Effectiveness of Three Postemergence Herbicides in Controlling an Invasive Annual Grass, *Microstegium vimineum*

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Abstract: Effective control of Nepalese browntop (*Microstegium vimineum*) is important to land managers in the eastern United States because invasions can suppress native vegetation, thus decreasing vegetation diversity and habitat quality for many wildlife species. We evaluated the effectiveness of herbicides with varying selectivity (glyphosate, imazapic, and clethodim) at full rates and half rates (based on labeled rates for annual grass control) on the control of japangrass and their effects on non-target vegetation. We conducted our experiment in three forested areas in east Tennessee. We measured species coverage using point transects before treatment, 60 days after treatment (60DAT), and one year after treatment (1YAT). Japangrass coverage 60DAT was similar for all six treatments (0%–8%), but differed from coverage in control plots (83%). The coverage of japangrass in all treatments was less than control plots 1YAT (10%–35% vs. 68%). However, full rates of glyphosate (2qt/ac) and imazapic (8oz/ac) were most effective in controlling japangrass 1YAT (17% and 10%, respectively). Percent coverage of non-target vegetation 60DAT and 1YAT were similar among the treatment and control plots. Our results suggest full rates of glyphosate and imazapic are the most effective postemergence options to control japangrass. Multiple applications should be evaluated across years and sites to gain a better understanding of the long-term effects of herbicide applications.

Key words: Japanese stiltgrass, glyphosate, imazapic, clethodim, invasive plants, *Microstegium vimineum*

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Invasive plants can have detrimental effects on native vegetation communities and ecosystems (Mack et al. 2000) by altering disturbance regimes such as changing fire frequency and intensity; altering soil chemistry, structure, and nutrient cycling; and limiting the establishment and growth of native plant communities (Schmidt and Whelan 1999, Brooks et al. 2004, Flanders et al. 2006, Weidenhamer and Callaway 2010). The introduction of cheatgrass (*Bromus tectorum*) into the sagebrush region of the western United States increased the frequency of fire in the region, thereby limiting native sagebrush communities and eliminating habitat for sage-grouse (*Centrocercus* spp.) and other wildlife (Knick et al. 2003) dependent on the native vegetation. Similarly, tall fescue (*Schedonorus arundinaceus*) reduces fire frequency in early successional communities in the eastern United States and limits the establishment of native grasses and forbs, thereby eliminating habitat for wildlife species dependent on early successional plant communities, such as northern bobwhite (*Colinus virginianus*) (Barnes et al. 1995, McGranahan et al. 2012).

Nepalese browntop (*Microstegium vimineum*, hereafter japangrass) is a non-native annual grass from southeast Asia currently found in 26 states (USDA 2014). Japangrass is a warm-season C_4 grass, which germinates in the spring and produces seed during late summer or early fall. It can invade and proliferate in areas with a wide variety of light conditions and is often found invading gaps in the forest canopy such as roads, log landings, and forest edges, as well as within closed-canopy forests (Winter et al. 1982, Cole and Weltzin 2004). Japangrass is a prolific seed producer and seeds are easily spread via water and human activities, such as timber harvests (Christen and Matlack 2009, Tekiela and Barney 2013). Infestations are accelerated either by anthropogenic or by natural disturbance, including understory deterioration through deer herbivory or flood scouring (Barden 1987, Eschtruth and Battles 2009). Infestations typically lead to dense monocultures limiting the establishment of native vegetation and the regeneration and growth of tree seedlings (Oswalt et al. 2007, Flory and Clay 2009, Marshall et al. 2009, Flory 2010, Aronson and Handel 2011). Japangrass infestations can also alter soil chemical properties, insect diversity, and insect abundance in forested areas (McGrath and Binkley 2009, Tang et al. 2012).

Various methods have been tested for control of japangrass, including hand-weeding, string-trimming, prescribed fire, postemergence herbicide, and preemergence herbicide (Judge et al.

