EVALUATING DORMANT-SEASON HERBICIDE APPLICATIONS FOR THE CONTROL OF CHINESE PRIVET (*LIGUSTRUM SINENSE*)

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ABSTRACT

Chinese privet (*Ligustrum sinense*) is an aggressive, nonnative shrub of the Southeastern United States. Its evergreen leaves allow for herbicide treatment in the dormant season when the impact to native species can be minimized. The purpose of this study was to determine which combination of chemical herbicide (glyphosate, metsulfuron, or a mixture of both) and application method (backpack sprayer or mistblower) applied during the dormant season would result in the greatest control of Chinese privet with minimal nontarget impacts. Study results suggest that herbicide, regardless of the chemical formulation, will kill more than 50 percent of the basal area of Chinese privet. However, glyphosate did impact native species that remained green and resulted in an increase in Japanese stiltgrass (*Microstegium vimineum*). Mistblowers were more effective at controlling Chinese privet than backpack sprayers regardless of herbicide. Although no differences in native species richness were found between the method of application, mistblowers also had fewer impacts on native flora, including tree and shrub reproduction, than backpack sprayers. Mistblowers are not commonly used for controlling invasive shrubs; however, their utility for controlling large and tall shrub infestations should be considered.

INTRODUCTION

Chinese privet (*Ligustrum sinense*) is a nonnative invasive shrub that has become ubiquitous throughout the Southeastern United States, especially in the region's floodplain and bottomland forests. Once prized as an ornamental hedge and favored for its glossy, often evergreen foliage and abundant panicles of white flowers, its bird- and water-dispersed fruit, rapid growth, and generalist habitat requirements have allowed Chinese privet to spread rapidly and form dense thickets, often impacting native flora and tree regeneration (Greene and Blossey 2014, Merriam and Feil 2002, Turner and others 2022, Wilcox and Beck 2007). Controlling large and dense invasive populations of Chinese privet has become a management priority for many natural areas in the Southeastern United States. However, its size and density can challenge resources, and subsequently, controlling it can have adverse consequences for native flora. For example, any individual stem control method, such as cut-stump applications or mechanical removal, is often extremely laborious and practically unfeasible at large scales.

Although generally considered evergreen to semi-evergreen, leaf retention on Chinese privet is variable and likely dependent on site and environmental factors, including shading, drought, and soil and air temperature (Munger 2003). Extended leaf phenology, whereby understory plants assimilate carbon prior to overstory canopy leaf expansion and after canopy senescence, is hypothesized as a trait of invasiveness (Fridley 2012). The evergreenness of Chinese privet and subsequently its extended leaf phenology are factors contributing to its success in deciduous hardwood forest understories. Extended leaf phenology may also confer an advantage for control with foliar herbicides. Because Chinese privet is capable of year-round photosynthesis (Morris and others 2002) and herbicide transport generally follows the

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direction of carbohydrates, which are moving toward the roots in winter, herbicide applications during this period may be quite effective (Harrington and Miller 2005, Miller 2005). However, low winter temperatures can slow herbicide uptake and transport (Frey and others 2007). Although foliar herbicide applications are less labor intensive than other methods (e.g., cut-stump, mechanical removal), broadcast herbicide applications are more likely to result in undesirable impacts on nontarget species, which suggests that applying foliar herbicides in winter may reduce undesirable nontarget impacts because most plants are dormant and leafless.

In field studies, foliar glyphosate applications demonstrate a high level of efficacy for the control of Chinese privet. Miller (2005) tested eight common herbicides and found glyphosate to be the most effective for growing-season Chinese privet control, followed by imazapyr and metsulfuron methyl (MSM). Harrington and Miller (2005) found that foliar glyphosate treatments at rates ranging from 1.7 to 6.7 kg acid equivalent per hectare provided up to 100 percent control in both fall (October and December) and spring (April) treatments. Ahuja (2003) also achieved 100 percent control with a December application of glyphosate. Glyphosate binds tightly and rapidly to soil particles, minimizing leaching or residual impacts to plants (Vereecken 2005) and several glyphosate formulations are approved for use near surface waters. However, glyphosate is highly nonselective and will kill or damage most plant types (Franz and others 1997). MSM has also been shown to be highly effective for controlling Chinese privet (Evans and others 2008, Miller 2005, Nespeca and Kemp 2006), although it has been less extensively tested in the dormant season. Several plants, including many grasses, have some resistance to MSM, which may be beneficial in broadcast applications. However, it does not bind as tightly to the soil as glyphosate and cannot be used near surface waters (Getsinger and others 2011). It does have the potential to cause residual impacts on some nontarget species, including canopy trees (Evans and others 2008). Subsequently, contrasting these herbicides for dormant-season applications of Chinese privet control and their resulting impact on nontarget flora is important for evaluating management trade-offs.

