

## Response of Japanese Stiltgrass (*Microstegium vimineum*) to Application Timing, Rate, and Frequency of Postemergence Herbicides<sup>1</sup>

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**Abstract:** Japanese stiltgrass is a nonnative invasive grass that occurs in a variety of habitats and is widely distributed throughout the eastern United States. In natural areas such as forests, herbicide options that selectively control Japanese stiltgrass while preserving native herbaceous and woody vegetation may be desired. The efficacy of three selective postemergence herbicides (fenoxaprop-P, imazapic, and sethoxydim) applied early season, midseason, or late season on monoculture understory stands of Japanese stiltgrass in forests was examined in an experiment conducted at a site in North Carolina and a site in Virginia from 2002 to 2004. The herbicides, averaged across application timings, controlled Japanese stiltgrass at the end of the growing season 83 to 89% and seedhead production 79 to 94% compared with nontreated plants. Seedling emergence was reduced in the spring of 2004 by 89, 70, and 78% by fenoxaprop-P, imazapic, and sethoxydim, respectively, applied in 2003. In another experiment at the North Carolina site in 2002 and 2003, fenoxaprop-P or sethoxydim applied twice (4 wk apart) at half-registered rates controlled Japanese stiltgrass. This study demonstrates that land managers have multiple POST herbicide and application timing, rate, and frequency options for Japanese stiltgrass control.

**Nomenclature:** Fenoxaprop-P; imazapic; sethoxydim; Japanese stiltgrass, *Microstegium vimineum* (Trin.) A. Camus #<sup>3</sup> MCGVM.

**Additional index words:** Invasive plant, annual jewgrass, bambooglass, flexible sesagrass, Japanese grass, Mary's grass, Nepalese browntop.

**Abbreviations:** 1X, maximum use rate.

### INTRODUCTION

Japanese stiltgrass is an invasive, summer annual grass (Brown 1977; Winter et al. 1982), family Poaceae, subfamily Panicoideae, and tribe Andropogoneae (Fairbrothers and Gray 1972). A native of Asia, it was first reported in the United States in 1919 near Knoxville, TN (Fairbrothers and Gray 1972), and is now widely distributed throughout the eastern United States, from New York to Texas, and Puerto Rico (Barden 1987; Fairbrothers and Gray 1972; Redman 1995; USDA, NRCS 2004). Japanese stiltgrass occurs in a variety of habitats, including river banks, flood plains, woodland thickets, roadside ditches, river bluffs, forest edges, and deep forest understory sites (Fairbrothers and Gray 1972; Hunt

and Zaremba 1992; Redman 1995). More recently, it has encroached into landscape plantings and turfgrass (Fairbrothers and Gray 1972; Senesac 1994). The species is a C<sub>4</sub> plant (Brown 1977) with unusual shade adaptation. Dry-matter production under 18% of full sunlight was no different than 100% sunlight, and growth continued down to 5% of full sunlight; in contrast, large crabgrass [*Digitaria sanguinalis* (L.) Scop.], another C<sub>4</sub> summer annual grass, failed to grow at 5% of full sunlight (Winter et al. 1982).

Japanese stiltgrass is one of the most troublesome invasive species in the eastern United States. Japanese stiltgrass was ranked the most problematic of the known 167 nonnative, invasive species present in the 8,100-ha Oak Ridge National Environmental Research Park, located in Tennessee (Drake et al. 2003). It is considered difficult to manage due to numerous, dense stands that occur in disturbed, early-successional habitats, and relatively nondisturbed, late-successional forest communities (Drake et al. 2003). Similarly, in an invasive species survey of 23 urban riparian forest sites within the Raleigh and Cary, NC, greenways systems, Japanese stiltgrass was the only species to occur at every site among

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<sup>3</sup> Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, Revised 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

the 26 invasive species inventoried (Vidra 2004). Likewise, the United States Department of Agriculture Forest Service lists Japanese stiltgrass as one of the top 33 invasive plants invading southern forests at an alarming rate, thus affecting forest productivity and degrading plant species diversity and wildlife habitat (Miller 2003).

