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Forest floor plant community response to experimental control of the invasive biennial, *Alliaria petiolata* (garlic mustard)[1]

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HOCHSTEDLER, W. W., B. S. SLAUGHTER, D. L. GORCHOV, L. P. SAUNDERS, AND M. H. H. STEVENS (Department of Botany, Miami University, Oxford, OH 45056). Forest floor plant community response to experimental control of the invasive biennial, *Alliaria petiolata* (garlic mustard). J. Torrey Bot. Soc. 134: 155–165. 2007.—The impact of invasive plant species on native plants is largely assumed to be negative, but supporting evidence is sparse. A common control method of non-native plants is herbicide application, but little is known about the effects of these chemicals on non-target plant populations, or differences in these populations before and after control measures are taken. We examined the response of the forest floor plant community to herbicide-mediated reduction of *Alliaria petiolata* in an old-growth and a second-growth forest stand in Hueston Woods State Park, Preble and Butler Counties, OH. Fifty 1 × 1 m plots were established in each stand, and 25 plots per stand were treated with Round-up© each November 2000–2004, which reduced cover of adult *Alliaria petiolata* but did not suppress recruitment. Percent cover of herbs and woody plants ≤0.85 m tall was assessed in May and June, 2000–2005. To determine compositional differences between sprayed and unsprayed plots in each stand we ordinated plots based on peak cover of each species using nonmetric multidimensional scaling, tested for differences in community composition with a multiple response permutation procedure, and compared total cover of growth forms with Kruskal-Wallis tests.

Five years of *Alliaria petiolata* control only modestly affected the forest floor vegetation. Neither species richness nor diversity differed significantly between sprayed and unsprayed treatments in any year of the study. Community composition differed each year between stands, but treatments differed significantly only in 2002 (in the second-growth stand), and marginally in 2004 and 2005 (in the old-growth stand). Treatment affected cover of some growth forms during the study, but only in some years: in the second-growth stand sprayed plots had significantly greater cover of spring perennials and graminoids in 2003 and marginally lower cover of annuals in 2005; in the old-growth stand sprayed plots had marginally more spring perennials in 2005. Wintergreen species, particularly the exotic annual *Stellaria media*, had lower cover in sprayed plots in the old-growth stand in 2005. We attribute the compositional differences we observed in the forest floor community to competitive impacts of *Alliaria petiolata*, but suggest that effects were modest due to the persistence of rosettes in the sprayed plots.

Key words: alien species, community composition, competition, deciduous forests, exotic species, multiple response permutation procedure, nonmetric multidimensional scaling ordination, *Stellaria media*.

Invasions by non-native species are of great concern to biologists, land managers and conservationists. While invasive species are considered the second-most significant threat to biodiversity, following habitat degradation and destruction (Wilcove 1998), claims that invasive plant species cause declines and extinctions of native species are often speculative, and evidence is sparse (Davis 2003, Gurevitch and Padilla 2004). Invasive plant populations have the potential to dominate the local flora by reducing survival, fecundity, and regeneration of native species (D'Antonio and Kark 2002, Merriam and Feil 2002, Miller and Gorchov 2004), and some introduced plant

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species are known to outcompete native species for resources, alter community structure and composition, and change soil function (Levine et al. 2003). Most studies, however, only compare composition and diversity in invaded versus uninvaded areas, so are correlational in nature (Levine et al. 2003, Gorchov 2005). Investment of money and time to control invasive plant species needs to be substantiated with knowledge that these organisms are actually causing population declines, and that their removal will have a positive impact on the community (Gurevitch and Padilla 2004).

One invasive plant species that is currently threatening broadleaf forests in the eastern United States is *Alliaria petiolata* (M. Bieb.) Cavara and Grande (Brassicaceae, garlic mustard) (Nuzzo 1993, Welk et al. 2002). A native of western Eurasia (Grime et al. 1987, Welk et al. 2002), *A. petiolata* establishes not only in disturbed areas along roads, river banks, and forest edges, but also in mature forest stands and dry upland slopes (Cavers et al. 1979, Nuzzo 1991, Byers and Quinn 1998, Carlson and Gorchov 2004).

Alliaria petiolata is an obligate biennial in the United States; seeds germinate in February or March in southern Ohio, and the juvenile basal rosettes live through the summer and remain green throughout the winter. In their second spring, adults flower in April and May, set seed in June, and senesce by mid-late July (Anderson et al. 1996). During the spring months, populations contain two cohorts, rosettes and adults, in addition to a seedbank remaining after spring germination (Byers and Quinn 1998).