Backpack sprayers are commonly used for foliar herbicide applications, but backpack-mounted mistblowers may be able to provide similar control using a lower volume of herbicide (Nespeca and Kemp 2006). Additionally, mistblowers produce smaller, more regulated droplets than backpack sprayers, resulting in greater penetration of dense canopies and greater leaf interception (Devine and others 1992). However, mistblowers are heavy and require the transport of fuel and their smaller droplet size is more likely to result in herbicide drift. Backpack sprayers have the advantage of being lighter and smaller but are harder to maintain constant pressure and their larger droplets are more likely to fall through foliage and encounter ground flora (Devine and others 1992). Further, evaluating the outcome of foliar herbicide treatment by applicator type may improve the control of dense and large Chinese privet infestations while reducing nontarget impacts.

This study sought to answer the following management questions: 1) Can we use dormant-season foliar herbicide to control Chinese privet with less impact on native flora? 2) Could a mistblower be more effective for controlling large and dense Chinese privet infestations than a traditional backpack sprayer? 3) Would MSM provide better results, both in terms of Chinese privet control and reduced nontarget impacts, than glyphosate? To address these questions, we developed the following study objectives: 1) compare bottomland hardwood forest sites invaded by Chinese privet to similar but less invaded sites to establish a reference condition, 2) compare treatment combinations (application type plus herbicide formula) for the control of Chinese privet, and 3) determine which treatment combination has the least impact to native plants.

MATERIALS AND METHODS

Congaree National Park (33°47’59”N, 80°47’18”W) is located in the upper coastal plain of South Carolina, about 32 km 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 6.0 cm in winter to 13.8 cm in summer. The park is situated in the floodplain of the Congaree River, and it experiences flooding an average of 10 times per year with an average of one flood per year that covers the majority of the park (Doyle 2009, Patterson and others 1985). The Congaree floodplain is a highly productive system, with trees exhibiting high growth rates and reaching a very large size (Doyle 2009). Much of the area has a history of agriculture and logging, with some salvage logging occurring as recently as 1990 following Hurricane Hugo.

Our study sites were located between 40 and 215 m from the Congaree River (fig. 1), primarily within the natural levee zone of the floodplain, becoming inundated only during the highest flooding events and usually for only a few days (Doyle 2009). Study sites were characterized by floodplain soils, primarily Congaree loam, with a small amount of Toccoa loam (Soil Survey Staff 2013). The forest is characterized by bottomland hardwood vegetation. Common tree species were boxelder (*Acer negundo*), sugarberry (*Celtis laevigata*), elms (*Ulmus* spp.), sweetgum (*Liquidambar styraciflua*), and pawpaw (*Asimina triloba*). Common understory species included false nettle (*Boehmeria cylindrica*), sedges (*Carex* spp.), Japanese stiltgrass (*Microstegium vimineum*), and lianas such as grapes (*Vitis* spp.), crossvine (*Bignonia capreolata*), and poison ivy (*Toxicodendron radicans*). Chinese privet distribution was variable within study sites. Some areas had dense Chinese privet thickets with a closed canopy and little understory vegetation, while others were more widely spaced, allowing for abundant growth of herbaceous species.

This study was designed as a randomized complete block experiment, with five blocks located in large Chinese privet populations (fig. 1). Within each block, seven 20-m by 20-m vegetation plots were installed. An additional plot within each block was established outside (uninvaded)