Control recommendations emphasize prevention of seed production by hand weeding, mechanical methods, or nonselective POST herbicides before flowering (Tu 2000). Previous research by Judge et al. (2005), conducted in containers, showed that PRE herbicides registered for large crabgrass control were equally or more effective on Japanese stiltgrass than on large crabgrass, including benefin plus oryzalin, dithiopyr, isoxaben plus trifluralin, oryzalin, oxadiazon, pendimethalin, prodiamine, or trifluralin. Likewise, selective POST herbicides (clethodim, fenoxaprop-P, fluazifop-P, and sethoxydim) and nonselective POST herbicides (glufosinate and glyphosate), with little or no soil residual, registered for large crabgrass control were equally or more effective on Japanese stiltgrass than on large crabgrass grown in containers. Other preliminary research supports the effectiveness of pendimethalin, oryzalin, or prodiamine applied PRE and clethodim, fenoxaprop-P, fluazifop-P, sethoxydim, glufosinate, or glyphosate applied POST (Gover et al. 2003; Senesac 1994). Therefore, in managed ecosystems, such as lawns and landscapes, many selective PRE and selective or nonselective POST herbicide options are available for Japanese stiltgrass control in addition to hand or mechanical removal. However, in forested ecosystems, not all of these options are feasible, as it is often desirable to control Japanese stiltgrass while minimizing impact on native herbaceous and woody vegetation, including native rushes (Juncaceae) and sedges (Cyperaceae), thereby facilitating native plant-community restoration. As seed is the sole means of reproduction, the primary goal of any Japanese stiltgrass management program should be to reduce or eliminate seed input into the soil seed bank. Japanese stiltgrass has a persistent seed bank (Barden 1987; Gibson et al. 2002); seeds can remain viable in the soil for up to 3 yr (Barden 1987; Woods 1989).

For selective POST control, fenoxaprop-P and sethoxydim are both effective (Judge et al. 2005). In preliminary research, imazapic applied PRE controlled Japanese stiltgrass (Gover et al. 2003). Fenoxaprop-P (Anonymous 2003a) and imazapic (Anonymous 2003b) are registered specifically for Japanese stiltgrass control. However, the three herbicides vary in their level of selectivity. Fenoxaprop-P selectively controls nearly all summer

annual and some perennial grasses without injuring dicots or tolerant grasses; sethoxydim selectively controls both annual and perennial grasses without injuring most dicots; and imazapic is registered for both PRE and POST control of annual and perennial grasses, sedges, and many annual broadleaf species without injuring rangeland and pasture species, some warm-season turfgrasses, perennial prairie grasses, and some roadside wildflower species (Vencill 2002). For wildflower establishment, reduced rates (0.04 to 0.07 kg ai/ha) did not injure annual phlox (*Phlox drummondii* Hook.), lanceleaf coreopsis (*Coreopsis lanceolata* L.), and sundial lupine (*Lupinus perennis* L.). Rates less than 0.04 kg ai/ha were required to reduce stunting and occasionally stand thinning on scarlet sage (*Salvia coccinea* Buc'hoz ex Etl.), blanketflower (*Gaillardia pulchella* Foug.), and black-eyed susan (*Rudbeckia hirta* L.) (Norcini et al. 2003).

