Experimental Control of Garlic Mustard [*Alliaria petiolata* (Bieb.) Cavara & Grande] in Northern Illinois Using Fire, Herbicide, and Cutting

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ABSTRACT: Garlic mustard [*Alliaria petiolata* (Bieb.) Cavara & Grande] is a naturalized European obligate biennial herb that invades forest communities in the midwestern and northeastern United States and southeastern Canada. Three potential control methods (prescribed fire, 3% v:v glyphosate, cutting) were tested in a densely infested oak forest in northern Illinois. Spring treatment with either glyphosate or mid-intensity fire reduced garlic mustard adult (rosette) density and seedling frequency, while fall treatment decreased rosette density only. Low-intensity fire did not affect garlic mustard presence. All successful treatments produced cascading effects observable one to two years after treatment. Treating seedlings in spring reduced adult density the following year, and treating adults in either spring or fall resulted in lower seedling frequency two years later. Cutting flowering plants at ground level resulted in 99% mortality and reduced seed production to virtually zero; cutting at 10 cm above ground level produced 71% mortality and reduced total seed production by 98%. Recommended management is to prevent seed production until the seed bank is exhausted by repeated applications of fire, herbicide, or cutting on an annual basis until garlic mustard is absent from the site for a minimum of three years.

INTRODUCTION

Garlic mustard (*Alliaria petiolata* (Bieb.) Cavara & Grande) is a naturalized European biennial herb that aggressively invades woodland communities in the midwestern and northeastern United States and southeastern Canada. This mustard is recognized as a severe threat to natural areas in the midwestern and eastern United States.

Distribution

Garlic mustard was first recorded in North America in 1868 in Long Island, New York (NYS[1]) in the United States, and in 1879 in Toronto, Canada (Cavers et al. 1979). European settlers may have introduced this garlic-flavored plant as a food or medicinal herb (Grieve 1959, Brooks 1983). By 1950 garlic mustard had spread to at least 14 U.S. states and 2 Canadian provinces, and in 1990 the plant was distributed in 27 midwestern and northeastern states, the District of Columbia, Oregon, Utah, and in southern Ontario, the St. Lawrence Valley in Quebec, and southern Vancouver (Strausbaugh and Core 1953, Jones and Fuller 1955, Patman and Iltis 1961, Radford et al. 1965, Bare 1970, McGregor et al. 1977, Cavers et al. 1979, Wherry et al. 1979, Brown and Brown 1984, Voss 1985, Mitchell 1986, Hitchcock and Cronquist 1987; F, MIN, WIS, CM, NYS).

The first Illinois collection was made in 1918 north of Chicago (F). By 1990 the plant was widespread through the northern half of the state and occurred in state parks, nature preserves, and other natural areas in at least 41 counties (Jones and Fuller 1955, Mohlenbrock and Ladd 1978, Swink and Wilhelm 1979, Nuzzo unpubl. data).

Life history

Garlic mustard is a cool-season monocarpic biennial herb with an effective three-year generation time. Seeds germinate in early spring of year 1 following the first or second warm rain, approximately April 1 in northern Illinois. Seedling density can be very high, averaging 20,000 seedlings/square meter (Trimbur 1973). Approximately 50% seedling mortality occurs by the end of May (Trimbur 1973, Cavers et al. 1979), and gradual mortality continues through the summer, fall, and winter: only 2% to 4% of the seedlings survive to flower the following spring (Cavers et al. 1979). Juveniles overwinter as green rosettes, and growth continues during periods of above-freezing temperatures (Cavers et al. 1979).

Garlic mustard is a strict biennial; all surviving plants, regardless of size, produce flowers in the spring of year 2 and subse-

[1] Herbarium specimens in Field Museum (F), Carnegie Museum (CM), University of Minnesota (MIN), University of Wisconsin-Madison (WIS), and the New York State Museum (NYS).

quently die (Cavers et al. 1979, Byers and Quinn 1988, Bloom et al. 1990). Flowers are self-compatible and likely self-pollinated, but are also cross-pollinated by a variety of insects including syrphid flies, midges, and bees (Cavers et al. 1979). Thus a single plant may theoretically be adequate to populate an entire site.

Adult garlic mustard plants set and disperse seeds in the summer of year 2. Plants produce an average of 165 to 868 seeds in Ohio, depending on habitat and population density (Trimbur 1973). Average seed production per square meter ranges from 19,060 (low density) to 38,025 (high density) in woods in Ohio (Trimbur 1973), and from 19,800 to 107,580 in dense stands in various habitats in Ontario (Cavers et al. 1979).

Seeds are ballistically dispelled from a linear silique for a distance of several meters. Seeds have low wind dispersal and do not float well, but attach to moist surfaces (Cavers et al. 1979). Long-distance dispersal and distribution modes are unclear. Lhotska (1975) stated that seeds are dispersed by human activity. Small and large mammals may also be vectors for seed dispersal, although no studies have been conducted to determine if animals transport garlic mustard seeds.

Seeds remain dormant in the soil for a 20-month period through year 3 and germinate in the spring of year 4 in North America (Cavers et al. 1979). In Europe, Kinzel (1926) found similar dormancy, but Roberts and Boddrell (1983) and Lhotska (1975) determined that seeds collected in England and Czechoslovakia, respectively, germinated the spring after ripening. Most germination occurs within two years after dormancy is broken, but seeds remain viable for up to five years (Lhotska 1975, Roberts and Boddrell 1983). Population levels may vary widely from year to year reflecting the biennial nature and delayed seed germination of this plant (Nuzzo pers. obs.).

