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RESEARCH ARTICLE

Integrating Management Techniques to Restore Sites Invaded by Mile-a-Minute Weed, *Persicaria perfoliata*

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Abstract

Efforts to suppress an invasive weed are often undertaken with the goal of facilitating the recovery of a diverse native plant community. In some cases, however, reduction in the abundance of the target weed results in an increase in other exotic weeds. Mile-a-minute weed (*Persicaria perfoliata* (L.) H. Gross (Polygonaceae)) is an annual vine from Asia that has invaded the eastern United States, where it can form dense monocultures. The host-specific Asian weevil *Rhinoncomimus latipes* Korotyaev (Coleoptera: Curculionidae) was first released in the United States in 2004 as part of a classical biological control program. At three sites invaded by mile-a-minute weed, biological control was integrated with pre-emergent herbicide use and two densities of native plantings. After 2 years, native plant cover differed significantly and was greater than 80% in the plots with plantings and pre-emergent herbicide but less than 30% in the planting treatments without herbicide. Where mile-a-minute cover decreased at the two sites with the greatest pressure from exotic plants, plots were dominated by another exotic weed, *Microstegium vimineum* (Trin.) A. Camus, Japanese stiltgrass. The combination of biocontrol, pre-emergent herbicide, and revegetation with native plants suppressed mile-a-minute weed, prevented invasion by Japanese stiltgrass, and increased the abundance of native plants. The selection of the management strategies used to control mile-a-minute weed determined the extent of recovery of the native plant community.

Key words: biological control, competitive plantings, integrated weed management, pre-emergent herbicide, *Rhinoncomimus latipes*.

Introduction

Classical biological control is increasingly viewed as a tool for the protection and management of natural ecosystems (Headrick & Goeden 2001; Van Driesche et al. 2010). The desired outcome of weed control in natural areas is a decrease in the target weed and concomitant increase in species diversity, abundance of native plant species, and ecosystem services (Denslow & D'Antonio 2005; Hulme 2006). Although biocontrol alone (without implementing additional management strategies) can succeed in restoring native plant communities (Barton et al. 2007), in some cases, the target weed may be reduced only to be replaced by another undesirable plant (Lesica & Hanna 2004; Reid et al. 2009; Stephens et al. 2009), that is, the invasive treadmill effect (Thomas & Reid 2007). One way to combat this invasive species treadmill and restore native plant communities is through integrated weed management, including restoration planting (Denslow & D'Antonio 2005; Reid et al. 2009).

In a review of biological control programs that succeeded in reducing the abundance or distribution of invasive weeds, Denslow and D'Antonio (2005) concluded that successful programs often used integrated weed management strategies. Planting native competitors as part of an integrated strategy may help to increase species diversity (Lesica & Hanna 2004), reduce the abundance of an invasive weed (Price & Weltzin 2003), and prevent invasion by exotics and facilitate colonization by natives (Bakker & Wilson 2004). Native plantings, when combined with biological control, can enhance the effectiveness of the biological control agent by increasing plant competition against a weed that has already been stressed by herbivory (Hulme 2006). Integrating biological control with herbicides, mechanical control, or grazing can be challenging because application must be timed to impact the plant without having deleterious effects on the biocontrol agent (Collier et al. 2007). Biological control has been successfully combined with herbicide application to control purple loosestrife (*Lythrum salicaria* L.) (Henne et al. 2005), and with herbicides and other management strategies to control *Mimosa pigra* L. (Fabaceae) (Paynter & Flanagan 2004) and leafy spurge (*Euphorbia esula* L.) (Lym 2005).

Here, we studied management techniques for an invasive species, mile-a-minute weed (*Persicaria perfoliata*), with a

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broader goal of restoring native plant communities. *Persicaria perfoliata* is a spiny annual vine of Asian origin that established in York County, Pennsylvania, in the 1930s (Moul 1948) and has since invaded 13 states in the eastern United States (Hough-Goldstein et al. 2008*a*, 2012). Mile-a-minute weed can form dense monocultures and outcompete native plants in a variety of habitats and thus poses a threat to natural ecosystems (Mountain 1989; Hough-Goldstein et al. 2008*a*). *Rhinoncomimus latipes* Korotyaev is a host-specific Asian weevil that was introduced to the United States in 2004 by the U.S. Forest Service as part of a classical biological control program against mile-a-minute weed (Wu et al. 2002; Ding et al. 2004). Weevil feeding damage reduces mile-a-minute weed growth and reproduction and decreases its competitive ability (Hough-Goldstein et al. 2008*b*, 2009; Guo et al. 2011; Lake et al. 2011). The objectives of this experiment were to evaluate the effect of native plant competition, in combination with pre-emergent herbicide and in the presence of *R. latipes*, on mile-a-minute weed and the associated plant community.