2005, Flory 2010, Ward and Mervosh 2012, Emery et al. 2013). For example, Emery et al. (2013) compared pendimethalin (1.34 kg ai/ha, Pendulum AquaCap, BASF), a preemergence herbicide, fluazifop-P-butyl (0.21 kg ai/ha, Fusilade DX; Syngenta Crop Protection, Inc.), a postemergence herbicide, prescribed fire, and the combination of fire and herbicide on the control of japangrass and reported only postemergence herbicide application decreased japangrass population growth. However, they reported repeated applications were necessary to deplete the seedbank. Along with fluazifop-P-butyl, two other grass-selective postemergence herbicides have been tested and identified as viable control options for japangrass: sethoxydim (0.5 kg ai/ha, Sethoxydim SPC, Nu Farm) and fenoxaprop-P (0.1 kg ai/ha, Acclaim Extra, Bayer) (Judge et al. 2005, Judge et al. 2008).

Grass-selective herbicides are commonly used in the control of japangrass because of the potentially reduced effects to the residual plant community (Judge et al. 2005, Judge et al. 2008, Flory 2010, Flory and Clay 2010). Optimally, control methods for invasive species effectively control the target species and minimally affect the residual plant community. The removal of a dominant invasive species can have positive or negative effects on the residual community. Flory and Clay (2010) reported an increase in native species diversity and forb richness, but a decrease in graminoid biomass following control of japangrass with fluazifop-P-butyl. However, Ogden and Rejmanek (2005) reported an increase in non-native grass coverage and no change in the native species diversity in areas treated with triclopyr (Garlon 3A, Dow AgroSciencies) to control fennel (*Foeniculum vulgare*).

We aimed to test the effects of postemergence herbicides, with varying plant selectivity, on the control of japangrass and the effects on the residual plant community. We chose to test three herbicides: clethodim, a grass-selective herbicide, untested in a field study; imazapic, a commonly used broad-spectrum selective herbicide in grassland restoration; and glyphosate, the most commonly used broad-spectrum herbicide. We tested all three herbicides at the recommended rate and half the recommended rate for annual grass control to identify if rates could be reduced and still provide control of japangrass. We hypothesized all herbicides at both rates would reduce the coverage of japangrass 60 days and one year after treatment and the coverage of native plants would increase following treatment.

Methods

We conducted our experiment on a 200-ha private property in Union County, Tennessee. Our study site was located approximately 32 km north of Knoxville and lies within the Southern Appalachian Ridge and Valley physiographic region. It averaged 137 cm of precipitation annually and soils were shallow, well-drained, and acidic Talbott series, with a silty clay-loam texture (Soil Survey Staff 2014). The site was primarily closed-canopy hardwood forests with an oak-hickory dominated overstory with some stands dominated by eastern redcedar (*Juniperus virginiana*) and Virginia pine (*Pinus virginiana*). Japangrass infestations were frequent within closed-canopy and regenerating stands, as well as near paved and logging roads.

Our experiment was conducted in three separate stands across the property with extensive japangrass infestations. In May 2012, we established seven 2 × 10 m plots in each of the three stands. Each plot was randomly assigned one of six treatments or control. Treatments included glyphosate full rate, glyphosate half rate, imazapic full rate, imazapic half rate, clethodim full rate, and clethodim half rate (Table 1). Herbicide rates were based on label recommendations for annual grass control and non-ionic surfactant (0.25% of spray solution; Surf-AC 820, Drexel, Memphis, Tennessee) was added to all herbicide solutions as per herbicide label recommendations. Herbicide applications were completed in June 2012 after japangrass was established in the herbaceous layer. Herbicides were applied using a 15-L backpack sprayer (Solo USA, Newport News, Virginia) and a 4-nozzle handheld boom (R&D Sprayers, Opelousas, Louisiana), with a 2-m swath width. The backpack sprayer was calibrated based on Zedaker and Nichols (2009) and one individual applied all treatments to ensure consistent application.

Coverage of japangrass and non-target species were measured using the point-intercept method (Bonham 2013). The presence of all species was recorded at 0.5-m intervals along a 10-m transect. If a species was present, it was recorded as a "hit" and percent coverage was quantified as the number of "hits" divided by the total number of samples per transect (20 samples). Sampling occurred prior to treatment, 60 days after treatment (60DAT; August 2012), and one year after treatment (1YAT; June 2013).

