Invasive Plant Science and Management 2013 6:381–390

Pale Swallowwort (*Vincetoxicum rossicum*) Response to Cutting and Herbicides

Antonio DiTommaso, Lindsey R. Milbrath, Todd Bittner, and F. Robert Wesley*

Effective control techniques for pale swallowwort (PSW), an invasive herbaceous vine of old fields and forest understories, are limited. We conducted a 3-yr cutting and herbicide study on an adjacent old-field and forest understory site near Ithaca, NY, for control of PSW. Plants in experimental plots were cut in early July and cut again or sprayed in late August for two seasons with the isopropylamine salt of glyphosate , or one of two rates (low or high) of either triclopyr triethylamine salt (i.e., SL, SH) or triclopyr butoxyethyl ester (EL, EH). The herbicide treatments were effective in reducing PSW cover, plant (stem) density, and aboveground biomass in the old-field site, but in several cases, only after 2 yr of cutting plus herbicide application. Only the cutting plus SH treatment did not reduce PSW cover relative to the unmanaged control in the forest understory and no treatment reduced biomass. In general, the cutting plus EH treatment was most effective in reducing PSW stem densities in the forest site. The most effective herbicide treatments differed between sites. Cutting plus EH reduced PSW cover by 84% and stem density (> 5 cm) by 86% in the old-field site. Cutting plus SH effectively decreased long and short (≤ 5 cm) stem densities by 86 and 96%, respectively. Cutting plants twice during each of two seasons increased PSW cover by 301% and density of stems > 5 cm by 73% at this site. In the forest site, cutting plus glyphosate, or cutting plus EH or cutting plus SL and EL resulted in the greatest reductions in PSW cover (80, 76, 66, and 56%, respectively). Cover in plots cut twice per year decreased by 19%. The EH or SL treatments decreased long-stem densities by 78 and 71%, respectively. The EH treatment decreased short-stem density by 37%. These findings suggest that integrated techniques may control PSW but that effective management strategies may be habitat constrained.

Nomenclature: Glyphosate; triclopyr butoxyethyl ester; triclopyr triethylamine salt; pale swallowwort, *Vincetoxicum rossicum* (Kleopow) Barbar., syn. European swallowwort, *Cynanchum rossicum* (Kleopow) Borhidi.

Key words: Dog-strangling vine, chemical control, forest understory, integrated weed management, invasive plant, mechanical control, natural areas, old field, vine.

Management of invasive plant species continues to be a major focus and challenge for researchers and land managers alike. Often, nonchemical options such as hand pulling or mechanical mowing are limited, impractical, or nonefficacious, particularly for large and rapidly expanding infestations. Use of selective biological control agents for the control of invasive plants in sensitive natural areas offers promise for sustained and effective long-term control (Van Driesche et al. 2010). However, few programs are at advanced enough stages of development to be implemented in the near term, especially for more recently targeted invasive species. Consequently, managing and containing invasive species in the short term using synthetic herbicides may be a best option. For this strategy to be successful, research is required that assesses the efficacy of herbicides commonly used in natural areas to control invasive plants.

One species well-suited for this approach is pale swallowwort (PSW) [*Vincetoxicum rossicum* (Kleopow) Barbar.], an invasive, nonnative vining herbaceous perennial in the Apocynaceae that is becoming increasingly problematic in the Lower Great Lakes basin of North America (DiTommaso et al. 2005). Established populations of PSW are present in at least 13 central New York State counties, and occurrences of this species have been documented in nine U.S. states and two Canadian provinces (DiTommaso et al. 2005; Kricsfalusy and Miller 2008). This invasive vine is native to southeastern Ukraine and adjacent southern Russia and was introduced into North America and New York State in the late 1800s,

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DOI: 10.1614/IPSM-D-12-00078.1

* First author: Associate Professor, Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853; second author: Research Entomologist, USDA-ARS Robert W. Holley Center for Agriculture and Health, Ithaca, NY 14853; third and fourth authors: Director of Natural Areas and Botanist, Cornell Plantations, Cornell University, Ithaca, NY 14850. Corresponding author's E-mail: ad97@cornell.edu

Management Implications

Pale swallowwort (PSW) is a highly invasive, difficult-to-control herbaceous vine that thrives in old fields but can also establish in shaded forest understories. This study sought to determine the efficacy of integrated management techniques in open-field and forest understory habitats. When PSW is cut in early July and followed in late August by application of an herbicide, the best control is obtained using different herbicides and rates in old-field compared with forest understory habitats. In the old field, two cuttings a year were ineffective and should be avoided. All herbicides reduced PSW cover, stem densities, and shoot biomass in the old field after 2 yr of combined mechanical and chemical treatments. However, cutting plus high rates of triclopyr, either as a triethylamine salt (4.87 kg ae ha^{-1}) or butoxyethyl ester (4.87 kg ae ha^{-1}), provided the best control. The cutting plus glyphosate treatment also provided effective control of PSW, but the cover of other species was significantly lower relative to three of four cutting plus triclopyr treatments. Regardless, it will take longer than two seasons of cutting plus herbicide applications to achieve total control of PSW in this old-field site. In the forest understory site, where PSW density was initially much lower than the old-field site, most cutting plus herbicide treatments were effective in reducing PSW cover. In general, the high rate of the triclopyr butoxyethyl ester formulation provided the best control of PSW, including a reduction in stem densities and increased cover of other species. Cutting PSW twice in each of two growing seasons was also ineffective as a management option in the forest site. Infestations of PSW in old fields will likely require higher rates of commonly used herbicides (e.g. glyphosate, triclopyr) relative to forest understory infestations largely because of greater densities and more vigorous populations in more favorable high-light old-field habitats.

likely as an ornamental (DiTommaso et al. 2005; Sheeley and Raynal 1996). Currently PSW is the target of biological control development programs that focus largely on evaluating the efficacy and host specificity of nonnative candidate insects (Hazlehurst et al. 2012; Maguire et al. 2011; Milbrath 2008; Weed and Casagrande 2010; Weed et al. 2011) or plant pathogens (Berner et al. 2011).

