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Management of *Microstegium vimineum* Invasions and Recovery of Resident Plant Communities

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Abstract

Restoration of communities invaded by exotic plants requires effective eradication of the invader and reestablishment of the resident plant community. Despite the commonly cited need for techniques to accomplish such goals, studies that test strategies for removing invasive plants, monitor effects on resident communities, and incorporate replicate sites are generally lacking. *Microstegium vimineum* is an exotic annual grass that is rapidly invading forests in the eastern United States and threatening to reduce biodiversity and inhibit forest regeneration. I conducted a field experiment at eight sites over two growing seasons in southern Indiana to evaluate hand-weeding (HW), a postemergent grass-specific herbicide (POST), and the postemergent herbicide plus a preemergent herbicide (POST + PRE) for removing *Microstegium*. Compared to reference plots (REF), the three treatments each reduced *Microstegium* biomass at the end of the growing seasons to relatively low levels. However, after the second year of the experiment, POST and POST + PRE resulted in very little spring cover of *Microstegium*, but HW plots were significantly reinvaded. HW and POST, but not POST + PRE, increased resident plant community productivity and spring resident community cover compared to reference plots. The amount of light at the research sites did not alter the effectiveness of treatments, but the recovery of resident communities was positively correlated with light availability under HW and POST + PRE. These results indicate that natural systems invaded by *Microstegium* can be restored using the POST or HW treatments, which will effectively remove the invasion and allow the resident plant community to recover when used over multiple growing seasons.

Key words: hand-weeding, invasive exotic grass, light availability, postemergent grass-specific herbicide, preemergent herbicide, resident community productivity.

Introduction

Invasions of exotic plants can reduce biodiversity (Mack et al. 2000), change the physical features of systems (Vitousek et al. 1987; Ehrenfeld 2003), and modify ecosystem functions (Mack & D'Antonio 1998; Titus & Tsuyuzaki 2003). Therefore, eradication of invasive plants is frequently a critical step in the restoration of degraded natural systems (Hulme 2006). However, for many invasive plant species, little is known about the efficacy of removal techniques or how removal methods affect resident plant community recovery. Rigorously tested methods for eradicating exotic plant invasions and restoring resident plant communities are a primary need of restoration practitioners (Clewell & Rieger 1997; Byers et al. 2002).

Although numerous techniques are available for managing exotic plant invasions, including herbicides, burning, mowing, biocontrol, and removal by hand (Czarapata 2005), few experiments have comprehensively tested these techniques within an ecological context (but see Carlson & Gorchov 2004; Adams & Galatowitsch 2006). Using removal methods without thoroughly testing their effectiveness and nontarget effects can lead to routine implementation of inappropriate techniques. Removal methods have commonly been used that do not efficiently remove the problem plant, significantly damage the resident plant community (Louda et al. 2005), or result in conditions that allow other invasive plants to recolonize the area (Musil et al. 2005). Furthermore, experiments to test removal techniques are often conducted in pots or mesocosms, at small scales in experimental fields, or at one or few field sites. Large-scale experiments, conducted over replicate sites and under realistic ecological conditions, are needed to test removal techniques across the range of biotic and abiotic conditions where a particular exotic plant invades. Many exotic plants colonize sites with a range of environmental characteristics, plant community types, and land use histories. Therefore, management strategies should consider how site variation might influence removal techniques and recovery of the resident plant community. If site conditions alter the effectiveness of techniques, nontarget impacts, or resident plant community recovery, then multiple management plans may need to be developed to successfully manage invasions by a single plant species.

In addition to considerations of site conditions, experiments should be conducted over multiple growing seasons to determine how removal techniques affect the degree to

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which an exotic plant reestablishes at a site in following years and whether removing the invasive plant results in resident plant community recovery. Monitoring populations over multiple seasons is particularly important if the invasive plant has suppressed native vegetation for an extended period of time such that the seed bank of resident species has been depleted (Cione et al. 2002; Marchante et al. 2004). If so, removing the invasive plant may result only in bare ground, which can encourage additional plant invasions (Masters & Sheley 2001). In such cases, a diverse mixture of seed from native species may need to be added to restore the resident plant community (Sheley & Half 2006).

Japanese stiltgrass (*Microstegium vimineum* (Trin.) A. Camus; Fig. 1) is an exotic annual C_4 grass that is rapidly invading forests of the eastern United States (Winter et al. 1982; Horton & Neufeld 1998). *Microstegium* is native to southeast Asia and was introduced to the eastern United States in the early 1900s (Fairbrothers & Gray 1972). It is currently found in at least 21 states and is listed as a noxious, banned weed in Alabama, Massachusetts, and Connecticut (USDA & NRCS 2005). Invasions of *Microstegium* create dense, monospecific stands that reduce native plant diversity and productivity, inhibit forest regeneration, and threaten to alter forest species composition and successional trajectories (Flory & Clay, unpublished data; Oswalt et al. 2007). Importantly, areas invaded by *Microstegium* are not easily recolonized by native species (Barden 1987). *Microstegium* produces hundreds of seeds per plant (Tu 2000), which are dispersed by water, animals, and anthropogenic activities. In addition, it can colonize nearby uninvaded areas through the production of lateral tillers (Cheplick 2006). *Microstegium* frequently invades moist areas such as bottomland hardwood forest, riparian areas, roadsides, and stream banks (Fig. 1; Redman 1995; Tu 2000), but it is also commonly found on ridgetops and in wildlife openings, blowdowns, and areas recently harvested for timber. It is highly shade tolerant (Horton & Neufeld 1998) and can produce seed in the deep shade of interior forests (Winter et al. 1982). Although *Microstegium* is invasive across a range of environmental conditions, recent experimental evidence suggests that it may have the greatest detrimental effects on native plants in part-shade environments (Flory et al. 2007).