We used an ANOVA within SAS 9.3 (2011) to evaluate the effects of herbicide application on the control of japangrass. We

Table 1. Herbicide information and rates for treatments applied in June 2012 for the control of japangrass, Union County, Tennessee.

Active ingredient	Trade name	Active ingredient (kg) per ha	Rate per acre	Manufacturer	Selectivity
Clethodim	Clethodim 2EC	0.2101	12 oz	Albaugh Inc.	Grass-selective
		0.105	6 oz		
Glyphosate	Gly-4 Plus	2.24	2 qt	Universal Crop Protection Alliance	Broad-spectrum
		1.12	1 qt		
Imazapic	Plateau	0.1401	8 oz	BASF	Broad-spectrum selective
		0.0701	4 oz		

used a randomized complete block design with a covariate, blocking on site to control variation among locations. We included pretreatment coverage of japangrass as a covariate in the model to test if japangrass coverage prior to treatment influenced the coverage after treatment, but it was removed because it did not have a significant effect. We used a repeated measures treatment design to assess treatment effects over time (60DAT and 1YAT), with time being our repeated factor. The same model was used to test the effects of treatments on non-target vegetation. A Fisher's LSD mean separation was used to determine differences among treatments. Significance for all tests was concluded at alpha = 0.05.

Results

The results of the ANOVA suggested japangrass coverage in all six treatments was less than control after treatment ($F = 15.38$, $P < 0.001$). The results also suggested there was an interaction between treatments and time after treatment ($F = 3.54$, $P = 0.024$). Japangrass coverage 60DAT within treated plots was less than control, 0%–8% and 83% respectively (Table 2). Similarly, coverage of japangrass in all treatments was less than control 1YAT, 10%–35% and 68% respectively (Table 2). The mean separation test suggested japangrass coverage within plots treated with a full rate of glyphosate or imazapic were similar 60DAT (0% and 2%) and 1YAT (17% and 10%). However, japangrass coverage increased between 60DAT and 1YAT for all other treatments (Table 2). Coverage of japangrass from 60DAT to 1YAT increased from 0% to 27% and from 2% to 35% for the full and half rates of clethodim, respectively. Coverage increased from 8% to 27% for the half rate of glyphosate and from 7% to 25% for the half rate of imazapic.

We observed 26 non-target species within our treatment and control plots; 20 were native and 6 were non-native. Coverage of native plants did not differ among treatments and control 60DAT or 1YAT ($F = 1.01$, $P = .0.46$). Native plant coverage ranged from 3%–12% within treatment plots and 30% within control 60DAT, and 18%–37% within treatment plots and 37% within control plots 1YAT (Table 3). Non-native plant coverage did not differ among treatments and control plots 60DAT or 1YAT ($F = 1.08$, $P = 0.42$). Non-native plant coverage was <10% in all treatment plots and control plots 60DAT and ranged from 0%–13% within treatments plots compared to 3% within control plots 1YAT (Table

Table 2. Japangrass coverage (% ± SE) in August 2012 (60DAT) and June 2013 (1YAT) for control, glyphosate, imazapic, and clethodim treatments. Treatments were applied in June 2012, Union County, Tennessee.

	60DAT[b]			1YAT[c]		
Treatment[a]	% Coverage	SE		% Coverage	SE	
Control	83.0	12.0	A	68.3	9.3	A
Glyphosate full	0.0	0.0	F	16.7	6.7	BCDEF
Glyphosate half	8.3	6.0	DFG	26.7	14.5	BCE
Imazapic full	1.7	1.7	F	10.0	5.0	CDEF
Imazapic half	6.7	1.7	EFG	25.0	2.9	BCD
Clethodim full	0.0	0.0	F	26.7	13.0	BCDE
Clethodim half	1.7	1.7	F	35.0	8.7	B

a. Treatment main effect was significant ($F = 15.38$, $P < 0.001$) and treatment*time interaction was significant ($F = 3.54$, $P = 0.024$). Means with the same letter are not different with respect to japangrass coverage across sampling periods.
b. 60 days after treatment was applied, August 2012
c. One year after treatment was applied, June 2013

Table 3. Non-target, native, and non-native plant coverage (% ± SE) in August 2012 (60DAT) and June 2013 (1YAT) for control, glyphosate, imazapic, and clethodim treatments. Treatments were applied in June 2012, Union County, Tennessee.