Timing of POST grass-herbicide applications impacts efficacy. For example, large crabgrass and smooth crabgrass [*D. ischaemum* (Schreb. ex Schweig.) Schreb. ex Muhl.] seedlings without tillers were more susceptible to fenoxaprop-P compared with plants in a more advanced growth stage that required higher rates or multiple applications for complete control (Chism and Bingham 1991; Neal et al. 1990). Additionally, the imazapic registration suggests that rates between 0.06 and 0.09 kg ai/ha only control Japanese stiltgrass less than or equal to 10 cm tall (Anonymous 2003b). In preliminary experiments, two applications of fenoxaprop-P, sethoxydim, or other selective grass herbicides at full registered rates were required to control Japanese stiltgrass (Judge et al. 2005); however, those trials were conducted with container-grown plants. Furthermore, Japanese stiltgrass produces both cleistogamous flowers (flowers that are closed and self-pollinating) and chasmogamous flowers (flowers that open and can cross-pollinate) (Williams 1998). Timing of the recommended fall treatment, whether manual, mechanical, or chemical, may be imprecise if the cleistogamous flowers are not readily visible. Additionally, reduced herbicide rates may be desirable in sensitive habitats (Williams 1998). Therefore, the objectives of this research were the following: (1) determine the efficacy of fenoxaprop-P, imazapic, and sethoxydim, on natural stands of Japanese stiltgrass; (2) compare control of nontillering and tillering plants at various rates and timings of fenoxaprop-P and sethoxydim; and (3) assess the impact of herbicide application on Japanese stiltgrass stand reduction the year after application.

## MATERIALS AND METHODS

### Efficacy as Affected by Herbicide and Application

**Timing.** The experiment was conducted in 2002 and repeated in 2003 in established forest understory monoculture stands of Japanese stiltgrass in both North Carolina and Virginia. In North Carolina, Schenck Memorial Forest (central Wake County), a mixed pine–hardwood forest, was the 2002 experimental site; in 2003, the experiment was repeated at Harris Lake Research Forest (southern Wake County), a hardwood forest. The Virginia experiment was conducted in a mixed pine–hardwood forest at the Hampton Roads Agriculture Experiment Station, Virginia Beach, VA.

The experiment was a factorial arrangement of treatments (three herbicides and three application timings, plus a nontreated) in a randomized complete block design with four replications. Plot size in North Carolina was 2.4 by 3.0 m and 1.8 by 3.0 m in Virginia. Selective POST herbicides included fenoxaprop-P, imazapic, and sethoxydim applied at 0.19, 0.07, and 0.56 kg ai/ha, respectively. Nonionic surfactant<sup>4</sup> (0.25% v/v) was added to fenoxaprop-P and imazapic. Each herbicide was applied early season (pretiller), midseason (tillering), or late season (before anthesis), and efficacy was compared with nontreated plants. In North Carolina, application dates in 2002 were May 10 (two to five leaves; 4 to 10 cm tall), July 18 (six to seven leaves, one to two tillers; 12 to 30 cm tall), and October 7 (multiple tillers; 30 to 40 cm tall); dates in 2003 were May 9 (four to six leaves; 15 to 30 cm tall), June 6 (six to seven leaves, zero to one tiller; 38 to 76 cm tall), and August 12 (multiple tillers; 76 to 80 cm tall). Herbicides were applied using a CO<sub>2</sub>-pressurized backpack sprayer equipped with two 8003 or two 8004 flat fan spray tips<sup>5</sup> in 2002 and 2003, respectively. The sprayer was calibrated to deliver 280 L/ha at 407 kPa and 280 L/ha at 234 kPa in 2002 and 2003, respectively. In Virginia in 2002, application dates were May 5 (two to five leaves; 8 to 30 cm tall), June 11 (six to seven leaves, two to five tillers; 28 to 58 cm tall), and July 22 (multiple tillers; 38 to 69 cm tall); dates in 2003 were May 8 (two to five leaves; 5 to 20 cm tall), June 11 (8 to 15 leaves, one to two tiller; 23 to 53 cm tall), and July 31 (multiple tillers; 48 to 69 cm tall). Herbicides were applied using a CO<sub>2</sub>-pressurized backpack sprayer equipped with two 8003 flat fan spray tips and calibrated to deliver 234 L/ha at 207 kPa. In 2002,

a drought severely affected plant growth at the North Carolina experimental site. Therefore, herbicides were applied later to coincide with the proper growth stage.

Percent biomass control was evaluated visually and compared with nontreated plants at the end of the season before senescence (North Carolina: November 4, 2002, and October 21, 2003; Virginia: October 24, 2002, and November 1, 2003), using a 0 to 100% scale, with 0 equal to no plant response and 100% equal to complete control. Additionally, seedhead reduction was also estimated in both sites in 2003. In North Carolina, visual estimates of percent of plants with seedheads were recorded on October 21 and converted to percent seedhead reduction. In Virginia, on October 20, terminal seedhead counts were made and converted to percent seedhead reduction compared with nontreated plants.