Habitat

Garlic mustard most commonly occurs in wooded communities under a partial canopy, but plants frequently grow in sites ranging from full sun to full shade. Plants produce greater growth in full sun than in partial or complete shade (Cavers et al. 1979), but are less invasive under extreme conditions of light or shade (Nuzzo pers. obs.).

Garlic mustard occupies sites with widely varying soil moisture levels, from communities flooded four months a year (Cavers et al. 1979) to dry sand forest (Maier 1976). While this species most frequently grows in moist shaded soil typical of floodplain forests (Gleason 1963, Trimbur 1973), and may rapidly increase in these communities during periods of drought, growing season inundation kills plants (Nuzzo unpubl. data) and thereby may limit invasion into wetland communities. Garlic mustard may initially colonize moist soils, and then subsequently spread to drier locations. Garlic mustard is also common in oak forest and savanna, and may occur in open fields (Byers and Quinn 1987). Disturbed areas such as roadsides and trail edges are frequent habitats in both wooded and partially open sites.

Garlic mustard has been recorded from a wide variety of soil substrates including loam, sand, clay, and gravel (Cavers et al. 1979), but has not been observed on undrained peat or muck soils. Its distribution appears to be associated with calcareous soils (Clapham et al. 1962 *in* Cavers et al. 1979) and the plant is noticeably absent from acid soils in Indiana, Kentucky, and Massachusetts, and from the Canadian Shield region in Canada (Cavers et al. 1979).

Disturbed forest communities appear to be most susceptible to rapid invasion and dominance by garlic mustard. In degraded oak forests in northern Illinois, garlic mustard has been observed to dominate the ground layer vegetation within ten years of initial invasion, paralleled by a dramatic decline in diversity and cover of native herbaceous plants. A potential relationship between high white-tailed deer (*Odocoileus virginicus*) population levels and garlic mustard abundance was observed in upland dry-mesic forests in Illinois: deer preferentially browsed native plant species and avoided garlic mustard, and deer trampling exposed soil suitable for colonization and brought garlic mustard seeds to the soil surface. This type of soil surface disturbance may be an important factor in the invasion and spread of garlic mustard, which often enters natural areas in localized disturbances created by treefalls or trail construction, or in the exposed soil at the base of large trees.

Research Objectives

Methods to effectively control garlic mustard have not been investigated. Garlic mustard appeared to decrease in abundance following prescribed fire in oak woodlands (Nuzzo pers. obs.; S. Packard, pers. comm. 1988), and to be killed by herbicide application (J.E. Schwegman, pers. comm. 1988). This study was undertaken to determine if garlic mustard could be controlled in a densely infested stand by the use of prescribed fire, herbicide application, or stem cutting. Specifically, the study was designed to answer three questions: (1) Does prescribed fire or glyphosate application reduce garlic mustard seedling presence and/or adult density? (2) Is the effectiveness of treatment related to the season or the number of treatments? and (3) Does cutting of the flowering stems reduce garlic mustard seed production or survival?

METHODS

Study Site

Research was conducted in northern Illinois in Camp Medill McCormick (Ogle County, T25N R11E 4PM), a 180-ha forested site bordering the Rock River in the Freeport Section of the Rock River Hill Country Natural Division of Illinois (Schwegman 1984). A 2-ha area of upland forest was selected for field trials. Elevation is approximately 260 m (msl), and underlying soil is Whalen loam 2-5% slopes, a well-drained soil formed in silty or loamy material (loess, till, or outwash) under forest vegetation, with fractured dolomitic bedrock at a depth of approximately 90 cm (Acker et al. 1980). The natural community is a degraded dry-mesic upland forest dominated by white oak (*Quercus alba*) and black oak (*Quercus velutina*) 30-45 cm dbh, associated with white ash (*Fraxinus americana*), slippery elm (*Ulmus rubra*), hackberry (*Celtis occidentalis*), and black cherry (*Prunus serotina*). Natural composition had been substantially altered since settlement by logging, grazing, and fire suppression. At the time this study was initiated, extensive browsing by white-tailed deer had produced an unnaturally open understory with a relatively low diversity of native herbaceous species, few tree seedlings, and very few saplings. Garlic mustard was abundant and formed a virtual carpet over the forest floor.

Experimental Treatments

Fire treatments

Seven fire plots were established in 1987, and fires were conducted in 1988 and 1989. The 50 m^2 plots were randomly assigned to receive one of six fire treatments or control. Treatments (Table 1) consisted of four single burns and two repeated burns conducted in April and November 1988, and April 1989, during the most favorable burn conditions. Fires were of mid-intensity (flame length up to 15 cm and burned through a majority of the plot) or low-intensity (flame length up to 3 cm, fire frequently extinguished within the plot). Fire treatments were not replicated, and fire intensity was an uncontrolled variable. Two parallel 25-m transects were randomly located within each plot, and data were recorded at 5-m intervals along each transect before treatment in April 1987 and after all treatments in June 1989 and June 1990 in all plots; additional data were collected in selected plots before and after treatments in spring or fall 1988 and 1989.

Adult (rosette) density was recorded by 0.5 m^2, and seedling frequency by 1 dm^2, within 20 0.5-m^2 quadrats located along the transects in each plot. Seedling density was so high that only frequency was recorded.

Herbicide treatments

Nine herbicide plots were established in 1988, and herbicide was applied in 1988 and 1989. Parallel 4 m x 50 m plots were randomly located at >10-m intervals and randomly assigned to receive one of eight treatments or control. Treatments consisted of four single and four repeated applications of a 3% v:v solution of glyphosate (Round-up) applied as a foliar spray on April 8 and November 2, 1988 and April 20 and November 30, 1989 (Table 1). Herbicide treatments were not replicated.

