EXPERIMENTAL CONTROL OF GARLIC MUSTARD (*Alliaria officinalis*) IN NORTHERN ILLINOIS USING FIRE, HERBICIDE AND CUTTING.

by

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ABSTRACT

Garlic mustard (*Alliaria officinalis*) is a naturalized European obligate biennial herb that invades forest communities in the Midwest and Northeastern United States and Ontario, Canada. Three potential control methods (prescribed fire, 3% v:v glyphosate, cutting) were tested in a densely infested oak forest in northern Illinois. Low intensity fire had no impact on garlic mustard presence. Mid-intensity fire and glyphosate reduced rosette (adult) density and, when conducted in spring, also reduced seedling frequency. Spring treatment had a carryover effect: the smaller seedling population resulted in fewer adults one year after treatment, and the reduced adult population resulted in lower seedling frequency two years after treatment. 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 seedbank is exhausted by repeated applications of fire, herbicide, or cutting on an annual or biennial basis until garlic mustard is absent from the site for a minimum of three years.

INTRODUCTION

Garlic mustard (*Alliaria officinalis* Andrz.) is a naturalized European biennial herb that aggressively invades woodland communities in the Midwest and northeastern United States and Ontario Canada. This mustard is recognized as a severe threat to natural areas in the midwestern and eastern United States but no information is available concerning effective control methods. This paper reviews existing literature and reports the effects of three control methods (burning, herbicide application and cutting) on garlic mustard seedling frequency and rosette density in a densely infested stand in northern Illinois.

Distribution

Garlic mustard was first recorded in North America in Toronto, Canada in 1879 (Cavers *et al.* 1979), and in the northeastern United States prior to 1889 (Gray *et al.* 1889). This garlic-flavored plant may have been introduced as a food or medicinal plant by European settlers (Grieve 1959). By 1950 garlic mustard occurred in at least five U.S. states and two provinces in Canada, and by 1990 the plant was distributed in 18 midwest and northeastern states, and in southern Ontario, St. Lawrence Valley in Quebec, southern Vancouver, and Portland Oregon (Bare 1970, Strausbaugh and Core 1953, Brown and Brown 1984, Cavers *et al.* 1979, Voss 1985, Jones and Fuller 1955, Hitchcock and Cronquist 1987, Wherry *et al.* 1979, McGregor *et al.* 1977, Mitchell 1986, Patman and Iltis 1961, Radford *et al.* 1965).

Garlic mustard was first recorded in Illinois between 1922 (Henry and Scott 1981) and 1940 (Jones and Fuller 1955) and now occurs in state parks, nature preserves and other natural areas in at least 36 counties (Nuzzo unpublished, Mohlenbrock and Ladd 1978, Swink and Wilhelm 1979) in northern and central Illinois.

Life history

Garlic mustard is a cool-season monocarpic biennial herb with an effective 3 year generation time (Figure 1). Seeds germinate in early spring of year 1 following the first or second warm rain. Seedling density can be very high, averaging 20,000 seedlings/square meter (Trimbur 1973). Approximately 50% seedling mortality occurs by the end of May (Cavers *et al.* 1979, Trimbur 1973), 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; growth may occur during periods of above-freezing temperatures when the plants are exposed to sunlight. Garlic mustard is an obligate biennial; all surviving plants, irregardless of size, produce flowers in the spring of year 2 and subsequently die (Cavers *et al.* 1979, Byers and Quinn 1988). 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, entrance of a single plant into a site may theoretically be adequate to populate the entire site.

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

Seeds remain dormant in the soil for an 18 month period through year 3 and germinate in the spring of year 4 in Canada (Cavers *et al.* 1979). Kinzel (1926) found similar dormancy in German seeds, but Roberts and Boddrell (1983) and Lhotska (1975) determined that English and Czechoslovakian seeds, respectively, germinated the spring after ripening, for an effective generation time of two years. Most germination occurs within two years after dormancy is broken, and seeds remain viable for up to 5 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.

Habitat

Garlic mustard occurs most frequently in moist shaded soil, and particularly in floodplain forests (Gleason 1963, Trimbur 1973). Although sites may be inundated for up to four months of the year (Cavers *et al.* 1979), frequent flooding will eliminate plants (Trimbur 1973). In northern Illinois garlic mustard appeared to rapidly increase in floodplain forests during the summer droughts of 1988 and 1989, when flooding was greatly reduced. However, flooding during the growing season in 1990 killed garlic mustard plants inundated for one week in floodplain forests (Nuzzo personal observation). This plant also occurs in drier and more upland habitats ranging from oak forest to savanna to open fields and abandoned gravel roads (Byers and Quinn 1987, Nuzzo personal observation). Roadsides and trail edges are frequent habitats in both wooded and partially open sites.