The effects of *Alliaria petiolata* on native plant communities are not well understood. McCarthy (1997) found that cover of several native and non-native forest species with high dispersal abilities (annuals, vines, and tree seedlings) rapidly increased following *A. petiolata* removal, and suggested long-term studies may be necessary to determine if plants with low dispersal ability (e.g., perennials, shrubs, and graminoids) regain cover following removal of *A. petiolata*. Meekins and McCarthy (1999) found that *A. petiolata* rosettes had a negligible competitive effect on seedlings of the forest annual *Impatiens capensis* Meerb. and tree *Acer negundo* L., but a significant negative effect on seedlings of the xeric forest tree *Quercus prinus* L. *Alliaria petiolata* adults can attain 1.5 m in height, so that portion of the life cycle may be more strongly competitive than the rosettes (Meekins and McCarthy 1999). Evidence for allelopathic effects of *A. petiolata* on seed germination is less conclusive (Kelley and Anderson 1990, McCarthy and Hanson 1998, Prati and Bossdorf 2004), but other species in the family Brassicaceae are known to inhibit germination (Vaughn and Boydston 1997).

Carlson and Gorchov (2004) initiated a 5-year experiment in 2000 to test the effects of dormant season spot-application of herbicide on *Alliaria petiolata* and the response of the forest floor plant community to *A. petiolata* control in two stands of broadleaf forest in southwestern Ohio. Prior to the first herbicide treatment, *A. petiolata* was the species with the highest percent cover in each stand (Carlson 2002; see Slaughter et al. 2007 for cover data) and plant community composition did not differ between the sprayed and unsprayed plots (Carlson and Gorchov 2004). Sprayed plots had significantly lower cover of *A. petiolata* adults in three of the five years (2001, 2003, and 2004), but treatment did not significantly affect rosette cover or recruitment of *A. petiolata* (Slaughter et al. 2007). Effects on the forest floor plant community for the first year of treatment (2001) were reported in Carlson and Gorchov (2004): in the old-growth stand the cover of spring perennial herbs was significantly greater in sprayed than in unsprayed plots, but there were no significant compositional changes in the second-growth stand.

In this paper we evaluate how dormant season spot-spraying of *Alliaria petiolata* affected the forest floor plant community in the last four years of this experiment, including some re-analysis of the 2000 and 2001 data. Long-term studies such as this are necessary where slow response times or annual fluctuations in community dynamics are important (Hobbie et al. 2003). We hypothesized that *A. petiolata* competes with native species, particularly those that fix most of their carbon in the spring before canopy leaf-out, when *A. petiolata* has high cover. Thus, we predicted sprayed plots would display higher species richness and diversity than unsprayed plots, and that shifts in species composition would occur in sprayed plots, particularly in the form of higher cover of spring perennials. To assess whether herbicide application had direct effects on non-target plant species, we also investigated treatment effects on the cover of species in leaf at the time of application.

Materials and Methods. STUDY SITE. This study was conducted in two stands in the Hueston Woods State Nature Preserve, a forested natural area occupying portions of Preble and Butler Counties in southwestern Ohio and managed by the Ohio Department of Natural Resources. The second-growth stand (16 ha, 39°34′33″ to 39°34′31″N, 84°45′41″ to 84°45′37″W) is dominated by 50–100 year-old *Liriodendron tulipifera* L. (tulip tree) and the old-growth stand (20 ha, 39°34′07″ to 39°34′00″N, 84°45′10″ to 84°45′02″W) is dominated by *Fagus grandifolia* Ehrh. (beech) and *Acer saccharum* Marsh. (sugar maple) with many trees > 200 years old (Runkle et al. 1984). Soils are moderately thick to thin loess over loamy glacial till of the Russell-Miamian series on the uplands of both stands, and Casco, Rodman, and Fox soils in the drainages of the old-growth stand (Lerch et al. 1969, Lerch et al. 1980, Branco 1992). *Alliaria petiolata* was recorded in this park as early as 1975 (*Baechle 41*, Miami University herbarium).