	Non-target coverage[a]						Native plant coverage[b]						Non-native plant coverage[c]					
	60DAT[d]			1YAT[e]			60DAT			1YAT			60DAT			1YAT		
Treatment	% Coverage	SE		% Coverage	SE		% Coverage	SE		% Coverage	SE		% Coverage	SE		% Coverage	SE	
Control	35.0	12.0	A	40.0	16.1	A	30.0	7.6	A	36.7	15.9	A	1.7	1.7	A	3.3	3.3	A
Glyphosate full	6.7	4.4	A	28.3	14.5	A	6.7	4.4	A	28.3	14.5	A	0.0	0.0	A	1.7	1.7	A
Glyphosate half	15.0	8.7	A	30.0	14.4	A	10.0	7.6	A	23.3	11.7	A	5.0	2.9	A	10.0	5.0	A
Imazapic full	3.3	1.7	A	31.7	9.3	A	3.3	1.7	A	28.3	10.9	A	0.0	0.0	A	3.3	1.7	A
Imazapic half	11.7	11.7	A	35.0	10.4	A	3.3	3.3	A	18.3	6.0	A	8.3	8.3	A	13.3	8.8	A
Clethodim full	10.0	7.6	A	30.0	2.9	A	8.3	8.3	A	25.0	2.9	A	1.7	1.7	A	5.0	5.0	A
Clethodim half	13.3	6.0	A	36.7	9.3	A	11.7	4.4	A	36.7	9.3	A	0.0	0.0	A	0.0	0.0	A

a. Treatment main effect was not significant ($F = 0.67$, $P = 0.67$) and treatment*time interaction was not significant ($F = 0.69$, $P = 0.49$). Means with the same letter are not different with respect to non-target species across sampling periods.
b. Treatment main effect was not significant ($F = 1.01$, $P = .0.46$) and treatment*time interaction was not significant ($F = 0.46$, $P = 0.83$). Means with the same letter are not different with respect to native plant coverage across sampling periods.
c. Treatment main effect was not significant ($F = 1.08$, $P = 0.42$) and treatment*time interaction was not significant ($F = 0.46$, $P = 0.83$). Means with the same letter are not different with respect to non-native plant coverage across sampling periods.
d. 60 days after treatment was applied, August 2012
e. One year after treatment was applied, June 2013

3). Although the overall coverage of the residual plant community within treated plots (3%–15%) was numerically less than control plots (35%) 60DAT, the difference was not significant ($F=0.67$, $P=0.67$). Non-target plant coverage was similar among treatments and control 1YAT, 28%–37% and 40% respectively (Table 3).

Discussion

Our results suggest all three herbicides reduced coverage of japangrass compared to the control, which supported our initial hypothesis. However, the full rates of imazapic and glyphosate were most effective 1YAT. We also hypothesized control of japangrass would increase the native plant coverage following treatment; however, native vegetation was neither enhanced nor suppressed by the treatment and control of japangrass 1YAT.

All treatments provided ≥90% control of japangrass 60DAT. Our results are consistent with studies who reported effective control of japangrass with postemergence herbicide applications. Judge et al. (2005) reported ≥79% reduction of japangrass seedheads eight weeks following treatment with grass-selective herbicides fenoxaprop-p and sethoxydim, and broad-spectrum selective imazapic. Emery et al. (2013) reported near zero seed production in plots treated with fluazifop-P-butyl, a grass-selective herbicide, at the end of the growing season.