This species occurs most often under the partial canopy characteristic of oak forests, savannas and floodplain forests. Although garlic mustard produces greater growth in full sun than in partial or complete shade (Cavers *et al.* 1979) it appears to be less invasive under extreme light conditions.

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 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).

Ecology

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 groundlayer vegetation within ten years of initial invasion, paralleled by a dramatic decline in diversity and cover of native herbaceous plants. A potential correlation between high white-tail deer (*Odocoileus virginicus*) population levels and garlic mustard abundance was noted in upland dry-mesic forests in Illinois: Deer preferentially selected native plant species and avoided garlic mustard, and deer trampling exposed soil suitable for colonization and brought garlic mustard seeds to the soil surface.

Soil disturbance appears to be an important factor in the invasion and spread of garlic mustard. The plant often enters natural areas in disturbance patches such as treefalls, windthrows, floodplains, trails and roadsides. Garlic mustard appears to initially colonize moist soils and then subsequently spread to drier locations.

Seeds are ballistically dispelled from a linear silique for a distance of several meters. Longer distance dispersal and distribution modes are unclear. Seeds have low wind dispersal and do not float well, but attach to moist surfaces (Cavers *et al.* 1979). Seeds may be transported to new sites on the skin and clothing of field workers.

Few mammals or insects have been observed to predate on garlic mustard in Illinois. In Canada, Cavers *et al.* (1979) report occasionally serious herbivory by cows, horses and possibly deer, and relatively non-injurious predation by insects and fungi including the European cabbage butterfly (*Pieris rapae*), *Pieris brassicae*, leaf minors, aphids, leaf hoppers, and flea beetles. Grasshoppers predated on garlic mustard plants in several locations in Illinois in 1990 (Nuzzo personal observation). Garlic mustard is a host plant for at least five mosaic or ringspot viruses in Europe and Ontario (Cavers *et al.* 1979).

Methods to effectively control garlic mustard have not been investigated. Garlic mustard appeared to decrease in abundance following prescribed fire in oak woodlands (Nuzzo personal observation, Steve Packard personal communication), and to be killed by herbicide application (John Schwegman personal communication). This study was undertaken to determine if garlic mustard could be controlled in a densely infested stand by 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 and/or survival.

METHODS

Study Site

Research was conducted in northern Illinois in Camp Medill McCormick (Ogle County, T25N R11E 4PM). This 180 hectare forested site borders the Rock River in the Freeport Section of the Rock River Hill Country Natural Division of Illinois (Schwegman 1984). A 2 hectare section of upland forest was selected for this study based on homogeneity of vegetation and garlic mustard distribution. The study area is located on rolling topography between 850 and 860 feet elevation msl. 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. Associates include white ash (*Fraxinus americana*), slippery elm (*Ulmus rubra*), hackberry (*Celtis occidentalis*) and black cherry (*Prunus serotina*). Natural composition has been substantially altered since settlement by logging, grazing and fire suppression. At the time this study was initiated, extensive browsing by white tail deer (*Odocoileus virginicus*) had produced an unnaturally open understory with 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

Prescribed fire was applied in 1988 and 1989 to six $50m^2$ plots, herbicide was applied in 1988 and 1989 to eight 4m x 50m plots, and cutting treatment was applied in 1989 to 50 plants in each of four plots. Each treatment type had a control, and plots were randomly assigned to receive treatments or control. Adult (rosette) density was recorded by $0.5m^2$, and seedling frequency by square decimeter, within twenty $0.5m^2$ quadrats along stratified random transects. Seedling density was so high (approximately $20,000/m^2$) that only frequency was recorded.

Fire Treatments

The six fire treatments (Table 1) consisted of four single burns conducted in spring or fall (4 plots), and two repeated burns (2 plots). Fires were conducted in April and November 1988, and early April 1989 during the most favorable burn conditions. Fires were of mid intensity (flame length up to 6" and burned through most of the plot) or low intensity (flame length up to 1", fire frequently extinguished within the plot).

Data were collected along two 25m parallel transects 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. Density data were collected in November 1989 and again in June 1990 in the control and one treatment plot to assess overwinter mortality.

Herbicide Treatments

The eight herbicide 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).

Pre-treatment data were collected along one 50m transect 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 June 1990. Additional data were collected in selected plots before and after treatments in spring or fall 1988 and 1989, and density data were collected in the control and two plots in November 1989 and June 1990.

Cutting Treatments

Two replicates of three plots each were randomly established May 25 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 but approximated 1.0-1.5 m^2 each. Plots within each replicate were randomly assigned to control or one of two treatments: cutting flowering stems at ground level, and at 10 cm above ground level.

