Research

Japanese Stiltgrass (*Microstegium vimineum*) Management for Restoration of Native Plant Communities

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Japanese stiltgrass is a nonnative invasive grass occupying a range of habitats in the eastern United States. Conventional management recommendations include hand-removal, mowing, or a nonselective herbicide application in autumn prior to flowering. However, no study has directly compared the ecological impacts of long-term management strategies on Japanese stiltgrass populations or recruitment and establishment of native flora. An experiment was initiated in 2002 and continued for three growing seasons in mixed pine-hardwood forests in central North Carolina. Conventional treatments included hand-removal, mowing, or an application of glyphosate (1.1 kg ai/ha) once in autumn, and selective removal by hand or fenoxaprop-P (0.19 kg ai/ha) season-long as needed. All treatments were compared to nontreated plots. Percent vegetation cover by species was recorded twice annually. Data were aggregated into five classes; Japanese stiltgrass, other exotic plants, native forbs, native monocots, and native woody plants. The soil seed bank of all species was estimated annually by extracting soil cores and documenting seedling emergence. All Japanese stiltgrass management treatments significantly reduced Japanese stiltgrass cover and seed bank over time compared to no management. However, recruitment and reestablishment of native plants and overall species richness were greater with selective Japanese stiltgrass management treatments including both hand-removal and fenoxaprop-P. Relative cover of other exotic plants decreased 2% to 49% after 3 yr with all Japanese stiltgrass management treatments except season-long hand-removal, which increased relative cover of other exotic plants 51%.

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

Key words: Fenoxaprop-P, glyphosate, invasive, nontarget impacts, soil seed bank, species richness.

Japanese stiltgrass [*Microstegium vimineum* (Trin.) A. Camus] is an invasive summer annual grass (Brown 1977) native to Asia (Tu 2000; Williams 1998) and was first reported in the United States near Knoxville, TN in 1919 (Fairbrothers and Gray 1972). Japanese stiltgrass has since spread rapidly throughout the eastern United States, from New York to Texas, and in Puerto Rico (Barden 1987; Fairbrothers and Gray 1972; Redman 1995; USDA, NRCS 2004). Common habitats include roadside ditches, utility easements, floodplains, streamsides, river bluffs, woodlands, fire trails, and logging roads (Barden 1987; Cusick 1986; Fairbrothers and Gray 1972; Hunt and Zaremba 1992; Redman 1995). Japanese stiltgrass has also been reported in landscape plantings and turfgrass (Barden 1987; Derr 2004; Fairbrothers and Gray 1972).

Dispersal of Japanese stiltgrass apparently occurs by floating fruits that disperse throughout wetland areas during high-water events and by adhering to fur-bearing animals, human clothes, or vehicles (Cole 2003; Mehrhoff 2000; Woods 1989). These modes of dispersal allow for long distance spread by establishing satellite populations within areas of disturbance (e.g., flooding) on patches of soil left bare of vegetation (Barden 1987; Gibson et al. 2002). Yet, Japanese stiltgrass occurs in both disturbed early successional habitats and relatively undisturbed late-

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Interpretive Summary

Five Japanese stiltgrass management treatments were compared in an effort to eradicate Japanese stiltgrass and restore native plants over time. Three conventional management treatments included hand-removal, mowing, or glyphosate applied in autumn prior to flowering of Japanese stiltgrass. Two season-long selective treatments were also evaluated including hand-removal and fenoxaprop-P applied as needed throughout the growing season. All Japanese stiltgrass management treatments significantly reduced Japanese stiltgrass cover and seed bank over time relative to no management. To deplete a seed bank of Japanese stiltgrass, large-scale management will require more than 3 yr of management. Although by the third and fourth years, spot treatments should be sufficient for management of the remaining population, rather than a broadcast manual, mechanical, or chemical management treatment. Increased recruitment and reestablishment of native plants and increased species richness was greater from selective Japanese stiltgrass management treatments including both hand-removal and fenoxaprop-P. The repetition of the nonselective glyphosate applications controlled populations of Japanese stiltgrass, but adversely impacted native woody plant populations and did not increase species richness. It has been demonstrated herein that management for multiple seasons is an effective strategy for decreasing populations of Japanese stiltgrass and selective management methods increase native plant recruitment, establishment, and species richness.

successional forest communities (Drake et al. 2003; Cole and Weltzin 2004).