Methods

The experiment was conducted at three sites in southeastern Pennsylvania, all with meadows where mile-a-minute weed had been present for at least 5 years. The first two sites were located at Brandywine Conservancy properties at the Laurels Preserve, near Buck Run (39°55′40.58″N, 75°46′51.97″W), and at Waterloo Mills Preserve (40°01′10.29″N, 75°24′57.41″W). The third site was located at the Kendal-Crosslands Communities (39°53′02.81″N, 75°39′01.51″W), near a small unnamed tributary to the Brandywine Creek. Vegetation within the study plots consisted primarily of annual and perennial forbs and cool season grasses (details in Lake 2011).

Four 6.1 × 6.1 m plots were established in mile-a-minute patches at each site in September 2008. The post-emergent herbicides triclopyr (Garlon 3A, Dow AgroSciences LLC, Indianapolis, IN, U.S.A.) and glyphosate were applied between 18 and 23 September 2008, at rates of 4.75 and 9.5 L/hectare, respectively. The tank mixture also included a methylated seed oil surfactant and Bullseye, a blue liquid colorant that facilitates uniform application of the herbicide (Milliken Chemical, Division of Milliken & Company, M-206, Spartanburg, SC, U.S.A.), applied at rates of 2.375 and 0.75 L/hectare, respectively. The herbicide mixture killed all vegetation in the study plots, and dead plant material was raked from the plots prior to planting.

Euthamia graminifolia (L.) Nutt., formerly *Solidago graminifolia* (L.) Salisb. (USDA ARS, 2011; flat-top goldentop), was selected for use as a native plant competitor because it is a vigorous perennial and grows 0.3–1.5 m tall (eFloras 2012). This species is native to much of the United States and Canada (USDA NRCS 2012), and was naturally present at all study sites. Plugs of *E. graminifolia* were purchased from North Creek Nurseries, Inc., Landenberg, PA, U.S.A. Planting perennial plugs facilitated the rapid establishment of plant competition that would not be harmed by the use of pre-emergent herbicide. The American elm (*Ulmus americana* L.) was selected as an additional competitor for this experiment because of its fast growth (eFloras 2012), potential to produce shade, and the availability of seeds from trees tolerant of Dutch elm disease, *Ophiostoma ulmi* and *O. nova-ulmi* (J. Slavicek 2008, U.S. Forest Service, Delaware, OH, U.S.A., personal communication). The meadows used in this experiment were undergoing natural succession. Thus, in addition to providing competition and shade, planting trees corresponded with management goals, although the spacing used to achieve rapid shade would necessitate managers thinning the trees in the future. The elm trees were started from seed in May 2008 and were approximately 0.6 m tall at the time of planting in October 2008.

Treatments at each site were randomly assigned to plots using PROC PLAN (SAS Institute 2008), and consisted of a low-density planting of *E. graminifolia*, a high-density planting of *E. graminifolia*, a low-density planting and elm trees, and a control. A 2.1-m tall deer fence (Benner's Gardens, Phoenixville, PA, U.S.A.) was installed around the elm plot at each site the week of 29 September 2008. In the low-density and elm plots, *E. graminifolia* plugs were spaced 0.6 m apart for a total of 100 plugs per plot (Fig. S1). In the high-density plots, plugs were spaced 0.3 m apart, for a total of 400 plugs per plot. A total of 25 elm trees were planted in each elm plot and were spaced approximately 1.1 m apart. The elm trees and plugs were planted between 1 and 13 October 2008 and were watered on the day they were planted and as needed thereafter.

Each plot was divided in half and randomly assigned the herbicide or no-herbicide treatment. It is recommended that pre-emergent be applied in March in Pennsylvania, although timing may vary based on the site, weather, and herbicide used (Gover et al. 2008). On 1 April 2009, the pre-emergent herbicide prodiamine (Barricade 65WG, Syngenta Crop Protection, LLC, Greensboro, NC, U.S.A.) was applied at a rate of 1.125 kg/hectare with water and Bullseye. All herbicide treatments were applied by Weeds, Inc. (Aston, PA, U.S.A.).