Individual plants were marked, and stem height and number of stems/plant were recorded immediately prior to cutting. Post-treatment data were collected August 25 1989 and consisted of mortality, stem height, number of stems/plant, number of siliques/plant, and number of seeds/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

Density and frequency values were tested for similarity between plots within each treatment type before and after all treatments. The impact of treatment over time was not tested for all treatments, as seedling frequency in one year could not be directly compared to either frequency or density the following year, and rosette density in one year was independent of density of a different generation the following year. 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. In addition, in 5 plots the same generation of rosettes was counted before and after winter to assess overwinter mortality.

Mean density and frequency values were computed for all plots within each treatment. All frequency values were arc-sine transformed prior to testing. Homogeneity of variances among plots was tested by Cochran's C test. Values greater than 0.05 were assumed to indicate adequate homogeneity, and one-way analysis of variance (ANOVA) was then used to test for mean differences. C values lower than 0.05 were obtained for the majority of plot data, reflecting the high variability in both mean density and mean frequency within individual plots, and the non-parametric Kruskal-Wallace test was therefore used to test for mean differences in rosette densities and seedling frequencies among plots. When differences were detected, least significant difference (LSD) multiple range tests were conducted to indicate which plots were similar or dissimilar.

Within selected plots, changes in rosette densities and seedling frequencies following treatments were tested by paired t-tests.

Rosette densities in five plots were tested for similarity before and after winter by the Kruskal-Wallace test. Within individual plots, changes in rosette density resulting from overwinter mortality, with or without herbicide treatment, were tested by paired t-tests.

Data Analysis: cutting treatment

Pre-treatment homogeneity of stem heights and numbers of stems/plant among plots was 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/plant, and number of seeds/silique were analyzed by independent t-tests between control and the 10 cm cut (lack of survival in the groundlevel cuts limited further comparisons).

Statistical analysis used Systat and Statgraphic software on an IBM compatible PC.

RESULTS

Fire

In 1987, garlic mustard occurred at similar low rosette densities ($X=0.26 \pm 0.5/m^2$) and high seedling frequencies ($X=97.8\% \pm 1.2\%$) in all plots (n=140). The lowest recorded seedling frequency within a quadrat was 72%; all frequencies less than 90%, and one third of frequencies between 90 and 100%, resulted from the presence of a tree, newly fallen log or deer trail within the quadrat.

In 1988, mean rosette density increased over 16,000 percent to 39.4 ± 5.6 rosettes/m^2 before fires were conducted. Densities were similar in all plots (F=.471, df=99, P=0.7568).

Following burns in 1988 and 1989, mean densities in the four mid-intensity burn plots in 1989 ranged from 2.8/m^2 to 8.6/m^2, 34% to 78% lower respectively than the 13.0/m^2 in the control in 1989 (Figure 2). Similar reductions in rosette density were achieved with mid-intensity spring and fall fires. The mean densities in the mid-intensity fire plots, as compared to the control and low-intensity fire plots, were significantly different when tested by the non-parametric Kruskal-Wallis test (X^2=19.4591, df=6, P=0.003). When tested by one-way ANOVA the probability of no differences among means was only 0.1301 (F=1.682 df=139, P=0.130).

The difference between mid- and low-intensity fire impacts was apparent when individual plots were assessed for pre- and post-fire density (Table 2). In 1988, mean rosette density decreased significantly in one plot from 35.0/m^2 to 17.8/m^2 following a mid-intensity spring fire (T=3.177, df=19, P=.005), while in the same time period mean rosette density in a different plot increased nonsignificantly from 37.6/m^2 to 53.9/m^2 following a low-intensity spring fire (T=1.631, df=19, P=0.119). No significant difference was detected between mean densities before and after a low-intensity fire in the same plot in 1989.

In 1989, mean seedling frequency was significantly lower in plots that received mid-intensity spring fire than in the control plot, or in plots that received low-intensity fires or were burned in the fall (X^2=52.7308, df=139, P=0.0000: Figure 3). Burning in spring reduced the seedling population to the point that noticeably fewer rosettes were present the following spring: After the mid-intensity 1988 spring fire, 1989 rosette density was 78% lower than in the control.

In 1990, one year after all fire treatments, seedling frequency was significantly lower in plots that received 1988 mid-intensity spring fires than in the control or other fire plots (X^2=59.6606, df=139, P=0.0000). The mid-intensity 1988 spring fires significantly reduced rosette density and therefore seed production in that year, resulting in the lowered seedling frequency in 1990.

Rosette densities in 1990 ranged from a mean of 31.9/m^2 to 67.7/m^2. Although the densities were significantly different among plots in 1990 (X^2=14.2929, df=139, P=0.0462), there was no observable relationship between density in 1990 and fire activity in 1988 or 1989. Overwinter mortality does not appear to be a factor in the differential rosette density (refer to following section).

Herbicide

Prior to treatment in 1988, mean rosette density ranged from 21.4/m^2 to 71.6/m^2, with 29.0/m^2 in the control. Densities in two plots were much higher than, and differed significantly from, the control and 3 other plots (X^2=130.9094, df=119, P=0.0000). The higher density plots were accepted as treatment plots.