Japanese stiltgrass relies on a soil seed bank for annual recruitment (Fairbrothers and Gray 1972; Mehrhoff 2000; Radford et al. 1968). Barden (1987) reported that following 2 yr of intentionally eliminating seed production, Japanese stiltgrass plants continued to emerge the following spring. However, no new plants emerged after 3 yr of eliminating seed production, suggesting 3 yrs' viability in the soil. The ability to create a persistent seed bank allows Japanese stiltgrass to maintain populations over time even if a catastrophic event, such as a herbicide application, occurs during 1 yr. Therefore, management efforts must endeavor to reduce or eliminate seed production, and thus inputs into the seed bank for multiple years to reduce or eradicate populations of Japanese stiltgrass (Tu 2000; Woods 1989).

Current management guidelines suggest prevention of seed production by hand-removal, mechanical methods (i.e., mowing), or nonselective postemergence (POST) herbicides (e.g., glyphosate) in autumn prior to flowering (Tu 2000). However, late season management treatments allow season-long Japanese stiltgrass growth and competition, potentially reducing the opportunity for native species recruitment or establishment. Furthermore, nonselective management treatments such as mowing or glyphosate applications may adversely affect desirable native vegetation.

Sethoxydim has been shown to control Japanese stiltgrass POST (Gover et al. 2003; Jones et al. 2004; Judge et al. 2005a; Judge et al. 2005b), but also controls a broader spectrum of grasses including both annual and perennial grasses (Senseman 2007). When considering how management of Japanese stiltgrass impacts desirable native vegetation such as perennial grasses, perhaps fenoxaprop-P will have fewer nontarget impacts. Fenoxaprop-P has also been shown to control Japanese stiltgrass POST (Jones et al. 2004; Judge et al. 2005a; Judge et al. 2005b) and does not injure dicots, rushes (Juncaceae), sedges (Cyperaceae), or most perennial grasses (Poaceae) (Senseman 2007).

Although Japanese stiltgrass is consistently listed among the most problematic of exotic plants in the eastern United States (Cole and Weltzin 2004; Drake et al. 2003; Miller 2003; Vidra 2004), no long-term studies have directly assessed the competitive interactions of Japanese stiltgrass with native vegetation, or determined the long-term effects of Japanese stiltgrass management on native vegetation recruitment, survival, and growth. Investigations during one season demonstrated that sethoxydim applied late July or mid-August controlled Japanese stiltgrass and released native dicot vegetation in eastern Tennessee (Woods 1989). POST applications of fenoxaprop-P, glyphosate, imazapic, and sethoxydim controlled Japanese stiltgrass equally well in Pennsylvania (Jones et al. 2004). Application of the selective grass herbicides—fenoxaprop-P and sethoxydim—resulted in higher species richness at the end of the growing season than glyphosate, imazapic, and no treatment (Peskin 2005). However, Japanese stiltgrass seedlings emerged from the persistent seed bank the following year, and diversity indices in treated plots were only slightly higher than nontreated plots.

The ecological impacts of Japanese stiltgrass management treatments—manual, mechanical, or chemical—on Japanese stiltgrass populations and native flora need to be assessed over multiple management seasons. Therefore, our objectives were to compare the relative effectiveness of selective season-long management of Japanese stiltgrass utilizing fenoxaprop-P or hand-removal with conventional management treatments, including autumn hand-removal, mowing, or a glyphosate application, and to compare the impacts of these management methods on populations of Japanese stiltgrass and native flora over multiple management seasons.