Data were collected as described under "Fire Treatment," in 20 0.5-m^2 quadrats located at 5-m intervals along a 50-m transect established in the center of each treated area and control. Pretreatment data were collected in 1988 in the control and 1988 treatment plots, and in 1989 in the 1989 treatment plots. Post-treatment data were collected in all plots in June 1989 and 1990. Additional data were collected in selected plots before and after treatments in spring or fall 1988 and 1989.

Table 1. Fire and herbicide treatments applied to garlic mustard (*Alliaria petiolata*).

	FIRE		HERBICIDE
	Low-intensity	Mid-intensity	
Spring 1988	X	X	X
Fall 1988		X	X
Spring & Fall 1988		X	X
Spring 1989	X		X
Spring 1988 & 1989		X	X
Spring & Fall 1989			X
Fall 1989			X
Fall 1988 & 1989			X

Cutting treatments

Six cutting plots were established in 1989 during peak flowering of garlic mustard plants, when plants had initiated silique production. Each plot contained 50 flowering garlic mustard plants; plot size varied according to plant density and approximated 1.0–1.5 m^2 each. Plots were randomly assigned to receive one of two treatments or control, with two plots assigned to each category. Treatments consisted of cutting flowering stems at ground level or at 10 cm above ground level.

Individual plants were marked, and stem height and number of stems per plant were recorded immediately prior to cutting on May 28, 1989. Post-treatment data, collected August 25, 1989, consisted of mortality, stem height, number of stems per plant, number of siliques per plant, and number of seeds per silique in one randomly selected silique per plant. Some plants underwent a second period of flower production in July and August and were forming additional siliques at the time of data collection. Seed production from this second blooming period was excluded from analysis due to problems in differentiating between partially and completely formed seeds within the siliques.

Data Analysis

Fire and herbicide treatments

Mean seedling frequency and rosette density were computed for each plot and year. Frequency values were arc-sine transformed prior to analysis. Mean density and frequency values were tested for homogeneity of variances by Cochran's C-test. Differences between homogeneous data sets ($P > 0.05$) were tested by one-way ANOVA. The nonparametric Kruskal-Wallace test was used for the majority of data sets, which were highly heterogeneous. When differences were detected, least significant difference (LSD) multiple range tests were conducted to indicate which plots were similar or dissimilar. The decision to conduct multiple treatments, and thereby forego replication, led to the inherent problems involved in pseudo-replication (*sensu* Hurlbert 1984). Statistical tests therefore provide insight into the effects of treatments, but the results of such tests are subject to interpretation.

All tests compared control to treatment plots within a given year. The impact of treatment over time was not tested, as seedling frequency in one year is not directly comparable to either seedling frequency or adult density the following year, and rosette density in one year is independent of rosette density in the following generation. However, in nine plots the same generation of plants was counted before and after treatment in spring, allowing direct testing of the effect of treatment over time by paired t-tests.

Cutting treatment
Pretreatment homogeneity of stem height and number of stems per plant among plots were tested by one-way ANOVA. Post-treatment homogeneity among replicates was tested by independent t-tests; no significant differences were detected so results of the treatments were pooled for further analysis. Differences in mortality after treatment were tested by Chi-square. Stem height, number of siliques per plant, and number of seeds per silique were analyzed by independent t-tests between control and the 10-cm cut (lack of survival in the ground level cut limited further comparisons).

Data were analyzed with Systat and Statgraphics software on an IBM compatible PC.

RESULTS

Fire Treatments

Garlic mustard had a homogeneous distribution in all burn plots prior to treatment. In 1987, rosette density in burn plots was uniformly low ($0.24/m^2 \pm 1.0$; $X^2 = 7.292$, df=6, $P<0.05$) and seedling frequency uniformly high (97.8% ± 1.2). In 1988, pretreatment rosette density in burn plots increased 160-fold to a mean of $39.4/m^2 \pm 5.6$. Densities were similar among all plots ($F=.471$, df=4,95, $P=0.7568$).

Fire impact on garlic mustard was related to fire intensity; mid-intensity fires reduced garlic mustard presence, and low-intensity fires had no apparent effect. Within-plot comparisons indicate that garlic mustard densities decreased significantly by 50% to 70% following a mid-intensity fire, and increased nonsignificantly following a low-intensity fire (Table 2). The consistent increase in density during the two-month period between counts is attributed to the larger size of rosettes and the presence of flower stalks in June, which increased visibility of the plants. In April, small rosettes were hidden by overlying tree leaves and adjacent larger rosettes, and therefore were easily overlooked.

Table 2. Garlic mustard (*Alliaria petiolata*) mean rosette density/m² in 4 plots (n=20 quadrats/treatment) before and after spring fire treatments in 1988 and 1989. Data collected in April (prefire) and June (postfire) in the year of treatment. Standard deviations in parentheses.

TREATMENT	1988		1989	
	prefire	postfire	prefire	postfire
Spring 1988 (mid-intensity)	36.9 (27.2)	12.4*** (11.8)		
Spring 1988/89 (mid-intensity)	35.0 (24.1)	17.8** (16.9)	3.9 (5.2)	3.1 (4.4)
Spring 1988 (low-intensity)	37.6 (26.2)	53.9 (51.5)		
Spring 1989 (low-intensity)			10.3 (11.1)	13.9 (19.0)

** significant at 0.01 level, one-tailed paired t-test ($T=3.177$, df=19, $P=0.005$)
*** significant at 0.001 level, one-tailed paired t-test ($T=4.541$, df=19, $P<0.001$)

Between-plot comparisons further support the interaction between fire intensity and rosette density. Following fires in 1988 and 1989, adult densities in mid-intensity fire plots were 34% to 78% lower than in the control plot ($2.8\text{-}8.6/m^2$ vs $13.0/m^2$; Figure 1). In contrast, densities in the low-intensity fire plots were similar to, and actually somewhat greater than, density in the control plot. In the remainder of this paper, results of fire treatments refer to mid-intensity burns unless otherwise noted.