In 1989, mean rosette density in the control plot was 13.1/m^2. All plots that received herbicide had lower densities than the control. In four plots these differences were significant, and densities averaged 0/m^2 to 1.9/m^2, 85% to 100% lower than the control (X^2=61.8748, df=119, P=0.0000: Figure 4).

Seedling frequency in 1989 was significantly lower in plots that received herbicide in spring 1989 than in the control or in plots treated in 1988 (X^2=90.7072, df=119, P=0.0000: Figure 5).

The impact of spring glyphosate application on rosette density and seedling frequency is apparent when individual plots are assessed for pre- and post-herbicide values (Table 3). A plot that received herbicide in spring 1988 exhibited a 91% reduction in rosette density two months after treatment, while a plot treated in 1989 exhibited a 100% reduction in density. In two plots seedling frequency decreased 56% and 60% following spring application of glyphosate in 1989.

In 1990 mean density in the control plot was 38.2/m^2. All plots that received herbicide in 1989 had significantly lower rosette densities (2.1/m^2 to 9.9/m^2) in 1990 than the control (X^2=138.108, df=179, P=0.0000). Plots that received 1988 herbicide treatment had rosette densities similar to or greater than the control in 1990 (41.5/m^2 to 85.6/m^2).

Seedling frequency in 1990 was significantly different among plots (F=33.710, df=179, P=0.0000). Two of the three plots that received herbicide in spring 1988 had low seedling frequency in 1990 (11% and 15.2%), while in the third plot seedling frequency was 66.2%, comparable to the 57.6% in the control plot.

Overwinter Mortality

Mean rosette densities in November 1989 in 4 plots (two control plots, a 1988 low-intensity spring fire plot and an untreated herbicide plot), ranged from 151.7/m^2 to 205.8/m^2 (n=20 per plot). Natural overwinter mortality in the first three plots averaged approximately 80%, with mean densities in spring ranging from 36.7/m^2 to 41.8/m^2. The fourth plot, treated with glyphosate after the fall density count, exhibited a 96.7% overwinter mortality rate (169.2/m^2 in November 1989, and 5.6/m^2 in May 1990). A fifth plot, treated with glyphosate in spring 1989 before the density count and retreated in November after the density count, exhibited a 65.6% overwinter mortality rate (6.1/m^2 in November 1989 and 2.1/m^2 in May 1990).

Cutting

Stem height (X=68.8 cm $\pm$ 22.4) and number of stems/plant (X=1.2 $\pm$ 0.5) were similar among all plots prior to cutting (Table 4). 86.7% of the 300 plants had single stems, 9% had 2 stems, 4% had 3 stems and 0.3% had 4 stems.

Cutting flowering stems significantly reduced survival, stem height, and total seed production (Table 5). Plants cut at groundlevel 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 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 226.1 seeds, and all plants combined produced approximately 21,250 seeds. Cutting plants at 10 cm reduced individual seed production 93.4% to 14.5 seeds/plant and reduced total seed production 98% to 420 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

Fire

Fires were very difficult to conduct in all seasons due to low fuel availability and the abundance of green garlic mustard plants, which on occasion literally extinguished fires. Oak leaves that provided some fuel in the late fall blew away or were 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. These poor burning conditions are characteristic of sites with abundant garlic mustard.

The effectiveness of prescribed fire in reducing garlic mustard presence was directly related to burn intensity; low-intensity burns had no effect on rosettes or seedlings, and mid-intensity fires reduced garlic mustard density by 34% to 78%. Although not statistically different, spring fires appeared to decrease rosette density more than the fall fire, despite the greater fuel availability in fall. Higher intensity ground fires, if attainable in stands with sufficient fuel, would potentially burn through the entire stand and produce greater reductions in rosette density.

Mid-intensity spring fires had the added benefit of reducing seedling frequency because the fires were conducted during the period of seed germination. Although parts of the forest floor appeared devoid of seedlings immediately after moderate spring fires, seeds continued to germinate. Seedling frequency in the plot with a 1989 mid-intensity spring fire had 66.4% seedling frequency 6 weeks after burning, compared to 97% in the control. Burning later in spring would produce a greater reduction of seedlings, but by that time the extensive carpet of green seedlings and the low fuel availability effectively extinguish fires. Fall burns had no effect on seedling frequency.

The greatest fire-effected reduction in rosette density was attained by a mid-intensity spring fire conducted in 1988. This fire substantially reduced the seedling population in 1988, and relatively few seedlings survived to overwinter as rosettes and be recorded in 1989. The reduction in rosette density in the year of treatment lowered overall seed production, evidenced by the significantly lower seedling frequency in 1990 in plots that received a 1988 mid-intensity spring fire (seeds produced in 1988 germinated in 1990).

