Nonchemical Methods for Managing Japanese Stiltgrass (*Microstegium vimineum*)

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Chemical, mechanical, and biological methods are used to manage invasive plants, but their effectiveness at removing specific plant invaders while preserving native communities varies widely. Chemical methods are used most extensively but the nontarget effects of some herbicides can have lasting effects on native plants. Nonchemical methods are needed for sites containing rare or threatened native species and where the cost of herbicides is prohibitive. Here we evaluate multiple nonchemical methods for removing Japanese stiltgrass, a nonnative annual grass that is rapidly invading eastern U.S. forests. We applied mowing, hand weeding, and spring and fall fire treatments to replicated plots at three forested sites in southern Indiana and compared the response of Japanese stiltgrass and native plants to untreated reference plots. Mowing and fall fires applied just before seed set were the most effective methods for removing Japanese stiltgrass. Mowing decreased invader cover by 70% and biomass by 95%, whereas fall fires reduced cover by 79% and biomass by 90% compared to reference plots. Spring fire reduced Japanese stiltgrass cover, but not biomass, and hand weeding did not significantly reduce invader cover or biomass compared to untreated plots. There were no significant differences in the response of the overall native plant community or of specific native plant functional groups to the removal treatments. In summary, mowing and properly timed fall fires may be effective nonchemical methods for managing Japanese stiltgrass invasions and restoring native communities. Future research should focus on evaluating the responses of Japanese stiltgrass, native species, and other plant invaders to removal treatments conducted over successive growing seasons across a range of invaded habitats.

Nomenclature: Japanese stiltgrass, *Microstegium vimineum* (Trin.) A. Camus.

Key words: Fire, mowing, hand weeding, reference plots, biomass, percentage of cover.

Nonnative plant invasions impact communities by reducing native plant abundance and diversity and altering ecosystem processes (e.g., Alvarez and Cushman 2002; Ehrenfeld 2003; Gorchov and Trisel 2003). Various chemical, mechanical, and biological methods are used to manage invasions (e.g., Czarapata 2005; DiTomaso 2000; Hobbs and Humphries 1995) but their effectiveness at removing specific plant invaders while having minimal effects on native species varies widely (Flory and Clay 2009; Miller and Miller 2004). Furthermore, although herbicides are often the preferred method for controlling plant invasions, environmental, economic, or social concerns limit their use in many systems (Guynn et al. 2004). For example, herbicides can have nontarget or residual effects on native plants and animals, including threatened or endangered species, and the costs associated with large-scale herbicide application are often prohibitive. Therefore, studies that test nonchemical methods (e.g., fire, hand removal, or mechanical techniques) for removing invasions and monitor treatment effects on native plant communities are needed (Simberloff et al. 2005).

In this study we evaluated multiple nonchemical methods (i.e., prescribed fire, mowing, and hand weeding) for removing *Microstegium vimineum* (Trin.) A. Camus (Japanese stiltgrass), an annual C_4 grass native to eastern Asia (Barden 1987). First reported in the United States in 1919 (Fairbrothers and Gray 1972), Japanese stiltgrass is now widespread throughout eastern deciduous forests, and occurs in more than 20 states (USDA and NRCS 2005). It frequently invades disturbed habitats such as naturally or anthropogenically created forest openings (e.g., windthrows and timber harvest areas), riparian areas, and areas along

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Interpretive Summary

Japanese stiltgrass (*Microstegium vimineum*) is one of the most problematic woodland invaders in much of the eastern United States, where it can reduce native species diversity and abundance and suppress tree regeneration. Land managers are in need of effective methods to remove Japanese stiltgrass invasions to restore native communities. Multiple chemical methods have been evaluated for managing Japanese stiltgrass but studies are needed to evaluate nonchemical techniques such as prescribed fire. We used multiple nonchemical methods to remove Japanese stiltgrass and compared the effectiveness of the treatments and the response of native plants to untreated reference plots. Japanese stiltgrass was removed with hand weeding and fall mowing, and with prescribed fires applied in the spring and fall. Spring fires were applied in late spring after Japanese stiltgrass had germinated and fall fires were applied just prior to seed set. Spring fire, fall fire, and mowing reduced the relative cover of Japanese stiltgrass, but only fall fires and mowing resulted in significantly lower invader biomass compared to untreated areas the following year. There were no significant differences in the response of native species to the removal treatments but there were trends for recovery of some native species. Mowing and fall fires conducted immediately before seed production are effective treatments for removing Japanese stiltgrass and may promote the return of native plant species. Regardless of the chemical or nonchemical method used to treat invasions, monitoring and removal over successive growing seasons is needed to reduce the effects of Japanese stiltgrass on native communities.