Pale swallowwort can grow in shallow, drought-prone soils and outcrops but is widely tolerant of many growing conditions and environments (DiTommaso et al. 2005; Douglass et al. 2009; Magidow 2010). The globally rare alvar (limestone) pavement barren communities along Lake Ontario are especially threatened by this invasive vine (DiTommaso et al. 2005). Encroachment by this vine decreases arthropod biodiversity and threatens rare native plant species in many ecosystems throughout its introduced range (DiTommaso et al. 2005; Ernst and Cappuccino 2005). It prefers high-light environments such as old fields, pastures, and forest edges but can also tolerate relatively low light conditions of open-forest understories (Averill et al. 2011; Hotchkiss et al. 2008; Milbrath 2008).

Several management strategies for PSW have been investigated and have focused primarily on the effects of mechanical control (clipping and mowing) and chemical control. Researchers using mechanical control have aimed to determine the optimal timing of mowing/cutting operations when carbohydrate root reserves are likely at their lowest. For instance, McKague and Cappuccino (2005) reported that cutting PSW plants at ground level in late June in Ontario, Canada, prevented seed production. However, Averill et al. (2008) reported that clipping PSW to a height of 8 cm in June and then again in July during two growing seasons increased the density of plants 1.5-fold. Thus, mowing plants even during two growing seasons may not be an effective management strategy, beyond possibly reducing seed production.

The perennial habit of PSW and its prolific below-ground growth has focused chemical control research on herbicides having systemic activity, including glyphosate (Cain and Irvine 2011; Christensen 1998; Lawlor and Raynal 2002; Mervosh 2009), triclopyr (Averill et al. 2008; Cain and Irvine 2011; Lawlor and Raynal 2002; Mervosh 2009), and, most recently, aminopyralid (Cain and Irvine 2011). Triclopyr offers the added advantage of selectively controlling dicot species. Most of these chemical control studies have been carried out in high-light environments, but few studies have assessed the efficacy of herbicidal control in low-light environments such as forest understories. Moreover, integrating a cutting treatment may increase the efficacy of herbicide treatments by stimulating regrowth or diminishing carbohydrate reserves by forcing regrowth (Delabays et al. 2008; Hewett 1985).

The main objective of this study was to compare the efficacy of six PSW treatment options during two growing seasons and the beginning of the third growing season (2008 to 2010) in high-light (old-field) and low-light (forest understory) habitats. Specific objectives included (1) comparing the efficacy of cutting plus herbicide application to a cutting-only (twice per season) treatment, (2) comparing the efficacy of low- and high-dose treatments of triclopyr, and (3) determining whether treatments varied in efficacy in the two habitats with different light availabilities.

Materials and Methods

Field Site Characteristics. An old-field and dry-forest understory site located on a nature preserve owned and managed by Cornell Plantations on the southeastern slope of Cayuga Lake near Ithaca, NY (42°31′20″N, 76°31′9″W) were used in this study. The two sites occur on a Tully limestone bedrock and the forest site encompasses a rare and sensitive dry lake cliffs ecosystem. Agricultural fields abandoned since the 1950s transition toward the lake to high-quality mature forest located directly above and upslope of the lake cliffs. The 34-ha (84-ac) preserve is home to 35 native plant species that are rare regionally or in New York State. Four species are listed on the state's endangered or threatened species lists: Drummond's rockcress [*Boechera stricta* (Graham) Al-Shehbaz], reflexed sedge (*Carex retroflexa* Muhl. ex Willd.), rock-cress (*Draba arabisans* Michx.), and Canadian ricegrass [*Piptatherum canadense* (Poir.) Dorn] (NYS-DEC 2012). Several species are found regionally only on the preserve, including early buttercup (*Ranunculus fascicularis* Muhl. ex Bigelow).

The old-field site is about 210 m (~ 700 ft) above the lake, which before the start of the study was dominated by shrubs and tree saplings, including common buckthorn (*Rhamnus carthartica* L.), gray dogwood (*Cornus racemosa* Lam.), white ash (*Fraxinus americana* L.), and herbaceous species such as early goldenrod (*Solidago juncea* Aiton), tall goldenrod (*Solidago altissima* L.), and timothy (*Phleum pratense* L.). The site has a 4% slope and was mechanically cleared using a New Holland skid steer and rotary mower and chain saws in late June 2008 to maintain it as a successional old field. Soils are moderately deep, somewhat poorly drained Ovid-Rhinebeck series (aeric ochraqualfs, fine, illitic, mesic) silt loams with pH 6.9 (NRCS 2011).

The forest site is about 300 m downslope from the old-field site and approximately 150 m above Cayuga Lake at a 13% slope. Dominant tree species include red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), sugar maple (*Acer saccharum* Marshall), and shagbark hickory [*Carya ovata* (Miller) K. Koch], with many hop hornbeams [*Ostrya virginiana* (Miller) K. Koch] in the understory. Soils are calcareous and classified as shallow rock outcrops (0 to 25 cm [0 to 10 in] to lithic bedrock) with an average depth of 13 cm (NRCS 2011).