Fire treatment significantly reduced garlic mustard density regardless of the season or number of fires. Mean adult densities following single fires in spring and fall were $2.8/m^2$ and $8.6/m^2$, respectively, while repeated fires on the same generation of plants resulted in mean densities of $6.3/m^2$ and $7.8/m^2$ (Figure 1). All densities were significantly lower than the $13.0/m^2$ density recorded in the control. The single spring fire resulted in the lowest density of all fire treatments.

Seedling frequency was directly reduced only by spring fire treatment. Mean seedling frequency two months after the 1989 spring fire was 66.3%, almost one-third less than that recorded in the control (Figure 2). In contrast, seedling frequency was consistently high (≥96.0%) in the low-intensity fire plots, in the fall-burn mid-intensity plots, and in the control.

A decrease in seedling frequency in one year generally resulted in reduced adult density the following year. Rosette density in 1989 was 78% lower than in the contol following the single 1988 mid-intensity

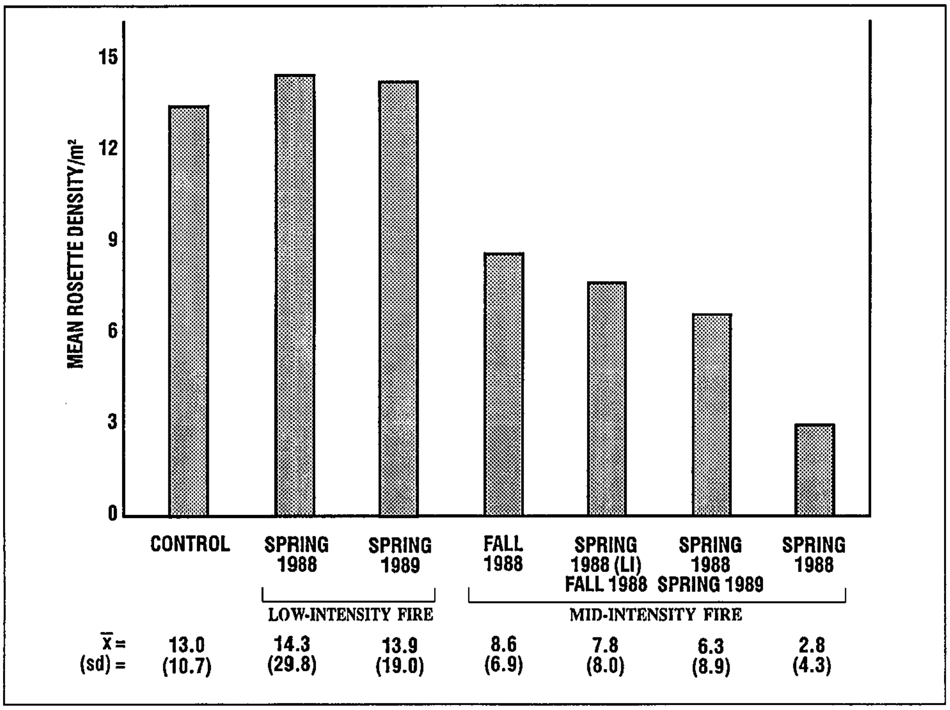

Figure 1. Mean rosette density/m² of garlic mustard (*Alliaria petiolata*) following single or repeated fires. Data collected June 1989, fires conducted April 1988, November 1988, April 1989 (n=20 quadrats/treatment). Low-intensity fire indicated by (LI). Densities differed significantly between plots (X^2=19.4591, P<0.05).