EXPERIMENTAL DESIGN. The experiment was initiated in May 2000, when 50 1 × 1 m plots were located in each of the two stands in areas of high *Alliaria petiolata* density with the stipulation that plots were spaced > 5 m apart and situated away from drainages, trails, and treefall gaps (Carlson and Gorchov 2004). Within each stand, 25 plots were randomly assigned as spray treatment and the other half as unsprayed control plots. Sample size was reduced in some years due to large limbs falling on plots (Hochstedler 2006). Each November after leaf-fall, from 2000 through 2004, *A. petiolata* individuals were spot-sprayed in the sprayed plots and in a 1 m buffer area surrounding each sprayed plot using backpack sprayers with a 1% solution of the glyphosate herbicide Roundup© PRO. The herbicide solution was prepared by dilution of 0.08 L Roundup© PRO (41% glyphosate, in the form of isopropylamine salt) with 7.6 L water.

DATA COLLECTION AND ANALYSIS. Cover of all forest floor plants ≤0.85 m tall in each 1 × 1 m plot was estimated with a point frame (Frank and McNaughton 1990) in early May and late June, 2000–2005 (2000–2001 data from Carlson and Gorchov 2004). Pins were dropped at 50 equally-spaced predetermined points in each plot, and each "touch" of a plant was counted as 2 % cover. Multiple touches of the same species on a single pin were counted separately, and cover could total > 100 %. Peak cover was calculated as the greater value from either May or June for each species in each plot. Nomenclature follows Gleason and Cronquist (1991).

We calculated species richness and diversity for each plot, 2000–2005. Species diversity of each plot was calculated using the Shannon-Wiener index ($H' = -\Sigma\, p_i \ln p_i$, where p_i = proportion of peak cover accounted for by species i). The effects of stand and treatment on species richness and diversity each year were determined using randomized complete block ANOVAs, with stands as blocks.

To assess treatment effect on forest floor plant community composition, ordination in species space of peak cover of all species (except *Alliaria petiolata*) was performed using nonmetric multidimensional scaling (NMDS; Kruskal 1964). The metaMDS function in package vegan version 1.8-2 (Oksanen et al. 2006) was used in an *R*-statistical environment, version 2.2.1 (Anon. 2005). NMDS summarizes ecological community patterns by rank ordering the differences in species composition between plots. Calculations are performed on distance matrices and points moved in ordination space to arrive at solutions of least stress, a measure of how the dissimilarity between the species in the ordination space correlates with the original dissimilarity in the data (McCune and Grace 2002). NMDS is the preferred ordination method for biotic community data sets because it is non-parametric, well suited to data that are non-normal and have a large proportion of zero values, and has been shown to yield the most accurate representation of the underlying patterns in ecological data (Minchin 1987, McCune and Grace 2002, Brehm and Fiedler 2004). Data from 2000 and 2001 that were previously ordinated using detrended correspondence analysis (Carlson and Gorchov 2004) were reanalyzed here using NMDS.

Cover data were square root transformed and then standardized using a Wisconsin double standardization (Oksanen 2006) to

Table 1. Growth forms of all taxa found in sample plots in the old-growth and second-growth stands at Hueston Woods State Nature Preserve. Nomenclature follows Gleason and Cronquist (1991). *Hydrophyllum appendiculatum*, a biennial, has been grouped with the spring perennials due to its similar phenology. There is disagreement on the native versus invasive status of *Galium aparine*. Malik and Vanden Born (1987) conclude that both native and invasive (from Europe) populations occur in North America. Spring perennial herbs were conspicuous in March, then flowered, fruited, and senesced by late May or early June. Summer perennial herbs were conspicuous in May, then flowered, fruited, and senesced by August or September. Taxa in leaf at the time of November herbicide treatment, "wintergreen" species, are noted with an asterisk (*). Introduced species are in **bold**.