roads and trails (Cole and Weltzin 2004; Marshall and Buckley 2008). Japanese stiltgrass can also invade interior forests with only minor disturbances such as tree falls (Cole and Weltzin 2004). Once established, it can dominate communities, resulting in reduced native plant abundance and diversity and suppressed forest regeneration (Flory et al. 2007; Flory and Clay 2009; Oswalt et al. 2007). Japanese stiltgrass is shade-adapted, produces seed prolifically, and is readily dispersed by animals, people, and water (Barden 1987; Gibson et al. 2002; Judge et al. 2005b, 2008), making it particularly difficult to manage.

Previous studies have evaluated selective and nonselective herbicides, hand weeding, and mowing for managing Japanese stiltgrass (Flory 2009; Flory and Clay 2009; Judge et al. 2005a, 2005b) but additional experiments that test specific nonchemical methods, such as prescribed fires, and monitor the response of native communities are needed. Control of Japanese stiltgrass invasions can be achieved with grass-specific herbicide (Flory 2009) and removal of invasions with this method results in greater native plant abundance and diversity and tree regeneration compared to untreated reference plots (Flory and Clay 2009). However, despite the effectiveness of herbicide treatments, the use of chemicals is restricted in many areas or is avoided because of sensitive native plant communities or sociopolitical pressure (Guynn et al. 2004). Hand weeding may also be used to remove Japanese stiltgrass and restore native species (Flory 2009; Judge et al. 2008) but this method can allow invasions to return the following spring (Flory 2009) and does not promote tree regeneration (Flory and Clay 2009). Properly timed mowing (i.e., just before seed set) has been shown to be effective for removing established plants, which can help reduce seed dispersal (Judge et al. 2008).

Mowing and hand weeding may be feasible options for local nonchemical control of Japanese stiltgrass, but at the landscape level other techniques such as prescribed fire may be needed to quickly treat large areas at low costs. Fires have been successfully used to treat other plant invaders including annual broadleaf and grass species such as yellow starthistle (*Centaurea solstitialis* L.) and barb goatgrass (*Aegilops triuncialis* L.), biennial broadleaves such as garlic mustard [*Alliaria petiolata* (Bieb.) Cavara & Grande], and perennial grasses such as smooth brome (*Bromus inermis* Leyss.; reviewed by DiTomaso et al. 2006). However, there are also many cases in which fires have promoted the invasive species targeted for management or other introduced plants (Brys et al. 2005; Emery and Gross 2005; Jacquemyn et al. 2005; Vila et al. 2001). For example, the interaction between fire and introduced grass species has been particularly problematic where fires promote the spread of invasive grasses and grass invasions in turn increase fire severity and extent (reviewed by Brooks et al. 2004; D'Antonio and Vitousek 1992). This same grass–fire cycle phenomenon may be occurring in Japanese stiltgrass–dominated systems. The abundant growth of Japanese stiltgrass results in a dense layer of fine fuels following plant senescence, which may promote more intense and widespread fires. However, by altering the timing of fires, invasions may be rapidly and affordably controlled at the landscape level. Evaluating the interaction between fire and Japanese stiltgrass is particularly important because fire is commonly used independently of invasive species management in eastern deciduous forests to encourage oak tree regeneration and other native plant species (Abrams 1992; Brose et al. 2001; Duncan et al. 2008; Iverson et al. 2008). Prescribed fires may be used to manage both invasive plants and desirable native plant communities but additional research is needed to determine how and when such fires should be applied, and when prescribed fires are ineffective or counterproductive for managing this and other plant invaders.

In this study, we used multiple nonchemical methods to remove Japanese stiltgrass invasions and evaluated the effectiveness of the removal treatments and the response of native plant communities the following growing season. We used hand weeding, spring and fall prescribed burns, and fall mowing just prior to seed production. We applied the treatments to replicated plots across three forested field sites with various environmental characteristics and land-use histories.