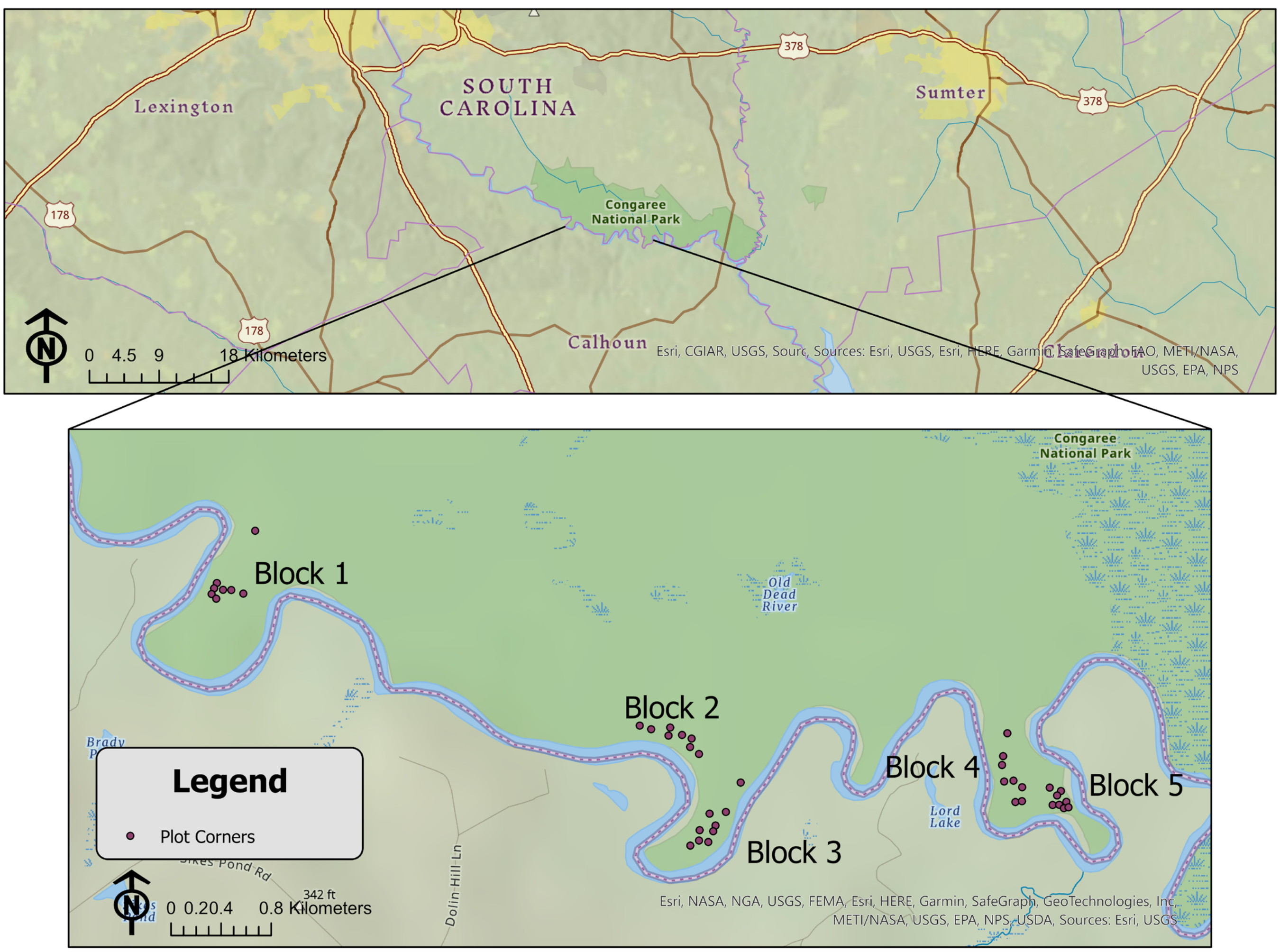

Figure 1—Study location and site locations for the Chinese privet project located within (above) the Congaree National Park with sites located in (below) the floodplain forest of the Congaree River in South Carolina.

of the Chinese privet infestation in an area similar to the invaded plots. Plots were quartered into four 10-m by 10-m modules. Corners were permanently marked with steel conduit stakes. All data were recorded on a per-module basis and divided into an 'herbaceous stratum' (height <50 cm) and a 'shrub stratum' (heights >50 cm, up to the maximum height of Chinese privet shrubs in the module). A visual estimate of cover was made for each species, including Chinese privet, by stratum. Woody stems >50 cm in height and rooted within the plot were tallied by size class and species. Any stem that branched from the main stem below 50 cm was considered an individual. Stems below breast height (137 cm) were tallied by height class (50–100 cm and >100–137 cm) and stems above breast height were tallied by diameter at breast height (d.b.h.) class (0–1, >1–2.5, >2.5–5, >5–10 cm, and 5 cm increments thereafter). For trees >40 cm d.b.h., individual measurements were recorded. Invaded plots were surveyed in the summer of 2011 prior to treatment. Posttreatment invaded plots and uninvaded plots were surveyed in the summer of 2012, 4 to 6 months following herbicide treatment.

Objective 1: Establish Reference Condition

To characterize differences between invaded and uninvaded communities, we compared plot averages from the midpoint of each cover class by species. We used total plot stem densities to compare woody abundance by species. We calculated species richness as 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 2021). Herbaceous-stratum species were grouped by growth form (annual herbs, perennial herbs, trees and shrubs, vines, ferns, sedges, and native grasses). Japanese stiltgrass was analyzed individually. Canopy tree species were analyzed as a group to investigate impacts on regeneration. This group included boxelder, bitternut hickory (*Carya cordiformis*), sugarberry, green ash (*Fraxinus pennsylvanica*), sweetgum, sycamore (*Platanus occidentalis*), laurel oak (*Quercus laurifolia*), cherrybark oak (*Quercus pagoda*), and elms. Analysis of variance (ANOVA) was used to compare structure of uninvaded plots to pretreatment 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 Chinese privet abundance and the abundance and diversity of nontarget plants.