Figure 1. Forest understory invaded by *Microstegium* at the Big Oaks National Wildlife Refuge—BURN site (top), close-up of *Microstegium* (inset), and resident community recovery in a POST-treated plot at the Big Oaks National Wildlife Refuge—OH site (bottom). The dashed line represents the approximate boundary of the 2 × 2–m plot.

Controlling the spread of *Microstegium* and restoring invaded areas are primary concerns of many land managers throughout the eastern United States (Czarapata 2005). Numerous pre- and postemergent herbicides are known to be effective in killing *Microstegium* (Judge et al. 2005*a*), but only a single study at two sites (Judge et al. 2005*b*) has examined the control of *Microstegium* in nature, and no study has monitored the restoration of native plant communities following *Microstegium* removal. Furthermore, because studies of herbicide effectiveness have been conducted in controlled greenhouse and outdoor container experiments (Judge et al. 2005*a*) or at few sites (Judge et al. 2005*b*), it is unknown how abiotic site variability might affect *Microstegium* removal efforts and restoration success. In addition to herbicides, other methods to remove *Microstegium* have included burning, mowing, string trimming, and hand-weeding (Tu 2000), but the effectiveness of these techniques and their impacts on resident plant communities have not been experimentally tested.

I conducted an experimental field study at eight sites in southern Indiana to examine the effectiveness of removal techniques for managing *Microstegium* invasions and the impact of those treatments on resident plant community recovery. In addition, I implemented a seed addition treatment to determine if recovery of resident plant communities was limited by resident plant seed availability. I evaluated the overall response of the resident community to the removal of *Microstegium* in terms of resident plant community productivity and the percent cover of resident plant species. An increase in productivity or cover would indicate that the resident community had been suppressed by *Microstegium* and was recovering following its removal. My goal was to answer the following specific questions: (1) Is hand-weeding, postemergent grass-specific herbicide, or postemergent grass-specific herbicide plus preemergent herbicide most effective in removing *Microstegium* invasions? (2) How do these removal treatments affect resident plant community recovery? (3) Does light availability at a site determine the effectiveness of removal treatments or recovery of resident plant communities? (4) Does the addition of native plant seed reduce future *Microstegium* invasions or aid in the recovery of native communities?

Methods

Study Sites

I established eight study sites at least 1 km apart at four public properties in southern Indiana, including two state forests, a national forest, and a national wildlife refuge (Table 1). I intentionally chose properties and sites that spanned a wide range of light availability, soil moisture, and forest successional ages and sites that had a variety of land use histories (Table 1).

The study sites consisted of mixed Oak (*Quercus*)–Hickory (*Carya*) or Beech (*Fagus*)–Maple (*Acer*) forests (Woodall et al. 2005) depending on the land use history of the site and the successional age of the forest. Other canopy tree species at the sites included Tulip poplar (*Liriodendron tulipifera*), Black walnut (*Juglans nigra*), and Elm (*Ulmus* spp.). Understory vegetation consisted of *Rubus* spp., Sassafras (*Sassafras albidum*), Greenbriar (*Smilax* spp.), Spicebush (*Lindera benzoin*), Sumac (*Rhus* spp.), and *Viburnum* spp. Southern Indiana receives an average of 102.10 cm of precipitation per year (Noble et al. 1990), and gravimetric soil moisture varied from 10.5 to 22.3% at the study sites when evaluated in late July 2005. The average daily maximum temperature in southern Indiana during the summer months is 29.4°C (Noble et al. 1990).

Experimental Design

In June 2005, I established forty 2 × 2–m plots at each site (320 plots total) with at least 2 m separating adjacent plots. Plots were arbitrarily arranged in areas within sites that had dense, continuous *Microstegium* populations, and plots were positioned to avoid large trees, downed logs, and standing water. Within each site, plots were randomly assigned one of four conditions (10 replicates per treatment per site): reference plots (REF), hand-weeded (HW), grass-specific postemergent herbicide (POST), or postemergent herbicide plus a preemergent herbicide (POST + PRE). The HW treatment consisted of pulling all *Microstegium*, while avoiding native species, and placing the *Microstegium* outside of the plot. The POST treatment consisted of 0.21 kg active ingredient (ai) per hectare of fluazifop-P-butyl (12 oz/ac Fusilade DX; Syngenta Crop Protection, Inc., Greensboro, NC, U.S.A.) mixed with 14.8 mL of a nonionic adjuvant surfactant (Surf Plus 584; Townsend Chemical Division, Muncie, IN, U.S.A.). For the POST + PRE treatment plots, the PRE herbicide was applied in the spring following the application of the postemergent herbicide. The PRE herbicide was 1.34 kg ai/ha of pendimethalin (19.2 oz/ac Pendulum AquaCap; BASF, Research Triangle Park, NC, U.S.A.). Both herbicides were applied with backpack sprayers at 40 psi. HW and POST treatments were conducted the fourth week of July 2005 and the third week of June 2006. During this time period in southern Indiana, *Microstegium* seeds have germinated and seedlings are approximately 10–20 cm in height. PRE applications were completed the first week of April 2006 and the second week of April 2007, which is 2–4 weeks prior to *Microstegium* seed germination.