Table 1. Location, number of plots, land use history, mean tree dbh,[a] and mean densiometer readings of the three study sites used to evaluate the effectiveness of non-chemical techniques for removing Japanese stiltgrass at Big Oaks National Wildlife Refuge.

Study site	Latitude/longitude	No. of plots	Land-use history	Mean[b] tree dbh (± SE)	Mean densiometer reading (± SE)
A	39°03′04″N, 85°23′15″W	20	Walnut and sycamore dominated forest, no known fire history	26.5 ± 2.1	72.4 ± 4.3
B	39°01′51″N, 85°24′19″W	10	Beech and sweetgum dominated forest, no known fire history	54.5 ± 3.9	95.1 ± 1.2
C	38°58′32″N, 85°27′58″W	20	Virginia pine and sweetgum dominated forest, prescribed fire every 3–4 yr	24.6 ± 4.1	94.9 ± 0.9

[a] Abbreviation: dbh, diam at breast height.

[b] Mean and SE tree dbh for study sites A to C were calculated using $n = 25$, 23, and 21 trees, respectively.

Materials and Methods

Study Area. We conducted this study at Big Oaks National Wildlife Refuge (BONWR), a 20,647-ha (51,018 ac) former military training facility located in southeastern Indiana. Experimental plots were established at three sites within BONWR that were invaded by dense stands of Japanese stiltgrass (> 80% cover). Sites had relatively level topography and variable histories of prior (< 60 yr) anthropogenic disturbances including prescribed fire (Table 1). We intentionally chose sites that varied in environmental conditions to test the generality of the removal treatments and responses of the native community. Sites were second-growth, uneven-aged mixed deciduous forests dominated by American beech (*Fagus grandifolia* Ehrh.), black walnut (*Juglans nigra* L.), Virginia pine (*Pinus virginiana* Mill.), and sweetgum (*Liquidambar styraciflua* L.). Other canopy tree species at the sites included tuliptree (*Liriodendron tulipifera* L.), American sycamore (*Platanus occidentalis* L.), and maple (*Acer* spp.). Understory communities were dominated by northern spicebush (*Lindera benzoin* (L.) Blume), *Viburnum* spp., and greenbriar (*Smilax* sp.). To characterize the site conditions, diameter at breast height (dbh) was recorded for all trees > 8 cm (3.2 in) dbh within ~ 30 m (98 ft) of the plots (Table 1). In addition, to quantify the relative light environment at each site, canopy openness was evaluated by taking spherical densiometer readings (Lemmon 1957) in each cardinal direction from the center of each plot (Table 1). The average annual precipitation for southern Indiana is 102.10 cm with an average daily maximum temperature of 29.4 C (85°F) during the summer months (Noble et al. 1990).

Experimental Design. To assess the efficacy of nonchemical techniques for removing Japanese stiltgrass and the effects of the treatments on native plant communities, we established 50 2-m by 2-m plots across three study sites in early June 2006. Sites A and C each contained four replicates of each treatment. Because of space constraints site B only had two replicates per treatment (Table 1). Plots were positioned within stands of Japanese stiltgrass to avoid the confounding effects of large trees, fallen logs, and standing water. Plots within sites were randomly assigned to be reference plots or to one of the four removal treatments: 1) hand weeding, 2) spring fire, 3) fall fire, or 4) fall mowing. Hand weeding consisted of removing all Japanese stiltgrass while avoiding native species, and placing the Japanese stiltgrass outside of the plots. A propane torch was used to introduce fire to the spring fire and fall fire plots and all plants (native and invasive) within each plot were spot-burned (Emery and Gross 2005; Tu 2000). Mowed plots were mowed to < 2 cm above ground level using a gas-powered string trimmer[1] as in Judge et al. (2008). Spring fire and hand weeded treatments were applied during early June 2006 when Japanese stiltgrass seedlings were 10 to 20 cm tall. The fall fire and mowing treatments were completed in early September 2006, which is just prior to Japanese stiltgrass seed set.