Objective 2: Compare Treatment Outcomes for Chinese Privet

Within each block, the seven plots were randomly assigned an herbicide by applicator treatment combination or as an untreated control. Herbicide treatments were applied on January 11, 2012, by an experienced contract crew. Mistblowers were Stihl SR model 450, which is a backpack-mounted unit with a 14-L capacity. Their specified range is 14.5 horizontal meters and 13.0 vertical meters, with a droplet size generally ranging from 60 to 130 μm (Jessop and Bateman 2007). Backpack sprayers used were SP Systems Yard Tender model 101 with a 20-L capacity, which was pressurized by a hand-pump. Spray range and droplet size varied according to pressure. Glyphosate was mixed in a 5 percent volume to volume (v/v) solution, 49.53 g/L of Rodeo® liquid concentrate [53.8 percent active ingredient (a.i.)]. The MSM solution contained 0.47 g/L of AmTide MSM 60DF® powder concentrate (60 percent a.i.). The combination treatment contained 49.53 g glyphosate and 0.47 g MSM/3.78 L (1 gallon). The water conditioner Choice (Loveland Industries, Inc., Loveland, CO, 0.25 percent by volume), and the surfactant Rebound (Red River Specialties, Inc., Shreveport, LA, 0.5 percent v/v) were added to all spray mixes. The volume of spray applied to each plot varied depending on the density of Chinese privet and privet was sprayed to wet. Spray volumes ranged from 5.68 to 9.46 L per 400 m^2 plot, or approximately 142 to 236 L/ha. During the 2012 surveys, Chinese privet stems were assessed as either dead or alive. Two-way ANOVAs were used to analyze treatment effectiveness based on a factorial model with site, applicator, herbicide, and herbicide x applicator interaction as model effects. Treatment effectiveness was quantified as a percentage control to account for differences in pretreatment privet densities. ANOVAs were run for percentage control of privet basal area, canopy cover, and stem density of small (50–137 cm height), medium (0–5 cm d.b.h.), and large stems (>5–15 cm d.b.h.). Due to treatment irregularities, nine modules and one whole plot were excluded from the analysis (Vaughn 2013).

Objective 3: Evaluate Treatment Outcomes for Native Plants

For diversity (richness and Simpson's Index) and abundance variables, pretreatment data were subtracted from posttreatment data to analyze the change. Herbaceous-stratum species were grouped by growth form (annual herbs, perennial herbs, trees and shrubs, vines, ferns, sedges, native grasses, and invasive plants) and plants that remain green in the winter (wintergreen) to analyze whether herbicide treatments disproportionately affected a particular plant type, based on the sum of the change in percentage coverage for all species in each group. Diversity and abundance variables were analyzed with ANOVAs with site and treatment as model effects. Linear contrasts were applied to test for effects of applicator, herbicide, and applicator x herbicide interaction.

RESULTS

Chinese Privet Invasion Alters Forest Structure and Composition

Regeneration of native trees differed between invaded and uninvaded plots. Generally, uninvaded plots had greater densities of tree reproduction than invaded plots, with significantly more stems in the >1- to 2.5-cm- and >2.5- to 5cm-d.b.h. size classes (table 1). The density of shrubs (excluding Chinese privet) and reproduction of understory trees was greater in uninvaded plots than in invaded plots, except for the largest size class (>5–10 cm d.b.h.). However, when Chinese privet was included, stem densities were greatest in invaded plots except for the >1- to 2.5-cm d.b.h. class. Herbaceous coverage, sedges, and the cover of Japanese stiltgrass were greater in the uninvaded plots (table 2). As the basal area (BA) and coverage of Chinese privet increased, herbaceous cover (BA: r = -0.41, P <0.01; cover: r = -0.34, P = 0.03), species richness (BA: r = -0.40, P <0.01; cover: r = -0.48, P <0.01), and the density of overstory tree reproduction (>1-5 cm d.b.h.) (BA: r = -0.34, P = 0.03; cover: r = -0.41, P <0.01) decreased. Simpson's Index was not significantly correlated with Chinese privet abundance.

Effectiveness of Privet Control

The interaction of herbicide by applicator was not significant for the control of Chinese privet, except for small Chinese privet stems (table 3). There was no difference detected for the control of Chinese privet between glyphosate or MSM for other variables. Conversely, the control of Chinese privet was affected by applicator type, with mistblowers being more effective at reducing Chinese privet abundance than backpack sprayers (fig. 2). Control plots showed no change or a slight increase in Chinese privet density, indicating that the decrease found in treatment plots was directly related to herbicide application.

Community Impacts from Chinese Privet Control

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 and a concomitant increase in Japanese stiltgrass (fig. 3). The backpack-MSM and backpack-glyphosate treatments showed a significant decrease in the coverage of tree and shrub seedlings (fig. 3). Linear contrasts did detect some overall herbicide and applicator effects. Specifically, backpack sprayer plots had larger decreases in cover than mistblower plots for trees and shrubs (P = 0.05). Glyphosate plots had larger decreases in sedge cover than MSM (P = 0.01) or combination plots (P = 0.03). Glyphosate (P = 0.02) plots showed greater decreases in the cover of wintergreen species than MSM plots. There were nonsignificant treatment effects on species richness, annual herb cover, perennial herb cover, native grass cover, nonnative cover,

Table 1—Density (stems/400 m^2) of overstory tree reproduction, shrub stems (Chinese privet excluded), understory tree reproduction, and all woody stems by size class for Chinese privet invaded and uninvaded plots at Congaree National Park