Experimental Design and Treatments. The study period was from July 2008 to June 2010, with treatments applied in 2008 and 2009. Because an initial assessment of PSW stem density and cover in mid-June 2008 indicated the level of PSW infestation to be uniform within each of the two study sites, we used a completely randomized design with seven replications in each site. Seven treatments were applied at each site to 4- by 4-m plots, for a total of 49 plots at each site, and included an unmanaged control treatment and plants-cut-twice treatment. The remaining five treatments included cutting plants with a string trimmer in combination with the use of various herbicides; hence, there were no "herbicide alone" treatments (Table 1). The herbicides used included a 2% solution of the isopropylamine salt of glyphosate (Roundup Pro®, Monsanto, St. Louis, MO), a 0.5% solution of the triethylamine salt of triclopyr (Brush-B-Gon®, The Ortho Group, Marysville, OH), a 2% solution of the triethylamine salt of triclopyr (Garlon 3A®, DowAgrosciences, Indianapolis, IN), and 1 and 2% solutions of the butoxyethyl ester of triclopyr (Garlon 4 Ultra®, DowAgrosciences). Because PSW stem densities were substantially lower in the forest site than the old-field site, herbicide volumes used in the forest were lower than the old-field site. Therefore herbicide rates applied in the old field and forest sites, respectively, were: glyphosate at 3.65 and 1.83 kg ae ha^{-1} (3.25 and 1.63 lb ae ac^{-1}), triethylamine salt of triclopyr (0.5%) at 0.93 and 0.46 kg ae ha^{-1}, triethylamine salt of triclopyr (2%) at 4.87 and 1.70 kg ae ha^{-1}, and the butoxyethyl ester of triclopyr at two rates: a low rate (1%) 2.99 and 0.43 kg ae ha^{-1}, and a high rate (2%) 4.87 and 2.27 kg ae ha^{-1}. The two rates of the triethylamine salt of triclopyr were used because the two commercial products (Brush-B-Gon = 5.74% ae and Garlon 3A = 31.8% ae) differ in concentration of the active ingredient, triclopyr, and only Brush-B-Gon was labeled for PSW. Herbicide rates were chosen on the basis of spot treatments labeled or Federal Insecticide, Fungicide, and Rodenticide Act 2(ee) supplemental label rates for PSW, or spot treatment labeled rates for species with similar physiognomy for each respective pesticide label.

Table 1. Herbicide formulations and rates used for the control of pale swallowwort (PSW) in an old field and forest understory site near Ithaca, NY. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008.

Formulation	Old field	Forest understory
	kg ae ha^{-1}	
Glyphosate[a]	3.65	1.83
Triclopyr salt (low)[b]	0.93	0.46
Triclopyr salt (high)[c]	4.87	1.70
Triclopyr ester (low)[d]	2.99	0.43
Triclopyr ester (high)[d]	4.87	2.27

[a] Roundup Pro, Monsanto.

[b] Brush-B-Gon, The Ortho Group.

[c] Garlon 3A, Dow AgroSciences.

[d] Garlon 4 Ultra, Dow AgroSciences.

All treatment plots were cut to a height of 5 cm in early July 2008 using a polycot-head brush cutter (FS-81 Stihl, Virginia Beach, VA) in the old-field site and a string trimmer (GT 225, Echo Inc., Lake Zurich, IL) in the forest site. All vegetation was cut in the old field; only PSW was cut at the forest site because of the presence of locally rare plant species in some test plots. These plants were present at very low densities (< 1 individual m^{-2}) in $< 10\%$ of plots and were marked with blue flagging tape to avoid being cut or sprayed. On July 1 and 2, 2009, PSW in all plots, except in control plots, was cut with a string trimmer in the old-field site. Only PSW was cut in the forest site plots, except in control plots.

Herbicides were applied using a 15.1-L (4-gal) CO_2 pressurized backpack sprayer (D. B. Smith-Field King, The

Fountainhead Group Inc., New York Mills, NY) equipped with one cone-style brass nozzle. A flow control valve (CFValve, Forestry Suppliers Inc., Jackson, MS) maintained spraying pressure at 100 kPa (14.5 psi). All herbicides were spot applied until foliage was wet, as is common management practice, and included a 1% (v/v) petroleum oil–based non-ionic surfactant (CleanCut, Arborchem, Mechanicsburg, PA). Herbicides were applied on August 20, 2008 and August 19, 2009 at the old-field site and on August 21, 2008, and August 24, 2009, at the forest site. Vegetation in the twice-mowed treatment plots at the old-field site was cut with a brush cutter on August 20, 2008. PSW in the twice-cut treatment plots was cut with a string trimmer at the forest site August 22, 2008, and cutting occurred August 19, 2009, in both sites.

Posttreatment Data Collection. Posttreatment assessments were made on June 17 and 19, 2009, and June 21 and 22, 2010, in the old-field site and on June 23, 2009, and June 18, 2010, in the forest site. Data were collected from a 1- by 1-m (11-ft^2) subplot centered at the intersection of two corner-to-corner plot transects. Cover of PSW, graminoids, other herbaceous dicots, and woody species in each subplot was visually estimated by the same observer in 2008, 2009, and 2010 at both sites. The density of PSW plants of ≤ 5 and > 5 cm height was also recorded each year. The main reason for this height separation was to better differentiate between treatment effects on seedlings, which are usually 5 cm or less in height, and larger, taller established plants (Smith et al. 2006). After cover and density data collection in June 2010 at both sites, PSW aboveground dry biomass was determined by cutting plants in each subplot at soil level, oven-drying tissues at 70 C (158 F) for 48 h, and weighing.