Materials and Methods

A field experiment was initiated in 2002 at two locations in central North Carolina; Duke Forest, Durham, Durham County and Schenck Memorial Forest, Raleigh, Wake County. The experimental area in Duke Forest is a floodplain managed for loblolly pine (*Pinus taeda* L.) production. In 2000, the mature pine stand was harvested with a shelter-wood regeneration cut. After harvest, much of the forest floor was disked to expose bare mineral soil to create optimum conditions for pine seedling establishment. With such a treatment, an overstocking of 20,000 to 25,000 pine seedlings per hectare (49,400 to 61,800 per acre) is expected. However, a heavy understory of Japanese stiltgrass soon developed, and fewer than 250 pine seedlings regenerated per hectare (J. Edeburn, forest manager, personal communication). The overstory was exclusively loblolly pine over a sparse shrub layer of sweetgum (*Liquidambar styraciflua* L.), eastern red cedar (*Juniperus virginiana* L.), and princess tree (*Paulownia tomentosa* (Thunb.) Sieb. & Zucc. ex. Steud.). Upon experiment initiation, the forest floor was dominated by Japanese stiltgrass. The experimental area in Schenck Memorial Forest is an upland mixed pine-hardwood forest with the overstory dominated by white ash (*Fraxinus americana* L.), American elm (*Ulmus americana* L.), loblolly pine, oak spp. (*Quercus* spp.). and sweetgum. Upon experiment initiation, Japanese stiltgrass and seedling sweetgum trees dominated the forest floor and shrub layer, respectively.

All Japanese stiltgrass management treatments were applied in 2002, 2003, and 2004. Three conventional management treatments were applied annually in autumn, prior to flowering: (1) selective hand-removal, where only Japanese stiltgrass was removed from plots, (2) nonselectively cutting all vegetation 1 to 2 cm in height with a gas-powered string trimmer, and (3) one application of 1.1 kg ai/ha (1.0 lb ai/ac) isopropylamine salt of glyphosate. Conventional treatments were compared to two season-long selective management treatments: (1) hand-removal or (2) applying the selective grass herbicide, fenoxaprop-P, once or twice per year at 0.2 kg ai/ha as needed. Nonionic surfactant (0.25% v/v) was added to fenoxaprop-P in 2002 and 2003, but was omitted from the 2004 application. Herbicides were applied using a CO_2 pressurized backpack sprayer equipped with two flat fan spray tips[1] and calibrated to deliver 280 L/ha (30 gal/ac).

The five treatments and nontreated control were replicated four times in a randomized complete block design at each site. Plots were 4 m^2 (44 ft^2) with 1-m wide vegetation-free buffer strips around plot borders. Plots were large enough to observe plants and treatment effects but small enough to clear and work without trampling. The buffer strips were necessary to minimize potential seed introductions from adjacent plots. In 2003 and 2004, erosion control matting was laid over the buffer strips to minimize movement of propagules between plots by surface water, although the authors recognize that this could not completely eliminate movement of propagules between plots. Each year, the buffer strips were kept free of vegetation by applying a 2% solution of the isopropylamine salt of glyphosate twice per growing season with a 15-L (4 gal) piston pump backpack sprayer[2] equipped with a wide-angle FloodJet[1] nozzle and calibrated to deliver 234 L ha. Plots were placed in an area between large overstory trees; thus, there were no overstory trees within plots. The only woody vegetation originating in the plots were primarily young sweetgum saplings < 5 cm in diameter. Therefore, at the onset of the experiment, existing woody vegetation in all plots was removed by dipping clippers in a 5% solution of triclopyr and cutting each plant at ground level as described by Kalmowitz et al. (1989). The woody vegetation was cut and treated May 22, 2002 at Duke Forest and May 9, 2002 at Schenck Memorial Forest.

Percent canopy cover was estimated at each site to determine homogeneity of the canopy environment. A spherical densiometer with a concave mirror was utilized to estimate the amount of canopy cover directly over the midpoint of each plot in four cardinal directions, and then the measurements were averaged (Lemmon 1956). Measurements at Duke Forest were recorded June 30, 2003 and June 8, 2004 and at Schenck Memorial Forest July 1, 2003 and June 8, 2004 and averaged separately for each site to obtain a summer canopy cover estimate. Using ANOVA, there were no differences in canopy cover across treatments at either site suggesting relative homogeneity of canopy cover at each site. Average summer canopy cover at Duke Forest was 66% and at Schenck Memorial Forest was 83%.