Data Collection. To quantify the effectiveness of the treatments in reducing Japanese stiltgrass cover and biomass and the effects of the treatments on native vegetation, percentage-of-cover analysis and a destructive harvest were completed in June 2007. The center 0.25-m^2 area of each 2-m by 2-m plot was sampled to minimize edge effects. Percentage of cover of four vegetation classes (i.e., graminoid, forb, woody, and Japanese stiltgrass) was quantified using a 0.5-m by 0.5-m polyvinyl chloride frame divided into 100 5-cm by 5-cm squares. The number of squares containing each one of the four vegetation classes were counted and recorded as a percentage. Following percentage-of-cover measurements, all vegetation except for trees larger than 1.5 cm diam at ground level was harvested

Table 2. Results of ANOVA evaluating Japanese stiltgrass cover and biomass at the three study sites (A to C) across the reference plots and four removal treatments (hand weeding, spring fire, fall fire, fall mowing).

		Japanese stiltgrass			
		Cover		Biomass	
Source	df	F	P	F	P
Site	2	0.11	0.89	6.84	**0.003**
Treatment	4	33.15	< **0.0001**[a]	26.30	< **0.0001**
Site × treatment	8	5.08	**0.0003**	2.82	**0.02**

[a] P-values ≤ 0.05 are bold.

from the 0.25-m^2 area, sorted into four vegetation classes in the lab (Japanese stiltgrass, graminoids, forbs, or woody species), dried at 60 C for 72 h, and weighed (± 0.01 g).

Data Analysis. We used ANOVAs to analyze the fixed effects of site, treatment (reference, hand weeding, spring fire, fall fire, and mowing), and potential interactions on Japanese stiltgrass cover and biomass; native graminoid, forb, and woody species cover and biomass; and total native community biomass (Proc GLM[2]). Cover and biomass data were log-transformed to improve normality (Shapiro–Wilks test) and equality of variances (Levene's test) when necessary. Post-hoc Tukey HSD tests were used to evaluate differences among treatments.

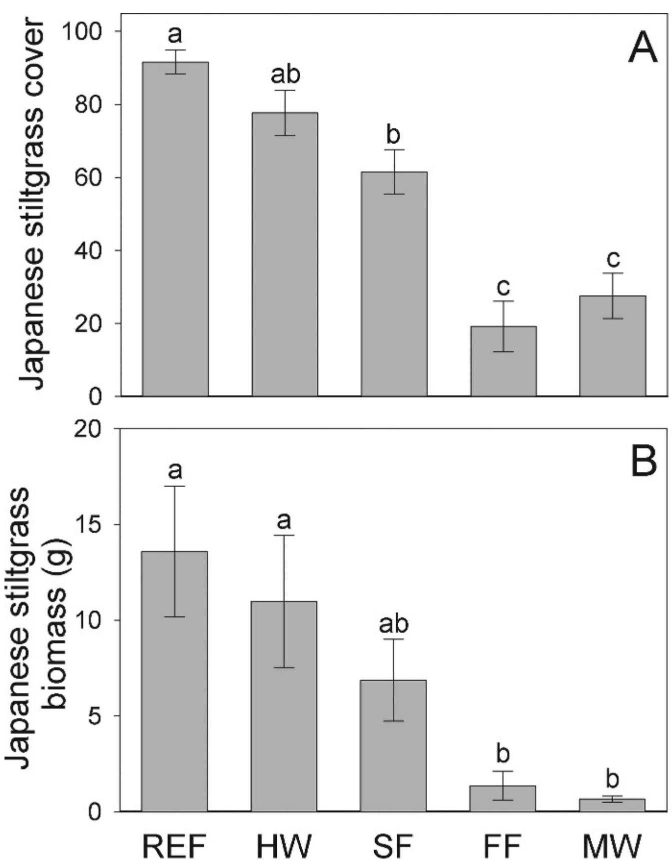

Figure 1. Average (± SE) (A) Japanese stiltgrass percent cover and (B) biomass in the reference (REF), hand weeded (HW), spring fire (SF), fall fire (FF), and mowed (MW) plots (0.25 m^2). Different letters indicate significant differences among treatments at $P < 0.05$.

