sites (Rinella et al. 2009), species (Franz et al. 1997), and even cultivars (Rimi et al. 2012). Herbicide activity is influenced by leaf and cuticle texture and thickness, leaf position and maturity, and physiological traits of the vascular system (Devine et al. 1993), all of which can vary dramatically among species. Available studies do not allow for reliable predictions of native plant response to foliar herbicide applications, necessitating a study of the specific plant communities present in the area to be treated.

This study was designed to evaluate which combination of herbicide type and application method would be the most effective for privet control while minimizing non-target impacts at Congaree National Park. The treatments involve the use of mistblowers and backpack sprayers to apply glyphosate and metsulfuron herbicides. It is expected that removal of Chinese privet will increase native plant cover and diversity in the long term due to the increase in light and belowground resources made available (Hanula 2009, Merriam and Feil 2002). However, the purpose of this study was to assess direct damage from herbicides that could limit the ability of native plant communities to recover or eliminate very sensitive species from treated areas.

Materials and Methods

Study Area

Congaree National Park (33°47’59”N, 80°47’18”W) is located in the upper coastal plain of South Carolina, about 20 miles southeast of Columbia. Mean monthly temperatures range from 7.7°C in winter to 26.9°C in summer, with significant year to year variation (Doyle 2009). The mean monthly precipitation ranges from 6.0cm in winter to 13.8cm in summer. The park is situated in the floodplain of the Congaree River, and it experiences flooding an average of 10 times per year (Doyle 2009) with an average of 1 flood per year that covers the majority of the park (Patterson et al. 1985). Study sites are located between 40 and 215m of the river, primarily within the natural levee zone of the floodplain, which becomes inundated only during the highest flooding events and usually for only a few days (Doyle 2009).

The forest is characterized by bottomland hardwood vegetation, and common tree species were *Acer negundo*, *Celtis laevigata*, *Ulmus* spp., *Liquidambar styraciflua*, and *Asimina triloba*. Common understory species included *Boehmeria cylindrica*, *Carex* spp., *Microstegium vimineum*, and lianas such as *Vitis* spp., *Bignonia capreolata*, and *Toxicodendron radicans*. The Congaree floodplain is a highly productive system, with trees showing high growth rates and reaching very large size (Doyle 2009). Study sites were characterized by floodplain soils; primarily Congaree loam, with a small amount of Toccoa loam (NRCS). Much of the area has a history of agriculture and logging, with some salvage logging occurring as recently as 1990 after Hurricane Hugo (M. Kinzer, pers. comm.). Privet distribution was variable within study sites. Some areas had dense privet thickets with a closed canopy and little understory vegetation, while others had with more widely-spaced privet shrubs, allowing for abundant growth of herbaceous species.

Experimental Design

This study was designed as a randomized complete block experiment, with blocks made up of five large privet populations (designated as Sites 1-5) located in similar habitat types. Within each site, seven vegetation plots were installed to correspond with six herbicide treatments plus a non-treated control (Table 4.1).

Plot design and data collection were based on the protocols of the Carolina Vegetation Survey (Peet et al. 1998). Pre-treatment surveys were conducted from May-July, 2011. The approximate outer boundary of the main privet population at each of the sites was mapped in a GIS, and this map was used to pre-select plot locations. Plots were sometimes relocated in the field to avoid areas of extensive soil disturbance or extremely dense privet with too few native plants for analysis (Rice et al. 1997). Plots were 20 x 20m, and were further divided into four 10 x 10m modules. Corners were permanently marked with steel conduit stakes.

All data was recorded on a per-module basis and divided into an herbaceous stratum (0-50cm in height) and a shrub stratum (50cm – maximum height of privet). A visual estimate of canopy cover was made for each species in the herbaceous stratum using the following cover classes: trace, 0-1%, 1-2%, 2-5%, 5-10%, 10-25%, 25-50%, 50-75%, 75-95%, and 95-100%. Cover estimates were also made for shrub-stratum privet and feral hog disturbance. Vines, regardless of total height, were documented by percentage cover of foliage in each stratum due to the difficulty of identifying stems and finding the rooting point; vines with no foliage visible were not included. All woody stems above 50cm in height and rooted in the plot were tallied into size classes by species. Any stem that branched from the main stem below 50cm was considered an individual. Stems below breast height (137cm) were tallied in height classes (50-100cm and 100-137cm) and stems above breast height were tallied into the following classes by dbh (cm): 0-1, 1-2.5, 2.5-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, and 35-40. For trees greater than 40cm in diameter, individual dbh measurements were recorded. Plots were re-surveyed from May-July of 2012, 4-6 months after treatment, using the same protocols.

Table 4.1. Herbicide treatments applied to plots. Each of these treatments was applied once per site for a total of 35 treatments.

Applicator	Herbicide	Rate
Mistblower	Glyphosate	6.5oz/gal (49.53g/L)
	Metsulfuron	0.0625oz/gal (0.47g/L)
	Combination	6.5oz glyph. + 0.0625oz met./gal
Backpack sprayer	Glyphosate	6.5oz/gal (49.53g/L)
	Metsulfuron	0.0625oz/gal (0.47g/L)
	Combination	6.5oz glyph. + 0.0625oz met./gal
Control		NA

Treatments

Herbicide treatments were applied on January 11, 2012 by an experienced contract crew. Mistblowers were Stihl brand SR model 450, which is a backpack-mounted unit with a 3.7 gallon capacity. Their specified range is 14.5 horizontal meters and 13.0 vertical meters, with a droplet size generally ranging from 60-130µm (Jessop and Bateman 2007). Backpack sprayers used were SP Systems brand Yard Tender model 101 with a 5.3 gallon capacity, which is pressurized by a hand-pump. Spray range and droplet size vary according to pressure.

Glyphosate was mixed in a 5% solution containing 6.5oz/gal (49.53g/L) of Rodeo® liquid concentrate (53.8% a.i.). The metsulfuron solution contained 0.0625oz/gal (0.47g/L) of AmTide MSM 60DF® powder concentrate (60% a.i.). The combination treatment contained 6.5oz glyphosate and 0.0625oz metsulfuron per gallon of spray mix. The water conditioner Choice (Loveland Industries, Inc., ¼% by volume), and the surfactant Rebound (Red River Specialties, Inc., ½% by volume) were added to all spray mixes. The volume of spray applied to each plot varied depending on the density of privet. Spray volumes ranged from 1.5 – 2.5 gallons (5.68-9.46L) per 400m^2 plot, or approximately 15 – 25 gal/acre (142-236 L/ha). Privet was sprayed to wetness, and privet-free gaps within plots were not sprayed.

Data Analysis

For all variables, data from the modules were averaged for each plot. A total of nine modules and one whole plot were rejected from all analyses due to treatment irregularities. Percentage cover values were based on the midpoint of each cover class, and the “trace” class was assigned a value of 0.01%. For diversity and abundance variables, pre-treatment data was subtracted from post-treatment data to analyze the change resulting from herbicide application. Species richness represents the average number of species per module. Diversity was calculated with Simpson’s Index ($D=\Sigma p_i^2$ where p_i is the proportion of the total made up by species i), using percentage cover data for the herbaceous stratum and number of stems for the shrub stratum. Simpson’s Index represents the probability that two randomly selected individuals will be of the same species, and the reciprocal ($1/D$) was used here so that the index increased with increasing diversity (Magurran 2004). Herbaceous-stratum species were grouped by growth form (annual herbs, perennial herbs, trees and shrubs, vines, ferns, sedges, and native grasses) to analyze whether herbicide treatments disproportionately affected a particular plant type, based on the sum of change in percentage cover for all species in each group. *Microstegium vimineum* and *A. gigantea* were analyzed individually, and non-native species were analyzed as a group. In addition, a group was designated of species expected to have foliage at the time of a dormant-season treatment, here called winter-green species. Species were categorized based on descriptions in Radford et al. (1968) , the PLANTS database (U.S. Department of Agriculture 2013), and observations at the time of treatment. The growth form groups and included species are shown in Table 4.2.

Level of significance was set to 0.1. Diversity and abundance variables were analyzed with ANOVA tests using JMP software (SAS Institute Inc. 2012), with site and treatment as model effects. Because herbaceous plant populations can fluctuate considerably from year to year, control plots were included in analyses to account for natural variation. Individual treatments were compared to control plots using the Student's t test. Linear contrasts were applied to test for effects of applicator, herbicide, and applicator x herbicide interaction (Table 4.3). When a significant herbicide effect was found, further contrasts were used to determine which of the three herbicide types differed. *A. gigantea* was present in too few plots to allow for a full analysis. The primary concern for this species was determining which herbicide caused greater impact, therefore only site and herbicide were included as model effects.

To investigate which species were most likely to appear or disappear following herbicide treatments, McNemar's test was used to detect significant changes in occupancy following treatments (Newton et al. 2012). All treated plots were included with no distinction between treatment types.

Table 4.2. Growth form categories used to analyze the herbaceous stratum. Species included in each group are shown; winter-green species are marked as ^{1} and non-native species as ^{2}.