Percent biomass control and seedhead reduction data were analyzed using the GLM procedure (SAS 1999) testing the hypothesis for mixed model ANOVA ( $\alpha = 0.05$ ) with error partitioning to reflect the factorial treatment arrangement. Data from the four experimental repetitions (North Carolina 2002 and 2003; Virginia 2002 and 2003) were combined after analysis showed nonsignificance for year, location, and year-by-location interactions.

In the spring of 2004, Japanese stiltgrass seedlings were counted in plots sprayed in 2003 at both the North Carolina and Virginia sites to determine impact of the POST herbicides on the seedling population the following season. In North Carolina on May 14, seedlings were counted in randomly placed 1-m<sup>2</sup> subplots in each plot and converted to percent stand reduction compared with nontreated controls, using a 0 to 100% scale, with 0 equal to no stand reduction and 100% equal to complete stand reduction. In plots with high population densities, seedlings were counted in three randomly placed 1-dm<sup>2</sup> subplots, and data were extrapolated to a 1-m<sup>2</sup> basis. In Virginia, seedlings were counted on April 28 in randomly placed 0.9-m<sup>2</sup> subplots in each plot and converted to percent stand reduction compared with nontreated plants.

Percent stand reduction data were analyzed using the GLM procedure (SAS 1999) testing the hypothesis for mixed model ANOVA ( $\alpha = 0.05$ ) with error partitioning to reflect the factorial treatment arrangement. Data from the two experimental repetitions (North Carolina and Virginia 2004) were combined after analysis showed nonsignificance for location. Means for significant main effects and interactions were separated using the Pdiff option in SAS (1999) at the 5% significance level. The Pdiff option provides an associated level of significance

<sup>4</sup> Latron AG-98, principal functioning agents—nonylphenoxypolyethoxy ethanol, butyl alcohol, Rohm and Hass Co., 100 Independence Mall West, Philadelphia, PA 19106-2399.

<sup>5</sup> Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60189-7900.

for each comparison. The mean square error is obtained by ANOVA and comparisons are equivalent to those determined with least significant difference.

**Efficacy as Affected by Herbicide, Rate, and Application Frequency.** The experiment was conducted in a mixed pine–hardwood forest at Harris Lake County Park (southern Wake County), NC, in 2002 and was repeated in 2003 in a nearby hardwood forest at Harris Lake Research Forest. Plot size was 2.4 by 3.0 m. The experiment was a factorial arrangement of treatments (two herbicides, two rates, two application frequencies, plus a nontreated) in a randomized complete block design with four replications. Herbicides included fenoxaprop-P at 0.10 (1/2×) or 0.19 kg ai/ha (maximum use rate or 1×) or sethoxydim at 0.28 (1/2×) or 0.56 kg ai/ha (1×). Nonionic surfactant (0.25% v/v) was added to fenoxaprop-P. Application frequency was once or twice (4 wk apart). Application dates in 2002 were May 23 (six to seven leaves, zero to one tiller; 30 to 33 cm tall) and June 17 (multiple tillers; 60 to 65 cm tall), 2002. In 2003, application dates were June 6 (six to seven leaves, zero to one tiller; 38 to 76 cm tall) and July 7 (multiple tillers; 76 to 80 cm tall). Herbicides were applied as previously described.

Percent biomass control was evaluated visually and compared with nontreated plants at the end of the season before senescence (November 4, 2002; October 21, 2003), using the 0 to 100% scale described previously. Percent biomass control data were analyzed using the GLM procedure (SAS 1999) testing the hypothesis for mixed model ANOVA ( $\alpha = 0.05$ ) with error partitioning to reflect the factorial treatment arrangement. Data from the two experimental repetitions (2002 and 2003) were combined after analysis showed nonsignificance for year. Means for significant main effects and interactions were separated using the Pdiff option in SAS (1999) at the 5% significance level.