Results and Discussion

Treatment Effects on Japanese Stiltgrass. Plots treated with spring fire, fall fire, and mowing each contained less cover of Japanese stiltgrass than untreated reference plots (Table 2; Figure 1A). Fall fire and mowing caused the greatest differences in Japanese stiltgrass cover compared to reference plots (Figure 1A) and were the only treatments that resulted in less stiltgrass biomass (Table 2; Figure 1B). Fall fires reduced Japanese stiltgrass cover by 79% and biomass by 90% and mowing reduced cover by 70% and biomass by 95% compared to reference plots. Hand weeding did not significantly change cover or biomass (Table 2; Figure 1). There were significant site-by-treatment interactions for both Japanese stiltgrass cover and biomass (Table 2) but these effects were due to differences in magnitudes of treatment effects, not because of opposite responses among the sites. Thus, all results are presented as averages across sites. Overall, these results demonstrate that at least two nonchemical methods (i.e., fall prescribed fires and fall mowing just before seed production) may be effective treatments for managing Japanese stiltgrass invasions.

Mowing has previously been shown to be a useful method for managing Japanese stiltgrass, but only after multiple years of treatment. Judge et al. (2008) found that Japanese stiltgrass cover increased by 10% after the first year of mowing but decreased by 69% and 82% respectively over the next 2 yr of treatment. Here we applied an identical treatment (i.e., mowing near ground level with a string trimmer) at the same time during the growing season (i.e., just before seed production). We found that invader cover and biomass were significantly lower in mowed plots compared to reference plots after a single treatment, although Japanese stiltgrass cover was still relatively high ($\sim 30\%$). The difference in results between the two studies could be explained by the length of time that Japanese stiltgrass has been present in each study area. If Japanese stiltgrass was invasive for many more years at the Judge et al. (2008) study sites than at our sites, a more abundant seed bank would allow for the return of Japanese stiltgrass after a single treatment to remove reproductive individuals. Thus, single mowing treatments may be more effective at sites where Japanese stiltgrass has only recently invaded, but at sites with established seed banks mowing treatments will need to be applied yearly until the seed bank is depleted. Further study is needed to determine if other mowing methods such as traditional tractor-pulled brush mowers that do not mow as close to the ground are as effective as the mowing method used here.

Hand weeding was not an effective method for removing Japanese stiltgrass in this study. Although there were trends for less Japanese stiltgrass cover (15%) and biomass (19%) compared to untreated plots, there were no statistically significant differences. These results differ from our previous study (Flory 2009; Flory and Clay 2009) where we found that a single hand weeding treatment in early summer (i.e., June) significantly reduced Japanese stiltgrass cover by 26% the following spring. Judge et al. (2008) found no difference when comparing hand weeding treatments applied once per growing season to hand weeding conducted throughout the year; both significantly reduced Japanese stiltgrass cover after 3 yr of treatment. However, season-long hand weeding increased the cover of other nonnative invasive species by 51% (Judge et al. 2008). These previous studies indicate that hand weeding is an effective, though labor-intensive, method for removing Japanese stiltgrass. It is unclear why hand weeding was less effective in this study. If hand weeding is used to manage Japanese stiltgrass, multiple years of hand weeding are needed to substantially reduce the size of invasions. In addition, it is likely that many years of repeated monitoring and treatment would be needed to completely eradicate Japanese stiltgrass with hand weeding alone.

A variety of late-season annual broadleaf and grass species have been successfully managed with prescribed fires in the western United States, but few eastern invasive plant species have been successfully controlled with prescribed fires (DiTomaso et al. 2006). For example, the invasive biennial garlic mustard can only be controlled with repeated burning under dry conditions (Nuzzo 1991). Here we show that both spring (32% less) and fall burns (79% less) can control Japanese stiltgrass and that fall burns can significantly reduce biomass compared to untreated plots (Table 2; Figure 1). These results contrast with those of Glasgow and Matlack (2007) who found that spring burns, especially high-intensity burns, promoted the establishment and growth of Japanese stiltgrass. The difference in our results is likely explained by the timing of spring burns. Glasgow and Matlack (2007) applied burns in early April prior to Japanese stiltgrass germination, whereas we conducted our burns in early June after seedlings emerged. Although most spring prescribed fires in eastern deciduous forests occur in early spring, our results show that conducting burns later in the spring may inhibit Japanese stiltgrass invasions. However, late spring fires may not carry as well or burn areas as completely because of differences in fuel quality and quantity, so artificial spot burning as we did here may be required if late spring burns are to be used to control Japanese stiltgrass.