Growth form	Species included
Annual herbs	*Acalypha rhomboidea, Ambrosia artmesiifolia, Bidens* sp., *Corydalis flavula*[1], *Erechtites heiracifolia, Impatiens capensis, Melothria pendula, Myosotis macrosperma, Packera glabella*[1], *Perilla frutescens*[2], *Persicaria longiseta*[2], *Pilea pumila, Ranunculus abortivus*[1], *Stellaria media*[1,2], *Urtica chamaedryoides*
Perennial herbs	*Acanthaceae* sp.*, Arisaema dracontium, Boehmeria cylindrica, Cayaponia quinqueloba, Clematis* sp., *Commelina virginica, Cryptotaenia canadensis, Dicliptera brachiata, Duchesnea indica*[1,2], *Eupatorium serotinum, Eupatorium* sp., *Galium triflorum*[1], *Gonolobus suberosus, Laportea canadensis, Liliaceae* sp.*, Lycopus virginicus, Mikania scandens, Oxalis stricta, Passiflora lutea, Persicaria virginiana, Phytolacca americana, Polygonum punctatum, Ranunculus recurvatus, Sanicula canadensis, Saururus cernuus, Solanum carolinense, Verbesina occidentalis, Viola affinis*[1]
Trees and shrubs	*Acer* sp.*, Asimina triloba, Carya aquatica, Carya* sp.*, Celtis laevigata, Crataegus* sp.*, Diospyros virginiana, Elaeagnus pungens*[1,2], *Fraxinus pennsylvanica, Ilex decidua, Ligustrum sinense*[1,2], *Lindera benzoin, Liquidambar styraciflua, Morus rubra, Nyssa aquatica, Populus deltoides, Quercus laurifolia*[1], *Quercus lyrata, Quercus pagoda, Quercus* sp.*, Rubus argutus, Rubus* sp.*, Sideroxylon lycioides*[1], *Solanum pseudocapsicum*[1,2], *Ulmus* sp.*, Vaccinium* sp.
Vines	*Ampelopsis arborea, Berchemia scandens, Bignonia capreolata*[1], *Campsis radicans, Cocculus carolinus, Lonicera japonica*[1,2], *Parthenocissus cinquefolia, Smilax bona-nox*[1], *Smilax sp.* [1], *Toxicodendron radicans, Vitis cinerea* var. *floridana, Vitis rotundifolia, Vitis sp.*
Ferns	*Asplenium platyneuron, Botrychium biternatum*[1], *Dryopteris ludoviciana*[1], *Macrothelypteris torresiana*[1,2], *Onoclea sensibilis, Polystichum acrostichoides*[1], *Thelypteris* sp.
Native grasses	*Arundinaria gigantea*[1], *Chasmanthium* sp.*, Dichanthelium commutatum, Elymus virginicus, Festuca subverticillata, Glyceria striata, Leersia virginica, Poa autumnalis*
Sedges	*Carex* spp. [1]

Table 4.3. Coefficients used in linear contrasts to test for effects of applicator, herbicide, and interaction. Two contrasts were required for tests of herbicide and interaction

Treatment		Applicator	Herbicide		Interaction	
			Cont. 1	Cont. 2	Cont. 1	Cont. 2
Mist-blower	Glyphosate	-0.33	0.25	-0.5	-0.5	-0.33
	Metsulfuron	-0.33	-0.5	0	0	0.33
	Combination	-0.33	0.25	0.5	0.5	-0.33
Backpack sprayer	Glyphosate	0.33	0.25	-0.5	-0.5	0.33
	Metsulfuron	0.33	-0.5	0	0	-0.33
	Combination	0.33	0.25	0.5	0.5	0.33
Control		0	0	0	0	0

Results

For most of the variables tested, individual treatments did not differ from the control. However, the backpack sprayer-glyphosate treatment showed a significant decrease in cover for sedges (Figure 4.1) and winter-green species (Figure 4.2) as compared to the control, and a greater increase for *M. vimineum* (Figure 4.3). The backpack-metsulfuron and backpack-glyphosate treatments showed a significant decrease in cover of tree and shrub seedlings (Figure 4.4) and the mistblower-glyphosate treatment showed a decrease in fern cover (Figure 4.5) as compared to the control.

Treatments did not differ from the control for any other variables, but linear contrasts did detect some overall herbicide and applicator effects. Backpack sprayer plots had significantly larger decreases in cover than mistblower plots for trees and shrubs (p=0.0497, Figure 4.4), winter-green species (p=0.0597, Figure 4.2), vines (p=0.0707, Figure 4.6), and total herbaceous cover (p=0.0737, Figure 4.7). Glyphosate plots had larger decreases in sedge cover than metsulfuron (p=0.0078) or combination plots (p=0.0266, Figure 4.1), but a larger increase in Simpson's Index for the herbaceous stratum than metsulfuron plots (p=0.0679, Figure 4.8). Glyphosate (p=0.0206) and combination (p=0.0801) plots both showed greater decreases in cover of winter-green species than metsulfuron plots (Figure 4.2).

Species richness (Figure 4.9), annual herb cover (Figure 4.10), perennial herb cover (Figure 4.11), native grass cover (Figure 4.12), non-native cover (Figure 4.13), shrub-stratum vine cover (Figure 4.14), and shrub-stratum density (excluding privet) (Figure 4.15) had no treatments differing from the control and showed no significant effects of applicator or herbicide. Rivercane showed no effect of herbicide for change in stem number (Table 4.4). Applicator x herbicide interaction was not found to be significant for any variable. The following species showed a significant decrease in number of treated plots occupied based on McNemar’s test (Table 4.5): *Asplenium platyneuron, Duchesnea indica, Packera glabella, Poa autumnalis, Ranunculus abortivus,* and *Viola affinis.* The species *Dicliptera brachiata* and *Phytolacca americana* showed a significant increase in occupancy of treated plots (Table 4.5).

Figure 4.1. Change in percentage cover of sedges following herbicide treatments (+1 SE). Metsulfuron caused a smaller decrease in cover than the glyphosate or combination treatments. Treatments that do not share a letter were significantly different at α=0.1.

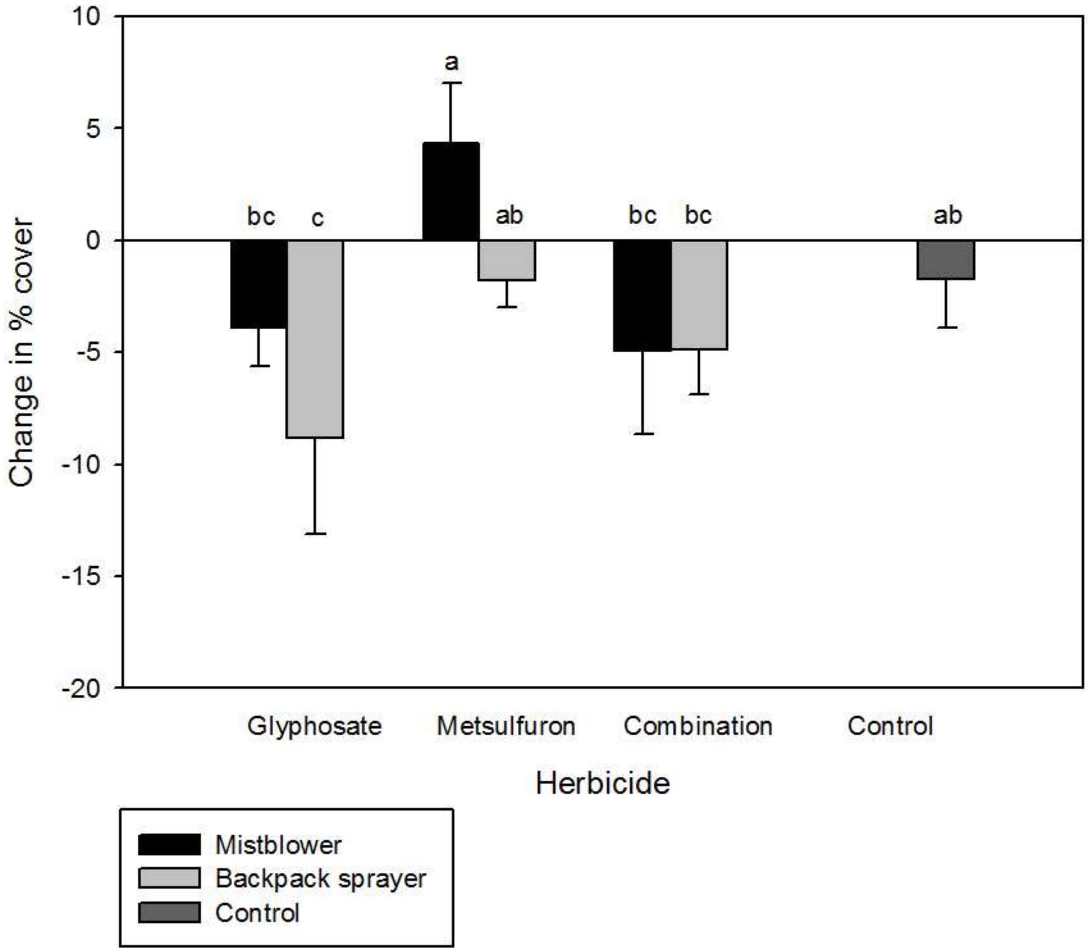

Figure 4.2. Change in percentage cover of winter-green species following herbicide treatments (+1 SE). Mistblowers caused a smaller decrease than backpack sprayers, and metsulfuron caused a smaller decrease than glyphosate or combination treatments. Treatments that do not share a letter were significantly different at α=0.1.

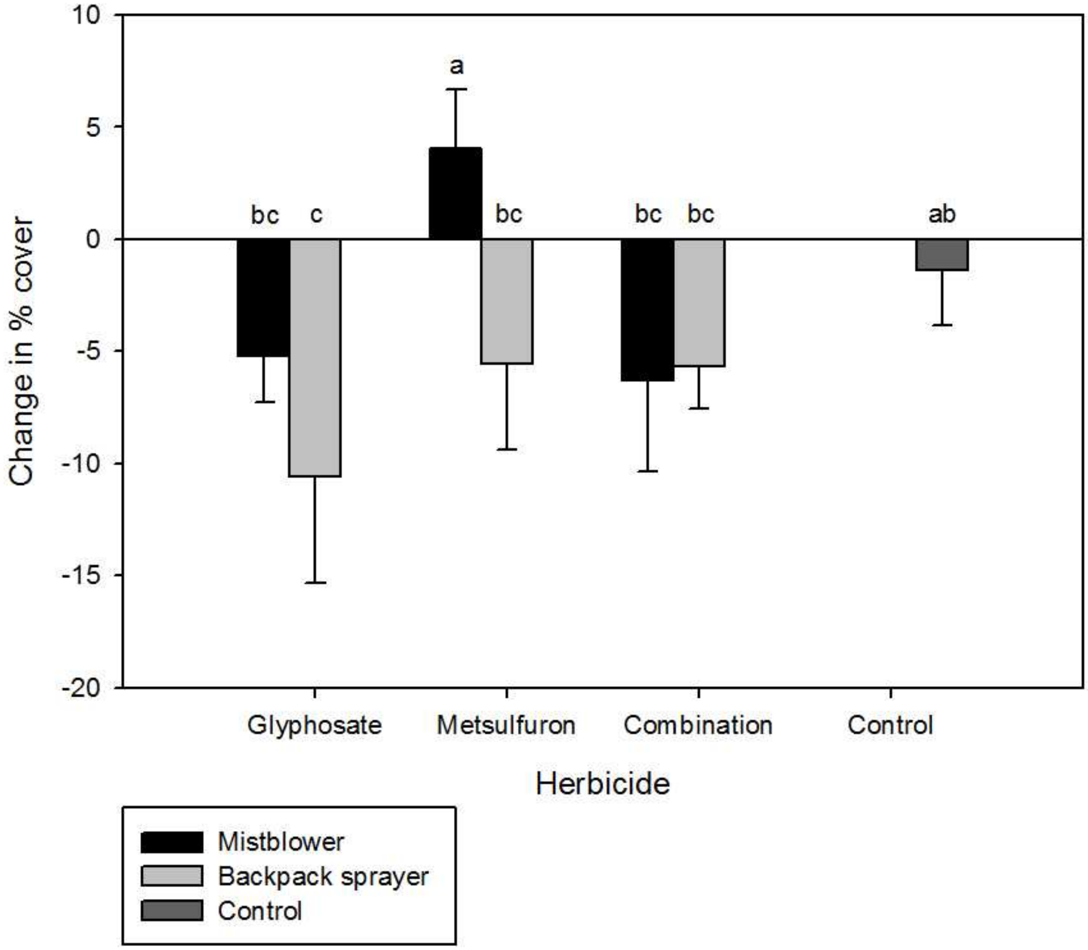

Figure 4.3. Change in percentage cover of *Microstegium vimineum* following herbicide treatments (+1 SE). There were no significant effects of applicator, herbicide, or interaction. Treatments that do not share a letter were significantly different at α=0.1.