## RESULTS AND DISCUSSION

**Efficacy as Affected by Herbicide and Timing Application.** No location or year effect or interactions were detected for Japanese stiltgrass control; therefore, data were pooled across locations and years (Table 1). Additionally, no herbicide, application timing, or interaction effects were present; therefore, data were pooled across application timings for each herbicide. Aboveground biomass of Japanese stiltgrass was reduced 83 to 89% by the herbicides (no difference among herbicides). Likewise, for seedhead reduction in 2003, no location

Table 1. Biomass reduction<sup>a</sup> (pooled across 2002 and 2003) and seedhead reduction<sup>b</sup> (2003) of Japanese stiltgrass at the end of the growing season at a site in North Carolina and a site in Virginia (pooled) by three postemergence herbicides applied at three timings (pretiller, tiller, preanthesis); and stand reduction<sup>c</sup> in 2004 at both sites from herbicides applied in 2003.<sup>d</sup>

Herbicide	Biomass reduction	Seedhead reduction	Stand reduction
	%		
Fenoxaprop-P	89	94	89
Imazapic	83	79	70
Sethoxydim	88	90	78
ANOVA	( <i>P</i> > <i>F</i> )		
Location	NS <sup>e</sup>	NS	NS
Year	NS	—	—
Herbicide <sup>f</sup>	NS	NS	0.0099
Fenoxaprop-P vs. imazapic	—	—	0.0113
Fenoxaprop-P vs. sethoxydim	—	—	NS
Sethoxydim vs. imazapic	—	—	NS
Application timing	NS	NS	NS
All interactions	NS	NS	NS

<sup>a</sup> Percent aboveground biomass reduction compared with nontreated controls was evaluated visually using a 0 to 100% scale; 0% = no plant response and 100% = complete control.

<sup>b</sup> In North Carolina, visual estimates of percent of plants with seedheads were recorded in October and converted to percent seedhead reduction; in Virginia, terminal seedheads were counted in October and converted to percent seedhead reduction compared with nontreated plants.

<sup>c</sup> Seedling density was determined in April or May; reduction as a percentage of nontreated controls.

<sup>d</sup> Means were pooled across locations, years (biomass data), and application timings.

<sup>e</sup> Abbreviation: NS, nonsignificant according to the *t* test on differences of least square means at *P* = 0.05.

<sup>f</sup> For stand reduction, herbicides were compared using *P*-values generated by PROC GLM using the Pdiff option (SAS 1999).

effect was present; therefore, data were pooled across locations. Additionally, no herbicide, application timing, or interaction effects were present; therefore, data were pooled across application timings for each herbicide. Herbicides reduced seedhead production by 79 to 94%, depending on the herbicide (no difference among herbicides).

Each herbicide and timing combination was equally effective on Japanese stiltgrass; therefore, land managers have flexibility in herbicide choice and application timing for selective POST Japanese stiltgrass control. Japanese stiltgrass was not as sensitive to application timing as was demonstrated by crabgrass seedlings (Chism and Bingham 1991; Neal et al. 1990). In contrast, Japanese stiltgrass may be controlled throughout the growing season. This wide window of application may be particularly important due to the cleistogamous flowering habit discussed previously. Additionally, the herbicides tested vary in selectivity, making it possible to control Japanese stiltgrass while maintaining desirable vegetation.

POST herbicide treatments in 2003 reduced Japanese stiltgrass stand density in 2004 (Table 1). No location