Growth form	Taxa included
Annuals	***Galium aparine****, *Impatiens pallida*, *Pilea pumila**, ***Stellaria media****
Ferns	*Botrychium dissectum**, *B. virginianum*
Graminoids	*Carex* spp.*, and other grass spp.*
Shrubs	*Asimina triloba*, *Lindera benzoin*, ***Lonicera maackii****, ***Rosa multiflora***, *Rubus allegheniensis*, *Rubus* sp., *Sambucus* sp.
Spring perennials	*Allium tricoccum*, *Aristolochia serpentaria*, *Cardamine concatenata*, *Claytonia virginica*, *Dicentra* spp., *Erigenia bulbosa*, *Erythronium americanum*, *Floerkea proserpinacoides*, *Hydrophyllum appendiculatum*, *Osmorhiza longistylis**, *Podophyllum peltatum*, *Polygonatum biflorum*, *Ranunculus abortivus*, *R. micranthus*, *R. recurvatus*, *Sanguinaria canadensis*, *Senecio obovatus**, *Trillium sessile*, *Viola* spp.*
Summer perennials	*Actaea alba*, *Agrimonia* sp., *Amphicarpaea bracteata*, *Arisaema triphyllum*, *Aster divaricatus**, *Circaea lutetiana*, *Cryptotaenia canadensis**, *Eupatorium purpureum*, *Eupatorium rugosum*, *Galium circaezans**, *Galium triflorum**, *Geum* spp.*, *Hackelia virginiana*, *Laportea canadensis*, *Oxalis* sp., *Panax quinquefolius*, *Phryma leptostachya*, *Polygonum virginianum*, *Sanicula* spp.*, *Senecio glabellus*
Trees	*Acer negundo*, *Acer saccharum* (including *A. nigrum*), *Aesculus glabra*, *Asimina triloba*, *Carpinus caroliniana*, *Carya cordiformis*, *Celtis occidentalis*, *Cornus florida*, *Crataegus* sp., *Fagus grandifolia*, *Fraxinus americana*, *Juglans nigra*, *Liriodendron tulipifera*, *Ostrya virginiana*, *Prunus serotina*, *Quercus muhlenbergii*, *Ulmus rubra*
Vines	*Parthenocissus quinquefolia*, *Rubus flagellaris*, *Smilax hispida**, *Toxicodendron radicans**, *Vitis* sp.

make species' abundances relevant and increase the importance of rare species. The Bray-Curtis index, calculated from the transformed cover data, was used as the dissimilarity measure to construct the distance matrix. To avoid local stress minima, ordinations were run with 100 random starts. Ordinations were assessed for stress as a function of dimensionality, and those with three dimensions (stress: 17.2–18.7) selected for additional analyses (Hochstedler 2006). All species were included in analyses, as removal of the rare species occurring in <5 % of the plots did not greatly improve stress values. Ordinations were examined for separate groupings of sprayed and unsprayed plots in each stand × year combination.

The null hypothesis of no difference in species composition between sprayed and unsprayed plots was tested with a multiple response permutation procedure (MRPP) on the Wisconsin double standardized peak percent cover for each stand × year combination. MRPP is a non-parametric multivariate test appropriate for community data sets which fail to meet assumptions of normality or homogeneity of variances (McCune and Grace 2002). MRPP calculates the fraction of permuted pairwise dissimilarities that are less than observed pairwise dissimilarities between the sampling plots (McCune and Grace 2002, Stevens and Oksanen 2006). We performed the MRPP in an *R*-statistical environment with the mrpp function in package vegan (Stevens and Oksanen 2006) using group size as a weighting factor, a Bray-Curtis distance index, and 10,000 permutations.

To assess whether specific growth forms in 2002–2005 responded to control of *Alliaria petiolata*, species were grouped as annuals, graminoids, spring perennials, summer perennial herbs, ferns, vines, shrubs, and trees according to Gleason and Cronquist (1991) (Table 1). Additionally, herbaceous species in leaf at the time of November herbicide treatment were grouped as "wintergreen species" to assess direct negative impacts of dormant season spraying on non-target species. Treatment effect on peak cover of each growth form and of wintergreen species was tested using a Kruskal-Wallis test with SAS PROC NPAR1WAY.

Table 2. Mean species richness, 2000–2005, in sprayed versus unsprayed 1×1 m plots in old-growth and second-growth stands, and statistics from randomized complete block ANOVA, contrasting treatments, with stands as blocks. **Bold** indicates significance at $\alpha = 0.05$, and * indicates marginal significance where $0.05 < P < 0.10$. Sample size was 25 per stand per treatment except where reduced 2003–2005 due to lost plots and treefall; (old-growth sprayed 2003: 22, 2004: 21, 2005: 20; old-growth unsprayed: 22, 20, 21; second-growth sprayed: 23, 23, 25).

	Old-growth		Second-growth		Stand			Treatment		
Year	Sprayed	Unsprayed	Sprayed	Unsprayed	df	*F*	*P*	df	*F*	*P*
2000	6.6	5.4	10.8	9.6	1, 99	48.79	**<0.0001**	1, 99	3.65	*0.0590
2001	8.9	7.7	11.1	11.4	1, 99	18.82	**<0.0001**	1, 99	0.37	0.54
2002	5.4	4.8	8.6	8.8	1, 99	54.21	**<0.0001**	1, 99	0.24	0.63
2003	7.4	7.0	7.8	7.0	1, 91	0.13	0.72	1, 91	1.38	0.24
2004	8.8	8.0	10.1	10.2	1, 88	7.40	**0.0079**	1, 88	0.20	0.65
2005	8.7	8.0	10.6	10.5	1, 90	13.77	**0.0004**	1, 90	0.25	0.62

Stellaria media (L.) Villars (Caryophyllaceae, common chickweed), an exotic annual which germinates in late fall or early spring (Defelice 2004), had one of the highest percent covers in the old-growth plots over the course of the study. We tested whether the change in *S. media* percent cover from 2000 to 2005 differed between the sprayed versus unsprayed plots with a Kruskal-Wallis test using SAS PROC NPAR1WAY.