Management Treatments. Conventional management treatments were targeted to Japanese stiltgrass just prior to flowering. The first application of season-long management treatments was targeted to six to seven leaf and zero to one tiller Japanese stiltgrass and repeated as necessary throughout the growing season (Table 1). A drought severely reduced plant growth and flowering at both sites in 2002, and treatments were applied later than in subsequent years to coincide with the target growth stages. At both locations, two applications of fenoxaprop-P were required for control of Japanese stiltgrass in 2002 and 2003; whereas, only one application was necessary in 2004 for control of Japanese stiltgrass.

Data Collection. *Vegetation Cover.* Percent cover of Japanese stiltgrass, other exotic vegetation, and native vegetation was recorded twice annually to monitor response of vegetation to the various Japanese stiltgrass management treatments. Estimates were obtained once prior to season-long treatments (summer) and once prior to conventional treatments (autumn) (Table 1). Surveys were recorded in 2003, 2004, and 2005 after one, two, and three seasons of management of Japanese stiltgrass, respectively. In 2002, vegetation surveys occurred prior to any treatment to determine homogeneity of research sites. Using the nomenclature provided by Radford et al. (1968), all species rooted within the plot boundaries were identified and percent cover of each species was visually estimated. Square plots were divided into four equal sized triangles by visualizing an "X" through the plot. Having one triangle equal to 25% cover, precise visual estimates of cover were

Table 1. Dates of Japanese stiltgrass management treatments and evaluations at Duke Forest and Schenck Memorial Forest throughout the study.

	Duke Forest	Schenck Memorial Forest
	2002	
Season-long fenoxaprop-P	June 26; October 7	July 18; October 7
Season-long hand-removal	June 26; October 7	July 18; July 29; October 7
Conventional treatments	October 7	October 7
Soil cores extracted	Not available	April 24
Percent cover evaluations	July 25; October 3	July 29; October 3
	2003	
Season-long fenoxaprop-P	June 13; July 10	June 12; July 1
Season-long hand-removal	June 30; September 4; September 15	June 12; July 1; September 3; September 15
Conventional treatments	September 15	September 15
Soil cores extracted	March 11	March 14
Percent cover evaluations	June 30; September 4	June 12; September 12
	2004	
Season-long fenoxaprop-P	June 16	June 16
Season-long hand-removal	June 16; June 13; August 19; September 16	June 16; July 13; August 19; September 16
Conventional treatments	September 16	September 16
Soil cores extracted	March 9	March 8
Percent cover evaluations	June 8; September 10	June 8; September 13
	2005	
Soil cores extracted	March 7	March 7
Percent cover evaluations	June 13; September 28	June 17; September 21

obtained. Because the plots included forbs, shrubs, and tree saplings less than 5 cm in diameter, many plots had multiple layers of vegetation and total percent cover exceeded 100%. Using the U.S. Department of Agriculture PLANTS database (USDA, NRCS 2004), each plant species was classified according to its status as native or exotic (nonnative to the United States). Additionally, each species was classified according to growth form such as forbs, monocot, or woody plant. Because of the limited presence of vines, they were included in their respective forbs, monocot, or woody plant category when present. Japanese stiltgrass was classified as its own growth form category. These growth forms were chosen as logical categorization on the basis of potential response to management treatments. For example, fenoxaprop-P should only impact summer annual grasses such as Japanese stiltgrass, but not native perennial grasses. Conversely, nonselective treatments impact all vegetation. Concurrent with vegetation surveys, species richness was also calculated as the number of species per plot. No regard was given to classification as native or exotic for species richness because the authors simply wanted to measure change over time and determine whether the experimental treatments of Japanese stiltgrass management were having a positive or negative impact on the number of additional species recruitment and establishment.