	Size class	Invaded	Uninvaded	*P*
Overstory tree reproduction[1]	**50 cm height, 1.0 cm d.b.h.**	0.3	0.2	0.8846
	>1.0–2.5 cm d.b.h.	0.7	3.4	0.0052
	>2.5–5.0 cm d.b.h.	1.3	4.8	0.0060
	>5.0–10.0 cm d.b.h.	3.1	3.8	0.5931
	Total	5.4	12.2	0.0218
Shrub (Chinese privet excluded) stems and understory tree reproduction[2]	**50–100 cm height**	17.7	38.8	0.0153
	>100–137 cm height	6.5	14.8	0.0147
	0–1.0 cm d.b.h.	8.7	20.2	0.0007
	>1.0–2.5 cm d.b.h.	9.9	31.4	<0.0001
	>2.5–5.0 cm d.b.h.	11.8	23.4	0.0007
	>5.0–10.0 cm d.b.h.	7.4	7.0	0.8659
	Total	62.0	135.6	0.0005
All woody stems (Chinese privet included)	**50–100 cm height**	122.7	45.2	0.0125
	>100–137 cm height	59.0	15.0	0.0378
	0–1.0 cm d.b.h.	85.9	20.8	0.0001
	>1.0–2.5 cm d.b.h.	37.4	35.0	0.6680
	>2.5–5.0 cm d.b.h.	48.8	28.4	0.0063
	>5.0–10.0 cm d.b.h.	26.1	10.8	0.0004
	Total	380.0	155.2	0.0005

[1] Overstory trees: bitternut hickory, sugarberry, green ash, sweetgum, sycamore, laurel oak, cherrybark oak, elms.
[2] Understory trees: all other species, excluding those identified as overstory species.

Table 2—Percent coverage by plant growth form for Chinese privet invaded and uninvaded plots at Congaree National Park

Plant growth form	Invaded	Uninvaded	*P*
	~ ~ percent coverage ~ ~		
Canopy trees	1.78	1.00	0.2565
Understory 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 (<50 cm)	3.20	1.94	0.3067
Vines (≥50 cm)	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
Japanese stiltgrass	3.41	22.20	0.0004

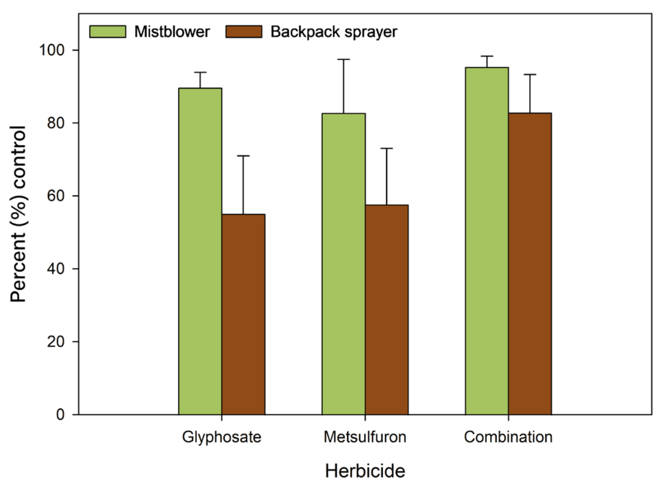

Figure 2—Percent control (+1 standard error) of Chinese privet stems by herbicide and applicator type at Congaree National Park.

Table 3—Model effects for Chinese privet control by herbicide, applicator, and their interaction and average percent control by applicator type for Chinese privet

Variable		*P*			Percent control	
		Applicator	Herbicide	Applicator x herbicide	Backpack	Mistblower
Basal area		0.0108	0.1640	0.5443	65.7	89.2
Stems[1] per 100 m²	**Small**	0.1551	0.8198	0.0254	90.8	94.5
	Medium	0.0213	0.4009	0.7394	84.6	92.5
	Large	0.0105	0.1542	0.4975	63.4	89.1
Canopy coverage		0.0321	0.6329	0.5105	90.3	98.0
Green stems[2]		0.0425	0.2092	0.3381	48.9	32.1

[1] Stem size: Small = 50–137 cm height; Medium = 0–5.0 cm d.b.h.; Large = >5.0–15.0 cm d.b.h.

[2] Values represent percentage of pretreatment 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.