Results. Species richness and Shannon-Wiener diversity were significantly higher in the second-growth stand than in the old-growth stand each year except 2003, but did not differ between sprayed or unsprayed plots in any year (Tables 2 and 3). Mean percent cover of all species in 2002–2005 is reported in Slaughter (2005) and Hochstedler (2006).

NMDS ordinations revealed compositional differences between old-growth and second-growth stands, but not between sprayed and unsprayed plots, for each year from 2001–2005 (Fig. 1). NMDS findings were confirmed by MRPP, which revealed no significant differences in composition between treatments, exception for the second-growth stand in 2002 (Table 4). In 2004 and 2005, composition was marginally different between treatments in the old-growth stand.

For the years 2002–2005, spray treatment only significantly affected the percent cover of growth forms in certain stand × year combinations (Table 5). In 2003, spring perennials and graminoids had higher cover in sprayed plots than in unsprayed plots in the second-growth stand (Fig. 2a). A trend existed toward greater cover of spring perennials in the sprayed plots in the old-growth stand in 2005 (Fig. 2b). Annuals tended to have lower cover in sprayed plots in the second-growth stand in 2005.

"Wintergreen" species in leaf at the time of dormant season herbicide treatment had lower cover in sprayed plots in the old-growth stand in 2002 and 2005 (Table 5). The most abundant of these wintergreen species, *Stellaria media,* increased in cover in the unsprayed plots from 2000–2005 in the old-growth stand

Table 3. Shannon-Wiener diversity indices, 2000–2005, in sprayed versus unsprayed 1×1 m plots in old-growth and second-growth stands, and statistics from randomized complete block ANOVA, contrasting treatments, with stands as blocks. See Table 2 for sample sizes. **Bold** indicates significance at $\alpha = 0.05$, and * indicates marginal significance where $0.05 < P < 0.10$.

	Old-growth		Second-growth		Stand			Treatment		
Year	Sprayed	Unsprayed	Sprayed	Unsprayed	df	*F*	*P*	df	*F*	*P*
2000	1.4	1.2	2.1	1.9	1, 99	63.20	**<0.0001**	1, 99	3.79	*0.0544
2001	1.8	1.6	2.0	2.0	1, 99	14.61	**0.0002**	1, 99	1.79	0.18
2002	1.3	1.0	1.7	1.7	1, 99	41.73	**<0.0001**	1, 99	2.38	0.13
2003	1.6	1.5	1.6	1.6	1, 90	0.19	0.66	1, 90	1.30	0.26
2004	1.8	1.5	1.9	1.9	1, 88	12.14	**0.0008**	1, 88	2.47	0.12
2005	1.7	1.4	2.0	2.0	1, 90	43.55	**<0.0001**	1, 90	2.78	*0.0991