Five of the 10 replicates per treatment per site were randomly selected to receive a seed addition treatment to determine if adding seed would increase resident species productivity and decrease future invasions of *Microstegium*. Seed of 10 species of native woodland herbaceous graminoids and forbs (Table 2; seeds collected from natural areas in Indiana by Heartland Restoration Services, Ft. Wayne, IN, U.S.A.) were mixed with sterilized sand to aid

Table 1. Properties, sites, locations, land use histories, and forest successional ages of the eight research sites.

Property—Site	*Location*	*Land Use History*	*Successional Age*
MMSF—ORC	lat 39°32′46″N, long 86°41′47″W	Old log yard	Early
MMSF—ROW	lat 39°33′35″N, long 86°42′24″W	Power line right-of-way	Not forested
JWSF	lat 38°84′57″N, long 86°05′00″W	Wildlife opening	Not forested
HNF—IL	lat 38°19′84″N, long 86°63′98″W	Old roadbed	Mid
HNF—SL	lat 38°05′95″N, long 86°65′86″W	Bottomland forest	Late
BONWR—WG	lat 39°04′98″N, long 85°38′82″W	Walnut-dominated forest	Late
BONWR—OH	lat 39°01′81″N, long 85°43′72″W	Old homesite	Mid
BONWR—BURN	lat 38°98′43″N, long 85°45′31″W	Agricultural land	Mid

Successional ages: early, less than 30 years; mid, 30–60 years; late, more than 60 years. MMSF, Morgan-Monroe State Forest; JWSF, Jackson-Washington State Forest; HNF, Hoosier National Forest; BONWR, Big Oaks National Wildlife Refuge.

Table 2. Species used in the seed addition treatment including their growth form and seeding rate per 2 × 2–m plot.

Species	*Growth Form*	*Estimated Number of Seeds Added per Plot*
Bidens cernua	Forb	190
Carex frankii	Sedge	195
C. stipata	Sedge	373
C. tribuloides	Sedge	385
C. vulpinoidea	Sedge	294
Eupatorium perfoliatum	Forb	77
E. rugosum	Forb	208
Heliopsis helianthoides	Forb	319
Rudbeckia triloba	Forb	66
Vernonia gigantea	Forb	72

The number of seeds added per plot was estimated by weight.

in spreading and broadcast over the selected plots during the first week of January 2006.

Data Collection

To quantify the effectiveness of the treatments in reducing *Microstegium* biomass and the impact of the treatments on the resident community, a destructive harvest was conducted during the third week of August 2005 and 2006. To minimize edge effects in the plots, the center 1-m^2 area of each 2 × 2–m plot was divided into four 0.5 × 0.5–m quadrats, and one quadrat was randomly selected to be harvested in 2005. The quadrat diagonally opposite from the quadrat harvested in 2005 was harvested in 2006. For each harvest, all vegetation except for trees larger than 2 cm basal diameter was removed from the selected quadrat in each plot, sorted to species in the lab, dried at 60°C for 72 hours, and weighed.

In the third week of June 2006 and 2007, I quantified the standing vegetation within each plot to determine if treatment effects persisted from one season to the next. I determined percent cover of *Microstegium* and resident species in 2006 and *Microstegium*, resident species, and bare ground in 2007 using a 0.5 × 0.5–m polyvinyl chloride (PVC) frame divided into hundred 5 × 5–cm squares. In spring 2006, the frame was placed over the quadrat diagonally opposite from the quadrat that was harvested in 2005. In spring 2007, the frame was placed over the next quadrat clockwise from the quadrat harvested in 2006. PVC legs (40 cm long) were attached to the frame so I could assess the vegetation cover while standing directly overhead.

To determine if the effectiveness of the treatments or the response of the resident community was correlated with available light at each site, I measured light above each plot in June 2006. I took one light measurement per plot by holding a light meter at waist height while standing on the north side of each plot (AccuPAR Linear PAR/LAI ceptometer; Decagon Devices, Inc., Pullman, WA, U.S.A.). All measurements were taken within an hour and a half of solar noon under cloudless skies. Measures of photosynthetically active radiation (PAR) were converted to percent available light by dividing the PAR value for each plot by the PAR value measured near each site in full sun on the same day.

Statistical Analysis

I used analyses of variance (ANOVAs) to analyze the effects of site, treatment (REF, HW, POST, and POST + PRE), and year (2005 and 2006) on *Microstegium* and resident community biomass (Proc GLM; SAS Institute, Inc. 2002). *Microstegium* and resident community biomass data were log transformed to meet assumptions of normality. I also used ANOVA to evaluate the effect of site, treatment, and seed addition treatment (native seed added vs. no seed added) only on the 2006 harvest data because the seed addition treatment had not been completed prior to the 2005 harvest. I analyzed the spring percent cover of *Microstegium*, resident species, and bare ground (2006 only) using separate ANOVAs with site, treatment, year, and seed addition treatment as effects. There were no significant effects of the native seed addition treatment on native plant cover, so data from seed addition plots were pooled with no seed addition plots in analysis of native plant cover. Post hoc Tukey tests were used to evaluate differences among treatments and years. I evaluated the effect of average percent available light at each site on *Microstegium* biomass and resident community productivity using linear regression analysis (Proc REG; SAS Institute, Inc. 2002).