Soil Seed Bank. To monitor the response of the seed bank to Japanese stiltgrass management treatments, soil cores were collected annually in late winter (Table 1). This collection time was determined because seeds of Japanese stiltgrass exhibit dormancy (Judge 2005), and seeds from soil collected in the spring germinate at high percentages, whereas seeds from soil collected in autumn do not germinate (Gibson et al. 2002). From each plot, two randomly selected soil cores were collected using a standard circular golf course cup cutter, each 10 cm in diameter and 5 cm in depth. Soil collected at 5 to 10 cm depth has been shown to have 10 times fewer Japanese stiltgrass seeds than soil collected at the surface 0 to 5 cm (Gibson et al. 2002). Each core of soil was placed in an individual sealed plastic bag and returned to the laboratory. Within two days of collection, the soil cores were broken apart and spread evenly over the surface of a 0.25-m^2 flat filled with sterile peat-based growth substrate[3]. The flats were placed in a greenhouse maintained at approximately 24/18 C (75/64 F) day/night temperatures. A natural photoperiod was maintained.

Emerged seedlings of Japanese stiltgrass and all other species were counted and identified to genus (and to species when possible) and removed. After germination ceased, the soil mix was stirred to break up crusted pieces and stimulate further germination. Seedling counts continued for 5 to 6 mo each year. In 2002, after counting seedlings, flats were placed in a cooler for 12 wk, and then returned to the greenhouse to induce further germination of potentially previously dormant seeds. However, subsequent seed germination was negligible and this procedure was not continued in subsequent years.

Data Analyses. Percent cover and seed bank counts of Japanese stiltgrass, other exotic plants, native forbs, native monocots, and native woody plants were expressed as relative differences from the nontreated plot in the same replication, calculated as $[((X_{\text{treatment}} - X_{\text{nontreated}})/X_{\text{treatment}}) \times 100]$. Therefore, relative differences of management treatments were expressed as percent increase or decrease from no management treatment. When values were less than 10% in any of the four nontreated plots, 10 was added to each to make calculations mathematically possible without affecting relative differences between treatment and no treatment. Analyzing relative differences rather than absolute differences minimized the effects of landscape heterogeneity and accounted for changes occurring over time not related to treatments (e.g., successional processes). Because relative percent cover and plant counts from soil cores' differences were calculated relative to the nontreated plots, nontreated data were subsequently omitted from data analysis. Further, calculating differences relative to the nontreated within each replication removed replication and location effects. Therefore, data for the two experimental sites were combined for analysis, providing eight replications (two sites by four within-site replications).

In 2002 prior to Japanese stiltgrass management treatments, there were no statistical differences initially in populations of Japanese stiltgrass, other exotic plants, native forbs, native monocots, or native woody plants based on relative percent cover or relative plant counts from soil cores demonstrating homogeneity of plant populations across sites prior to experimental treatments (data not shown). For Japanese stiltgrass, when treatment differences were compared for each season of percent cover evaluations (summer and autumn) within a year, there was a treatment by season interaction. However, the interaction was an artifact of the timing of Japanese stiltgrass management treatments. In other words, when populations of Japanese stiltgrass were evaluated, summer evaluations accounted for the previous season's application of management treatments; whereas, autumn evaluations accounted for only the season-long selective management treatments from the current year. Therefore, for Japanese stiltgrass, only data from summer evaluations of percent cover were analyzed because these evaluations compared the effects of all of the previous year's management treatments equally. However, there were no statistical differences in relative percent cover of other exotic plants, native forbs, native monocots, or native woody plants for summer or autumn evaluations in 2003, 2004, or 2005. Therefore, for these classes, data were pooled across season of evaluation within a year for treatment comparisons.

Species richness was calculated as the number of species per plot. Percent relative cover data, percent relative plant count data from soil cores, and species richness data were subjected to ANOVA using the general linear models procedure of the SAS software. Means were separated using Fisher's protected LSD in the SAS software (1999) at the 5% significance level.