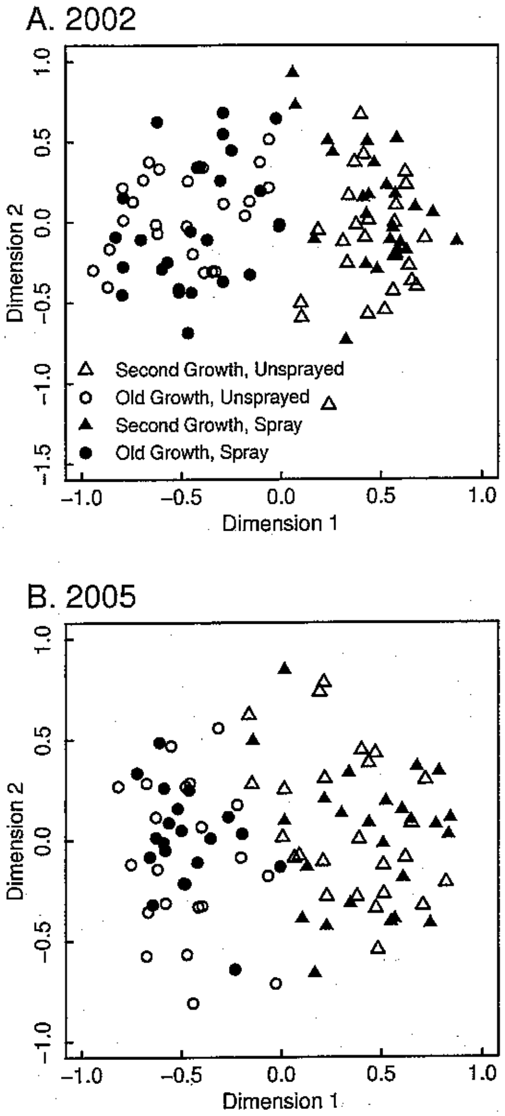

FIG. 1. Nonmetric multidimensional scaling (NMDS) ordination of (a) 2002 and (b) 2005 peak percent covers of all species except *Alliaria petiolata* in sprayed (solid symbol) and unsprayed (open symbol) plots in the old-growth (circles) and second-growth (triangles) stands at Hueston Woods State Park, OH. The only year when composition in sprayed versus unsprayed treatments differed significantly based on MRPP (Table 4) was 2002 (in second-growth stand only). Ordinations for all years showed discrimination of old-growth versus second-growth stands on dimension 1, but no discrimination of treatments.

(Fig. 3). The change in *S. media* cover over this time was significantly greater for unsprayed plots than sprayed plots (Kruskal-Wallis df = 1, $\chi^2 = 3.88$, $P = 0.0475$).

Discussion. We hypothesized that *Alliaria petiolata* competes with forest floor plants and predicted higher species diversity and greater cover of spring perennial herbs where this invasive was controlled. Dormant-season herbicide was successful at decreasing *A. petiolata* adult cover, but recruitment was not reduced and rosette cover did not differ between sprayed and unsprayed plots in any year of the study (Slaughter et al. 2007). Even with the suppression of *A. petiolata* adults, we did not find a change in forest floor plant community richness or diversity. Apparent year-to-year fluctuations in species richness are likely explained by different sampling periods as well as summer drought in 2002.

Only early in the study, in 2002 in the second-growth stand, was there a significant difference in community composition between the sprayed and unsprayed plots. As predicted, spring perennials tended to have higher cover in sprayed plots, but this treatment effect was only significant in 2001 in the old-growth stand (Carlson and Gorchov 2004) and in 2003 in the second-growth stand, as well as marginally significant in 2005 in the old-growth stand. Treatment effects were rarely significant for other growth forms. We attribute the compositional differences we observed in the forest floor community to the negative impacts of *Allaria petiolata,* but suggest that the reason the changes were relatively modest was due to the persistence of rosettes in the sprayed plots. Frequent removal of all *A. petiolata,* including rosettes, throughout each of three growing seasons resulted in greater effects on the forest floor community (McCarthy 1997). In the second year of that study *A. petiolata* was present only as rosettes in the control plots, but diversity was still lower than in the removal plots (McCarthy 1997), indicating that rosettes suppress native plants. Competition is the likely mechanism (Meekins and McCarthy 1999), although allelopathy (Kelley and Anderson 1990, McCarthy and Hanson 1998, Prati and Bossdorf 2004) is also possible.

Alliaria petiolata may also affect other plants indirectly via its effect on mycorrhizal fungi. Like other members of the Brassicaceae, *A. petiolata* has anti-fungal properties (Roberts and Anderson 2001) due to production of glucosinolates (Vaughn and Berhow 1999) and perhaps other compounds that may enter the soil as root exudates (Prati and Bossdorf

Table 4. Effect of treatment (sprayed versus unsprayed) on peak forest floor community cover in the old and second-growth stands as determined by multiple response permutation procedure (MRPP). The MRPP test statistic, A, is the chance-corrected within-group agreement describing the amount of similarity within a group (McCune and Grace 2002). See Table 2 for sample sizes. **Bold** indicates significance at $\alpha = 0.05$, and * indicates marginal significance where $0.05 < P < 0.10$.

Stand	Year	A	P
Old-growth	2001	0.0048	0.1088
	2002	0.0062	0.1054
	2003	−0.0045	0.8172
	2004	0.0070	*0.0989
	2005	0.0073	*0.0988
Second-growth	2001	−0.0005	0.5241
	2002	0.0071	**0.0299**
	2003	0.0017	0.2903
	2004	0.0004	0.4142
	2005	−0.0011	0.6124

Table 5. Mean percent cover of each growth form and for "wintergreen" species in each stand 2002–2005 with Kruskal-Wallis test statistic (df = 1) for difference between sprayed and unsprayed treatments. See Table 2 for sample sizes. Growth forms that never exceeded 4 % cover (vines, ferns) are not shown. **Bold** indicates significance at $\alpha = 0.05$. Asterisk (*) indicates marginal significance where $0.05 < P < 0.10$.