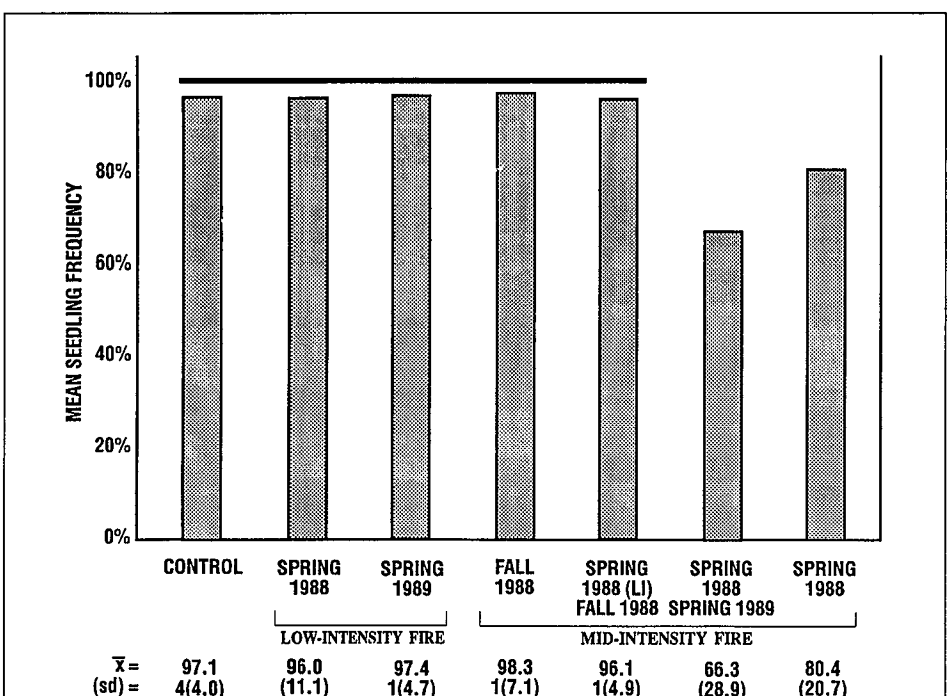

Figure 2. Mean seedling frequency of garlic mustard (*Alliaria petiolata*) following single or repeated fires. Data collected June 1989, fires conducted April 1988, November 1988, April 1989 (n=20 quadrats/treatment). Low-intensity fire indicated by (LI). Treatments linked by a horizontal bar are not significantly different. Unlinked fire treatments are significantly different from each other and from the linked treatments (X^2=52.7308, P<0.05).

spring fire (Figure 1). However, this effect was varied. The 1989 mid-intensity spring fire resulted in the lowest seedling frequency that year (Figure 3) and the lowest adult density the next year (Table 4), but this density did not differ significantly from the control (Table 4). Also, the plot with the second lowest seedling frequency in 1989 had the highest adult density in 1990.

A reduction in rosette density in one year was followed by lower seedling frequency two years after treatment. Spring fires reduced adult populations and thereby lowered seed production, resulting in lower seedling frequency two years later. Following the 1988 mid-intensity spring fires that reduced adults by 65% and 45%, 1990 seedling frequencies were some 37% lower than, and significantly different from, the control (Table 4). Seedling frequency values in the other fire plots were similar to or higher than in the control.

Herbicide Treatments

Garlic mustard had a heterogeneous distribution in the herbicide plots prior to treatment. In 1988, mean rosette densities in herbicide plots ranged from 21.4/m² to 71.6/m², with 29.0/m² in the control. Densities in two plots were much higher than, and differed significantly from, the control and three other herbicide plots (X^2=30.9094, df=5, P<0.001), but were accepted as treatment plots.

All herbicide treatments reduced adult density. Within-plot comparisons indicate that rosette densities decreased significantly by 91% to 100% two months after herbicide application (Table 3). Between-plot comparisons support this finding: following herbicide applications in spring and fall 1988, and in spring 1989, rosette densities in 1989 averaged 0.0/m² to 5.5/m², 58% to 100% lower than in the control (13.1/m²; Figure 3). Likewise, all plots treated with herbicide in 1989 had mean rosette densities significantly lower than the control in 1990; densities ranged from 2.1/m² to 9.9/m² in the 1989 treated plots, compared to 38.2/m² recorded in the control (Table 4).

These data indicate that herbicide treat-

Table 3. Garlic mustard (*Alliaria petiolata*) mean rosette density/m² (bold) and mean seedling frequency (italics) in 3 plots and control (n=20 quadrats/plot) before and after spring glyphosate treatment. Data collected in April and June in the year of treatment. Standard deviations in parentheses.

TREATMENT	1988		1989	
	pre-herbicide	post-herbicide	pre-herbicide	post-herbicide
Spring 1988	**59.4** (33.5)	**5.5***** (4.0)		
Spring 1989			**7.6** (6.8)	**0.0*****
			83.6% (23.7)	*13.8%**** (10.4)
Spring 1988/89	**26.0** (16.6)	—	**2.3** (4.3)	**0.2*** (0.6)
			79.0% (17.5)	*14.4%**** (6.9)
Control	**29.0** (19.4)			**13.1** (11.2)

* significant at 0.05 level, one-tailed paired t-test.
*** significant at 0.001 level, one-tailed paired t-test.

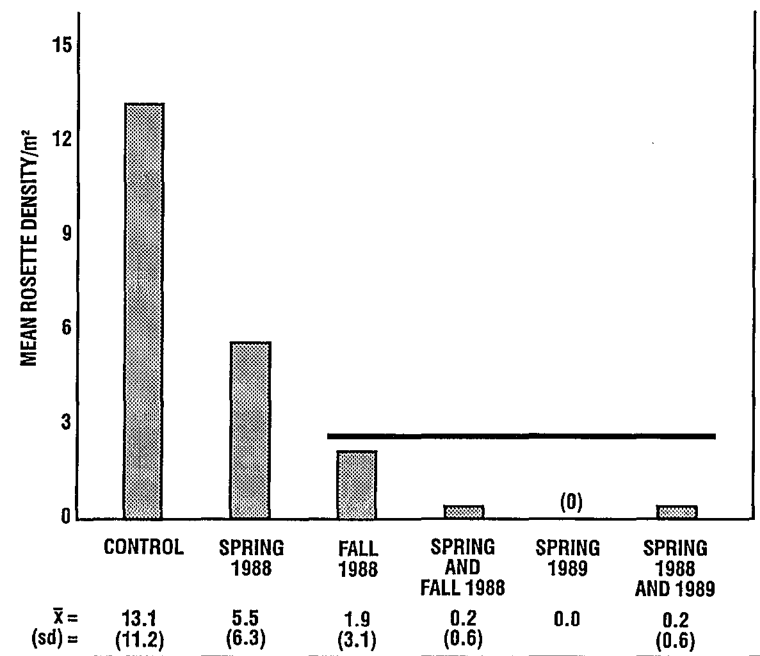

Figure 3. Mean rosette density/m² of garlic mustard (*Alliaria petiolata*) following single or repeated applications of glyphosate. Data collected June 1989, glyphosate applied April 1988, November 1988, April 1989 (n=20 quadrats/treatment). Treatments linked by a horizontal bar are not significantly different. Unlinked treatments are significantly different from each other and from the linked treatments (X^2=61.8748, P<0.05).

ment reduced garlic mustard density regardless of number or season of applications. Herbicide applied to the same generation of plants in either spring or fall, or in combinations of spring and fall, consistently reduced densities of adult plants relative to the control (Table 4, Figure 3).