Results

Treatment Effects on *Microstegium*

The three removal treatments varied in their effectiveness at reducing *Microstegium* biomass compared to the REF plots, and there were large differences in treatment effects between the 2 years of the experiment. HW and POST reduced the biomass of *Microstegium* by 98 and 99%, respectively, compared to the REF plots ($\bar{X} \pm$ SE *Microstegium* biomass in REF plots 37.7 ± 3.1 g/0.25 m^2) at the end of the 2005 growing season (Table 3; Fig. 2A). Although the POST treatment was statistically more effective than HW at reducing *Microstegium* biomass in 2005 (Fig. 2A), both treatments resulted in less than 1.0 g of *Microstegium* biomass per 0.25-m^2 quadrat. In 2006, the HW treatment was less effective at reducing *Microstegium* biomass (87% reduction) than either the POST treatment (99% reduction) or the POST + PRE treatment (99% reduction), which did not differ from each other (Table 3; Fig. 2A). The HW treatment was not as effective in 2006 as it was in 2005, but the effectiveness of the POST treatment did not differ between the 2 years.

In 2006 and 2007, all three treatments reduced the spring cover of *Microstegium* compared to the REF plots. Among the treatments, POST + PRE was consistently more effective than POST, which was more effective than

Table 3. Results of four separate ANOVAs for the effects of site, treatment, year, and interactions on *Microstegium* biomass, *Microstegium* cover, resident community biomass, and resident community cover.

		Microstegium Biomass		*Microstegium Cover*		*Resident Community Biomass*		*Resident Community Cover*	
Source	*df*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Site	7	32.77	**<0.0001**	35.65	**<0.0001**	18.11	**<0.0001**	20.60	**<0.0001**
Treatment	3	1807.28	**<0.0001**	4.67	**0.0031**	21.29	**<0.0001**	799.02	**<0.0001**
Year	1	0.09	0.77	35.81	**<0.0001**	7.51	**0.0063**	75.70	**<0.0001**
Site × treatment	21	10.25	**<0.0001**	1.05	0.40	1.84	**0.0128**	6.14	**<0.0001**
Site × year	7	5.52	**<0.0001**	2.72	**0.0089**	3.67	**0.0007**	4.02	**0.0003**
Treatment × year	3	47.44	**<0.0001**	1.78	0.15	0.47	0.71	10.90	**<0.0001**
Site × treatment × year	21	3.46	**<0.0001**	1.98	**0.006**	1.65	**0.0351**	2.78	**<0.0001**

Biomass data are from the fall of 2005 and 2006, and cover data are from the spring of 2006 and 2007. Resident community results reported here are from data averaged across plots, regardless of the seed addition treatment ($n = 10$ per treatment per site). See text for the results of the seed addition treatment. Bold indicates significance at $p < 0.05$. *df*, degrees of freedom.

HW (Table 3; Fig. 2B). The POST + PRE treatment was equally effective at reducing *Microstegium* cover in spring 2006 and 2007, resulting in less than 2% cover for both years. The POST and HW treatments were both more effective at reducing *Microstegium* spring cover in the second year of the experiment than the first year, but neither was as effective as the POST + PRE treatment. POST reduced spring *Microstegium* cover by 74% in 2006 and 95% in 2007, whereas HW reduced *Microstegium* cover by 26% in 2006 and 37% in 2007 (Table 3; Fig. 3a).