		Old-growth		Second-growth	
Growth Form	Year	Sprayed	Unsprayed	Sprayed	Unsprayed
Annuals	2002	34.9	41.8	2.2	3.8
	2003	20.5	29.2	2.0	2.7
	2004	43.0	28.2	3.4	3.1
	2005	33.7	52.6	*6.2	*7.8
Graminoids	2002	5.1	7.4	11.6	7.0
	2003	2.4	2.4	**5.4**	**1.4**
	2004	2.2	6.1	9.4	8.3
	2005	1.7	4.0	6.6	8.9
Shrubs	2002	2.3	2.3	6.8	2.6
	2003	2.1	2.1	4.0	1.4
	2004	4.3	1.2	3.6	3.8
	2005	4.6	5.3	3.4	2.2
Spring perennials	2002	13.5	16.2	39.7	39.6
	2003	39.3	31.6	**27.4**	**20.0**
	2004	44.0	39.3	29.7	34.3
	2005	*71.3	*56.0	30.6	29.7
Summer perennials	2002	3.0	2.0	15.7	19.0
	2003	1.5	0.9	6.8	10.6
	2004	1.7	2.5	13.7	19.4
	2005	2.2	1.4	13.5	13.4
Trees	2002	8.8	8.7	5.0	6.2
	2003	6.5	4.4	1.9	3.8
	2004	11.4	9.2	8.5	9.1
	2005	5.1	5.9	6.9	7.4
Wintergreen species[†]	2002	**34.6**	**57.5**	54.5	53.9
	2003	23.7	33.1	28.5	25.0
	2004	46.8	29.8	37.0	45.8
	2005	**29.2**	**55.8**	31.6	38.0

[†] When *Stellaria media* was removed from this growth form, mean percent cover was not significantly different between the sprayed and unsprayed plots in 2002 and 2005.

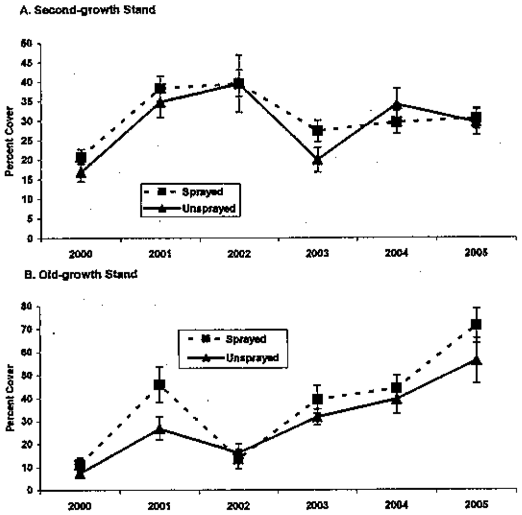

FIG. 2. Spring perennial percent cover (mean ± SE), (a) second-growth and (b) old-growth stands, 2000–2005. Means based on 1 × 1 m plots; see Table 2 for sample sizes.

2004) or from leaf litter (Stinson et al. 2006). One of these glucosinolates, glucotropaeolin, is found at significantly greater levels in rosette roots than adult roots (Vaughn and Berhow 1999), but it is not known if this compound plays a role in the anti-fungal qualities of the root exudates (Stinson et al. 2006). *Alliaria petiolata* disrupts arbuscular mycorrhizal fungi associations, thereby reducing growth of native tree seedlings (Stinson et al. 2006), and may interfere with other native forest floor herbs with high mycorrhizal dependency. Rosettes remaining in the sprayed plots may have reduced mycorrhizal fungi, and in this way indirectly affected other forest floor plant species (Roberts and Anderson 2001).