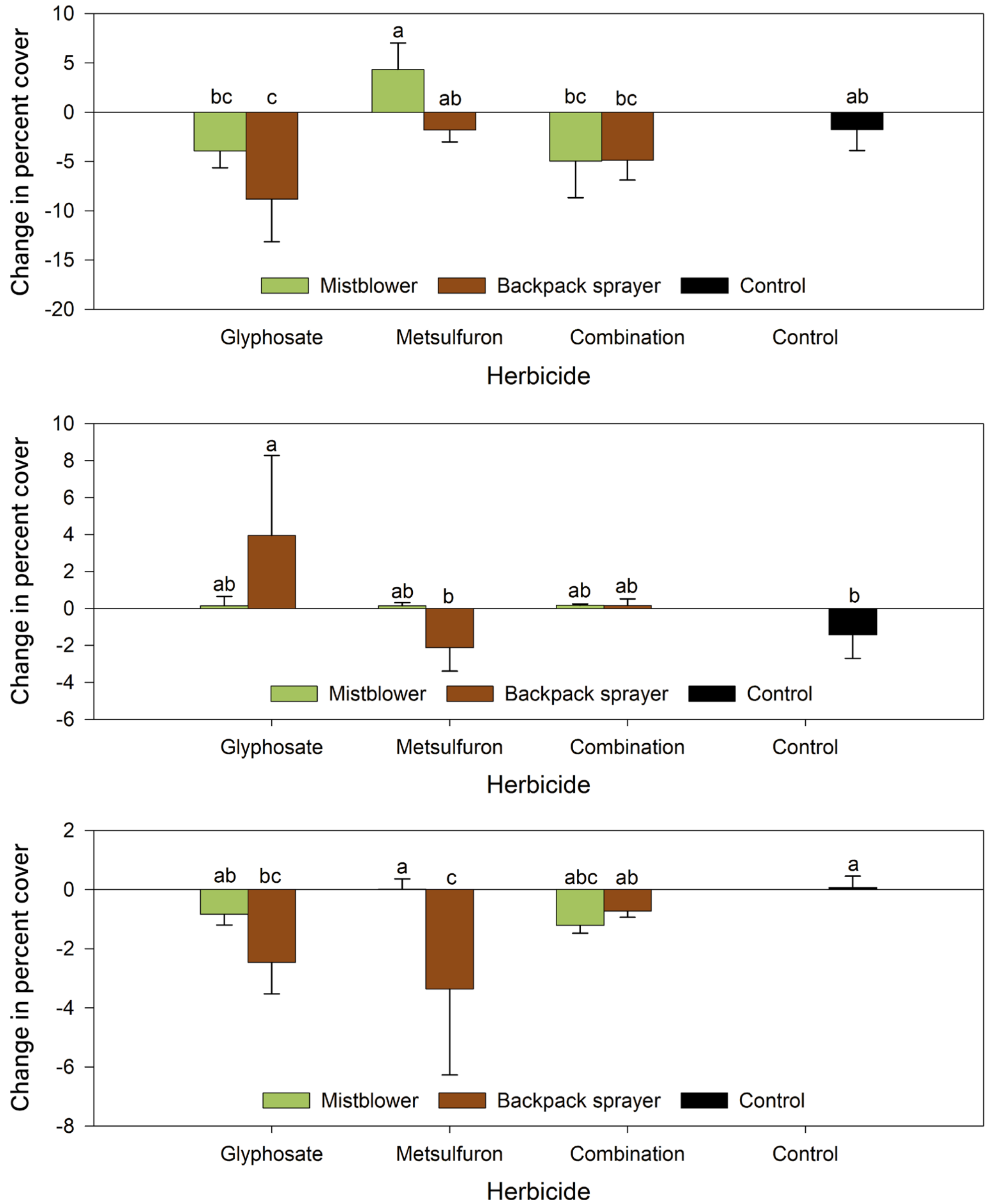

Figure 3—Change in percentage of cover (+ 1 standard error) following treatment for (top) sedges, (middle) Japanese stiltgrass, and (bottom) trees and shrubs. Treatments within graphs that do not share the same letter were significantly different at α = 0.05.

shrub-stratum vine cover, and shrub-stratum density when compared to the control.

DISCUSSION

Dense Chinese privet infestations change forest structure by increasing the net total density of the shrub layer. This increased shrub layer is associated with reduced canopy tree reproduction, potentially having long-term influences on forest structure, supporting findings that Chinese privet can lower the growth and survival of tree seedlings (Greene and Blossey 2014, Turner and others 2022). Chinese privet-invaded areas had lower sedge cover, but dense Chinese privet infestations may also inhibit Japanese stiltgrass. Species richness, diversity, and the cover of most growth forms did not differ between invaded and uninvaded plots. However, many of the invaded plots did not have closed canopies, and correlation analysis showed that richness, herbaceous cover, and canopy tree reproduction decreased as Chinese privet density and cover increased. Observational studies covering large geographic areas and a variety of habitat types have found similar results (Greene and Blossey 2014, Loewenstein and Loewenstein 2005, Merriam 2003). Chinese privet removal experiments have shown increases in cover (Hanula and others 2009) and growth (Osland and others 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 (Hanula and others 2009, Vidra and others 2007). While covarying factors must be considered, the weight of evidence suggests that direct competition with Chinese privet is a factor in the reduction of native plant abundance in invaded sites. Further, the potential long-term impacts on canopy regeneration and recruitment lend support to the justification of Chinese privet control efforts, although the effects of other sources of disturbance should also be considered.

Herbicide type was not found to be a significant factor in this study. Glyphosate and MSM were both effective, as seen in previous studies (Harrington and Miller 2005, Miller 2005). In the absence of significant differences in effectiveness between herbicides, glyphosate adsorbs tightly to soils, limiting the chance of offsite transport (Vereecken 2005). Metsulfuron, however, is soil-active and while it may reduce impacts on sedges and rivercane, it has an increased risk 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. Based on observation, sections of the Chinese privet canopy were generally either completely defoliated or appeared completely healthy with no signs of herbicide damage. Damage from both glyphosate and MSM can appear as yellow or brown spots on leaves, or leaf or vein discoloration (Obrigawitch and others 1998). The lack of visible damage or deformity suggests that the remaining live stems were not contacted by herbicide spray, and that differences between treatment combinations were primarily a reflection of the spray coverage from the applicator and not the herbicide type.