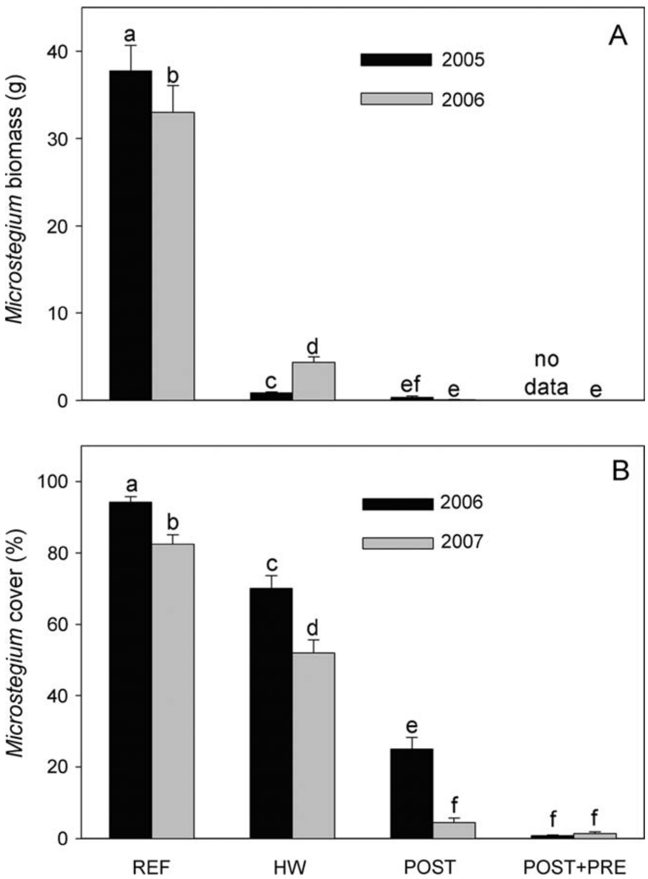

Figure 2. (A) Average (± SE) *Microstegium* biomass per 0.25-m^2 quadrat at the end of the season in 2005 and 2006 and (B) average (± SE) *Microstegium* cover per quadrat in the spring of 2006 and 2007 for the REF, HW, POST, and POST + PRE plots. Different letters indicate significant differences at $p < 0.05$. No data are shown for *Microstegium* biomass under POST + PRE in 2005 because the PRE treatment had not yet been applied.

Treatment Effects on Resident Plant Communities

In 2005, the HW and POST treatments did not affect the productivity of the resident plant community compared to the REF plots (Table 3; Fig. 3A). However, in 2006, removal of *Microstegium* using the HW and POST treatments resulted in a significant recovery of the resident plant community such that there was 48% greater resident community productivity under the HW treatment and 38% greater productivity under the POST treatment (Figs. 1 & 3A) compared to the REF plots. There was also a marked but nonsignificant ($p = 0.11$) 37% increase in productivity under the POST + PRE treatment (Table 3; Fig. 3A).

Resident plant community cover in spring 2006 was significantly greater under the HW and POST treatments than in the REF plots, but the POST + PRE treatment did not affect resident plant community cover (Table 3; Fig. 3B). By the spring of 2007, the resident community had recovered equally under all three treatments, but the percent cover of resident species under the POST + PRE treatment was not significantly greater than in the REF plots. HW increased resident community cover by 16%, POST by 18%, and POST + PRE by 11% (Table 3; Fig. 3B).

The effectiveness of POST + PRE in removing *Microstegium* and the corresponding lack of resident plant community recovery resulted in increased bare ground under the POST + PRE treatment ($F_{[3,288]} = 12.53$, $p < 0.0001$; Fig. 5). There was no difference in percent bare ground between the REF plots and the other treatments ($p > 0.05$).

Effects of Light Availability

The average percent available light at each site had a significant positive effect on the biomass of *Microstegium* in

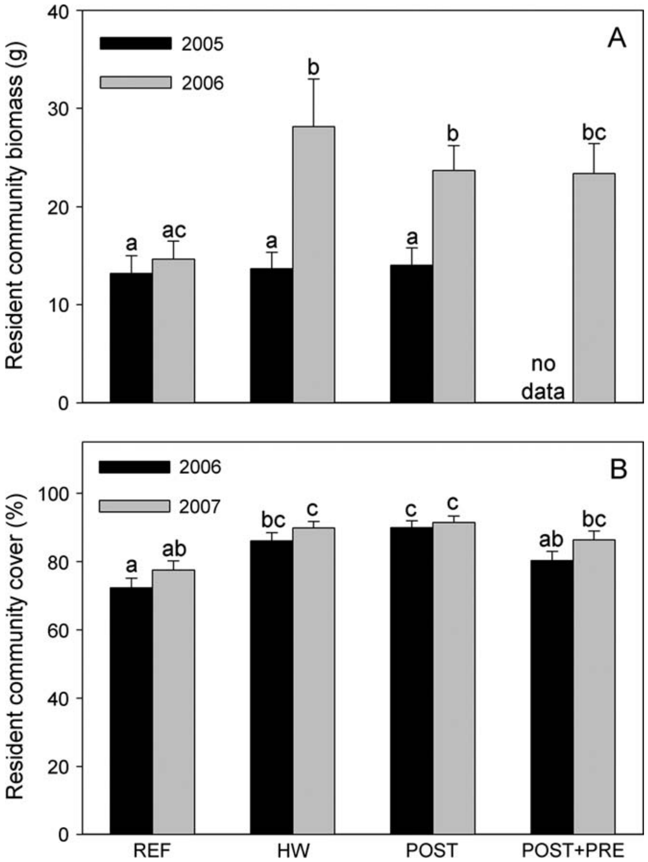

Figure 3. (A) Average (± SE) resident community biomass per 0.25-m^2 plot at the end of the season in 2005 and 2006 and (B) average (± SE) resident community cover per plot in the spring of 2006 and 2007 for the REF, HW, POST, and POST + PRE plots. Different letters indicate significant differences at $p < 0.05$. No data are shown for resident community biomass under POST + PRE in 2005 because the PRE treatment had not yet been applied.