Seedling frequency was reduced only by spring treatment. Following spring herbicide application in 1989, seedling frequency two months later was 85% lower than recorded in the control, or in plots treated either in fall or the prior spring (Figure 4).

As was observed with fire treatments, a reduction in one generation of garlic mustard plants produced a cascading effect noticeable one year after treatment of seedlings, and two years after treatment of adults. Rosette densities in 1989 and 1990, one year after seedling populations were reduced by herbicide applications, were 58% and 81% lower, respectively, than the controls in each year (Figure 3, Table 4). Seedling frequencies in 1990, two years after adult populations were reduced by herbicide treatment in spring 1988, were significantly lower in two plots than in the control (Table 4). Seed production by adjacent untreated plants was not affected, and the high seedling frequency in the third plot is assumed to reflect the entrance of seeds into the plot.

Cutting

Mean stem height (68.8 cm ± 22.4, range 12–199) and number of stems per plant (1.2 ± 0.5) were similar among all plots prior to cutting. Of the 300 plants, 86.7% had single stems, 9% had two stems, 4% had three stems, and 0.3% had four stems.

Cutting flowering stems significantly reduced survival, stem height, and total seed production (Table 5). Plants cut at ground level experienced 99% mortality and plants cut at 10 cm experienced 71% mortality, compared to 6% natural mortality in control plants. Surviving plants produced new but significantly shorter single stems, averaging 27.7 cm on plants cut at 10 cm. A single 10-cm stem developed from the surviving plant cut at ground level. None of the cut plants produced more than one

Table 4. 1990 Mean rosette density/m^2 and mean seedling frequency in all fire and herbicide treatment plots. Data collected June 1990, treatments conducted April and November 1988 and 1989 (n=20 quadrats/treatment). Low-intensity fire indicated by (LI). Standard deviations given in parentheses. Within each treatment type and size class, superscript letters indicate statistical similarity.

	Rosette Density/m^2		Seedling Frequency (%)	
Fire Treatments				
Mid-Intensity				
Spring 1988	67.7^{B}	(49.7)	48.6^{A}	(30.5)
Spring 1988/1989	31.9^{A}	(23.6)	44.8^{A}	(31.9)
Spring 1988(LI)/Fall 1988	45.0^{A}	(20.2)	64.6^{B}	(20.3)
Fall 1988	55.7^{B}	(39.8)	75.5^{B}	(19.0)
Low-Intensity				
Spring 1988	34.9^{A}	(27.8)	68.4^{B}	(18.2)
Spring 1989	41.8^{A}	(22.7)	91.7^{C}	(8.9)
Control	36.7^{A}	(20.5)	76.8^{B}	(21.5)
Herbicide Treatments				
Spring 1989	7.1^{A}	(6.8)	29.6^{B}	(17.9)
Fall 1989	5.6^{A}	(4.5)	70.9^{C}	(22.4)
Spring/Fall 1989	2.1^{A}	(7.6)	58.5^{C}	(17.2)
Spring 1988/1989	6.3^{A}	(5.4)	13.6^{A}	(10.9)
Fall 1988/1989	9.9^{A}	(8.2)	29.5^{B}	(16.4)
Spring 1988	79.8^{B}	(30.2)	66.2^{C}	(25.7)
Fall 1988	85.6^{B}	(35.0)	19.9^{A}	(14.5)
Spring/Fall 1988	41.5^{C}	(17.0)	10.8^{A}	(10.3)
Control	38.2^{C}	(26.6)	60.6^{C}	(21.4)

Fire treatments, rosette density: X^2= 14.293, P<0.046
Fire treatments, seedling frequency: X^2= 59.661, P<0.001
Herbicide treatments, rosette density: X^2=138.108, P<0.001
Herbicide treatments, seedling frequency: F = 33.710, P<0.001

stem.

Control plants produced an average of 15.8 (±12.3) siliques/plant, and 14.3 (±3.3) seeds/silique. Individual plants produced an average of 225.9 seeds, and the 94 surviving plants produced a combined total of approximately 21,238 seeds. Cutting plants at 10 cm reduced individual seed production 93.7% to 14.3 seeds/plant and reduced total seed production 98% to 414 seeds. Seed production was effectively zero in plants cut at ground level; the surviving plant produced two small siliques with an undetermined number of seeds.

Thirteen percent of the control population produced additional siliques during a second period of flower production. None of the cut plants experienced a second bloom period.

DISCUSSION

All herbicide and mid-intensity fire treatments were effective in reducing garlic mustard presence. Glyphosate produced a more noticeable impact than fire, in part due to the difference in plot coverage inherent in the two methods. Glyphosate was applied evenly within a relatively small area, resulting in complete or near complete coverage of the entire treated area. Fire burned patchily through a much larger area, resulting in untreated sections within each plot, and uneven fire intensities within the burned areas. Fires were difficult to conduct in all seasons due to low fuel loads and the abundance of green garlic mustard plants, which on occasion literally extinguished fires. Oak leaves that provided the majority of fuel were frequently too moist to effectively burn in fall, and were blown away or trampled by spring, leaving insufficient and discontinuous fuel on the forest floor. Fires were consequently patchy and many garlic mustard plants were missed, particularly those at the bases of trees or sheltered by down logs. Fire intensity, in the context of this study, was related to fire coverage: low-intensity fires frequently extinguished within a plot, and mid-intensity fires burned through most of a plot.