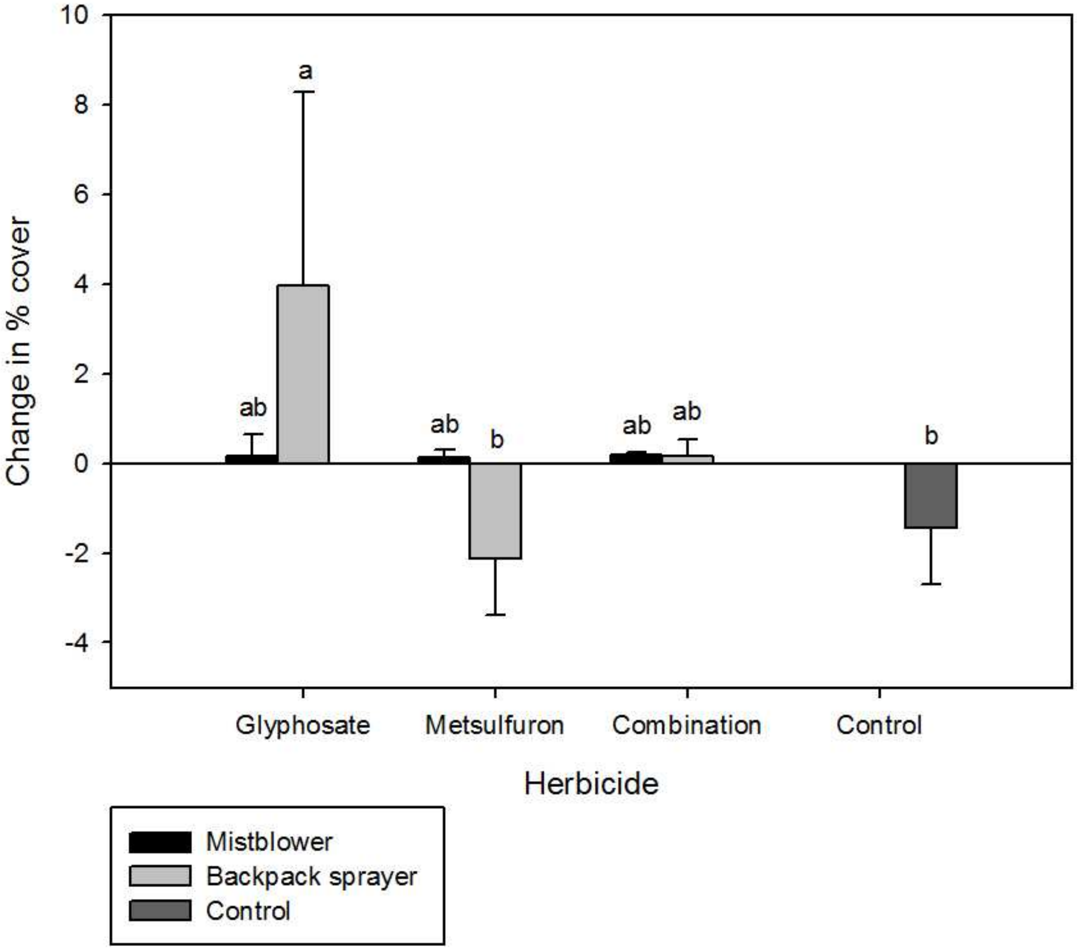

Figure 4.4. Change in percentage cover of trees and shrubs (<50cm in height) following herbicide treatments (+1 SE). Mistblower plots showed a significantly smaller decrease in cover than backpack sprayer plots. Treatments that do not share a letter were significantly different at α=0.1.

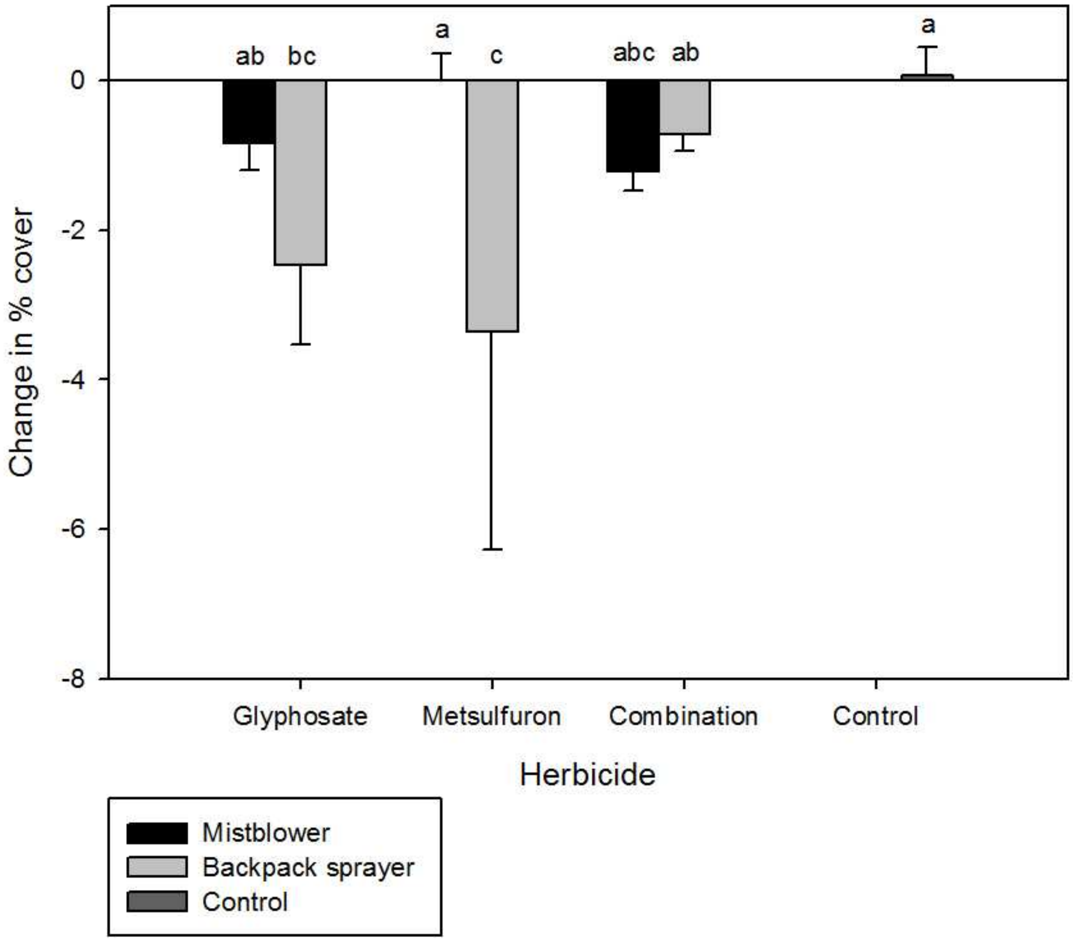

Figure 4.5. Change in percentage cover of ferns following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

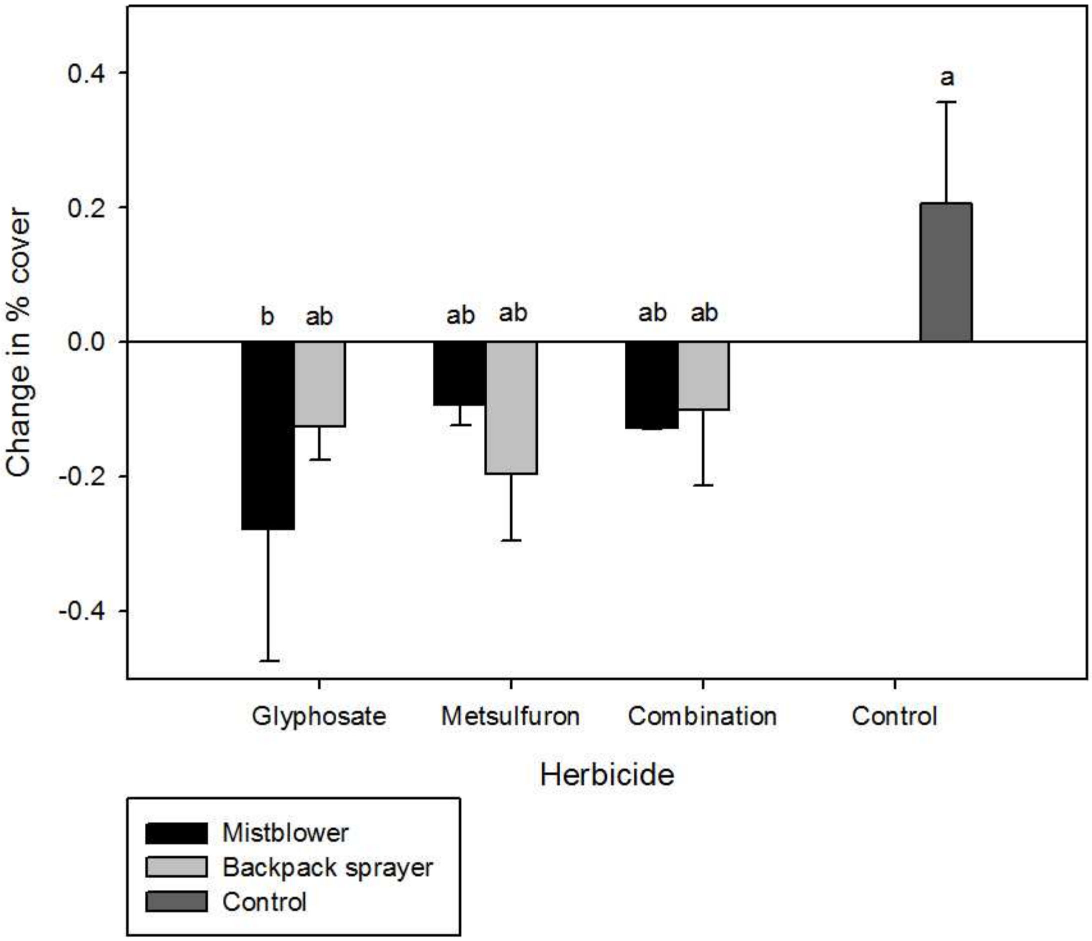

Figure 4.6. Change in percentage cover of vines (<50cm in height) following herbicide treatments (+1 SE). Mistblower plots showed a significantly smaller decrease in cover than backpack sprayer plots. Treatments that do not share a letter were significantly different at α=0.1.