Statistical Analysis. Given the inherent differences in plant communities and edaphic features between the old-field and forest sites, data for the two sites were analyzed separately. Cover, PSW aboveground biomass, and density data were analyzed for differences between treatments using ANOVA (SigmaPlot 12, Systat Software Inc., San Jose, CA). A two-factor (year and treatment) ANOVA was used to compare the influence of year and treatment and their interaction on cover of PSW and other vegetation groups (i.e., graminoids, other herbaceous species). The effects of year and treatment on the density of PSW plants in the ≤ 5 and > 5 cm height groupings were also determined. A one-factor (treatment) ANOVA was used to determine the influence of treatment on PSW aboveground dry biomass after 2 yr of treatments. Cover (percent) data were arcsine square root transformed before analysis, biomass data log transformed, and number of PSW plants in the two height groupings square root transformed to improve normality and heterogeneity of variance.

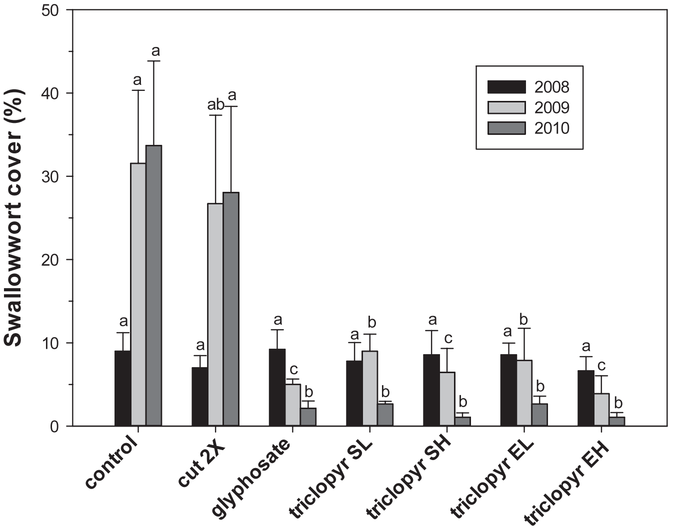

Figure 1. Mean (± SE, back-transformed, $n = 7$) pale swallowwort cover (%) in each of seven treatments in an old-field site near Ithaca, NY, during a 3-yr study. The 2008 data are pretreatment values. Means within year having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$ level. A significant year by treatment interaction ($P < 0.001$) was detected. With all herbicide treatments, pale swallowwort (PSW) in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

Results and Discussion

Temperatures and precipitation did not vary substantially during the 3 yr of the study (2008–2010) nor from the 30-yr average at the two sites (data not shown). Pretreatment (June 2008) PSW cover and density levels served as a baseline against which to compare the efficacy of the different treatments applied.

Old Field Site. *PSW Cover.* The cover of PSW in the old-field plots averaged 8% in late June 2008 several weeks after the field-clearing operation and before the implementation of first year treatments in early July and August. PSW cover did not differ between plots (Figure 1). In late June 2009, approximately 1 yr after the first treatment application, PSW cover in the unmanaged control and twice-cut plots was generally greater than the cover in all the cutting plus herbicide treatment plots. This effect increased by June 2010 after 2 yr of treatment application; thus, a year by treatment interaction effect on PSW cover was observed ($F_{12,126} = 4.04$, $P < 0.001$; Figure 1). The large increase in PSW cover in old-field control plots in 2009 was likely due to the release of PSW from interspecific competition, coupled with a seed bank response, after the initial clearing of the site in mid-June 2008. PSW cover increased more than threefold in the twice-cut plots by June 2010 relative to pretreatment levels and did not differ from cover in unmanaged control plots. Application of all herbicide treatments after cutting significantly reduced PSW cover after 2 yr with glyphosate, the triclopyr salt applied at 4.87 kg ae ha^{-1}, and the high rate of the triclopyr ester, achieving > 75% reductions in PSW cover (Figure 1). Several workers have previously examined the efficacy of glyphosate and triclopyr on PSW growth in open, sunny habitats like our old-field site. Mervosh (2009) found that when applied once in mid-June in a heavily infested PSW open-field site on a mountain slope in Massachusetts, glyphosate (1.12 kg ae ha^{-1}) achieved slightly better control than the triclopyr salt applied at 1.27 kg ae ha^{-1}. Lawlor and Raynal (2002) reported foliar applications of glyphosate (3.1 and 7.8 kg ae ha^{-1}) and the butoxyethyl formulation of triclopyr (1.9 kg ae ha^{-1}) to be equally effective in reducing PSW cover and biomass in a central New York field site. The integrated use of cutting and herbicides for the control of PSW was investigated by Averill et al. (2008). Application of the ester form of triclopyr at 1.9 kg ae ha^{-1} in late June in a shallow limestone site near Lake Ontario in New York State followed by cutting 4 wk later resulted in an 80% reduction in PSW cover. Consistent with our findings, Averill et al. (2008) found that cutting plants twice during a single season resulted in no differences in PSW cover compared with the unmanaged control and is therefore not recommended as a method of managing this herbaceous perennial vine. Although mowing can minimize seed set, it would need to be done every year (McKague and Cappuccino 2005).