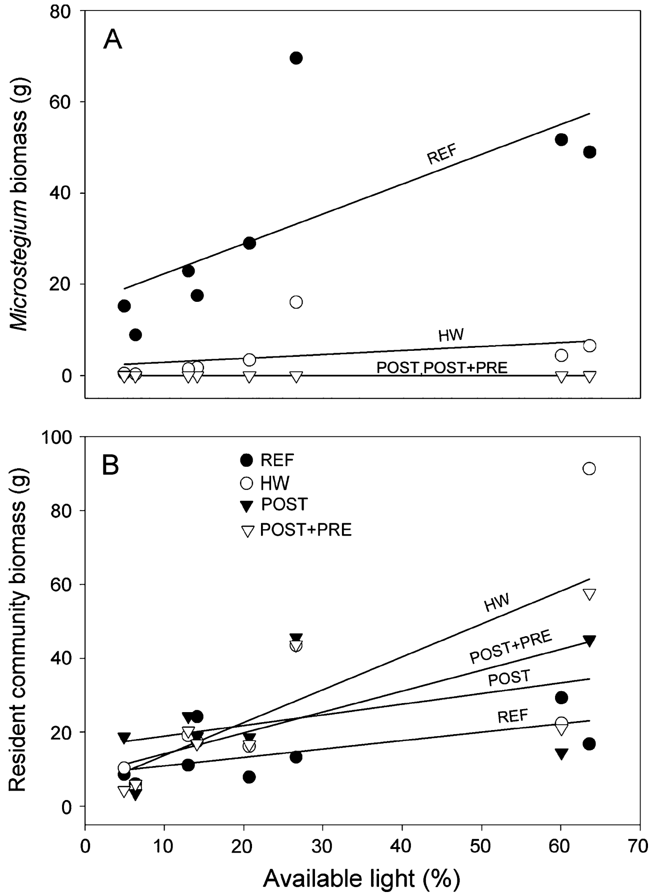

Figure 4. (A) Average *Microstegium* biomass and (B) resident community biomass (g) per 0.25-m^2 quadrat as a function of the average percent available light at each site for the REF, HW, POST, and POST + PRE plots in the fall of 2006.

the REF plots ($p = 0.04$, $r^2 = 0.49$; Fig. 4A). Percent available light did not, however, alter the effectiveness of the three treatments in reducing *Microstegium* biomass ($p > 0.05$ for all treatments). Light availability had a strong positive effect on resident community productivity under the HW ($p = 0.04$, $r^2 = 0.54$) and the POST + PRE ($p = 0.05$, $r^2 = 0.51$) treatments, but there was no effect of light availability on resident productivity under the POST treatment ($p = 0.26$) or within the REF plots ($p = 0.09$; Fig. 4B).

Seed Addition Treatment

Adding seeds of native woodland herbaceous species to the plots reduced resident community productivity by 28% overall ($F_{[1,256]} = 6.09$, $p = 0.01$), and the effect was consistent across all the *Microstegium* removal treatments (seed addition × treatment; $F_{[3,256]} = 0.49$, $p = 0.69$). However, although the seed addition treatment reduced resident community productivity, there was no effect of the seed treatment on the biomass of *Microstegium* ($F_{[1,256]} = 1.66$, $p = 0.20$). The seed addition treatment did not affect the percent bare ground in the plots for any of the three treatments ($p > 0.05$; Fig. 5).

Discussion

Treatment Effects on *Microstegium*

The POST treatment reduced *Microstegium* biomass at the end of the growing season to very low levels in both years of the experiment. These results are largely consistent with studies that have reported effective control of *Microstegium* using postemergent herbicides. Judge et al. (2005*a*) tested multiple postemergent herbicides and found that fluazifop-P, the active ingredient in the POST treatment used here, reduced *Microstegium* abundance by 97% 8 weeks after treatment when used at a concentration of 0.3 kg ai/ha. Fluazifop-P was as effective in this study, even though it was applied at a lower concentration (0.21 kg ai/ha), which may cause less damage to native perennial graminoids.

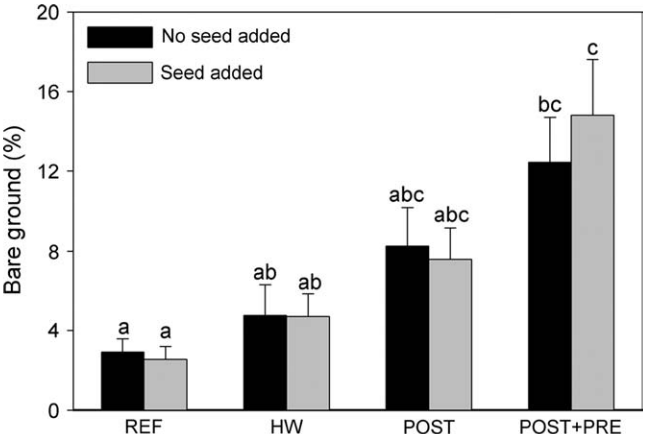

Figure 5. Average (± SE) percent bare ground per plot for seed added and no seed added plots within the REF, HW, POST, and POST + PRE treatments in the spring of 2007. Different letters indicate significant differences at $p < 0.05$.