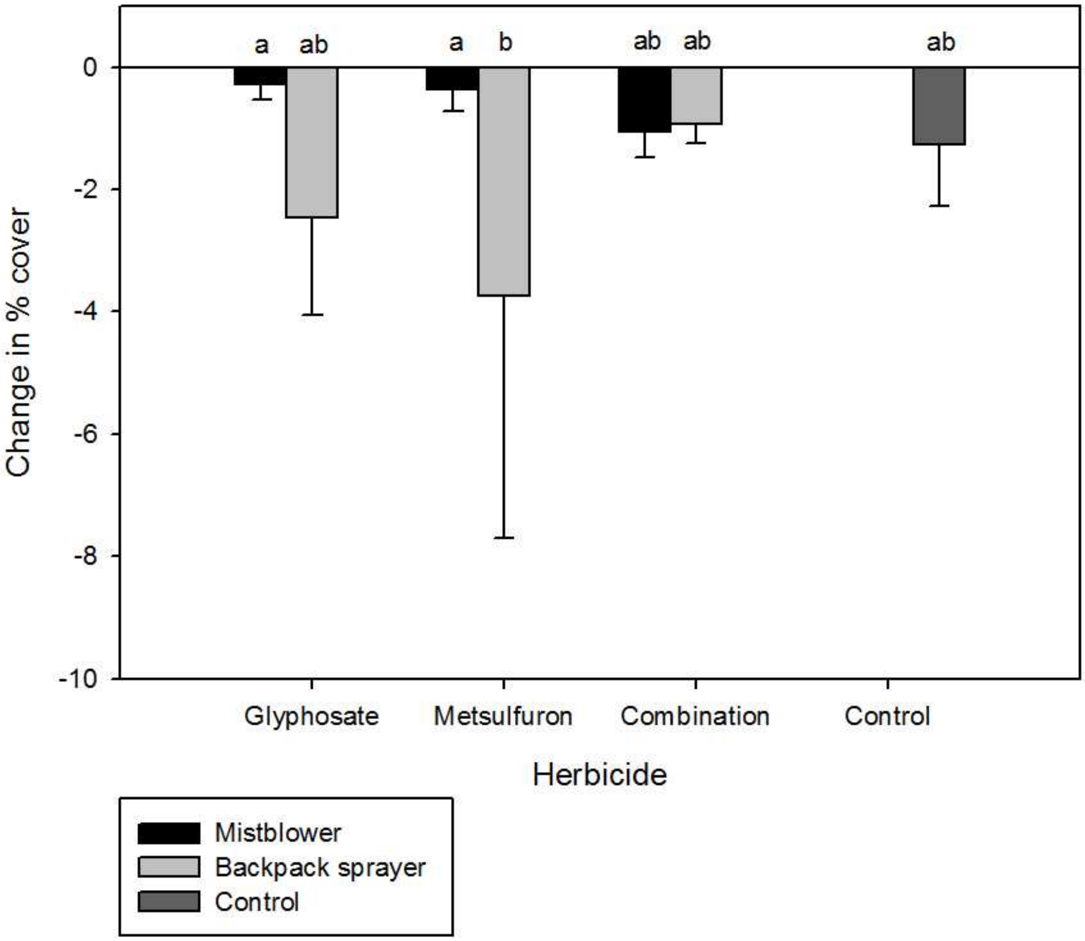

Figure 4.7. Change in total cover of herbaceous-stratum species (<50cm in height) following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

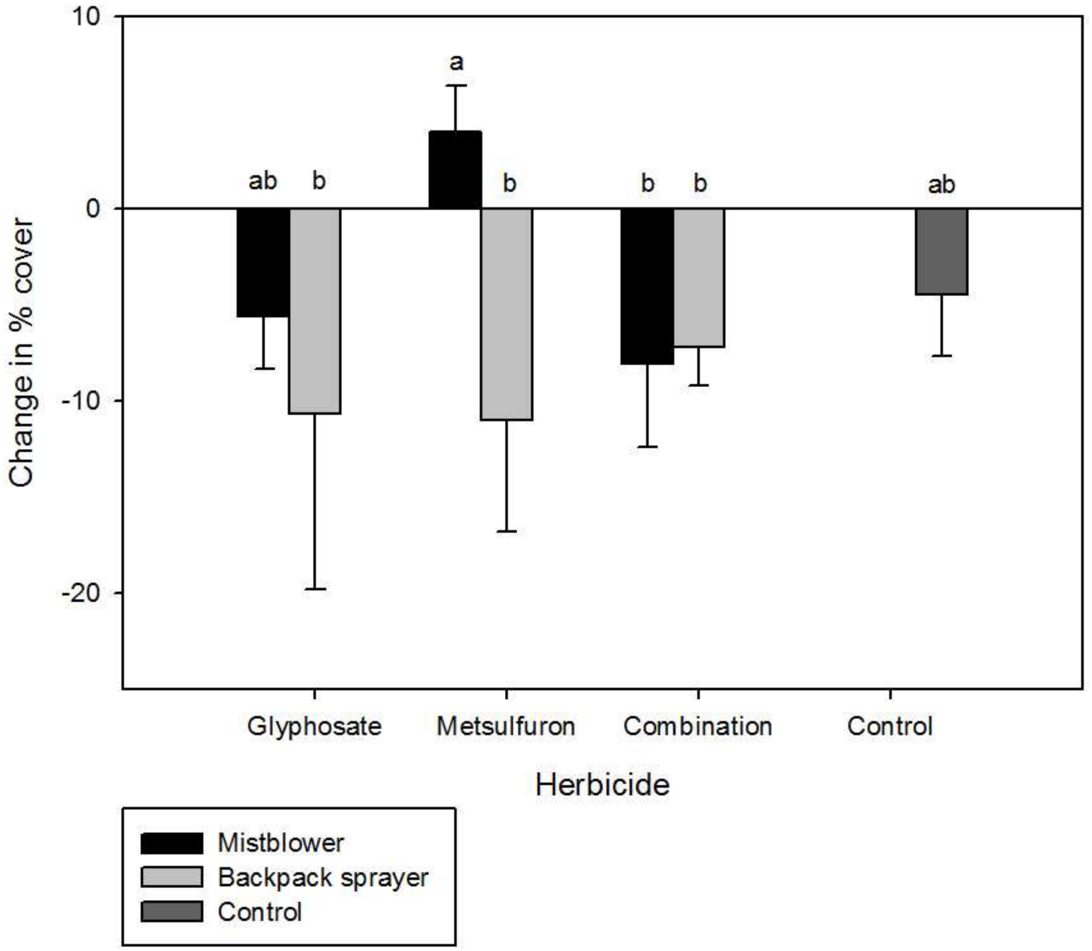

Figure 4.8. Change in Simpson's Diversity Index (1/*D*) for the herbaceous stratum following herbicide treatments (+1 SE). Glyphosate plots showed a significantly greater increase in diversity than metsulfuron plots. Treatments that do not share a letter were significantly different at α=0.1.

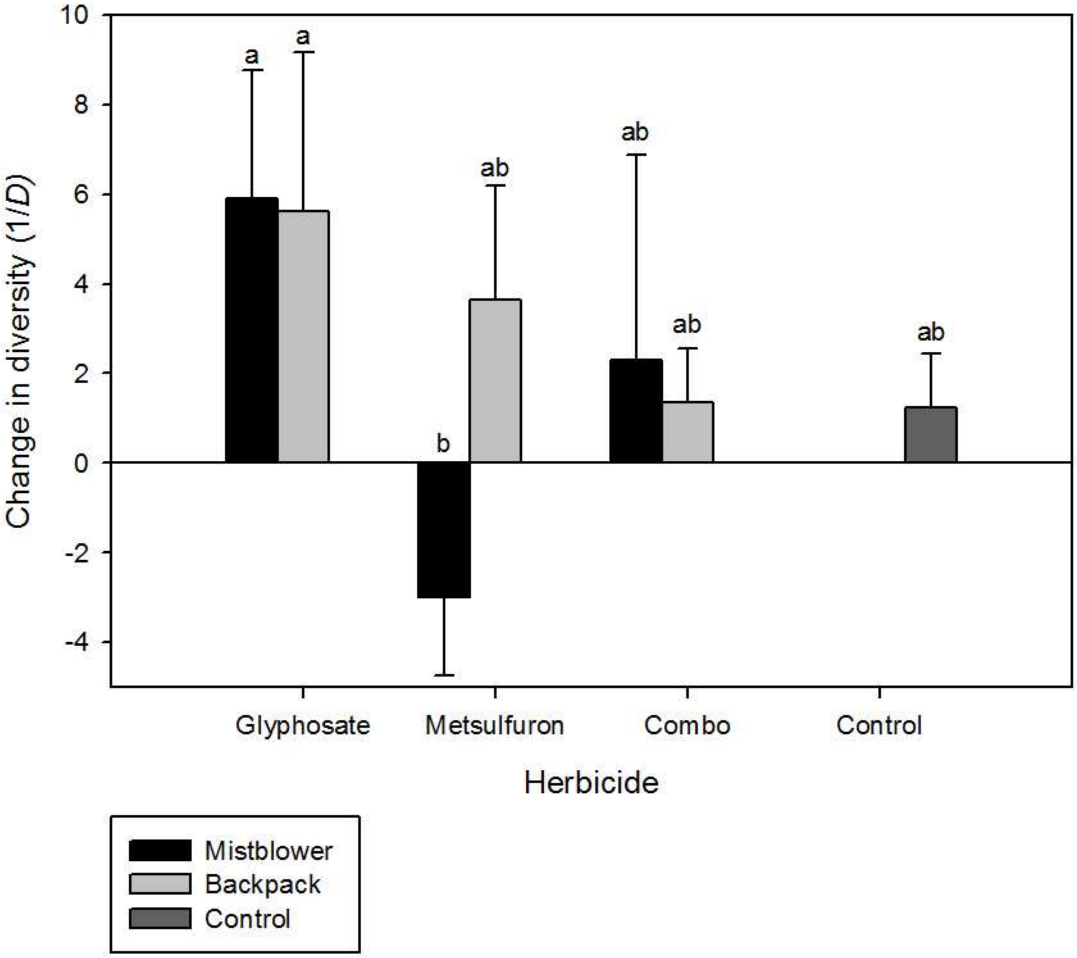

Figure 4.9. Change in species richness following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