A second possible reason for the modest changes in community composition is herbivory by white-tailed deer, which has been shown to decrease plant growth and reproduction (Russell et al. 2001). Deer activity is evident in the Hueston Woods Nature Preserve from the abundant deer trails, tracks, and scat present (pers. obs.), although current density numbers are unknown (Lonnie Snow, HWSP, pers. comm. 2006). Rooney et al. (2004) found declines in some understory species to be particularly great in forested areas where hunting was restricted. During this study, we observed top browse on *Podophyllum peltatum* L. (Berberidaceae, may-apple) and *Impatiens pallida* Nutt. (Balsaminaceae, jewel-weed). Greater deer herbivory on plants in the sprayed plots than the unsprayed plots may have masked native plant recovery after *Allaria petiolata* removal at Hueston Woods. Deer browse on *A. petiolata* is rare in North America (Cavers et al. 1979, Nuzzo 1991), and it is possible that the higher cover of adult *A. petiolata* in the unsprayed plots deterred deer from browsing native plants.

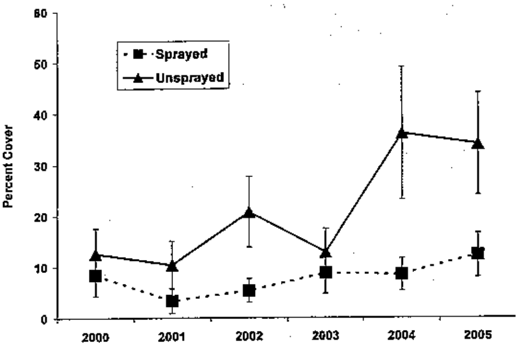

FIG. 3. *Stellaria media* percent cover (mean ± SE) in the old-growth stand from 2000–2005. Means based on 1 × 1 m plots; see Table 2 for sample sizes.

Glyphosate is a non-selective herbicide and may negatively affect species other than *Alliaria petiolata* that were in leaf at the time of the herbicide application. "Wintergreen" species had lower cover in sprayed than in unsprayed plots in 2005 in the old-growth stand. This effect was also found in 2001 and 2002 in this stand (Carlson and Gorchov 2004), but was not found in a comparable study in Illinois (Nuzzo 1996). Direct impacts of spraying was invoked by Carlson and Gorchov (2004) as the explanation for lower density of wintergreen herbs in sprayed plots than in unsprayed plots. In 2005, the treatment effect on wintergreen species was attributable to its effect on the most common of these, the exotic annual, *Stellaria media*. When *S. media* was excluded from the wintergreen species in the analysis of 2005 cover, the remaining species did not show a treatment effect. In our study area, much of the *S. media* population germinated in the fall, and seedlings in close proximity to *A. petiolata* rosettes likely experienced direct mortality due to herbicide exposure.

Stellaria media is commonly documented as a weed in agricultural settings, disturbed areas and waste places (Defelice 2004), but we are unaware that it has received attention as a potential threat to intact, undisturbed forest floor communities. The phenology and life history of *S. media* suggest it competes with spring perennial herbs and will be difficult to control once established. In our study area, much of the *S. media* population germinated in the fall, over-wintered, and was in leaf at the time of spring perennial emergence, often over-topping native species by early May. Unlike *Alliaria petiolata* rosettes, *S. media* senesces by early June and may not influence growth of the forest floor plant community throughout the summer. As many as 30,400 seeds can be produced per plant, and these can remain viable for at least 7, and possibly 30, years, in the soil (Thompson et al. 1997, Lutman et al. 2002, Defelice 2004).

Conclusions. While the continued presence of the rosettes in the sprayed plots made it impossible to determine the full effect of *Alliaria petiolata* on the forest floor plant community, the modest changes we have documented over this five year study suggest *A. petiolata* is competing with members of the plant community. Future assessment of native plant response to *A. petiolata* control measures in the field should be conducted after *A. petiolata* adult and rosette density has been significantly reduced for multiple years. The management decision to use dormant-season herbicide focuses on the adult life stage of *A. petiolata,* and may prolong effects rosettes have on forest floor communities. Similar consideration should be taken for other methods of control, including hand-weeding and select biological control agents (Skinner and Blossey 2005). Further determination of allelopathic properties of *A. petiolata*, as well as other trophic levels affected by its presence, will benefit our understanding of how this species interacts with native communities.

Based on the current evidence, the impacts of *Alliaria petiolata* are not as great as those of some other invasive plants in similar forests, such as the shrub *Lonicera maackii* (Rupr.) Maxim. (Caprifoliaceae, Amur honeysuckle) (Gould and Gorchov 2000, Collier and Vankat 2002, Gorchov and Trisel 2003, Hartman and McCarthy 2004, Miller and Gorchov 2004, Hartman and McCarthy 2007). Future research and restoration of invaded communities should weigh the effects of all invasive species in an area to determine management priority, as well as how multiple invasive species affect the same area (Huenneke and Thomson 1995).

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