Results and Discussion

Japanese Stiltgrass. Based on percent relative cover data and plant count data of Japanese stiltgrass obtained from soil cores, there were no differences across management treatments (Table 2). All management treatments reduced Japanese stiltgrass populations similarly. However, number of years of management significantly impacted populations of Japanese stiltgrass. After 1 yr of management, cover of Japanese stiltgrass averaged across treatments increased 10% relative to nontreated plots, but decreased 69% after 2 yr and 82% after 3 yr of management (Table 3). Further, the seed bank of Japanese stiltgrass decreased 52%, 88%, and 93% after 1, 2, and 3 yr of management, respectively, based on soil core count data. Although seed inputs were eliminated from within the plots, the seed bank had an ample supply for new recruits of Japanese stiltgrass 1 yr after seed rain was halted. These results follow observations reported previously where 1 yr of seed bank management had no long-term effect (Peskin 2005). The present authors (Judge et al. 2005b) previously reported that single applications of several herbicides reduced the aboveground biomass of Japanese stiltgrass the following spring. However, when the same plots were observed the following autumn after completion of the experiment, treated plots appeared no different, in terms of Japanese stiltgrass cover, than nontreated plots (personal observation). In the present experiment, 3 yr of preventing seed inputs did not completely deplete the seed bank of Japanese stiltgrass, contrary to Barden's prior observation (1987). While some seed immigration may have occurred by animals or water, the buffer area and erosion matting minimized it. While most previous management trials have only evaluated Japanese stiltgrass management for 1 to 2 yr (Jones et al. 2004; Peskin 2005; Woods 1989), these data highlight the importance of more than 2 yr of management for long-term removal.

Other Exotic Plants. In addition to Japanese stiltgrass, other exotic plants were present including autumn olive (*Eleagnus umbellata* Thunb.), bristlegrass (*Setaria* Beauv.), Japanese honeysuckle (*Lonicera japonica* Thunb.), and mimosa (*Albizia julibrissin* Durazz.) at Duke Forest and Chinese lespedeza [*Lespedeza cuneata* (Dun.-Cours. G.

Table 2. ANOVA of main effects when analyzing percent relative cover data and percent relative plant count data obtained from soil cores.

	Percent relative cover[a]				
Main effects	Japanese stiltgrass	Other exotics	Native forbs	Native monocots	Native woody plants
Treatment[b]	NS[c]	P < 0.0001	NS	P < 0.0001	P < 0.0001
Year[d]	P < 0.0001	NS	P = 0.0031	P = 0.0003	NS
Treatment × year	NS	NS	NS	NS	NS

	Percent relative plant counts from soil cores[a]				
Main effects	Japanese stiltgrass	Other exotics	Native forbs	Native monocots	Native woody plants
Treatment	NS	NS	NS	NS	NS
Year	P < 0.0001	NS	P = 0.0172	NS	NS
Treatment × Year	NS	NS	NS	NS	NS

[a] Relative percent cover and relative percent plant counts were calculated relative to cover and counts from nontreated plots in each corresponding replication.

[b] Conventional treatments included hand-removal, mowing, or glyphosate in autumn prior to flowering and season-long selective treatments included hand-removal or fenoxaprop-P as needed throughout the growing season.

[c] NS, nonsignificant according to the *t* test on differences of least square means at P = 0.05.

[d] Year effects refer to 2003, 2004, and 2005 after 1, 2, and 3 yr of management treatments, respectively.

Don)], Chinese privet (*Ligustrum sinense* Lour.), and Japanese honeysuckle at Schenck Memorial Forest. Each of these exotic plants is considered invasive (Miller 2003; Miller et al. 2004).

Japanese stiltgrass management treatments significantly impacted relative cover of other exotic plants (Table 2); whereas number of years of management was not significant for relative cover of other exotic plants. Neither treatment nor year affected plant count data of other exotic plants obtained from soil cores. Averaged across years, glyphosate reduced relative cover of other exotic plants by 49% (Table 4). Mowing, conventional hand-removal, and season-long fenoxaprop-P treatments each reduced populations of other exotic plants by lesser amounts (23%, 8%, and 2%, respectively). Most of the exotic plants were woody. Glyphosate, as a systemic herbicide, is the most effective of the treatments evaluated herein at controlling woody vegetation. Mowing also has a direct impact on

Table 3. Percent relative cover[a] and relative plant counts from soil cores, by growth form, where year was a significant main effect.