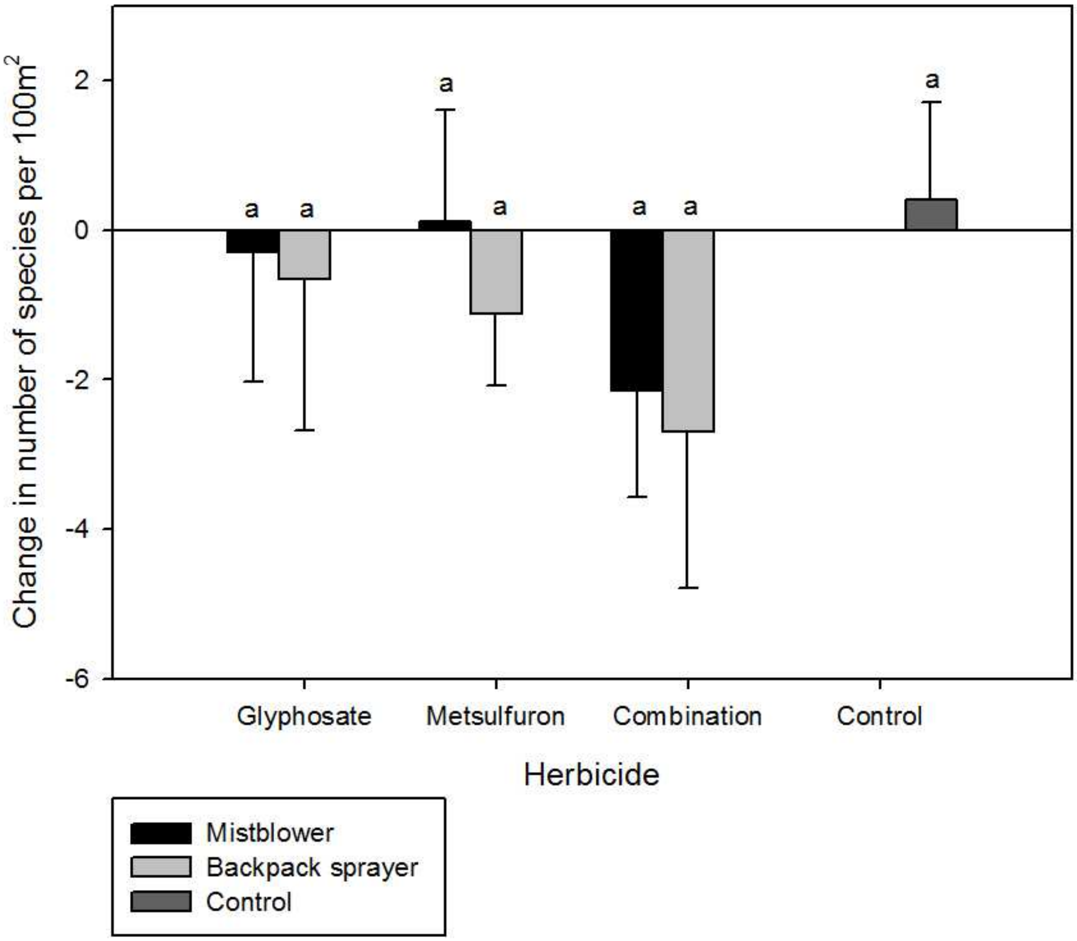

Figure 4.10. Change in percentage cover of annual herbs following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

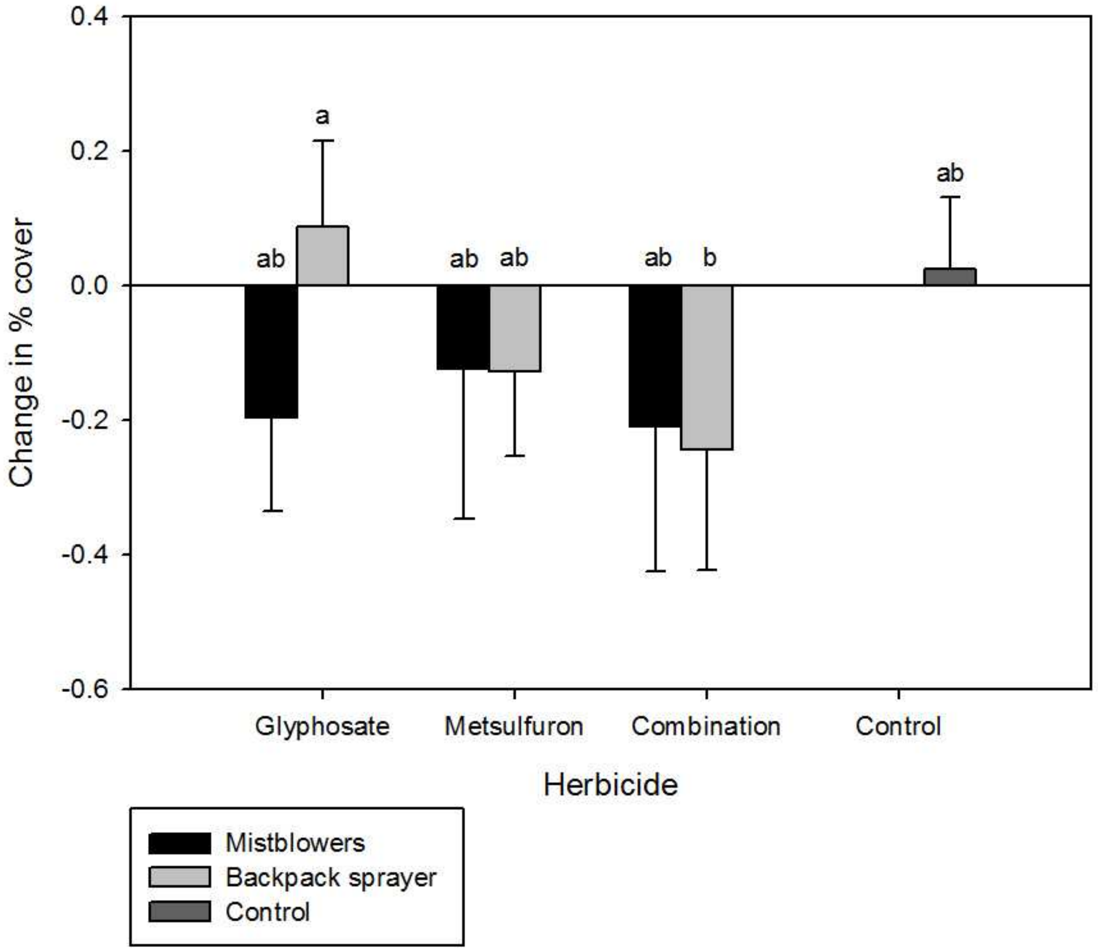

Figure 4.11. Change in percentage cover of perennial herbs following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

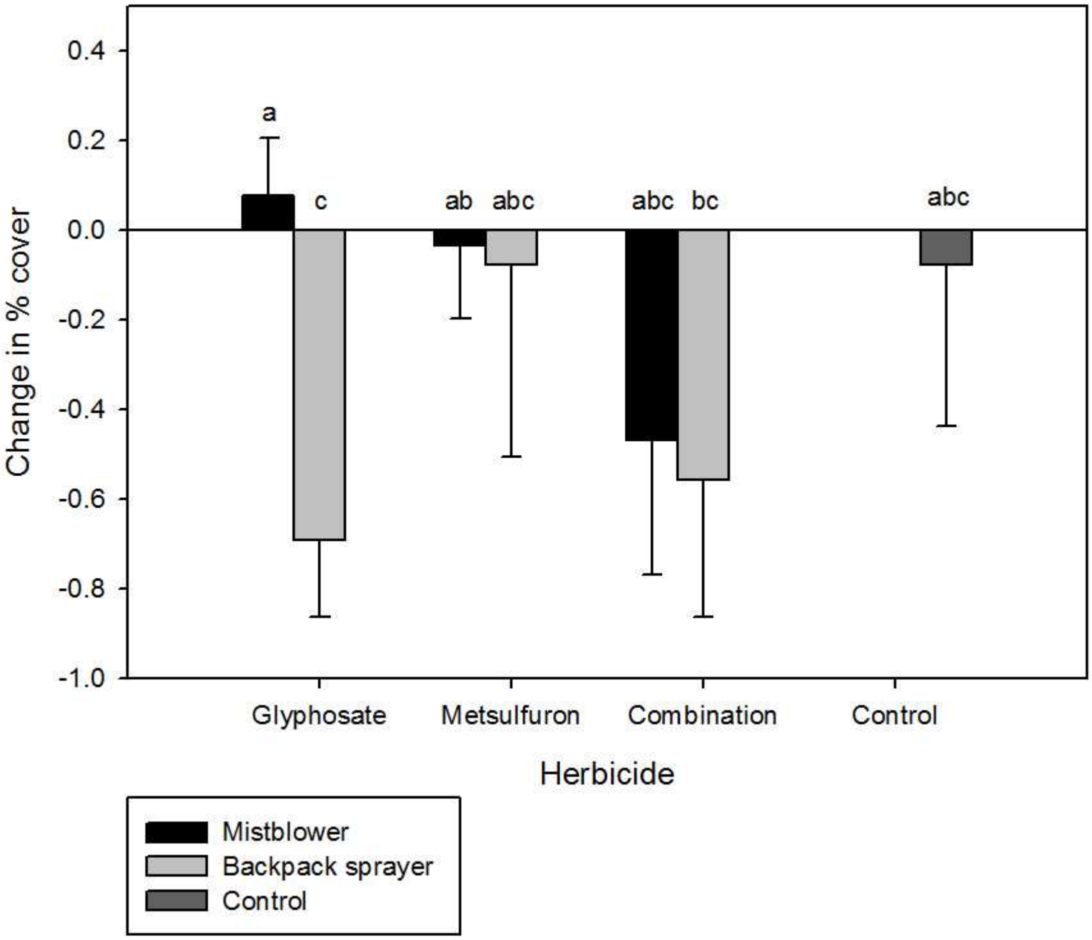

Figure 4.12. Change in percentage cover of native grasses following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