effect was present; therefore, data were pooled across locations. The main effect of herbicide was significant ( $P = 0.0099$ ); however, other main effects and interactions were not significant. Nontreated plots averaged 18,600 and 500 seedlings per m<sup>2</sup> in North Carolina and Virginia, respectively. Averaged across application timings, stand reduction in the fenoxaprop-P treated plots was 89%, similar to sethoxydim (78% reduction) but greater than imazapic (70% reduction) (Table 1). Stand reduction in the sethoxydim- and imazapic-treated plots were similar. Because imazapic treated plots had the lowest stand reduction, herbicide residues were not considered a factor in germination the following spring. These results suggest that reducing seed production greater than 79%, as noted previously, for just one growing season has substantial impacts on emergence from the transient and persistent seed bank the following season. However, if not completely controlled, surviving seedlings will likely result in 100% cover by the fall and replenish the seed bank. Further research needs to be conducted to determine what level of control and how many seasons of control will be required to completely deplete the seed bank. Therefore, fenoxaprop-P, imazapic, or sethoxydim applied anytime throughout the growing season, but before flowering, will control both Japanese stiltgrass biomass and seed production and reduce seedling emergence the next growing season. Selectively controlling Japanese stiltgrass and depleting the seed bank may allow reestablishment of native vegetation, a critical component to reclamation of an invaded plant community (Miller 2003; Neal et al. 2004).

**Efficacy as Affected by Herbicide, Rate, and Application Frequency.** No year effect or treatment interactions with year were present for percent biomass reduction; therefore, data were pooled across years (Table 2). Averaged across years, response of Japanese stiltgrass to fenoxaprop-P and sethoxydim was similar. However, rate ( $P = 0.0133$ ), frequency ( $P \leq 0.0001$ ), and rate-by-frequency interaction ( $P = 0.0133$ ) were significant. The herbicides applied twice at 1/2× or 1× (4 wk apart) resulted in 92% control. However, one application of either herbicide at 1/2× rate reduced biomass by only 53%, whereas a single application at 1× reduced biomass by 77%. In this experiment, two applications were more effective than one application, even at the full-registered rate, while control was adequate with only one application in the previously mentioned experiment. Reduced rates are a feasible control option if herbicides are applied sequentially 4 wk apart. However, the lowest effective rate needs to be determined. Furthermore, as rates

Table 2. Biomass reduction of Japanese stiltgrass in 2002 and 2003 (pooled) as affected by postemergence applications of fenoxaprop-P and sethoxydim (data pooled across herbicides).

Herbicide rate <sup>a</sup>	Application frequency <sup>b</sup>	Biomass reduction <sup>c</sup>
		%
1/2×	1 application	53
1/2×	2 applications	92
1×	1 application	77
1×	2 applications	92
ANOVA <sup>d</sup>		( $P > F$ )
Rate		0.0133
Frequency		<0.0001
Rate by frequency		0.0133

<sup>a</sup> Fenoxaprop-P (1/2× = 0.10 kg ai/ha, 1× = 0.19 kg ai/ha); sethoxydim (1/2× = 0.28 kg ai/ha, 1× = 0.56 kg ai/ha).

<sup>b</sup> Herbicides were applied either once or twice (4-wk interval).

<sup>c</sup> Percent aboveground biomass reduction estimated visually using a 0 to 100% scale, where 0% = no plant response and 100% = complete control.

<sup>d</sup> Nonsignificant main effects and interactions are not shown.

are reduced, growth stage may become a significant variable (Anonymous, 2003b; Chism and Bingham 1991). Regardless, it is critical to understand how reduction in biomass affects seed production and contributions to the seed bank to effectively determine what level of control is needed.

These studies demonstrate that Japanese stiltgrass can be selectively controlled POST. Fenoxaprop-P, imazapic, or sethoxydim applied anytime throughout the growing season, but before flowering, will control Japanese stiltgrass biomass and seed production and reduce seedling emergence the following growing season. Furthermore, when applied twice at 4 wk apart, either fenoxaprop-P or sethoxydim applied at half of the full registered rate controlled Japanese stiltgrass. These results confirm that fenoxaprop-P, imazapic, and sethoxydim can be used for POST Japanese stiltgrass control in naturally occurring stands (Gover et al. 2003; Judge et al. 2005). For each of the POST herbicides, it will be necessary to confirm the site specificity of the product labels due to the complex range of ecosystems where Japanese stiltgrass control is desired. Depending on the management goals and level of selectivity desired, land managers of an invaded site have multiple POST herbicide treatment options for Japanese stiltgrass control.

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