Cover of Other Species. The cover of other species (i.e., graminoids, herbs, and woody plants) in the old-field site increased during the 3 yr of the study ($F_{2,126} = 112.26$, $P < 0.001$), from 8% (± 1) in 2008 to 35% (± 3) in 2009, and was highest at 59% (± 3) in the June 2010 survey. However, the highest cover of other species was observed in plots receiving the cutting plus triclopyr applications, except for the low rate of the triclopyr salt treatment, which did not differ from the glyphosate, twice-cut, and control treatments ($F_{6,126} = 2.71$, $P < 0.017$; Figure 2). In these plots, the cover of naturalized grasses such as Kentucky bluegrass (*Poa pratensis* L.), orchardgrass (*Dactylis glomerata* L.), and timothy increased markedly during the study period. Graminoids comprised between 40 and 52% of the cover in plots treated with triclopyr regardless of formulation and rate. In contrast, graminoids comprised, on average, 26% of the cover of non-PSW species in the non-triclopyr plots. These results are not unexpected given the selectivity of triclopyr for controlling dicots relative to the nonselectivity of both glyphosate and repeated cutting. However, these naturalized grasses can be considered invasive in restoration areas where establishment of native species may be preferred; thus, this tradeoff between the two herbicides needs to be considered. Similarly, Mervosh (2009) reported that glyphosate was less selective and left plots with fewer grasses than triclopyr. Averill et al. (2008) found that the percent cover of species other than PSW was reduced in clipped-only plots compared with plots treated with triclopyr applied in late June. The use of triclopyr for restoring PSW-invaded old-field sites may be preferred because this herbicide has little negative effect on resident grasses.

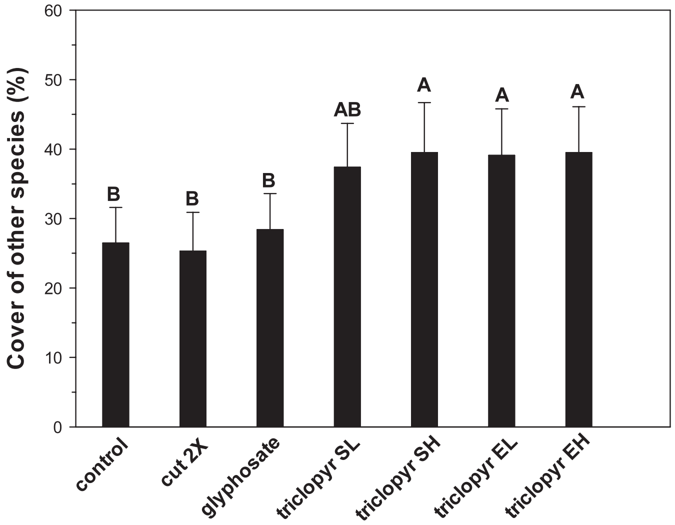

Figure 2. Mean (± SE, back-transformed, $n = 21$) cover (%) of other species in each of seven treatments in an old-field site near Ithaca, NY. Means having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

PSW Stem Densities and Biomass. The density of PSW plants > 5 cm in height varied by year and treatment ($F_{12,126} = 3.26$, $P < 0.001$). By June 2009, 1 yr after application of treatments, PSW densities in the twice-cut plots had increased 78% from pretreatment levels and were not different from densities in unmanaged control plots, which increased nearly 85% in 1 yr (Figure 3). PSW density was reduced 62 and 59% 1 yr after the cutting and glyphosate and triclopyr ester high-dose application, respectively. After 2 yr of treatment applications, cutting plus the triclopyr salt and ester high-dose applications had reduced PSW density by 86% relative to pretreatment

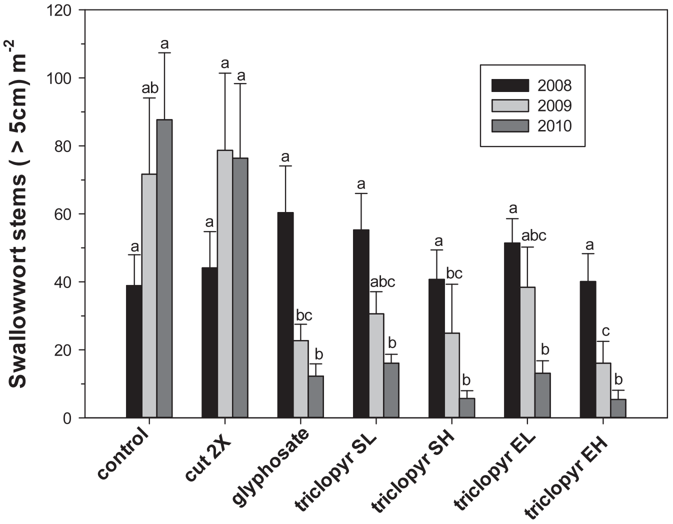

Figure 3. Mean (± SE, back-transformed, $n = 7$) number of pale swallowwort stems per square meter of > 5 cm in height in each of seven treatments in an old-field site near Ithaca, NY, during a 3-yr study. The 2008 data are pretreatment values. Means within year having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. A significant year by treatment interaction ($P < 0.001$) was detected. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