Five permanent 1-m^2 quadrats were randomly positioned within the herbicide and no-herbicide areas of each plot, but not within 0.25 m of the edge of the planting treatment plot or within 0.5 m of the line demarking the division between the herbicide and no-herbicide side of the plots (Fig. S1). Mile-a-minute seedlings were counted in each monitoring quadrat within a 0.5 × 1–m frame each year (2009, 2010, and 2011) between early May and mid-June. Each 1-m^2 quadrat was monitored monthly from 15 July through 2 October 2009, and 1 June through 12 October, 2010, for number of weevils, percent cover of mile-a-minute, and percent cover of other plants. The percent cover of live foliage in each quadrat was estimated by looking down at the frame, which was marked in 10-cm intervals. Using this bird's-eye view, plant cover was not permitted to exceed 100%.

Weevils were present at low densities at all sites prior to the start of this experiment, and were supplemented through release of insects reared at the NJ Department of Agriculture

Phillip Alampi Beneficial Insect Rearing Laboratory (Trenton, NJ, U.S.A.). During June 2009, 125 weevils were released weekly in each plot along the herbicide application line, for a total of 500 weevils per plot.

To assess the plant community, all plots were surveyed with a botanist between 7 and 16 September 2010. Each plant within the monitoring quadrats was identified to species and its percent cover was estimated. Estimates of absolute plant cover for each species were made by one individual in order to minimize observer error. Relative cover was calculated by dividing the absolute cover by the total plant cover in each quadrat to determine the percent cover of natives, mile-a-minute weed, *E. graminifolia*, and Japanese stiltgrass (*Microstegium vimineum* [Trin.] A. Camus). The native status of each species was assigned according to the PLANTS Database (USDA NRCS 2012). Plants classified as both native and introduced in the database usually represented a very low percentage of plant cover, and neither these plants nor elm trees were included in any plant cover measures.

Statistical analysis

The mean of the five subsample quadrats was calculated for each combination of herbicide and planting treatment at each site (Fig. S1). Analysis of variance using the mixed procedure (PROC MIXED within the SAS system) was used to analyze this split-plot experiment, with herbicide and planting treatments considered as fixed effects and sites as random effects (Littell et al. 2002; SAS Institute 2008). Because weevils were found only on mile-a-minute weed, weevil populations were expressed as density of weevils/m^2 of mile-a-minute cover. Differences in weevil density and percent cover of mile-a-minute weed were analyzed using repeated measures (the REPEATED statement, SAS Institute 2008; SAS noted that the estimated G matrix was not positive definitive in all PROC MIXED analyses).

Mile-a-minute seedling counts, community species richness, and percent cover of all native species, *E. graminifolia* alone, and *M. vimineum*, were also analyzed with the mixed procedure, using the mean of the five subsample quadrats for each split plot. Linear contrasts were used to compare the control to all the planting treatments as a group within the herbicide and no-herbicide plots. The LSMEANS statement with the Tukey–Kramer adjustment was used to compare the individual planting treatments to the control and each other within the herbicide and no-herbicide plots (Littell et al. 2002; SAS Institute 2008). Seedling count and species richness data were square-root transformed and percent cover data were arcsine square-root transformed prior to analysis, to improve normality and homoscedasticity of variances. Non-transformed means and standard errors are presented in figures.

The proportion of total, native, and introduced species at the three sites was analyzed using a chi-square test of goodness of fit assuming equal proportions (PROC FREQ; SAS Institute 2008).

Results

Weevils were present at all sites at an average density of 15.4 weevils/m^2 of mile-a-minute weed cover in no-herbicide plots in July and August 2009, and 43.9 weevils/m^2 in no-herbicide plots in July and August 2010. Their density was lower in the plots treated with herbicide in both 2009 ($F_{[1,7.83]} = 17.28$, $p = 0.0033$) and 2010 ($F_{[1,14.9]} = 4.66$, $p = 0.0476$), averaging 3.8 in July and August 2009, and 22.9 weevils/m^2 in July and August 2010 (details in Lake 2011).