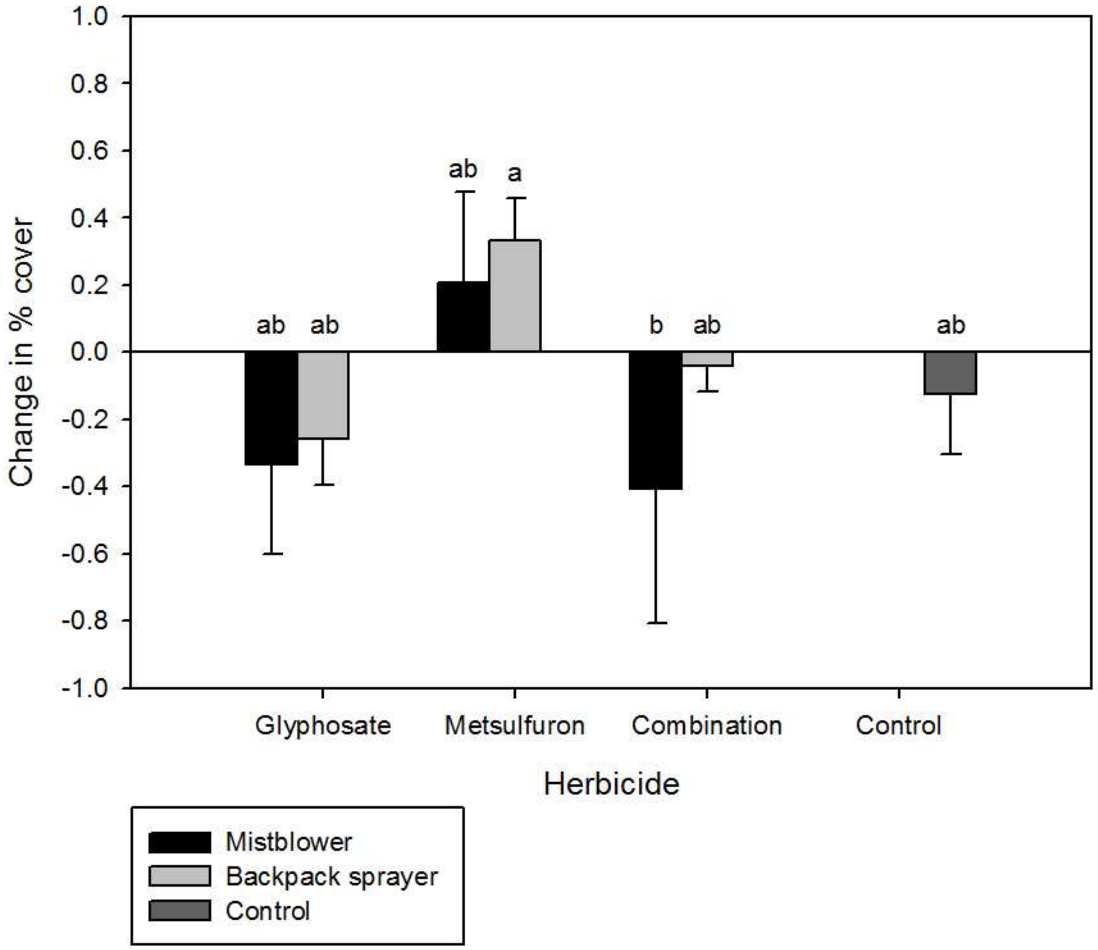

Figure 4.13. Change in percentage cover of non-native species (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

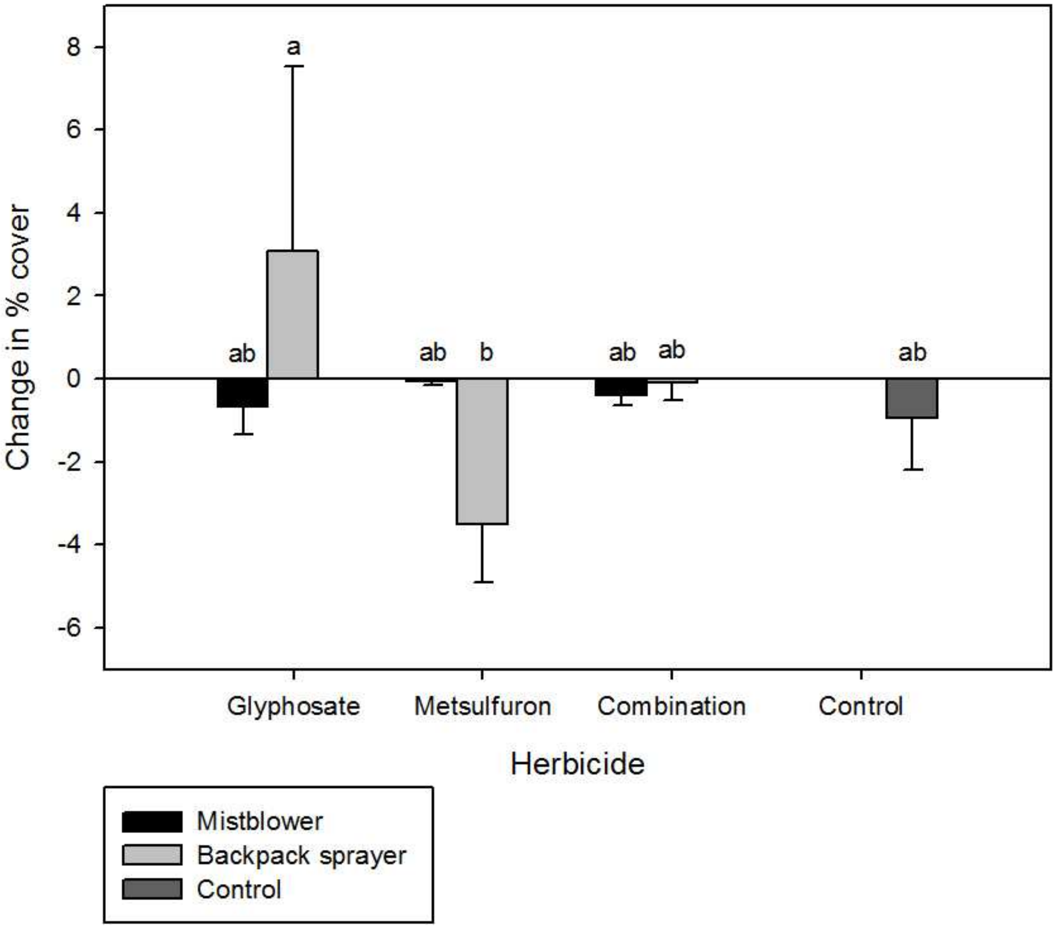

Figure 4.14. Change in percentage cover of vines (>50cm height) following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

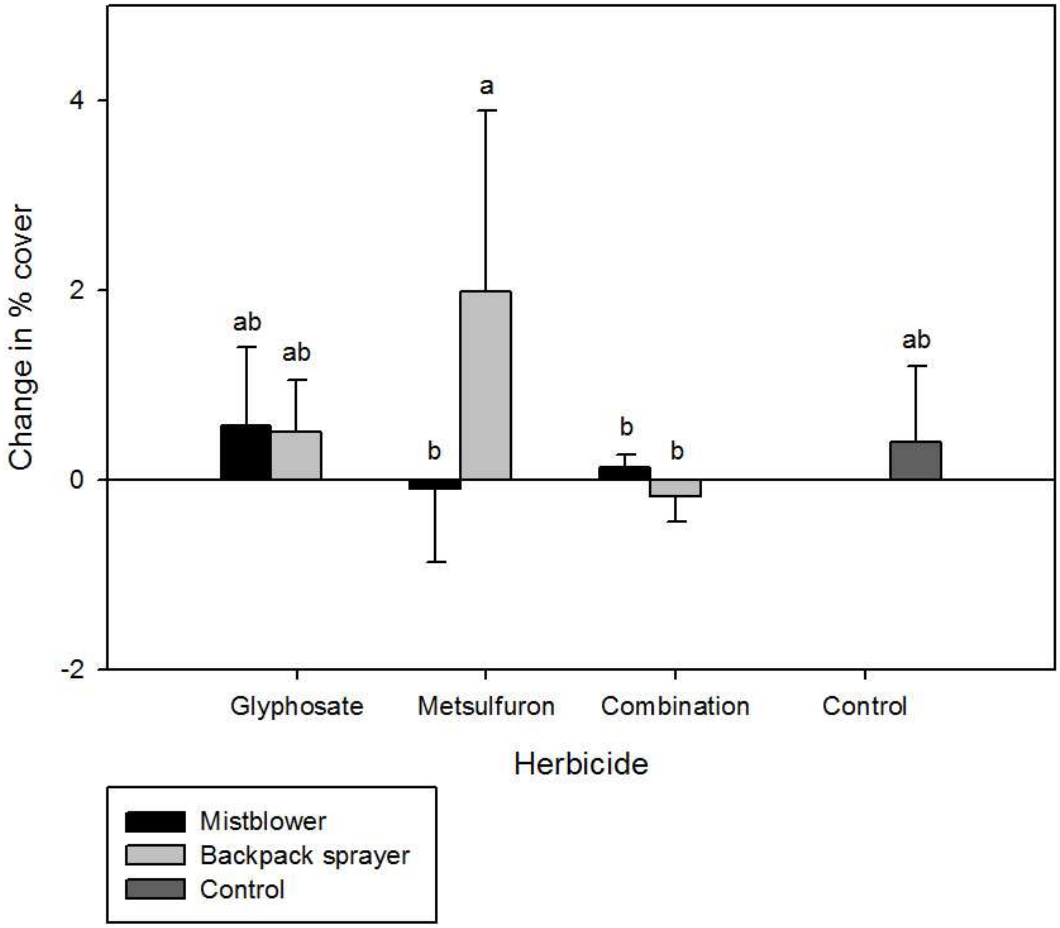

Figure 4.15. Change in density of woody stems (excluding privet) following herbicide treatments (+1 SE). Treatments that do not share a letter were significantly different at α=0.1.