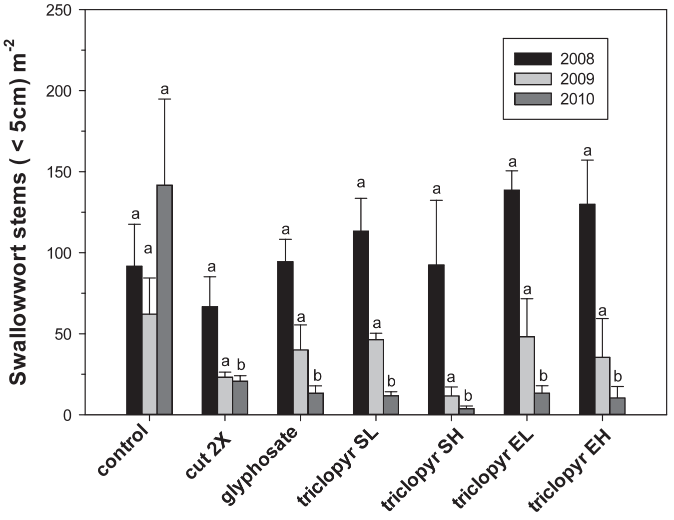

Figure 4. Mean (± SE, back-transformed, $n = 7$) number of pale swallowwort stems per square meter of ≤ 5 cm in height in each of seven treatments in an old-field site near Ithaca, NY, during a 3-yr study. The 2008 data are pretreatment values. Means within year having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. A significant year by treatment interaction ($P = 0.004$) was detected. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

levels, but these reductions did not differ from plant densities for the other cutting plus herbicide treatments (Figure 3). In contrast, the twice-cut and unmanaged control treatments resulted in a 73 and 126% increase in the densities of PSW plants > 5 cm in height, respectively. The large increase in PSW density for plants > 5 cm in height may have been due to the release of PSW from interspecific competition, coupled with a seed bank response, after the initial clearing of the site in mid-June 2008. Cain and Irvine (2011) similarly noted from trials at three sites in southern Ontario that glyphosate (4.32 kg ae ha^{-1}) applied to large PSW plants provided $< 60\%$ control when applied once annually but 81 to 84% control when applied twice in 1 yr. Higher levels of control were only possible with three applications in 2 yr, potentially cost-prohibitive to many land managers. Similarly, Cain and Irvine (2011) reported that the ester form of triclopyr (1.92 kg ae ha^{-1}) provided 58% control after 1 yr.

After 2 yr of treatment applications, all cutting plus herbicide treatments reduced PSW densities of plants ≤ 5 cm in height by at least 86%, whereas the twice-cutting treatment decreased densities by 69% relative to pretreatment levels (Figure 4). The mean density of PSW plants ≤ 5 cm tall in unmanaged control plots increased from 91 to 144 plants m^{-2} (55% increase) during the 3-yr study. The decrease in density of shorter PSW plants within twice-cut plots may reflect losses due largely to the transitioning of shorter plants into the higher height class (> 5 cm), especially as competition for light is reduced with the removal of vegetation at least 5 cm tall from cutting. All cutting plus herbicide treatments resulted in lower PSW aboveground biomass relative to the twice-cut or control treatments, with no differences in efficacy between the herbicide treatments (Table 2).

Initial PSW densities at this old-field site were lower than those reported by Sheeley (1992) but similar to levels found by Averill et al. (2008) at their site. In their study, Averill et al. (2008) reported June-measured densities of plants > 10 cm in height of 38 ± 6 m^{-2} for the triclopyr plus cutting treatment, 200 ± 10 m^{-2} for the twice-cutting treatment, and 170 ± 10 m^{-2} for unmanaged control plots. These PSW densities are similar to those we obtained for plants ≥ 5 cm in height in the triclopyr plus cutting treatments in June 2009. These workers also

Table 2. Aboveground biomass (g m^{-2}) (± SE) of pale swallowwort in June 2010 from plots in an old-field and forest site near Ithaca, NY, that were subjected to various management treatments for two growing seasons beginning in 2008. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008.

	Site[a]	
Treatment	Old field	Forest
Control (unmanaged)	83.1 (22.4) a	4.0 (1.0) a
Two cuttings	46.9 (17.3) a	5.1 (3.0) a
Glyphosate	3.0 (0.8) b	1.2 (0.6) a
Triclopyr salt (low)	4.4 (1.0) b	1.1 (0.4) a
Triclopyr salt (high)	1.7 (0.6) b	4.4 (1.5) a
Triclopyr ester (low)	7.2 (2.9) b	1.7 (0.7) a
Triclopyr ester (high)	2.2 (1.3) b	1.3 (0.5) a

[a] Means within a site having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. See text or Table 1 for high and low rate values of the triethylamine salt and triclopyr butoxyethyl ester formulations used at each site.

reported that densities of plants > 10 cm tall differed little between the triclopyr plus cutting and triclopyr-only treatments. In contrast, the density of plants ≤ 10 cm was five times higher in the herbicide-only plots compared with the triclopyr plus cutting treatment in June, although this difference disappeared by August. Moreover, Averill et al. (2008) concluded that the two cuttings per year used alone did little to reduce PSW densities and growth. These findings imply that the integration of mechanical and herbicidal strategies may enhance management of PSW compared with either approach used alone, but it may be specific to certain life stages or parameters being measured.

Forest Site. *PSW Cover.* Percent cover of PSW was lower at the June 2010 (2.7 ± 0.5) survey relative to the 2009 (4.4 ± 0.5) and 2008 (7.0 ± 0.6) surveys ($F_{2,126} = 22.39$, $P < 0.001$). All cutting plus herbicide treatments, except the triclopyr salt high-dose treatment, decreased PSW cover by the end of the study relative to the unmanaged control ($F_{6,126} = 4.27$, $P < 0.001$; Figure 5). PSW cover did not differ in plots that were cut twice annually compared with other treatments, including control plots. The observed decline in PSW cover at this forest site by the third year of the study may have been due to the particularly stressful growing environment in terms of low light and water availability. It is known that although PSW can tolerate such low resource habitats, optimal growth and performance occurs in much more open, mesic habitats where light, water, and nutrient availabilities are adequate (Averill et al. 2011; Ho et al. 2010; Hotchkiss et al. 2008).