The two plots that received repeated fires exhibited similar reductions in rosette density. Both plots were burned in spring 1988: the second fire in each plot impacted the same generation of adults, in fall 1988 in one plot and spring 1989 in the other plot. These results support the finding that spring and fall fires were similarly effective in reducing rosette density.

Herbicide

All herbicide treatments reduced garlic mustard rosette density. Plants that were not directly killed by glyphosate were usually deformed and produced few flowers or siliques. Although there was no significant difference between treatments, spring application appeared more effective than fall application, possibly due to the physiological condition of the plants (actively growing in spring, versus semi-dormant in fall) and/or to the abundance of oak leaves that covered rosettes in the fall and intercepted the herbicide. By spring the leaves had blown away or been compressed, exposing the rosettes.

Differences in post-treatment rosette density between fire and herbicide treated plots probably reflect the degree of treatment coverage. Glyphosate was applied evenly within a relatively small area; fire burned patchily through a much larger area resulting in untreated sections within each plot.

Seedling frequency was significantly reduced in the year of treatment when plots were treated in spring with either glyphosate or fire. The difference in seedling reduction--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 concluded by the latter date), or fire may have stimulated germination from a seedbank.

As was observed in the fire treatments, the reduction of seedling frequency in the year of treatment resulted in fewer adults the following year. While both glyphosate and fire reduced density the year after treatment, herbicide consistently produced a greater reduction.

Seedling frequency two years after herbicide treatment was significantly lower in two plots, and approximately equal in a third plot, when compared to the control. The 1988 spring herbicide significantly reduced rosette density, and is assumed to have also reduced seed production. However, seed production by adjacent untreated plants was not affected, and seeds from these plants potentially fell in the treatment areas, obscuring the carryover effect of spring herbicide treatment. The apparent difference in 1990 seedling frequency between fire and herbicide plots two years after treatment is interpreted as a result of plot size, and not a differential response to treatment. The large fire plots presumably experienced lower immigration of seeds than the narrow herbicide plots.

In 1990, one and two years after all fire treatments, mean rosette densities ranged from approximately equal to more than double that of the control ($31.7/m^2$ - $67.6/m^2$, versus $36.7/m^2$ in the control). Similarly, 1990 rosette densities in plots treated with herbicide in 1988 also ranged from approximately equal to more than double that of the control ($41.5/m^2$ - $79.8/m^2$, versus $38.2/m^2$ in the control). No direct relationship between 1990 density and prior fire treatment or 1988 herbicide treatment was detected, and the variability may be a result of variable seedbank contribution, or other natural variability. Rosette densities in 1988, prior to all experimental treatments, were also very heterogenous (mean densities ranged from $21.4/m^2$ to $71.6/m^2$ in all plots), and the observed variability may reflect natural fluctuation through space in rosette density.

Overwinter mortality reduced rosette density by approximately 80%. Fall glyphosate treatment compounded natural mortality; in a fall-treated plot, less than 4% of the rosettes present in November 1989 survived to produce flowers in May 1990. When compared to the control, the effective reduction in rosette density with fall application of glyphosate was approximately 85%, independent of overwinter mortality. A similar reduction was recorded in the prior year.

Cutting

Plants that were cut at ground level contributed virtually no seeds to the seedbank. While only 71% of the plants cut at 10 cm died, the surviving plants produced fewer seeds than uncut plants and total seed production was reduced by 98%.

Cutting killed adult plants and decreased seed production. However, unlike fire and herbicide treatments, cutting did not affect the seedling population or the next year's rosettes. It is not known whether the cut flower stems produced viable seed, an effect demonstrated in teasel (*Dipsacus laciniatus*), an invasive European herb (Solecki 1989), and other herbaceous species (Gill 1938).

Conclusions

The results of this study indicate that:

1. Mid-intensity spring fires decreased garlic mustard rosette density and seedling frequency, and mid-intensity fall fires decreased rosette density only.
2. Similarly, spring application of a 3% v:v glyphosate solution decreased both rosette density and seedling frequency, while

fall application decreased only rosette density.

3. Cutting plants decreased rosette density and reduced seed production, but did not affect seedling abundance.
4. Treating garlic mustard in the spring with either fire or glyphosate had a carryover effect, resulting in fewer adults in the year after treatment, and fewer seedlings two years after treatment. Cutting did not reduce adult density the year after treatment.
5. Neither fire nor herbicide completely eliminated garlic mustard from the study plots in a single treatment; seedlings germinated from the seedbank following treatment in the same or succeeding year. Similar germination would be expected to occur in the spring following cutting.

MANAGEMENT RECOMMENDATIONS

All methods that remove adult rosettes apparently kill the plant and prevent seed production. Seeds germinate only in spring and treatments that affect seedlings (fire and glyphosate) decrease seedling frequency after spring treatment, which in turn reduces the number of adult plants present the following year. The degree of seedling control is related to the percent of germination that has occurred by the time of control. Generations overlap for two to three 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.