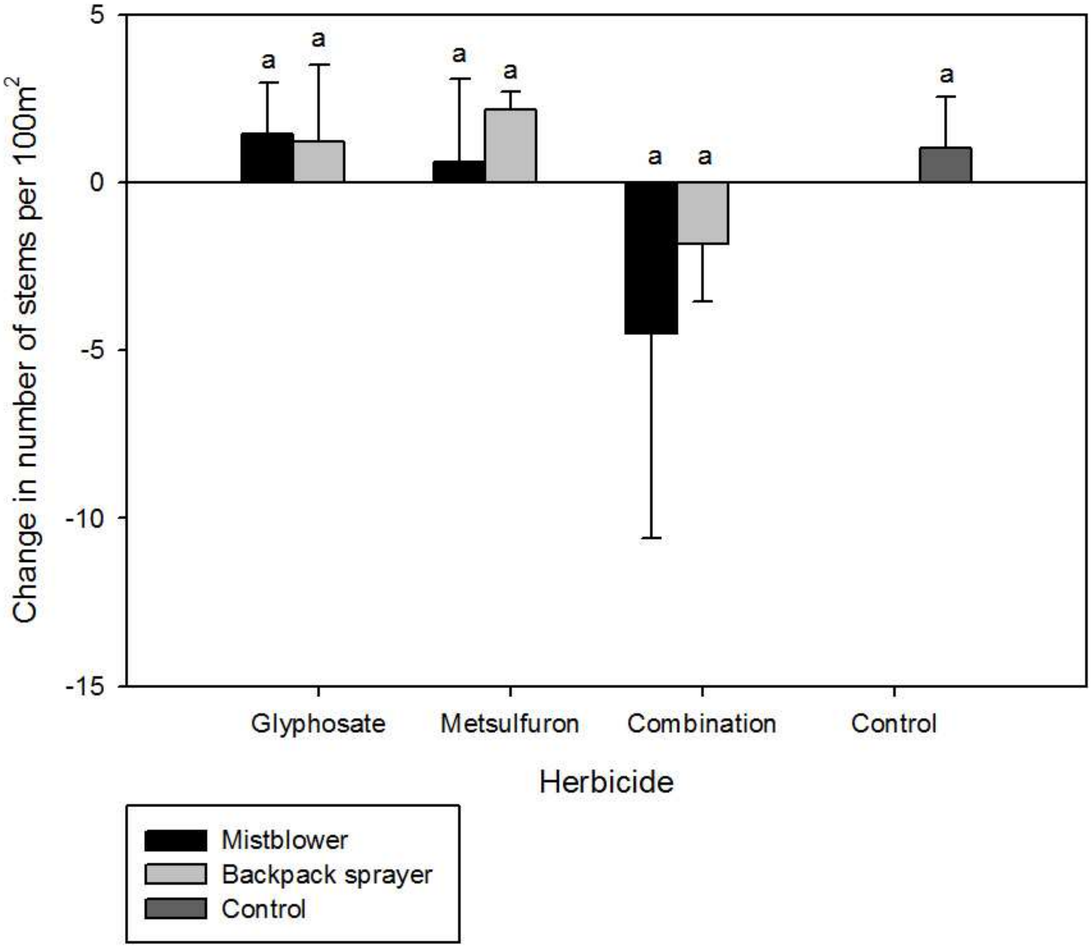

Table 4.4. Change in number of stems per $100m^2$ of *Arundinaria gigantea* by herbicide type. Differences between herbicides were not significant (p=0.4047).

Herbicide	Change in stems/$100m^2$
Metsulfuron	+1.44
Glyphosate	-2.31
Combination	-8.28
Control	+1.33

Table 4.5. Species showing a significant change in number of plots occupied following herbicide treatment based on McNemar's test (α=0.1).

Species	Number of plots			P-value
	Occupied pre-treatment	Vacated post-treatment	Colonized post-treatment	
Asplenium platyneuron	19	12	1	0.0034
Dicliptera brachiata	10	1	7	0.0339
Duchesnea indica	8	6	0	0.0313
Packera glabella	15	6	0	0.0313
Phytolacca americana	11	3	11	0.0574
Poa autumnalis	7	5	0	0.0625
Ranunculus abortivus	12	8	0	0.0078
Viola affinis	20	13	0	0.0002

Discussion

No single combination of applicator and herbicide was clearly superior at minimizing impacts to native plant communities; no interaction terms were found to be significant, and results were not consistent across variables. Overall, negative impacts to native plants appear to have been limited. Most treatments did not differ from control plots for any variable measured, indicating that changes were within the range of natural variability for this system. Herbaceous plant populations can vary considerably in abundance between years due to fluctuations in precipitation, temperature, other environmental factors (Hochstedler et al. 2007).

However, some treatment effects were detected, which appeared to primarily relate to changes in sedge cover. Sedges (*Carex* spp.) dominated the herbaceous layer in many areas, and had cover values of up to 45% in study plots. Sedges could not be consistently identified to the species level, but at least eight species were present (*C. blanda*, *C. corrugata*, *C. godfreyi*, *C. grayi*, *C. intumescens*, *C. radiata*, *C. styloflexa*, and *C. tribuloides*). The backpack-glyphosate treatment caused a significant reduction in sedge cover as compared to the control. Glyphosate caused more impact to sedges than metsulfuron, as supported by the findings of Nuzzo (1996), who reported negative impacts to sedges from glyphosate. Metsulfuron is primarily used for control of broadleaf weeds in grass crops like wheat and barley, and many grass species are resistant (AmTide LLC. 2007). *Carex* spp., however, are not agricultural species and their sensitivity to metsulfuron has not been tested. It appears that the species of *Carex* present in this study were not negatively affected by metsulfuron, and an overall increase in sedge cover was observed on metsulfuron plots. Another factor may be direct competition with the non-native grass *Microstegium vimineum,* which showed a significant increase in backpack-glyphosate plots. The presence of recently-killed clumps of sedges within treated plots suggests that sedges were killed by herbicide and *M. vimineum* rapidly took advantage of the resources made available.

The results for the winter-green category were primarily controlled by changes in sedge cover, and the backpack sprayer-glyphosate treatment similarly caused greater impact than the control. Along with sedges, the semi-evergreen vine *Bignonia capreolata* showed relatively large declines (up to 9.5%) in a few plots. Some individuals of *B. capreolata* and *Smilax* spp. exhibited leaf deformation indicative of herbicide damage, but plants often overcome this type of visible damage in a relatively short time (Obrigawitch et al. 1998, Marrs et al. 1989). The genus *Smilax* is typically resistant to herbicide control (Funderburg 2011). Studies indicate that even among winter-green species, responses are individualistic. For example, Nuzzo (1996) noted several semi-evergreen species that were unaffected by dormant-season glyphosate treatments. Winter annuals were not adequately represented, and may have been heavily impacted. During a visual inspection of plots approximately two months after treatment, a clear line in the herbaceous vegetation could be seen along plots boundaries. However, this vegetation appeared to be primarily made up of only a few very abundant species, including *Galium spp.*, *Stellaria media*, and *Corydalis flavula* (pers. obs). It is assumed that the winter flora is less diverse than the spring and summer flora, but a winter vegetation survey would help to determine whether there are species present that need special protection.

Herbaceous-stratum tree and shrub cover significantly declined in the backpack-metsulfuron treatment, with a decrease of 3.22%. The change in tree and shrub cover was heavily influenced by two plots with unusually high cover of maple (*Acer* spp.) seedlings (7.5%) that showed corresponding large decreases (5.6 and 6.7%). This may have been due to large crops of seedlings produced by a few individual trees, which experienced subsequent high mortality. The only other treatment that differed from controls was the mistblower-glyphosate treatment, which caused a significant reduction in fern cover. The overall reduction from this treatment was only 0.28%, but the species *Asplenium platyneuron* was eliminated from three plots, and *Onoclea sensibilis* from one plot.

Some further overall effects of applicators and herbicides were found, but with no significant differences between individual treatments and control plots. While this provides some support for recommending one treatment type over another, it indicates that the effects were not strong. Mistblowers overall showed fewer impacts than backpack sprayers, which caused a greater reduction in total herbaceous cover, trees and shrubs (<50cm), vines (<50cm), and winter-green species. This may be related to the difference in the size of spray droplets produced by these applicator types. The larger droplets produced by backpack sprayers are more likely to fall through the foliage of the privet canopy and contact lower layers of vegetation. Mistblower droplets are more likely to be intercepted by leaves and stems of the shrub canopy (Devine et al. 1993).

However, backpack sprayers may sometimes be preferred for logistical reasons. For example, they are smaller and lighter, do not require the transport of fuel, and do not require special permission for use in a wilderness area. There is also a greater probability of spray drift from mistblowers, although this can be reduced by monitoring wind conditions and directing the spray stream inward toward the treatment area (S. Frock, pers. comm.).

Among the herbicide types, metsulfuron appeared to cause fewer impacts, particularly to sedges. Glyphosate plots showed larger decreases in sedge cover than metsulfuron plots, and both glyphosate and combination plots showed larger decreases in winter-green cover. This study did not detect any difference between herbicides for rivercane, but Nespeca and Kemp (2006) observed that glyphosate impacted rivercane while metsulfuron did not. The ability to detect differences was limited by small sample size, and rivercane should be considered a sensitive species when planning for glyphosate treatments. It was also expected that metsulfuron would cause less impact to native grasses, but no difference between herbicides was found. Diversity of the herbaceous stratum increased after most treatments, but the increase was significantly greater in glyphosate plots than in metsulfuron plots. One factor could be the ability of metsulfuron to remain active in the soil and enter plants through their roots (Ferenc 2001), whereas glyphosate is quickly deactivated in the soil. However, it appears that the increase in diversity is primarily a product of the decrease in sedge cover. Sedges made up the majority of cover in many plots, and dominance by a single species lowers the value of Simpson’s Index. In this case, the dominance was overstated because there were actually multiple sedge species per plot. A decrease is sedge cover increased evenness and thereby diversity. While a major goal of privet removal is to increase native plant diversity, it would preferably result from an increase in species richness or the abundance of less-common species. Diversity is expected to increase in the long-term following privet removal due to increased availability of light and belowground resources.