Fall fires and fall mowing were the most effective treatments for removing Japanese stiltgrass (Table 2; Figure 1). We conducted fall fires in early September just before seed set when Japanese stiltgrass was still photosynthetic, which coincides with the timing of fall burns in eastern forests. We applied fall fires with a propane torch and prescribed fires may behave much differently if dry fuels are not present in sufficient abundance in invaded areas to carry fire. We did not evaluate pretreatment fuel availability or quality but we found no differences in litter mass among the management treatments or reference plots ($P > 0.05$, data not shown) when we collected data the following spring. The quality and abundance of fuels and the amount of green plant material may differ during the treatment periods, which could alter prescribed fire intensity and the success of management efforts. For example, burns conducted over larger areas with varying fire intensity may produce variable results and the long-term response of Japanese stiltgrass populations may differ from what we found here. The success of burns in eastern forests varies widely among years due to differences in weather patterns and fuel moisture conditions. More research is needed to determine if spring and fall fires can be consistently used under natural conditions to reduce Japanese stiltgrass populations. We can find no other study that has evaluated the use of prescribed burns to manage Japanese stiltgrass. Thus, this study provides an important first step in studying the interaction between fire and Japanese stiltgrass, but more research is needed to determine if large-scale prescribed fires would produce similar results. Further, additional research is needed on the response of native species at different points in the growing season and after multiple years of treatment. Comprehensive studies of fire and other nonnative grasses have shown overall positive invasive responses (Brooks et al. 2004; D'Antonio and Vitousek 1992; Hughes et al. 1991; Vila et al. 2001) so additional study is needed before prescribed fires are integrated into Japanese stiltgrass management plans.

Treatment Effects on the Native Community. There were no significant differences in total native community

Table 3. Results of ANOVAs evaluating total native community biomass and native graminoid, forb, and woody species cover and biomass at the three study sites (A to C) across the reference plots and the four removal treatments.

Source	df	Total native community biomass		Graminoid Cover		Graminoid Biomass		Forb Cover		Forb Biomass		Woody Cover		Woody Biomass	
		F	P	F	P	F	P	F	P	F	P	F	P	F	P
Site	2	11.89	< **0.0001**[a]	3.25	**0.05**	7.01	**0.003**	44.17	< **0.0001**	4.57	**0.02**	3.36	**0.05**	1.84	0.19
Treatment	4	0.45	0.77	1.29	0.29	1.97	0.13	1.66	0.18	0.07	0.99	0.62	0.65	0.17	0.95
Site × treatment	8	2.12	0.06	0.65	0.73	0.29	0.96	2.11	0.06	1.14	0.36	0.82	0.59	0.98	0.47

[a] P-values ≤ 0.05 are bold.

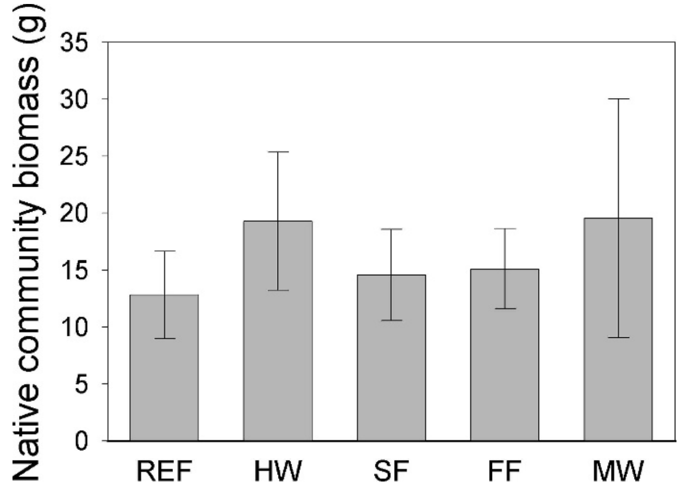

Figure 2. Average (± SE) total native community biomass in the reference (REF), hand weeded (HW), spring fire (SF), fall fire (FF), and mowed (MW) plots (0.25 m^2).

biomass (Table 3; Figure 2) or the cover or biomass of specific plant functional groups (Table 3; Figure 3) between the Japanese stiltgrass removal treatments and the untreated reference plots. There were also no differences among the management techniques in their effects on native plant communities. These results indicate that the nonchemical methods we used to remove Japanese stiltgrass do not have immediate negative consequences for native species. The lack of negative effects of the removal treatments on native species was surprising given the destructive nature of the mowing and fire treatments and the significant reductions in invader abundance with mowing and fall fire. We predicted that mowing and fire would at least temporarily reduce native plant abundance. In contrast, we observed trends for recovery of some native plant functional groups after only 1 yr of treatment.