Although we reported a ≥90% reduction in japangrass coverage 60DAT for all treatments, there was an increase of japangrass in plots treated with both rates of clethodim and half rates of imazapic and glyphosate from 60DAT to 1YAT. Imazapic and glyphosate at full rates had similar coverage of japangrass 60DAT and 1YAT, but coverage still exceeded 10% 1YAT. Presence of japangrass 1YAT likely was from seed germinating in the seedbank. Japangrass seed remains viable in the seedbank for three years and each plant can produce hundreds of seeds, facilitating a build-up of japangrass seed (Barden 1987). Thus, multiple applications over time are necessary to deplete the seedbank reserve. Our results suggest management with postemergence herbicides will not completely eliminate japangrass, but can be used to reduce coverage, potentially reducing the negative impact on residual vegetation. However, without continued control of japangrass over at least a few years, areas will likely be reinvaded by japangrass within two years. Emery et al. (2013) suggested postemergence control of japangrass with fluazifop-P-butyl, compared to prescribed fire and preemergence control with pendimethalin, was the only treatment able to reduce japangrass population growth past one year, but long-term control could not be achieved without applications across multiple years. Our results differ from Judge et al (2005), who reported fenoxaprop-p (a grass-selective herbicide) was more effective at reducing japangrass 1YAT compared to imazapic, 89% and 78% reduction respectively. However, the imazapic rate used by Judge et al. (2005) was similar to our half rate (0.0701kg/ha). Flory (2010) reported a 74% reduction in japangrass coverage in plots treated with fluazifop-P-butyl 1YAT, but a 95% reduction after two years of repeated treatment.

Removal of invasive species can enhance native species diversity within treated areas (Biggerstaff and Beck 2007, Flory 2010, Flory and Clay 2009). However, removal of one invasive species may facilitate spread of others (Ogden and Rejmanek 2005, Hulme and Bremner 2006, Mau-Crimmins 2007, Lake et al. 2014). Non-target vegetation coverage was not increased or decreased with the control of japangrass by herbicides in our study. Also, the coverage of native and non-native plants did not differ among treatments. However, other studies have reported an increase of native vegetation after treatment with herbicides (Judge et al. 2008, Flory and Clay 2009, Flory 2010). We likely did not see a response from non-target vegetation because our treatments were located within closed-canopy forests, and a lack of sunlight reaching the forest floor can limit establishment of understory vegetation.

The lack of sunlight reaching the forest floor can limit establishment of understory vegetation. McCord et al. (2014) reported light availability increased six fold following a 30% reduction in canopy coverage, resulting in a 40% increase in coverage by understory vegetation, compared to control stands. Flory (2010) reported light availability in areas where japangrass was controlled was important in reestablishment of native vegetation. On another stand within our study site, oak woodland restoration efforts reduced canopy cover by 30%–40%, and after eight years and six prescribed fires, groundcover was 93% (represented by 53 native species), compared to 35% groundcover in control plots (represented by 11 native species) (C. A. Harper, University of Tennessee, unpublished data).

Controlling japangrass prior to timber stand improvement or regeneration practices is important. Increased light availability following management can facilitate spread of japangrass (Cole and Weltzin 2004, Glasgow and Matlack 2007, Oswalt et al. 2007). Oswalt et al. (2007) reported an increase in japangrass biomass following four different levels of canopy reduction and infestations inhibited native tree regeneration. Japangrass growth and recruitment were greater in canopy gaps compared to closed canopy forests (Weltzin 2004, Glasgow and Matlock 2007).

We did not realize a benefit to using selective herbicides, possibly because of sparse non-target coverage. Effects of herbicide selectivity on residual vegetative communities likely will be more pronounced on different sites with varying non-target plant coverage and light conditions. Using a selective herbicide can be a useful tool to limit damage to non-target plants. Judge et al. (2008) and Flory and Clay (2009) both reported differences in non-target plant responses among japangrass control methods. Application of grass-selective herbicides resulted in an increased abundance of native forbs and tree seedlings, but decreased abundance of grasses within treated plots (Flory and Clay 2009). Continued monitoring on areas where japangrass was controlled will help elucidate the long-term effects on the native plant community.

Management Implications

Where japangrass coverage is extensive and non-target vegetation is not of concern, we recommend a broadcast application of imazapic (8oz/ac) or glyphosate (2qt/ac) to effectively control japangrass. Where non-target vegetation is a concern, imazapic should be considered as it does not control various forbs, brambles, and grasses (Anonymous 2012). Clethodim, a grass-selective herbicide, should be considered if other plant forms are present and of concern. However, regardless of herbicide, one treatment will not eliminate japangrass; follow-up applications will be necessary. Japangrass control is important prior to any forest management practice that would add sunlight to the forest floor. Additional research is needed to document the long-term response of non-target vegetation following control of japangrass on multiple sites with various vegetation composition and light conditions.

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