Mistblowers provided more complete control of Chinese privet than did backpack sprayers. They achieved higher percentage control of shrub-stratum Chinese privet measured as density, basal area, and cover. Mistblower plots also had a lower percentage of stems remaining green after treatment. The height of spray appears to be a major factor in the superior performance of mistblowers for controlling Chinese privet. Generally, mistblowers overall showed fewer nontarget impacts than backpack sprayers. Backpack sprayers had greater reductions in total herbaceous cover, trees and shrubs, vines, and wintergreen 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 Chinese privet canopy and contact lower layers of sensitive vegetation. Logistical issues, such as weight and maneuverability of equipment, complications related to use of motorized equipment in a wilderness, cost per acre, 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, but impacts to sedges and other herbaceous-stratum plants may still be anticipated.

Several factors must be weighed in planning invasive plant treatments, including the size and density of the targeted invader and the potential for nontarget impacts based on the control method used. Many Chinese privet stems are taller than the practical field range of either backpack sprayers or mistblowers. Further, no single combination of applicator and herbicide was clearly superior at minimizing impacts on native plant communities and overall, negative impacts on native plants were limited. However, the backpack-glyphosate treatment reduced the coverage of sedges and increased the coverage of Japanese stiltgrass. The presence of recently killed sedge clumps in treated plots suggested that Japanese stiltgrass readily invaded following the disturbance caused by management. Conversely, tree and shrub cover significantly declined in the backpack-MSM treatment. The change in tree and shrub cover was heavily influenced by two plots with unusually high cover of maple (*Acer* spp.) seedlings. Winter vegetation surveys of treatment areas would help to prepare and mitigate potential nontarget impacts when using broadcast herbicide applications. Canebrakes, dense sedge populations, rare plants, or potentially sensitive or valued wintergreen species could be detected during the preplanning process. In general, impacts to nontarget plants are expected to be relatively small and the long-term benefits to canopy tree regeneration and herbaceous plant cover are expected to outweigh the short-term negative impacts of herbicide application.

CONCLUSIONS

Bottomland forests invaded by Chinese privet have midstory densities that are greater than uninvaded reference conditions. While this increase in the shrub layer may diminish the establishment and growth of Japanese stiltgrass, it also impedes native tree regeneration. Our study suggests that both glyphosate and MSM are effective for controlling Chinese privet in the dormant season. However, glyphosate may also impact native sedge species resulting in opportunities for secondary invasion by Japanese stiltgrass. Mistblowers may be more effective at reaching the tops of tall invasive shrubs and through their smaller droplet size result in greater foliar interception and subsequent mortality of targeted plants and reduced risk to nontarget plants by fewer droplets falling through the invasive canopy.

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REFERENCES

Ahuja, G. 2003. Chemical control of Chinese privet (*Ligusrtum* [sic] *sinense*). M.S. thesis. Athens, GA: University of Georgia. 47 p.

Devine, M.; Duke, S.O.; Fedtke, C. 1992. Physiology of herbicide action. Englewood Cliffs, NJ: PTR Prentice Hall. 441 p.

Doyle, T.W. 2009. Modeling flood plain hydrology and forest productivity of Congaree Swamp, South Carolina. Scientific Investigations Report 2009-5130. Denver, CO: U.S. Geological Survey. 46 p. https://doi.org/10.3133/sir20095130.

Evans, C.; Bargeron, C.; Moorehead, D. [and others]. 2008. Invasive plants of Georgia's forests: Identification and control. BW-2008-01. Athens, GA: Georgia Forestry Commission, University of Georgia, and U.S. Department of Agriculture Forest Service. 10 p.

Franz, J.E.; Mao, M.K.; Sikorski, J.A. 1997. Glyphosate: a unique global herbicide. Monograph 189. Washington, DC: American Chemical Society. 653 p.

Frey, M.N.; Herms, C.P.; Cardina, J. 2007. Cold weather application of glyphosate for garlic mustard (*Alliaria petiolata*) control. Weed Technology. 21: 656–660. https://doi.org/10.1614/WT-06-153.1.

Fridley, J.D. 2012. Extended leaf phenology and the autumn niche in deciduous forest invasions. Nature. 485: 359–362. https://doi.org/10.1038/nature11056.

Getsinger, K.D.; Netherland, M.D.; Stubbs, D.R. 2011. Aquatic herbicide registration new model. In: Leslie, A.R.; Westbrooks, R.G., eds. Invasive plant management issues and challenges in the United States: 2011 overview. ACS Symposium Series vol. 1073. Washington, DC: American Chemical Society: 45–50. https://doi.org/10.1021/bk-2011-1073.ch005.