Despite the almost complete eradication of *Microstegium* under the POST treatment at the end of the 2005 growing season, there was significant reinvasion of *Microstegium* in POST plots in the spring of 2006. This was probably due to abundant seed production by the few plants that were missed by the 2005 treatment, seed transport into the plots from the surrounding area, or germination of seeds from a persistent seed bank. Although it is unknown if any or all of these hypothesized mechanisms contributed to the spring reinvasion, the possibility of a persistent seed bank is supported by previous studies. Barden (1987) reported that *Microstegium* seed can remain viable for up to 3 years, and additional seeds germinate readily once an existing cohort of plants is removed. Gibson et al. (2002) also documented *Microstegium* emergence from soil where seed was not dispersed the previous season. The much lower spring cover of *Microstegium* in the POST-treated plots in the spring of 2006 further supports this hypothesis because the seed bank would have been depleted after multiple cohorts of seed had germinated and were eliminated by the POST treatment. The decline in *Microstegium* abundance after 2 years under the POST treatment indicates that invasions can be managed at levels that are not ecologically damaging if POST is applied repeatedly over multiple growing seasons to deplete the seed bank. However, because the POST treatment does not remove all *Microstegium* plants, the treated area should be monitored for the return of *Microstegium* the following year and surrounding natural areas should be examined for new invasions.

The POST + PRE treatment was as effective as the POST treatment in removing established *Microstegium*, but in contrast to the POST treatment, the POST + PRE treatment resulted in almost no spring emergence of *Microstegium*. This was the expected result because the postemergent herbicides were equivalent in the two treatments and the preemergent herbicide was intended to kill germinating *Microstegium* seeds. In a previous study, pendimethalin reduced *Microstegium* emergence by 98% 8 weeks after treatment when applied at a rate of 3.4 kg ai/ha (Judge et al. 2005*a*). The use of 1.34 kg ai/ha in this study provided similar results, suggesting that a lower concentration of this preemergent herbicide is as effective for preventing *Microstegium* emergence while also providing monetary savings and increasing the potential for resident species germination and emergence.

The HW treatment was more effective in the first year of the experiment than the second, possibly because the treatments were applied about 1 month later in the first year when the *Microstegium* had grown larger and self-thinned to a greater degree (Guo et al. 1998). Self-thinning would have resulted in fewer small seedlings that could easily be missed as student laborers and I sought to remove the *Microstegium* without damaging resident vegetation. In 2006, when the HW was completed earlier in the growing season and the plants were smaller, more *Microstegium* plants were likely missed simply because they were more difficult to locate among the resident vegetation. The seedlings that were missed, or less likely seedlings from seeds that germinated following treatment, produced a considerable number of seeds, which subsequently germinated the following spring and resulted in significant *Microstegium* spring cover in both years of the experiment. Multiple HW treatments throughout a single growing season, particularly late in the growing season but prior to seed maturity, would help to prevent invasions of *Microstegium* the following spring.

Treatment Effects on Resident Plant Communities

The results from previous studies differ regarding the vegetation that replaces invasive exotic plants once an invader has been eradicated. Some studies have found that native plant communities can recover (D'Antonio et al. 1998; Alvarez & Cushman 2002; Carlson & Gorchov 2004), but other studies report that treatments to remove invasive plants can damage native vegetation (e.g., Louda et al. 1997) or that other exotic plants take the place of the original invader (Masters & Sheley 2001; Ogden & Rejmanek 2005; Mau-Crimmins 2007). For example, Carlson and Gorchov (2004) found that when they removed *Alliaria petiolata* invasions from an old-growth forest, spring ephemeral cover increased. Similarly, D'Antonio et al. (1998) reported that eradicating invasions of perennial grasses in Hawaii increased the growth of two fast-growing shrub species. In contrast to studies reporting native plant community recovery following invasive plant removal, Mau-Crimmins (2007) found that removing a dominant perennial grass from abandoned fields in Arizona allowed other exotic species to invade, and Ogden and Rejmanek (2005) reported that removing invasive fennel in California increased exotic grass cover.

Here, I found that removing *Microstegium* using the HW and POST treatments increased resident plant community productivity and spring cover, but POST + PRE did not allow for resident community recovery. When we conducted the HW treatment, the goal was to selectively pull *Microstegium* while leaving the resident vegetation intact. This should have resulted in the competitive release of existing perennial resident species (Flory et al. 2007) and increased soil disturbance, providing quality sites for resident seed germination. The increased productivity of the resident community under HW in the second year of the experiment, but not the first, suggests that recovery of the resident community may have been through recruitment of new individuals, not growth of existing plants. The POST treatment was a grass-specific herbicide, so although it removed *Microstegium* and increased resident productivity and cover overall, it likely had a suppressive effect on resident graminoid species. However, the POST treatment was not designed to inhibit seed germination, so forb species should have been able to colonize areas where *Microstegium* was removed.

I hypothesized that adding the preemergent herbicide to the POST treatment (POST + PRE treatment) would result in a similar competitive release as in the POST treatment, but there would be no recruitment of native forbs. This seemed to be the case because there was a nonsignificant trend toward increased resident productivity in the POST + PRE plots, probably due solely to increased growth of existing perennial species. The lack of significant resident community recovery under POST + PRE, however, confirmed that plant community recovery occurs at least in part through germination of new individuals. These results were surprising given that *Microstegium* has only recently been invasive in southern Indiana, suggesting that *Microstegium* can quickly eliminate resident plants from a population.

Anecdotal observations indicate that for most forested habitats in Indiana, there is some amount of forest floor not covered by herbaceous vegetation. Therefore, even when the removal of a dense herbaceous layer of *Microstegium* aids in the recovery of the resident plant community, restored areas should not be expected to have complete resident plant community coverage. In this experiment, POST and HW were nearly as effective as POST + PRE for removing *Microstegium*, but only POST + PRE increased the amount of bare ground. This indicates that the inhibition of seed germination under POST + PRE that prevented resident community recovery was also responsible for the increase in bare ground.