Spring treatment by either fire or herbicide impacts two generations of plants, lowering both adult density and seedling frequency. Spring treatments appeared to reduce adult density more effectively than fall treatments, although no significant differences were detected. The apparent differences may reflect (1) different physiological conditions of plants (actively growing in spring versus semi-dormant in fall), (2) seasonal differences in fine fuel moisture levels, or (3) seasonal variation in leaf cover (higher in fall and thus decreased exposure of rosettes to herbicide, versus lower in spring and increased exposure of rosettes).

Seedling frequency was affected by spring treatment because the treatments were conducted during the period of seed germination. The difference in seedling reduction in 1989—85% with glyphosate and 33% with fire—may reflect the patchy coverage of fire as compared to the more even application of herbicide, or may be a response to the different times of treatment (in 1989, fire was conducted April 6 and glyphosate applied April 20; germination may have nearly concluded by the latter date), or fire may have stimulated germination from a seed bank. Further study is warranted.

Treatments that reduced seedling frequency resulted in fewer adults the following spring. Treatments that reduced adult density also produced a cascading effect, noticeable two years later: the smaller adult popula-

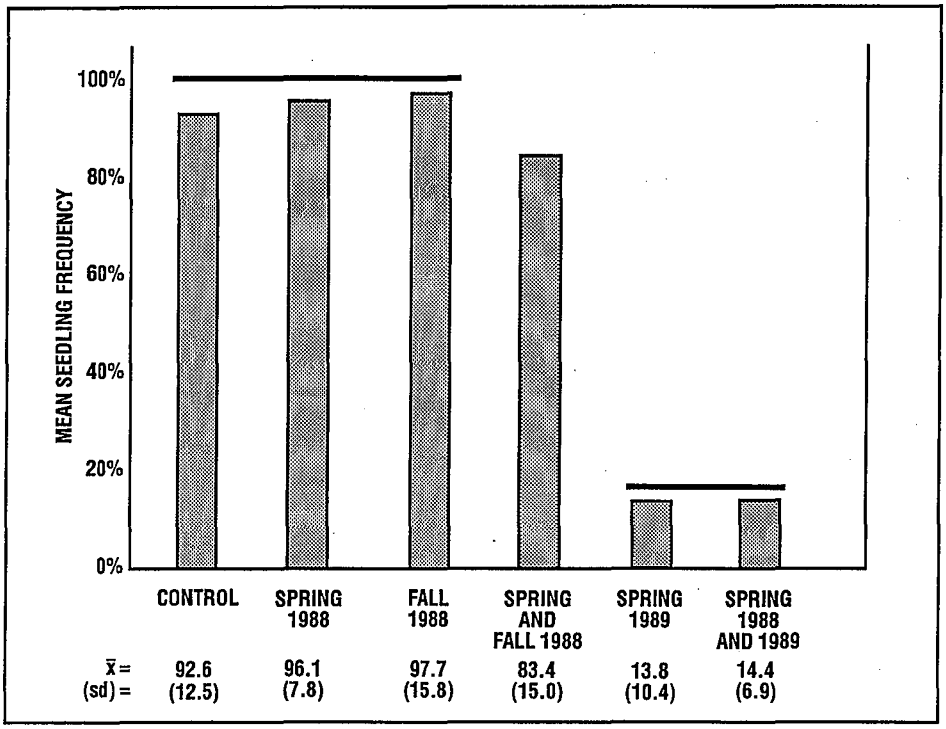

Figure 4. Mean seedling frequency of garlic mustard (*Alliaria petiolata*) following single or repeated applications of glyphosate. Data collected June 1989, glyphosate applied April 1988, November 1988, April 1989 (n=20 quadrats/treatment). Treatments linked by a horizontal bar are not significantly different. Linked treatments are significantly different from each other and from the unlinked treatment (X^2=90.7072, P<0.05).

Table 5. Response of garlic mustard (*Alliaria petiolata*) to cutting of flowering stems at ground level and 10 cm above ground level: mortality, mean stem height, mean number of siliques/plant, and mean number of seeds/silique, in 6 plots (n=50 plants/plot) in a degraded dry-mesic upland forest in Ogle County Illinois. Treatment conducted May 25, 1989, data collected August 12, 1989. Standard deviations indicated in parentheses, ranges indicated in brackets.

TREATMENT	Mortality[a]	Stem Height[b] (cm)	Siliques/ Plant[c]	Seeds/ Silique[d]	Average #Seeds/ Plant	Total Seeds Produced
Control	6%	68.67 (19.11) [33-108]	15.8 (12.3) [2-58]	14.3 (3.3) [3-23]	225.9	21,238
Cut at 10 cm	71%***	27.72*** (8.22) [12-44]	2.8*** (2.5) [1-12]	5.1*** (3.4) [0-11]	14.3	414
Cut at ground level	99%***	10.00***	2.0***	—	—	—

[a] Mortality X^2=76.412, df=2, P<0.001
[b] Stem height T=11.195, df=121, P<0.001
[c] Siliques/plant T= 5.630, df=121, P<0.001
[d] Seeds/silique T=12.769, df=115, P<0.001
*** significant at 0.001 level.

tion produced fewer total seeds, which resulted in lower seedling frequency two years after spring treatment (seeds have a 20-month dormancy period). This effect was variable, however, as seeds were produced by untreated plants growing within the fire plots and adjacent to the herbicide plots. A lower seedling frequency would be expected 2½ years after fall treatment of adults.