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 of this plant requires elimination of the seedbank by depleting existing reserves and preventing additional contributions to the seedbank. In this study plants produced an average of 225.9 seeds/plant (range 32-829), and grew at a mean density of $42.2/m^2$ (range $0\text{-}108/0.5m^2$). Thus, seed production per square meter averaged 9,533 seeds, and potentially ranged from 0 to 48,794. While these counts are considerably lower than reported by Trimbur (1973) and Cavers *et al.* (1979), and may reflect the small sample size in this study (n=96), they represent a substantial contribution to the seedbank.

Seeds produced in one year, such as 1989, will germinate 2 to 6 years later, from 1991 through 1995. The majority of germination will occur in 1991 and 1992, and a lower percentage of seeds will potentially germinate through 1995. Repeated applications of fire, herbicide or cutting will be required during this time period to prevent production and contribution of seeds to the seedbank. Additional research should be conducted to determine if different management activities will reduce seedbank longevity by either stimulating germination, or decreasing viability, of seeds in the seedbank.

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

Once garlic mustard is established in a community, the recommended management goal is to prevent seed production until the seedbank is exhausted, potentially a six 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 or biennial basis until garlic mustard is absent from the site for a minimum of three years.

In fire-adapted communities the recommended management is a mid- to high- intensity fire, conducted as late in the spring as feasible to reduce both rosettes and seedlings. In addition to directly reducing garlic mustard presence in upland forests, prescribed fire may indirectly limit garlic mustard by stimulating growth of native groundlayer species (White 1987) 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 by Round-up, otherwise as a dormant season application. Because seedling populations are affected only by the spring applications, 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 non-selective herbicide that affects all green vegetation: In diverse communities with early spring flora a dormant season spray may be less damaging to native groundlayer vegetation than a growing season application. A more detailed testing of different types and concentrations of herbicides would provide guidelines to effectively reduce garlic mustard presence with the least impact upon the groundlayer.

Appropriate management in areas with small infestations, or with species sensitive to dormant season spray, is to cut flowering stems at groundlevel 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 desireable herbaceous vegetation limits use of a weedeater when cutting close to the ground. Determining at which height to cut may be a balance between the amount of initial labor required to eliminate blooming plants (greater with groundlevel cutting) and the amount of labor required in future years due to reproduction from plants cut above groundlevel.

Pulling flowering plants would potentially have the same effect as cutting at ground level. When non-flowering plants are pulled, the degree of control is dependent upon removal of the root system; plants with intact roots frequently produce new shoots.

Garlic mustard is an invasive species; once removed from a site it is important to monitor annually for new invasions and to remove all plants observed prior to flower production.

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 savanna.

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LITERATURE CITED

Acker, L.L. M.S. Hodges, G.T. Keller, and R. Rehner. 1980. Soil survey of Ogle County, Illinois. Illinois Agricultural Experiment Station Report No. 113. USDA-Soil Conservation Service and Illinois Agricultural Experiment Station.

Bare, J.E. 1970. Wildflowers and weeds of Kansas. The Regents Press of Kansas. Lawrence KS.

Brown, M.L. and R.G. Brown. 1984. Herbaceous plants of Maryland. University of Maryland. College Park MD.

Byers, D.L. and J.A. Quinn. 1987. The effect of habitat variation in *Alliaria petiolata* on life history characteristics. Abs. American Journal of Botany 74:647.

Byers, D.L. and J.A. Quinn. 1988. Plant size as a factor in determining flowering time and reproductive output in *Alliaria petiolata*. Abs. American Journal of Botany 75:71.

Cavers, P.B., M.I. Heagy and R.F. Kokron. 1979. The biology of Canadian weeds. 35. *Alliaria petiolata* (M. Bieb.) Cavara and Grande. Canadian Journal of Plant Science 59:217-229.

Clapham, A.R., T.G. Tutin and E.F. Warburg. 1962. Flora of the British Isles. Cambridge University Press.

Gill, N.T. 1938. The viability of weed seeds at various stages of maturity. Annals of Applied Biology 25:447-456.

Gleason, H.A. 1963. The new Britton and Brown illustrated flora of the northeastern United States and adjacent Canada. Vol. 2. Hafner Publishing Co. NY, NY.

Gray, A., S. Watson and J.M. Coulter. 1889. Manual of the botany of the northern United States, including the district east of the Mississippi and north of North Carolina and Tennessee. American Book Co. NY, NY.

Grieve, M. 1959. A modern herbal. Volume 2. Hafner Publishing Co. NY, NY.

Henry, R.D. and A.R. Scott. 1981. Time of introduction of the alien component of the spontaneous Illinois vascular flora. American Midland Naturalist 106:313-317.