	Percent relative cover[a]		
Year[b]	Japanese stiltgrass	Native forbs	Native monocots
2003	10a	107a	60a
2004	-69b	182a	175b
2005	-82b	325b	213b

	Percent relative plant counts from soil cores[a]	
Year	Japanese stiltgrass	Native forbs
2003	−52a	1a
2004	−88b	18ab
2005	−93b	48b

[a] Relative percent cover and relative percent plant counts were calculated relative to cover and counts from nontreated plots in each corresponding replication.

[b] Year refers to 2003, 2004, and 2005 after 1, 2, and 3 yr of management treatments, respectively.

Table 4. Percent relative cover[a], by growth form, where management treatment was a significant main effect.

Treatment[b]	Other exotics	Native monocots	Native woody plants
Conventional			
Hand-removal	−8b	265c	114b
Mowing	−23ab	183bc	−10a
Glyphosate	−49a	4a	−31a
Season-long			
Hand-removal	51c	166bc	64b
Fenoxaprop-P		128b	93b

[a] Relative percent cover was calculated relative to cover from nontreated plots in each corresponding replication.

[b] Conventional treatments included hand-removal, mowing, or glyphosate in autumn prior to flowering and season-long selective treatments included hand-removal or fenoxaprop-P as needed throughout the growing season.

woody vegetation, but often, adventitious stems of deciduous woody plants regenerate. Hand-removal of Japanese stiltgrass or fenoxaprop-P has no direct impact on the spectrum of other exotic plants present, with the exception of bristlegrass, an annual grass. However, season-long hand-removal increased relative cover of other exotic plants by 51%. It is unclear why an increase occurred with season-long hand-removal and not conventional hand-removal because the only difference was the number of times throughout the growing season that Japanese stiltgrass was removed. Further, the other season-long Japanese stiltgrass management treatment, fenoxaprop-P, did not increase relative cover of other exotic plants.

Native Plants. Native forbs, monocots, and woody plants were typical southern Piedmont species, yet varied at each location (Judge 2005). On the basis of percent relative cover data and plant count data of native forbs obtained from soil cores, all Japanese stiltgrass management treatments affected changes in populations of native forbs similarly (Table 2). However, there was a significant difference in native forb populations based on the number of years of Japanese stiltgrass management treatments. Averaged across management treatments, relative percent cover of native forbs increased 107%, 182%, and 325% after 1, 2, and 3 yr of Japanese stiltgrass management, respectively. Seed bank of native forbs increased 1%, 18%, and 48% after 1, 2, and 3 yr of management, respectively, based on soil core counts. The removal of competition of Japanese stiltgrass is likely the explanation for the significant increase in native forb recruitment and subsequent regeneration.

Both Japanese stiltgrass management treatments and number of years affected native monocot relative cover; however, there was not a treatment by year interaction (Table 2). There was no treatment or year effects on plant counts of native monocots obtained from soil cores. Averaged across treatments, relative cover of native monocot increased 60%, 175%, and 213% after 1, 2, and 3 yr of management, respectively (Table 3). Averaged across years, the conventional glyphosate treatment resulted in the smallest population increase (4%), whereas season-long fenoxaprop-P increased native monocots 128%, season-long hand-removal 166%, conventional mowing 183%, and conventional hand-removal 265% (Table 4). Fenoxaprop-P is a selective grass herbicide, but many of the native monocots were perennial grasses, rushes, or sedges that were not adversely impacted by fenoxaprop-P. Therefore, all of the management treatments increased native monocot populations, with glyphosate having the least influence, and multiple years of Japanese stiltgrass management further increased relative cover of native monocots.