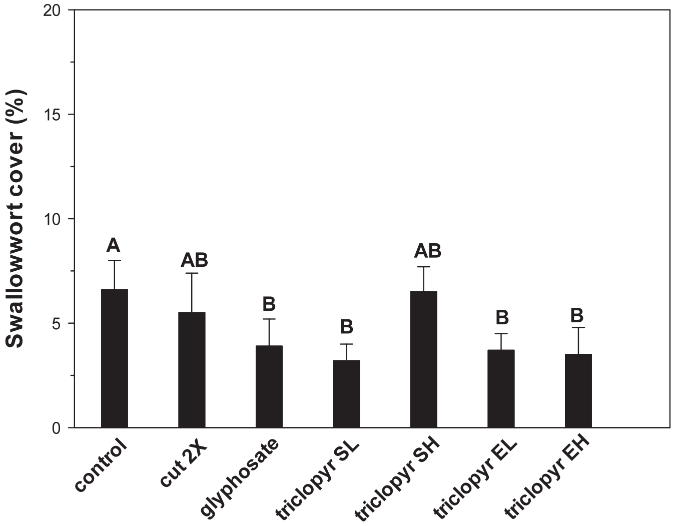

Figure 5. Mean (± SE, back-transformed, $n = 21$) pale swallowwort cover (%) in each of seven treatments in a forest site near Ithaca, NY. Means for treatments having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

Cover of Other Species. The cover of other species at this site was lower (9 ± 1) in June 2010 than the cover in 2008 (16 ± 2) and 2009 (14 ± 2) ($F_{2,126} = 3.08$, $P = 0.049$) despite decreases in PSW cover in some of the treatment plots. Plots subjected to the cutting plus triclopyr salt high-dose and cutting plus triclopyr ester low-dose treatments experienced the greatest declines in cover of other species ($F_{6,126} = 2.77$, $P < 0.015$; Figure 6). This finding is consistent with the view that this forest understory habitat is particularly stressful, not only for PSW but for other plants as well, which could be why several rare, threatened, or endangered species are only found on this site regionally (e.g., early buttercup, rock-cress) and are known to tolerate the stressful growing conditions on this site, in part, because of the reduced competition from other species.

Stem Densities and Biomass. Year ($F_{2,126} = 35.59$, $P < 0.001$) and treatment ($F_{6,126} = 3.02$, $P < 0.001$) had an effect on the density of PSW plants > 5 cm in height. There were fewer plants of this height group during the 2009 (8 ± 1) and 2010 (10 ± 1) surveys compared with pretreatment surveys (41 ± 6). Application of the cutting plus triclopyr ester high-dose and salt low-dose treatments resulted in a 78 and 71% reduction in PSW density by the end of the study. These reductions differed only relative to

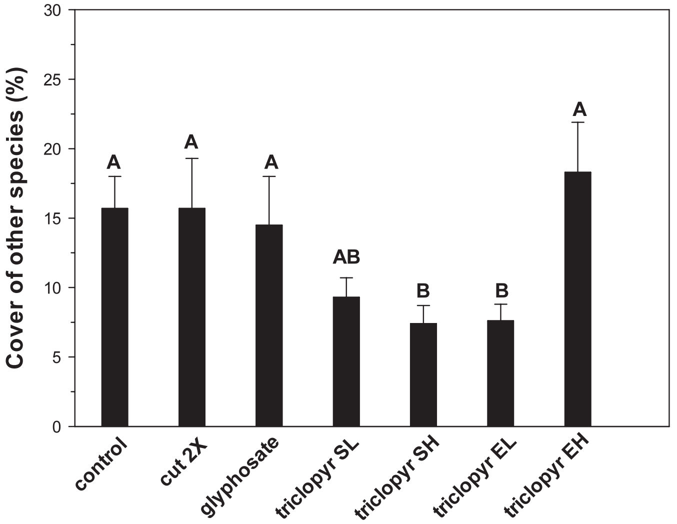

Figure 6. Mean (± SE, back-transformed, $n = 21$) cover (%) of other species in each of seven treatments in a forest site near Ithaca, NY. Means having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

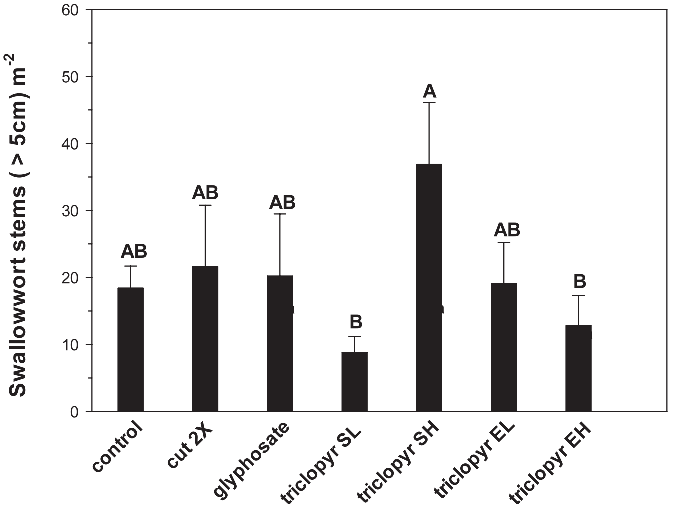

Figure 7. Mean (± SE, back-transformed, $n = 21$) number of pale swallowwort stems per square meter of > 5 cm in height in each of seven treatments in a forest site near Ithaca, NY. Means for treatments having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

the cutting plus triclopyr salt high-dose treatment, which was least effective in reducing stem densities (Figure 7). The likelihood that this forest understory site may be inherently limiting to PSW growth is also supported by the relatively greater initial plant densities reported in several other studies performed in shaded environments. For instance, our initial average density levels of $\sim$ 56 plants (stems) m^{-2} (includes plants ≤ 5 cm) were much lower than the 780 stems m^{-2} reported by Sheeley (1992) and slightly lower than the 99 stems m^{-2} reported by Christensen (1998).