Hitchcock, and Cronquist. 1987. Flora of the Pacific Northwest. University of Washington Press. Seattle WA.

Jones, G.N., and G.D. Fuller. 1955. Vascular plants of Illinois. University of Illinois Press, Urbana IL.

Kinzel, W. 1926. Neue Tabellen zu Frost und Licht als beeinflussende Krafte bei der Samenkeimung. Stuttgart.

Lhotska, M. 1975. Notes on the ecology of germination of *Alliaria petiolata*. Folia Geobot. Phytotax. (Praha) 10:179-183.

McGregor. R.L., T.M. Barkley, R.E. Brooks and E.K. Schofield. 1977. Flora of the Great Plains. University Press of Kansas. KS.

Mitchell, R.S. 1986. A checklist of New York State plants. Bulletin No. 458. New York State Museum. University of the State of New York. Albany NY.

Mohlenbrock, R.H. and D.M. Ladd. 1978. Distribution of Illinois vascular plants. SIU press. Carbondale IL. 282 pp.

Patman, J.P. and H.H. Iltis. 1961. Preliminary reports on the flora of Wisconsin. No. 44 Cruciferae--mustard family. Wisconsin Academy of Science, Arts and Letters 50:17-72.

Radford, A.E., H.E. Ahles, and C.R. Bell. 1965. Atlas of the vascular flora of the Carolinas. Technical Bulletin No. 165. University of North Carolina. Chapel Hill NC.

Roberts, H.A. and J.E. Boddrell. 1983. Seed survival and periodicity of seedling emergence in eight species of Cruciferae. Annals Applied Biology 103:301-304.

Schwegman, J.E. 1984. Comprehensive plan for the Illinois Nature Preserves System, part 2, the natural divisions of Illinois. Illinois Nature Preserves Commission. Springfield IL.

Solecki, M.K. 1989. The viability of cut-leaved teasel (*Dipsacus laciniatus* L.) seed harvested from flowering stems: management implications. Natural Areas Journal 9(2):102-105.

Strausbaugh, P.D. and E.L. Core. 1953. Flora of West Virginia. Seneca Books, Inc. Grantsville WV.

Swink, F. and G. Wilhelm. 1979. Plants of the Chicago Region. The Morton Arboretum. Lisle IL. 922 pp.

Trimbur, T.J. 1973. An ecological life history of *Alliaria officinalis*, a deciduous forest "weed". M.S. thesis. Ohio State University. 56 pp.

Voss, E.G. 1985. Michigan flora part II. Cranbrook Institute of Science and University of Michigan Herbarium. Bulletin 55. Ann Arbor MI.

Wherry, E.T., J.M. Fogg, Jr., and H.A. Wahl. 1979. Atlas of the flora of Pennsylvania. Morris Arboretum. University of Pennsylvania. Philadelphia PA.

White, A.S. 1986. Prescribed burning for oak savanna restoration in central Minnesota. Research Paper NC-266. St. Paul MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

TABLE 1: Fire and herbicide treatments applied to garlic mustard (*Alliaria officinalis*) arranged by season and year of application.

	FIRE Low-intensity	FIRE Mid-intensity	HERBICIDE
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

TABLE 2: Garlic mustard (*Alliaria officinalis*) mean rosette density/m^2 in 3 plots (n=20 quadrats/treatment) before and after spring fire treatment. Data collected in April and June in the year of treatment. Standard deviations in parentheses. **=significant at 0.01 level, one-tail paired t-test (T=4.541)

TREATMENT	1988 <fire	1988 >fire	1989 <fire	1989 >fire
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)

TABLE 3: Garlic mustard (*Alliaria officinalis*) mean rosette density/m^2 (**bold**) and mean seedling frequency/m^2 (*italics*) in 3 plots (n=20 quadrats/treatment) before and after spring glyphosate treatment. Data collected in April and June in the year of treatment. Standard deviations in parentheses. * =significant at 0.05 level, one-tail paired t-test. ***=significant at 0.001 level, one-tail paired t-test.

TREATMENT	1988		1989	
	<herbicide	>herbicide	<herbicide	>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)	

TABLE 4: Garlic mustard (*Alliaria officinalis*) mean stem height and mean number of stems/plant in 6 plots (n=50 plants/plot) in a degraded dry-mesic upland forest in Ogle County Illinois, measured May 25 1989.

	Mean	S.D.	Range	F	DF	P
Stem Height (cm)	68.8	22.4	12-199	1.777	299	0.117
Stem Number/Plant	1.2	0.5	1-4	1.704	349	0.133

TABLE 5: Response of garlic mustard (*Alliaria officinalis*) to cutting of flowering stems at ground level and 10 cm above groundlevel: 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.