There was a significant difference in native woody plant relative cover among Japanese stiltgrass management treatments (Table 2). However, there was no effect of years of management on relative cover of native woody plants. Further, there was no treatment or year effects on plant counts of native woody plants obtained from soil cores. Averaged across years, all selective Japanese stiltgrass management treatments (conventional hand-removal, season-long hand-removal, and season-long fenoxaprop-P) resulted in increased relative cover of native woody plants 64 to 114% (Table 4). Nonselective Japanese stiltgrass management treatments (conventional mowing and glyphosate) decreased relative native woody plant cover 23 to 49%. Consistently, the nonselective treatments were more detrimental to woody plants than selective treatments for both exotic and native woody plants, as described previously. While the nonselective treatments were effective at reducing populations of Japanese stiltgrass, they also negatively impacted recruitment and establishment of desirable native woody plants.

Species Richness. In this study, species richness was measured as the number of plant species per plot before and after each season of Japanese stiltgrass management treatments to determine if overall number of species present increased, decreased, or remained the same after

Table 5. Changes in species richness[a] over time and across Japanese stiltgrass management treatments.

Treatment[c]	Year of evaluation[b] 2002	2003	2004	2005
Nontreated	7 a A	8 a AB	10 a AB	9 a A
Conventional				
Hand-removal	7 a A	9 a AB	14 b CD	16 b B
Mowing	6 a A	9 b AB	12 c BC	15 d B
Glyphosate	7 a A	7 a A	8 a A	9 a A
Season-long				
Hand-removal	8 a A	12 b C	15 c D	17 c B
Fenoxaprop-P	8 a A	10 b BC	14 c CD	17 c B

[a] Species richness refers to the number of plant species per plot.

[b] Year of evaluation refers to 2002 prior to any management treatments and 2003, 2004, and 2005 after 1, 2, and 3 yr of management treatments, respectively. Because of the treatment by year interaction, comparisons among years are in lower case letters and can only be compared within a row.

[c] Conventional treatments included hand-removal, mowing, or glyphosate in autumn prior to flowering and season-long selective treatments included hand-removal or fenoxaprop-P as needed throughout the growing season. Because of the treatment by year interaction, comparisons among treatments are in uppercase letters and can only be compared within a column.

3 yr of Japanese stiltgrass management. In fact, species richness was affected by Japanese stiltgrass management treatments and number of years of management, and there was a treatment by year interaction (Table 5). Prior to initial Japanese stiltgrass management treatments, species richness was homogenous across treatments (six to eight species). After three seasons of Japanese stiltgrass management, all treatments resulted in increased species richness (15 to 17 species) compared to the nontreated (nine species) with the exception of the conventional glyphosate treatment (nine species), which controlled Japanese stiltgrass but did not increase species richness. Reducing populations of Japanese stiltgrass by any method evaluated herein with the exception of repeated glyphosate applications allowed for increased species richness. After three seasons of Japanese stiltgrass management, species richness increased, but other exotic plant populations did not increase, with the exception of the season-long hand-removal treatment. Therefore, it remains to be seen beyond the scope of this experimental timeframe whether the increased species richness lends to reduced susceptibility (e.g., Elton 1958; Tilman 1997) or increased susceptibility (e.g., Stohlgren et al. 2003; Stohlgren et al. 1999) to Japanese stiltgrass or other exotic plants.

Overall, all management treatments reduced populations of Japanese stiltgrass over time. Selective management treatments resulted in greater increases in native plant populations and species richness. Mowing was detrimental to native woody plant populations, yet species richness still increased with this management treatment. Repeat glyphosate applications were least effective as they were detrimental to recruitment and reestablishment of woody plants and did not increase species richness. Large-scale management will require more than 3 yr of management, although by the third and subsequent years, spot treatments should be sufficient for retaining control of populations of Japanese stiltgrass, rather than a broadcast manual, mechanical, or chemical management treatment.

Sources of Materials

[1] Flat fan spray tips and wide-angle FloodJet nozzle, Spraying Systems Co., P.O. box 7900, Wheaton, IL 60189-7900.

[2] Piston pump backpack sprayer, Solo, Inc., 5100 Chestnut Ave., Newport News, VA 23605.

[3] Middleweight Mix #4-P: peat moss, perlite, vermiculite, and processed pine bark, Conrad Fafard, Inc., P.O. box 790, 770 Silver St., Agawam, MA 01001-0790.

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