The pre-emergent herbicide application in 2009 was not 100% effective because some mile-a-minute seedlings had started to germinate prior to application. Nevertheless, mile-a-minute seedling counts were much lower in the herbicide than in the no-herbicide plots in 2009 (Fig. 1a; $F_{[1,8]} = 48.72$, $p = 0.0001$). Overall seedling numbers were very low in 2010, but still significantly lower in the plots that had been treated with herbicide the previous year than in the no-herbicide plots (Fig. 1b; $F_{[1,8]} = 14.12$, $p = 0.0056$). There was a slight rebound in seedling numbers in the no-herbicide plots in 2011, and again the herbicide plots had significantly fewer seedlings (Fig. 1c; $F_{[1,8]} = 15.90$, $p = 0.0040$). There were no significant differences by planting treatment and no significant interactions in any year.

Mile-a-minute weed percent cover was also significantly lower in the herbicide than in the no-herbicide plots in both 2009 ($F_{[1,8.91]} = 71.43$, $p < 0.0001$) and 2010 ($F_{[1,8.51]} = 8.69$, $p = 0.0173$), again with no significant difference by planting treatment, but with a significant interaction between herbicide and planting treatment in 2009. In 2010, mean mile-a-minute cover was less than 18% in all plots.

A total of 127 plant species from 48 families were identified in the study plots in September 2010. There was no difference in the proportion of total, native, or introduced species among the study sites (Table 1). Species richness did not differ by herbicide use ($F_{[1,16]} = 1.53$, $p = 0.2341$) or planting treatment ($F_{[3,16]} = 0.19$, $p = 0.9025$) and there was no significant interaction.

When all three sites were used as replicates, the cover of native plants in September 2010 was higher in the herbicide than in the no-herbicide plots ($F_{[1,8]} = 29.64$, $p = 0.0006$), but there were no differences by planting treatment ($F_{[3,6]} = 0.42$, $p = 0.7466$) and no significant interaction ($F_{[3,8]} = 0.77$, $p = 0.5433$). However, the plant surveys indicated that the Laurels site had much higher naturally occurring *Euthamia graminifolia* cover than Crosslands and Waterloo Mills, which could have confounded the effects of the planted *E. graminifolia* on the plant community in comparison with the control. Therefore, the Crosslands and Waterloo Mills sites were also analyzed separately. At these two sites, both total native plant cover (including *E. graminifolia*) and *E. graminifolia* cover alone were significantly higher in the herbicide than in the no-herbicide plots (Fig. 2a & 2b), while Japanese stiltgrass showed the opposite response, with significantly higher percent cover in the no-herbicide compared to the herbicide plots (Fig. 2c). There was a significant planting treatment effect at these two sites, with

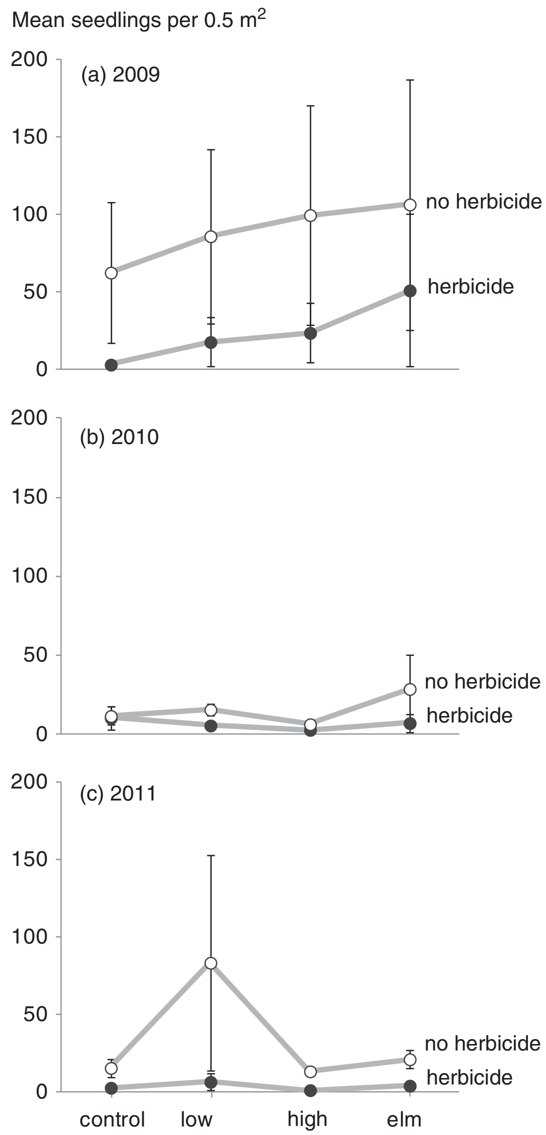

Figure 1. Spring seedling counts (mean ± SEM) of mile-a-minute weed in (a) 2009, (b) 2010, and (c) 2011. Seedling counts were significantly higher in the no-herbicide than the herbicide plot each year.