Single treatments with either fire or herbicide were similar in effect to double treatments applied to the same generation of plants (spring and fall in the same year, or fall in one year and spring the next year, or two consecutive springs). Neither fire nor herbicide completely eliminated garlic mustard from the study plots in a single treatment. Some adult plants were missed by treatment, or recovered after treatment, and seedlings germinated from the seedbank following treatment in the same or succeeding year. Management efforts should therefore focus on single applications to successive generations of plants.

Cutting killed adult plants and thereby decreased seed production. Plants that were cut at ground level contributed virtually no seeds to the seed bank. Plants cut at 10 cm above ground level produced significantly fewer seeds, and total seed production was reduced by 98%. It is not known whether the cut flower stems produced viable seeds, an effect demonstrated in teasel (*Dipsacus laciniatus*; Solecki 1989) and other herbaceous species (Gill 1938).

Cutting was applied only to adult flowering plants in early summer, while fire and herbicide were applied to both seedlings and nonflowering adults in the fall and early spring. Although the season and mode of operation differed, all three treatments reduced adult populations of garlic mustard and thereby limited seed production.

MANAGEMENT RECOMMENDATIONS

Short-term control may be attained by reducing garlic mustard's presence in a community by any of the three methods tested. However, long-term control requires depleting existing seed bank reserves and preventing further seed production. In this study plants produced an average of 225.9 seeds and grew at a mean density of 42.2/m^2 in 1989. Thus seed production per square meter averaged 9533 seeds, considerably lower than that reported by Trimbur (1973) and Cavers et al. (1979) but still a large contribution to the seed bank.

Seeds germinate only in spring, and treatments that decrease seedling frequency reduce the number of adult plants present the following year. The degree of seedling reduction is related to the percent of germination that has occurred by the time control is implemented. Generations overlap for approximately two months each spring, beginning in April with germination and ending in mid- to late-June as rosettes begin to die; control conducted during this period impacts two age classes of plants.

Seeds produced in one year, such as 1990, will germinate two to six years later, from 1992 through 1996. Most germination will occur in 1992 and 1993, and a low percentage of seeds will potentially germinate through 1996. Repeated applications of fire, herbicide, or cutting will be required during this time period to prevent production and contribution of seeds to the seed bank. Additional research should be conducted to determine if different management activities will reduce seed bank longevity by either stimulating germination or decreasing viability of seeds in the seed bank.

In natural areas where garlic mustard is not established the recommended deterrent is to monitor annually and to remove all plants prior to seed production. In fire-tolerant communities an ongoing prescribed burning program will deter entrance of this species and, in many communities, will enhance growth of native ground layer vegetation (White 1986).

Once garlic mustard is established in a community, the recommended management goal is to prevent seed production until the seed bank is exhausted, potentially a five-year period. Based on the results of this study and the species characteristics, this will require repeated applications of fire, herbicide, cutting, or pulling on an annual basis until garlic mustard is absent from the site for a minimum of three years. The choice of management tool is influenced by the size of the infestation and the type and quality of natural community.

In fire-adapted communities the recommended management is a mid-intensity fire, conducted as late in the spring as feasible to reduce both rosettes and seedlings. Adults that survive the fire should be cut at ground level or treated with glyphosate to prevent seed production. In addition to directly reducing garlic mustard presence in upland forests, prescribed fire may indirectly limit garlic mustard by stimulating growth of native ground layer species (White 1986) and decreasing habitat availability. Increased herbaceous cover may reduce the rate of invasion, as garlic mustard enters communities in soil disturbances and areas lacking ground vegetation (Trimbur 1973).

In fire-intolerant communities recommended management is the use of glyphosate, applied in the spring if there are few or no native species that will be damaged, otherwise as a dormant season application. Because seedling populations are affected only by spring application, the conclusion could be drawn that glyphosate should be applied in spring to eliminate garlic mustard from a natural community. However, glyphosate is a systemic, nonselective herbicide that affects all green vegetation. In diverse communities with early spring flora a dormant-season spray may be less damaging to native ground layer vegetation than a growing-season application. A more detailed testing of different types and concentrations of herbicides would provide guidelines for effectively reducing garlic mustard presence with the least impact upon the ground layer.

Appropriate management in areas with small infestations, or with species sensitive to dormant-season spray, is to cut flowering stems at ground level or remove the entire plant by pulling. In all communities the entire infestation should be treated to prevent seed production. Cutting plants is a labor-intensive practice that requires considerably more effort than either herbicide application or prescribed burning. Cutting plants at ground level is more time-consuming than cutting at 10 cm, particularly if the presence of desirable herbaceous vegetation limits use of a weed-eater when cutting close to the ground. Determination of cutting height may be a matter of weighing the initial amount of labor required to eliminate blooming plants (greater with ground level cutting) against the amount required in future years due to reproduction from plants cut above ground level. Viability of seeds produced on cut flower stems was not tested. As a safeguard, cut flower stems should be removed from the site when feasible.

Pulling flowering plants would potentially have the same effect as cutting at ground level. When nonflowering plants are pulled, the degree of control is dependent upon how much of the root system is removed; plants with intact root crowns frequently produce new shoots.

Garlic mustard is an invasive species; once it has been removed from a site, annual monitoring for new invasions, followed by removal of all plants prior to flower production, is necessary.

This study examined three management methods in a single natural area, a degraded oak forest. Additional research should be conducted to determine if these results are applicable to other natural communities that garlic mustard invades including floodplain forests, mesic forests, sand forests, and oak savannas.

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