Effects of Light Availability

Some researchers have reported that *Microstegium* is more successful in open habitats with greater light availability (Barden 1996; Cole & Weltzin 2004; Glasgow & Matlack 2007), but others have found that there was no relationship between light availability and the growth of *Microstegium* (Vidra et al. 2006; Morrison et al. 2007). The results of this experiment support the former observations. The discrepancy in these results may be due to the inability of researchers in previous studies to separate the effects of light availability from differences in soil moisture. If light availability and soil moisture are separated in a factorial design, *Microstegium* performs best under high light and high soil moisture conditions (Droste et al., unpublished data). In this study, despite greater *Microstegium* biomass under high light conditions, the amount of available light at the research sites was not important in determining the effectiveness of removal techniques. When *Microstegium* was more abundant in a plot, there was additional work to conduct the HW, but the treatments continued to be effective in removing the invasion.

The amount of available light was correlated with the productivity of resident plant communities under the HW- and POST + PRE-treated plots, indicating that perennial plants released from competition with *Microstegium* and newly germinated seedlings responded positively to greater light availability. The influence of abiotic site conditions in the recovery of plant communities following invasive plant eradication has been reported previously by Hartman and McCarthy (2004) who found that microenvironmental site conditions, including soil moisture, pH, and percent open canopy, may have determined the survivorship of native tree seedlings planted into sites where an invasive shrub had been removed. Although all treatments were effective for removing *Microstegium* in this experiment regardless of light availability, researchers should be aware of the potential influences of treatment types and abiotic site conditions on the recovery of resident plant communities following invasive plant removal.

Seed Addition Treatment

Although not observed in this study, removing exotic plants without a corresponding recovery of the resident community can result in invasions of other exotic species (Masters & Sheley 2001; Mason & French 2007; Mau-Crimmins 2007). Thus, the purpose of the seed addition treatment was to supplement the resident community seed bank and increase resident community recovery (Sheley & Half 2006). However, the seed addition treatment did not aid resident community recovery for any of the treatments or decrease the amount of bare ground. Quite unexpectedly, the addition of seed actually reduced resident community productivity. There is no clear explanation for this effect of the seed addition treatment, but it is possible that adding native seed may have attracted seed predators or increased soil pathogen activity, thereby inhibiting emergence of seedlings from the existing seed bank and preventing resident community recovery. Further research is needed to evaluate possible techniques for encouraging resident plant community recovery, particularly when the native seed bank has been depleted due to long-term invasions.

Conclusions

In this study, I evaluated the use of HW and two herbicide treatments for eradicating invasions of *Microstegium* and monitored the recovery of resident plant communities. The results indicate that HW can be used to remove *Microstegium* during the growing season but that even after 2 years of treatment, the invasion returns the following spring. In addition, the labor and time required to conduct the HW treatment prohibit its use except for small, isolated invasions. POST was more effective at eradicating *Microstegium*, particularly after 2 years of treatment, and resulted in only a small spring reemergence of *Microstegium.* Both HW and POST resulted in increased resident plant community productivity and spring cover. Although POST + PRE was also an effective treatment for removing *Microstegium* biomass and the most effective treatment for preventing reinvasions in the spring, POST + PRE did not allow for resident plant community recovery.

These results suggest that *Microstegium* invasions can be managed using HW if implemented over multiple growing seasons but that multiple treatments and careful monitoring will be needed for the invasion to be completely eradicated. Given the effects of POST + PRE on resident plant communities, it should only be used in cases where other treatments have been ineffective such as the treatment of dense, persistent invasions with established seed banks. Following eradication using POST + PRE, it may be possible to reestablish the native plant community using additional methods not investigated in this study. POST is the most promising method for eradicating *Microstegium* invasions and restoring resident plant communities because its effectiveness is not dependent on light conditions or the biomass of *Microstegium*, and it allows the resident plant community to recover. Natural areas managers should vigilantly monitor properties for *Microstegium* invasions and promptly remove infestations using HW or POST to prevent invasions from having detrimental effects on resident plant communities.

Implications for Practice

- Postemergent grass-specific herbicide effectively removed *Microstegium vimineum* invasions, prevented reinvasion of treated areas the following spring, and promoted the recovery of resident plant communities.
- The use of a preemergent herbicide was effective for removing standing *Microstegium* and prevented spring invasions in treated plots, but it inhibited the recovery of resident plant communities.
- HW was effective for removing *Microstegium* and promoting resident plant community recovery, but treated areas were substantially reinvaded the following spring. Multiple HW treatments throughout a growing season may decrease the degree of reinvasion but because HW is extremely labor intensive, it cannot feasibly be implemented at a large scale.
- The addition of native seed to treated plots was not effective for reducing *Microstegium* invasions or encouraging resident plant community recovery. However, regardless of the seed addition treatment, resident plant communities recovered after removal of *Microstegium*, suggesting that resident plant seed banks do not need to be supplemented to recover from invasions.
- Management efforts for *Microstegium*, and other rapidly spreading invasive annual plants, should focus on early detection of invasions, rapid removal of new populations, and careful monitoring throughout the growing season in order to eliminate seed production and promote resident plant community recovery.

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