Although there were no statistical differences in the native community among the removal treatments, there were some notable trends in the data that suggest differences may arise after multiple seasons of treatment. For example, there were trends for greater overall native community biomass under the mowing (52%) and hand weeding (50%) treatments compared to reference plots (Figure 2). These nonsignificant patterns were likely affected by the response of graminoid species. There were also trends for greater cover of graminoids under all removal treatments compared to untreated reference plots. In particular, mowed plots had 145% more graminoid cover compared to reference plots (Figure 3A). Similarly, average graminoid biomass was 125% greater under the mowing treatment and 116% greater with hand weeding compared to reference plots (Figure 3B), suggesting that native grass species may respond positively to these removal methods. Previously, we showed that removing Japanese

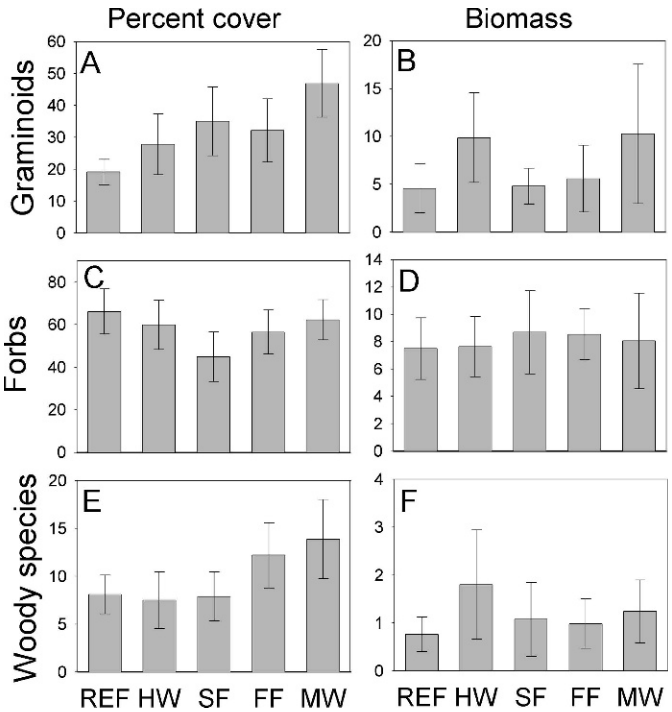

Figure 3. Average (± SE) percentage of cover and biomass for (A,B) native graminoids, (C,D) forbs, and (E,F) woody species in the reference (REF), hand weeded (HW), spring fire (SF), fall fire (FF), and mowed (MW) plots (0.25 m^2).

stiltgrass with hand weeding over two growing seasons resulted in significantly more graminoid cover and species richness, more tree regeneration, and increased plant species diversity compared to reference plots (Flory and Clay 2009). Judge et al. (2008) found substantial increases in the relative cover of forbs and monocots after removing Japanese stiltgrass with a variety of methods. Removing Japanese stiltgrass over multiple growing seasons with the nonchemical methods described here may promote native species establishment and growth but additional studies conducted over multiple years are needed.

Our results show that both fall mowing and fall fires conducted immediately before seed set are effective nonchemical methods for managing Japanese stiltgrass invasions. Both methods resulted in significantly less Japanese stiltgrass cover and biomass compared to untreated plots without causing declines in native plant species. Managers should carefully time both of these treatments because applying them after Japanese stiltgrass has begun to produce seed may promote rather than inhibit invasions. This study provides some of the first information on how prescribed fires can be used to manage Japanese stiltgrass and supplies a baseline for more comprehensive multi-year studies on the interaction between fire and Japanese stiltgrass invasions. Future studies should focus on conducting larger prescribed fires, applying fires and other nonchemical treatment methods over multiple seasons, evaluating spring vs. fall fires, and documenting the effects of nonchemical management methods on native species.

Sources of Materials

[1] Gas powered string trimmer, FS 200, Stihl Inc., Virginia Beach, VA.

[2] SAS Institute Inc., Cary, NC.

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