the control plots showing less native plant cover and more Japanese stiltgrass than the planting treatments (considered together) within both the herbicide and the no-herbicide plots (Fig. 2; native cover in herbicide: $F_{[1,8]} = 27.29$, $p = 0.0008$ and no herbicide: $F_{[1,8]} = 6.48$, $p = 0.0344$; stiltgrass cover in herbicide: $F_{[1,7]} = 35.77$, $p = 0.0006$ and no herbicide: $F_{[1,7]} = 11.36$, $p = 0.0119$).

The plots without herbicide showed poor growth of the planted *E. graminifolia*, with cover after 2 years not higher in the planted treatments than in the unplanted control (Fig. 2b). The elm trees had an overall survival rate of 88%, and this rate did not differ by herbicide treatment or site. However, elms planted in the no-herbicide plots were significantly shorter than those in the herbicide plots (data in Lake 2011).

Table 1. Total number, and number (and percent) of native and introduced species at three experiment sites in early September 2010. Plant status according to the PLANTS Database (USDA NRCS 2012).

		Number (%)	
Site	*Total*[a]	*Native*[b]	*Introduced*[b]
Crosslands	66	47 (73.4%)	17 (26.6%)
Laurels	63	46 (82.1%)	10 (17.9%)
Waterloo Mills	63	35 (62.5%)	21 (37.5%)
Chi-square	0.0938	2.0781	3.8750
p	0.9542	0.3538	0.1441

[a]The total includes unknowns and plants categorized as native and introduced.
[b]Chi-square test of goodness of fit assumed equal proportions at each site.

Discussion

Pre-emergent herbicide in this experiment provided control of susceptible grasses, including Japanese stiltgrass, and annual broadleaf weeds, including mile-a-minute. Significantly fewer mile-a-minute seedlings germinated from the herbicide than the no-herbicide plots in all three years of the study, even though the herbicide was only used the first year. Reducing mile-a-minute seed production is critical to the management of this annual weed, because the existence of a seed bank can enable one successful colonization event to result in long-term persistence of a population (Turnbull et al. 2000). Low and stable mile-a-minute seedling numbers in most of the herbicide-treated plots 2 years after treatment suggest that a combination of herbivory by *Rhinoncomimus latipes* and competition with other plants were preventing mile-a-minute from producing enough seed for the population to increase in any of the herbicide-treated plots.

This experiment did not test the effectiveness of the biological control agent, which was present in all plots; however, weevil densities observed here were comparable to those in other studies where mile-a-minute growth and seed production were shown to be suppressed by the insect (Hough-Goldstein et al. 2009; Lake et al. 2011; Hough-Goldstein & LaCoss 2012; Cutting & Hough-Goldstein 2013). Feeding damage by *R. latipes* decreases the competitive ability of mile-a-minute by stressing the plant and altering plant architecture (Hough-Goldstein et al. 2008*b*). Stem-boring by the larvae decreases mile-a-minute internode distance, while larval damage coupled with the feeding of adult weevils in the terminal tips disrupts apical dominance. Both of these effects can be critical for plants competing for light, because they reduce vertical growth (Irwin & Aarssen 1996; Hough-Goldstein et al. 2008*b*). In field cages, the combination of herbivory and competition delayed the onset of seed production and killed more than 60% of *Persicaria perfoliata* plants (Hough-Goldstein et al. 2008*b*).