Greene, B.; Blossey, B. 2014. Patterns of privet: urbanizing watersheds, invasive *Ligustrum sinense*, and performance of native plant species in piedmont floodplain forests. Ecosystems. 17: 990–1001. https://doi.org/10.1007/s10021-014-9774-4.

Hanula, J.L.; Horn, S.; Taylor, J.W. 2009. Chinese privet (*Ligustrum sinense*) removal and its effect on native plant communities of riparian forests. Invasive Plant Science and Management. 2: 292–300. https://doi.org/10.1614/IPSM-09-028.1.

Harrington, T.B.; Miller, J.H. 2005. Effects of application rate, timing, and formulation of glyphosate and triclopyr on control of Chinese privet (*Ligustrum sinense*). Weed Technology. 19: 47–54. https://doi.org/10.1614/WT-03-220R2.

Jessop, N.; Bateman, R. 2007. Optimising the use of motorised knapsack mistblowers for control of insect pests of cocoa. International Pest Control. 49: 86–88.

Loewenstein, N.J.; Loewenstein, E.F. 2005. Non-native plants in the understory of riparian forests across a land use gradient in the Southeast. Urban Ecosystems. 8: 79–91. https://doi.org/10.1007/s11252-005-1420-7.

Magurran, A.E. 2021. Measuring biological diversity. Current Biology. 31: R1174–R1177. https://doi.org/10.1016/j.cub.2021.07.049.

Merriam, R.W. 2003. The abundance, distribution and edge associations of six non-indigenous, harmful plants across North Carolina. Journal of the Torrey Botanical Society. 130: 283–291. https://doi.org/10.2307/3557546.

Merriam, R.W.; Feil, E. 2002. The potential impact of an introduced shrub on native plant diversity and forest regeneration. Biological Invasions. 4: 369–373. https://doi.org/10.1023/A:1023668101805.

Miller, J.H. 2005. Chinese privet control with herbicide foliar sprays. Wildland Weeds. 8(3): 5–7.

Morris, L.L.; Walck, J.L.; Hidayati, S.N. 2002. Growth and reproduction of the invasive *Ligustrum sinense* and native *Forestiera ligustrina* (Oleaceae): implications for the invasion and persistence of a nonnative shrub. International Journal of Plant Sciences. 163: 1001–1010. https://doi.org/10.1086/342632.

Munger, G.T. 2003. *Ligustrum* spp. In: Fire Effects Information System. Missoula, MT: U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory.

Nespeca, M.C.; Kemp, C. 2006. Chinese privet control: economic viability and efficacy of dormant season foliar low-volume herbicide treatments. The Nature Conservancy.

Obrigawitch, T.T.; Cook, G.; Wetherington, J. 1998. Assessment of effects on non-target plants from sulfonylurea herbicides using field approaches. Pesticide Science. 52: 199–217. https://doi.org/10.1002/(SICI)1096-9063(199803)52:3<199::AID-PS696>3.0.CO;2-Yopen_in_newISSN0.

Osland, M.J.; Pahl, J.W.; Richardson, C.J. 2009. Native bamboo [*Arundinaria gigantea* (Walter) Muhl., Poaceae] establishment and growth after the removal of an invasive non-native shrub (*Ligustrum sinense* Lour., Oleaceae): implications for restoration. Castanea. 74: 247–258. https://doi.org/10.2179/08-036R2.1.

Patterson, G.G.; Speiran, G.K.; Whetstone, B.H. 1985. Hydrology and its effects on distribution of vegetation in Congaree Swamp National Monument, South Carolina. Water-Resources Investigations Report 85-4256. Columbia, SC: U.S. Department of the Interior, Geological Survey. 31 p. https://doi.org/10.3133/wri854256.

Soil Survey Staff. 2013. Web soil survey. U.S. Department of Agriculture, Natural Resources Conservation Service. http://websoilsurvey.sc.egov.usda.gov/. [Date accessed: January 10, 2013].

Turner, T.N.; Dean, T.J.; Kuehny, J.S. 2022. Long-term suppression of hardwood regeneration by Chinese privet (*Ligustrum sinense*). Frontiers in Forests and Global Change. 4: 725582. 7 p. https://doi.org/10.3389/ffgc.2021.725582.

Vaughn, K.H. 2013. Evaluation of dormant-season herbicide treatment methods for Chinese privet at Congaree National Park. M.S. thesis. Clemson, SC: Clemson University. 101 p.

Vereecken, H. 2005. Mobility and leaching of glyphosate: a review. Pest Management Science. 61: 1139–1151. https://doi.org/10.1002/ps.1122.

Vidra, R.L.; Shear, T.H.; Stucky, J.M. 2007. Effects of vegetation removal on native understory recovery in an exotic-rich urban forest. Journal of the Torrey Botanical Society. 134: 410–419. https://doi.org/10.3159/1095-5674(2007)134[410:EOVRON]2.0.CO;2.

Wilcox, J.; Beck, C.W. 2007. Effects of *Ligustrum sinense* Lour. (Chinese privet) on abundance and diversity of songbirds and native plants in a southeastern nature preserve. Southeastern Naturalist. 6: 535–550.