Although metsulfuron caused less damage to native plant populations, glyphosate may be a better choice of herbicide for Congaree National Park. Although glyphosate is a highly non-selective herbicide and causes damage or mortality to most types of plants (Franz et al. 1997), it binds quickly and tightly to soil particles, and is therefore rapidly deactivated and has a decreased chance of being transported off-site (Vereecken 2005). It also has aquatic formulations available that allow for spraying near surface waters (Getsinger et al. 2011). Metsulfuron-methyl, on the other hand, does not bind as well to soil particles and has a greater chance of being transported off-site during rain and flood events. It remains active in the soil and can enter plants through both the foliage and the roots (Ferenc 2001). The AmTide® label recommends waiting up to 34 months before planting certain crops in fields that have been sprayed (AmTide LLC. 2007). The most serious concern is that metsulfuron will impact canopy trees, especially if any are not fully dormant at the time of treatment. Canopy foliage is out of reach and will not be impacted by glyphosate treatments.

Although some non-target impacts were detected, it is notable that no treatments differed from controls for species richness, total herbaceous cover, or diversity (1/*D*). Similar studies of dormant-season treatments for invasive plant control have also found minimal effects of herbicides on richness and diversity of non-target plant communities (Hochstedler et al. 2007, Frey et al. 2007, Nuzzo 1996). In a park setting, herbicides are usually applied at the minimum effective rate, making complete elimination of any species (including the target) less likely. Most plant categories showed no significant treatment effects, and change in cover was generally small.

Although impacts to species richness were limited, six species showed a significant decrease in occupancy in treated plots, indicating a greater risk of localized extirpation following herbicide treatments. These species included deciduous and evergreen perennials, winter annuals, a grass, and a fern. None of these species were eliminated from every plot where they were present. Most had very low percentage cover before treatment, making them vulnerable to stochastic events, such as feral hog disturbance. Two perennial herb species, *Dicliptera brachiata* and *Phytolacca americana*, showed an increase in occupancy, suggesting that they are likely to colonize new areas following privet control.

There is a concern that other non-native species will rapidly invade and replace privet after control efforts, leading to continued suppression of native plant growth. By far the most abundant non-native species aside from privet was *M. vimineum*; it was present in every plot, with up to 27% cover. Cover of *M. vimineum* increased slightly for most treatments, with a 3.95% increase for backpack-glyphosate plots that was significantly higher than in control plots. A single plot within this treatment showed a 21.25% increase. This increase may have been related to the decrease in sedge cover in backpack-glyphosate plots; this species may be in more direct competition with species of similar growth form than with privet. However, an increase in *M. vimineum* has been seen in other privet removal studies (Osland et al. 2009, Hanula 2009), and this possibility is further supported by the significantly greater cover of *M. vimineum* in un-invaded than invaded plots (see Chapter 2). If larger areas of privet are sprayed and more light is reaching the ground, *M. vimineum* (and other non-native species) may show an even greater increase. *M. vimineum* is likely more difficult to control than privet and would require growing-season treatments. Westman (1990) noted a tendency for park managers to target easy-to-treat invasive species, which may lead to greater problems in the future. However, both privet and *M. vimineum* may inhibit canopy regeneration (Oswalt et al. 2007, Merriam and Feil 2002), and it seems likely that this effect is amplified in sites with both species present. Greene and Blossey (2012) found that transplanted native seedlings showed higher growth in *M. vimineum*-dominated sites than in privet-dominated sites, suggesting that privet removal may still be advisable even if it results in an increase in *M. vimineum*. Further investigation of the relative impacts of these species would be warranted. Although a number of other non-native species were present (including *Lonicera japonica*, *Perilla frutescens*, and *Solanum pseudocapsicum*), no species other than *M. vimineum* showed a dramatic increase in any plot. Non-native species as a group primarily decreased in cover.

Although this study found non-target impacts to be relatively small, these results only apply to the conditions present during the study. Some species in the potential treatment area were not well-represented in study plots. Willows (Willoughby 1996) and persimmon (Johnson et al. 2010) could be damaged by winter glyphosate application, but their susceptibility to metsulfuron is unknown. Because there was relatively low cover of herbaceous-stratum privet, spray was primarily directed at the privet shrub canopy. An influx of privet seedlings or root sprouts would require that sprays be directed toward the ground, which might cause greater impact to the herbaceous layer. Plant responses to herbicide may vary from year to year (Hochstedler et al. 2007), and changes in soil moisture could affect herbicide uptake (Devine et al. 1993). Data was collected only 4-6 months after treatment, which is not adequate time to reflect the effects of changing competitive interactions following privet removal. Even when changes in cover or density are not detected, herbicide application can decrease reproduction in perennial species (Crone et al. 2009, Ferenc 2001, Franz et al. 1997), although this has not been studied for dormant-season treatments. Crone et al. (2009) recommend maintaining as large an interval as possible between herbicide applications in order to minimize this possibility.

The results of this study may have been influenced by non-native, feral hogs. Congaree provides year-round, high-quality habitat and supports a large number of hogs, whose rooting behavior causes significant disturbance to the soil and ground-layer vegetation (Friebel and Jodice 2009). Disturbance from hogs may have increased the variability of results, making it more difficult to detect differences between treatments. It was assumed that damage was randomly distributed among treatments, and an ANOVA test of post-treatment percentage cover of hog disturbance did not detect significant differences between treatments.

In conclusion, the benefits to plant diversity expected from privet removal (Merriam and Feil 2002) are likely to outweigh short-term negative impacts from herbicides. No single treatment can be recommended as the preferred method for privet control in all areas. Mistblowers may have some advantage for minimizing damage to native plants. Metsulfuron caused less impact to sedges, but its advantages may be outweighed by potential risks to canopy trees. Vegetation surveys of treatment areas will be needed to identify species of concern that require special consideration. Areas with large sedge, rivercane, willow, or persimmon populations may need to be targeted for alternative treatments, such as cut-stump. There is potential for recruitment limitation in large treatment areas (Rinella et al. 2009), but these sites are surrounded by high-quality protected habitat, and planting or seeding of native species is not expected to be necessary. As with any invasive plant control effort, follow-up treatments will be required, and sites should be monitored to ensure that desired results are being achieved.

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CHAPTER FIVE

CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

Privet populations at Congaree appear to change the structure of the forest by increasing the density of the shrub layer. Privet-invaded areas show a reduced density of both shade tolerant and intolerant canopy tree species in the regeneration layer, particularly in the 1-5cm dbh size range. This could have a significant influence on the future structure of the forests of Congaree, particularly when combined with the effects of feral hog disturbance. Privet-invaded areas also showed a reduction in cover of sedges, although privet may inhibit the spread of the invasive grass *Microstegium vimineum*. Species richness, diversity, and cover of most growth forms did not differ between invaded and un-invaded plots. However, many of the invaded plots did not have closed canopies, and correlation analysis showed that richness, herbaceous cover, and canopy tree density (1-5cm dbh) are expected to decrease as privet density and cover increases. The potential impacts to canopy regeneration lend support to the justification of privet control efforts, although the effects of other sources of disturbance must also be considered.

No single combination of herbicide and applicator can be recommended as the best all-around herbicide treatment for Chinese privet at Congaree National Park. However, based on properties of the herbicides, glyphosate applied by mistblower may be the most feasible treatment method for the majority of privet-invaded areas at Congaree. The use of glyphosate over metsulfuron would simplify the timing and application of treatments. It would not be as crucial to monitor precipitation following treatments or ensure that canopy trees had not broken dormancy. Glyphosate is expected to damage sedge populations, but this effect may be reduced by applying it with mistblowers rather than backpack sprayers. Sedges are widespread throughout the park, which would make it difficult to protect them from glyphosate application, but also means that there are ample populations to recolonize treated areas. Also, the greater cover of sedges in un-invaded plots may indicate that sedges will be among the species that benefit most from privet removal. Rivercane is also expected to be damaged, but was uncommon in study plots. If privet overlaps with significant canebrakes in some areas, a more targeted treatment method or a metsulfuron application may be needed. Metsulfuron treatments showed significant impacts to some non-graminoid species groups, including ferns and tree and shrub seedlings.

Mistblowers in general appeared to have advantages over backpack sprayers both for privet control and limiting non-target impacts. They achieved a higher percentage control of privet, primarily due to their greater height of spray. Both applicator types almost completely defoliated privet within the spray zone, but mistblower treatments had a lower percentage of stems with live cambium remaining. This suggests that mistblower treatments worked more thoroughly and may have fewer re-sprouts in the future. Very little re-sprouting or germination of new privet seedlings was observed at 4-6 months following treatments, but more seedlings may establish after flooding. Mistblower treatments also showed lower impacts to tree and shrub seedlings, winter-green species, vines (<50cm), and total herbaceous cover. Backpack sprayers may also be feasible if they are the preferred applicator for logistical reasons. Measures such as extension wands may be needed to improve their height of spray, and somewhat greater impacts to sedges and other herbaceous-stratum plants would be expected.

A number of factors must be weighed in planning treatments. Many privet stems are taller than the practical field range of either backpack sprayers or mistblowers. Foliar sprays may not achieve satisfactory control of privet if the tallest stems are not first controlled with basal treatments, such as cut-stump or basal spray. Winter vegetation surveys of treatments areas would help to best prepare for potential non-target impacts. Canebrakes, dense sedge populations, rare plants, or potentially sensitive or valued winter-green species could be located and included in the planning process. In general, impacts to non-target plants are expected to be relatively small. Control of privet at Congaree would improve conditions in densely invaded areas, and prevent less-dense areas from spreading into a closed privet canopy. It is difficult to predict long-term changes in herbaceous plant communities due to changing competitive interactions, potential spread of other non-native species, and increases or decreases in feral hog populations. However, the long-term benefits to canopy tree regeneration and herbaceous plant cover are expected to outweigh the short-term negative impacts of herbicide application.