The implementation of biocontrol alone at sites invaded by mile-a-minute appeared to result in an increase in non-natives, including Japanese stiltgrass, at sites that did not have high levels of existing native cover (Lake et al. 2011), although plant community surveys were not done. In this study, the reduced dominance of mile-a-minute weed had very

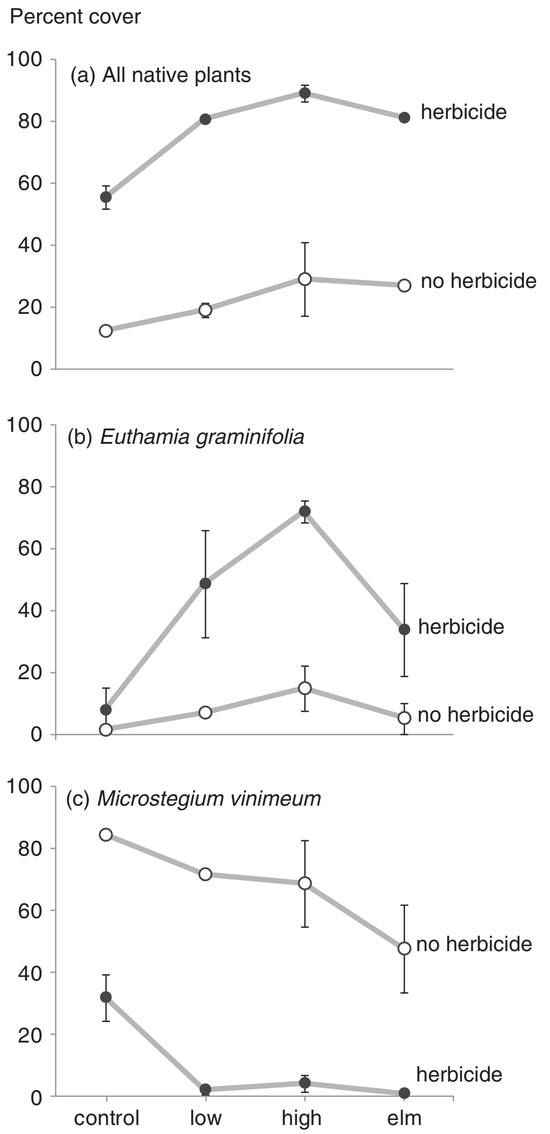

Figure 2. (a) Native plant percent cover (including *Euthamia graminifolia*), (b) *E. graminifolia* percent cover, and (c) *Microstegium vimineum* percent cover (mean ± SEM) at Crosslands and Waterloo Mills in September 2010. The control plots had significantly less native plant cover and significantly more stiltgrass cover compared to the planting treatments considered together, in both the herbicide and no-herbicide plots (p-values in text and results comparing individual treatments in Lake 2011).

different consequences for the plant community depending on whether or not other management strategies were integrated with biological control. Although more than 60% of species present in all plots were native, the relative cover of native species was less than 30% at two of the three sites in the plots not treated with herbicide, while in the planted treatments with pre-emergent herbicide native plant cover was greater than 80% after 2 years.

Assessment of the existing plant community may help determine the most appropriate weed control strategies on a site-by-site basis. Here, when the sites were surveyed in 2010, the control plots not treated with pre-emergent herbicide at the Laurels had $94.1 \pm 1.0\%$ native plant cover with more than 50% due to naturally occurring *Euthamia graminifolia*. The combination of the weevil and the pre-emergent herbicide application was sufficient to restore the native community at the Laurels. In contrast, Crosslands and Waterloo Mills had 13.2 ± 4.4 and $11.2 \pm 1.8\%$ native cover, respectively. At these sites, as mile-a-minute cover declined in the no-herbicide plots, it was largely replaced by Japanese stiltgrass, and revegetation with native competitors was critical to the recovery of the plant community. The invasive annual Japanese stiltgrass alters the composition of plant communities by inhibiting the establishment and growth of native plants (Flory & Clay 2010). In addition to direct competition from live stiltgrass, senesced stiltgrass forms a dense mat (Flory & Clay 2009, 2010), which may have limited native plant germination and growth in the no-herbicide plots in our study.

The combination of post- and pre-emergent herbicide applications (in fall 2008 and spring 2009, respectively) essentially negated 2 years of both the mile-a-minute and stiltgrass seed banks. However, mile-a-minute seeds can be viable for up to 6 years (Hough-Goldstein et al. 2008*a*) and Japanese stiltgrass seed can persist for at least 3 years (Barden 1987). Thus, both weeds have the capability to reinvade, and in fact stiltgrass reinvaded the herbicide control plots at Crosslands and Waterloo Mills during 2010, but was unable to establish large populations in the revegetated herbicide plots.