The density of plants 5 cm or less in height was not influenced by year ($F_{2,126} = 0.55$, $P = 0.580$) but was affected by treatment ($F_{6,126} = 2.56$, $P < 0.023$). By the June 2010 sampling, plant density was lower in plots subjected to the cutting plus triclopyr ester high-dose treatment relative to the cutting plus triclopyr salt high-dose treatment (Figure 8); otherwise, no differences between treatments were observed. The minimal effect of treatments on the density of shorter PSW plants may have been due to increased germination and emergence of PSW seedlings within the less dense vegetation cover of plots relative to the much denser cover in old-field plots. The aboveground biomass of PSW plants at final sampling in June 2010 at the forest site did not differ between treatments (Table 2), although there was a trend toward less biomass with most cutting plus herbicide treatments.

These findings suggest that integrated techniques might control PSW but that effective management strategies could be habitat mediated. For old-field PSW populations in which conditions are more optimal, cutting plus high rates of either the triclopyr ester or triclopyr salt provided greater PSW control than low rates, and cutting plus herbicide was much better than cutting twice per season. The cutting plus glyphosate treatment also provided effective control of PSW, but the nonselectivity of this herbicide also negatively affected the growth (cover) of other species. In the forest understory, where PSW is less vigorous because of nonoptimal conditions, all cutting and herbicide treatments except the high rate of triclopyr salt yielded significant reductions in PWS cover relative to the control. However, because none of the herbicide and cutting treatments were more effective in reducing < 5 cm or > 5 cm stem densities relative to the control or twice-cut treatment, effectiveness of any of these treatments in accomplishing control or local eradication management goals within dry, shaded sites appears limited. Further studies of the environmental factors responsible appear warranted.

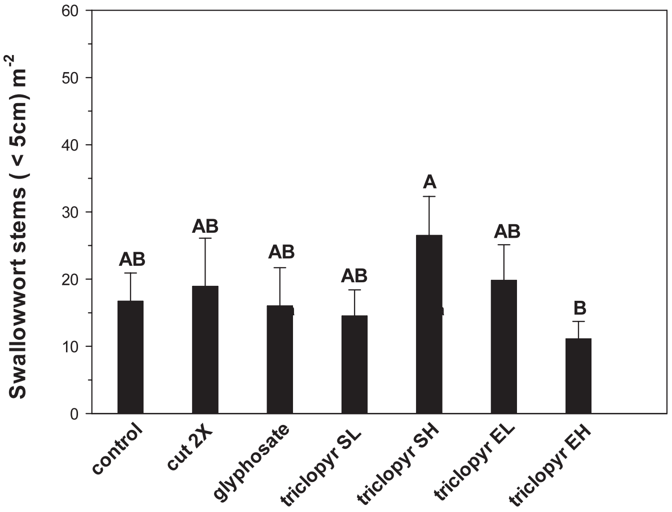

Figure 8. Mean (± SE, back-transformed, $n = 21$) number of pale swallowwort stems per square meter of ≤ 5 cm in each of seven treatments in a forest site near Ithaca, NY. Means for treatments having the same letter are not significantly different according to the Holm–Sidak test for pairwise comparisons at the $P > 0.05$. With all herbicide treatments, PSW in each plot was cut once in July 2008 and in July 2009. PSW in control plots were cut only in July 2008. SL and SH refer to the triclopyr triethylamine salt low-rate and high-rate formulations, respectively, and EL and EH refer to the triclopyr butoxyethyl ester low-rate and high-rate formulations, respectively.

In selecting management strategies within natural areas, land managers should also take into account potential off-target effects on rare, endangered, or sensitive species and on herbicide selectivity, soil activity, and soil mobility factors to determine the most appropriate, site specific PSW management strategies that minimize risk to off-target species.

These results have both short-term and long-term application. Although a biological control program is being developed for PSW, land managers still need control options during the several years that it could take to discover, screen, and receive approval to release a biological control agent. Should releases of agents occur, the potential remains that additional suppression might be needed in the same habitat as the released agent or that agents might not be available or establish in all the habitats that PSW invades. Practitioners therefore will need traditional control tools to integrate with biological control (e.g., Lym 2005).

Acknowledgments

We thank Scott Morris (Cornell) for assistance with all field operations. We thank Sandy Bonanno and George Spak for carrying out the herbicide applications. Thanks also to Jeromy Biazzo (USDA-ARS) and several undergraduate students for their assistance with data collection. We thank Joe Buttafuoco for help setting up the plots. We are grateful to Elizabeth Buck for help with early versions of the manuscript. Financial support was provided by the U.S. Department of Agriculture (USDA)–Agricultural Research Service project 1907-22620-003-01S. Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. USDA is an equal opportunity provider and employer.

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Received October 10, 2012, and approved March 25, 2013.