Flory (2010) repeatedly applied a pre-emergent herbicide in combination with a post-emergent herbicide to control Japanese stiltgrass, and found that although the stiltgrass was effectively controlled, the pre-emergent herbicide inhibited the recovery of the native plant community. In our study, the one-time pre-emergent application largely prevented recruitment of both native and non-native seeds from the seed bank in 2009, but enabled the perennial *E. graminifolia* plugs and the elm tree seedlings to establish with reduced competition. These plantings helped to stabilize the disturbance created during the installation of the experimental plots, and appear to have subsequently facilitated recruitment of other, mostly native plants. In contrast, stiltgrass dominated the no-herbicide plots by fall 2010, which greatly reduced the cover of *E. graminifolia*, a species that was specifically selected as a robust competitor, and significantly suppressed elm growth compared to the herbicide plots (Lake 2011).

Our study demonstrates that the selection of strategies used to manage an invasive weed may determine the fate of the native plant community. In other studies, the resulting plant community also differed depending on the management strategy used to control invasive plants, including Japanese stiltgrass (Flory & Clay 2009; Flory 2010), English ivy (*Hedera helix* L.) (Biggerstaff & Beck 2007), and bitou bush (*Chrysanthemoides monilifera* spp. *rotundata*) (Mason & French 2007). The act of managing an invasive plant often causes a disturbance (Mason & French 2007), whether through collateral damage in the case of chemical or mechanical controls (Bush et al. 2007), by enabling the invasive treadmill effect (Reid et al. 2009) or by other means. These disturbances may lead to changes in resource availability, which can increase the invasibility of a community (Davis et al. 2000). Integrated weed management, particularly management that includes revegetation, offers a way to mitigate the impact of disturbance on a community and decrease its invasibility by reducing resource availability (Davis et al. 2000) and niche opportunities (Shea & Chesson 2002).

Integrating management techniques may provide more effective control of an invasive weed than any technique in isolation (Paynter & Flanagan 2004; Henne et al. 2005; Lym 2005) and may increase recovery of the native plant community, particularly if revegetation with natives is part of the management plan (Biggerstaff & Beck 2007). Cutting and Hough-Goldstein (2013) integrated weevil releases and plant competition in the form of a seed mix of native grasses and forbs to restore sites invaded by mile-a-minute weed. They also excluded the weevils from some plots using a systemic insecticide. Mile-a-minute biomass was lowest and plant community diversity was highest in the plots that included the weevils and the restoration seeding. In the experiment reported here, perennial forbs were used along with a pre-emergent herbicide, which could not have been used with native seeding because it affects germinating seeds. The most appropriate form of revegetation will vary by system, but together the two studies demonstrate the potential of integrated weed management that includes planting of native plants.

Increased replication in this study may have provided more resolution of the effectiveness of the different planting treatments on the resulting plant community. Plantings significantly increased native cover and decreased Japanese stiltgrass cover compared to the controls with and without herbicide, but given the lack of differences between the planting treatments, land managers could save resources by planting at a low density. Additionally, a pre-treatment assessment of the plant community would have been useful to determine if the combination of existing native plant diversity and Japanese stiltgrass abundance could be used to predict how the plant community would respond to the removal of mile-a-minute weed. This would enable land managers to implement the minimal amount of treatment options needed to restore the plant community.

A restored native plant community may be better able to resist re-invasion by exotic weeds and facilitate colonization by native plants (Bakker & Wilson 2004). This diverse plant community also has broader ecosystem-wide benefits, as it is able to support greater arthropod abundance and diversity, which then supports higher trophic levels (Haddad et al. 2009; Tallamy et al. 2010). In this study, the integration of biological control, pre-emergent herbicide, and revegetation with competitive natives suppressed mile-a-minute weed, prevented the invasive treadmill effect with Japanese stiltgrass, and increased native plant abundance.

Implications for Practice

- Percent cover of native and non-native plants may provide a more accurate assessment of the plant community than species richness; here, species richness did not differ by treatment, but native plant cover was much higher in plots that integrated the three management techniques.
- Pre-assessment of the plant community to determine the abundance of natives and propagule pressure from exotics may enable land managers to determine the most appropriate invasive management technique(s) to implement.
- Management efforts should target both the focal weed and any undesirable effects of the disturbance that weed control creates, including promotion of undesirable replacement species.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Experimental design at each of the three sites. The inset illustrates the herbicide and no-herbicide treatment areas and the five monitoring quadrats that were established within each herbicide and planting treatment combination.