	Mortality[1]	Stem Height[2] (cm)	Siliques/ Plant[3]	Seeds/ Silique[4]	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***	---	---	---

*** = Significant at 0.001 level

[1] Mortality X^2=76.412, df= 2, P=0.000
[2] Stem height T=11.195, df=121, P=0.000
[3] Siliques/plant T= 5.630, df=121, P=0.000
[4] Seeds/silique T=12.769, df=115, P=0.000

FIGURE 1: Life cycle of garlic mustard (*Alliaria officinalis*): Germination occurs in spring, plants grow through the summer and overwinter as rosettes, surviving plants reproduce in summer, seeds enter seedbank and are dormant 20 to 80 months, then germinate in spring to repeat the cycle. The larger circle represents a three year period, the smaller circles represents continued seed dormancy.

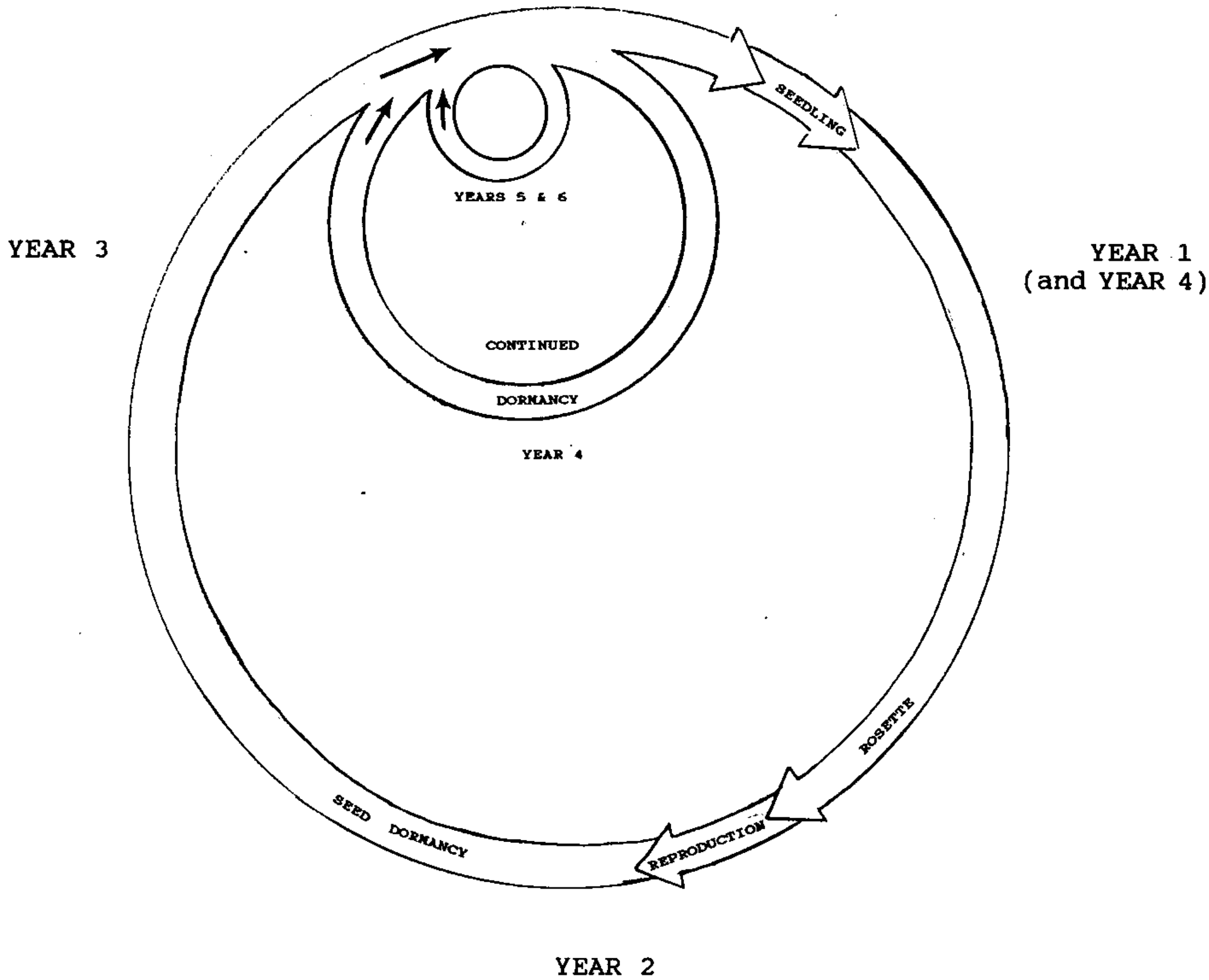


FIGURE 2: MEAN ROSETTE DENSITY/M² OF GARLIC MUSTARD (<u>Alliaria</u> <u>officinalis</u>) FOLLOWING SINGLE OR REPEATED FIRES: Date collected June 1989, fires conducted April 1988, November 1988, April 1989 (n=20 quadrats/treatment).

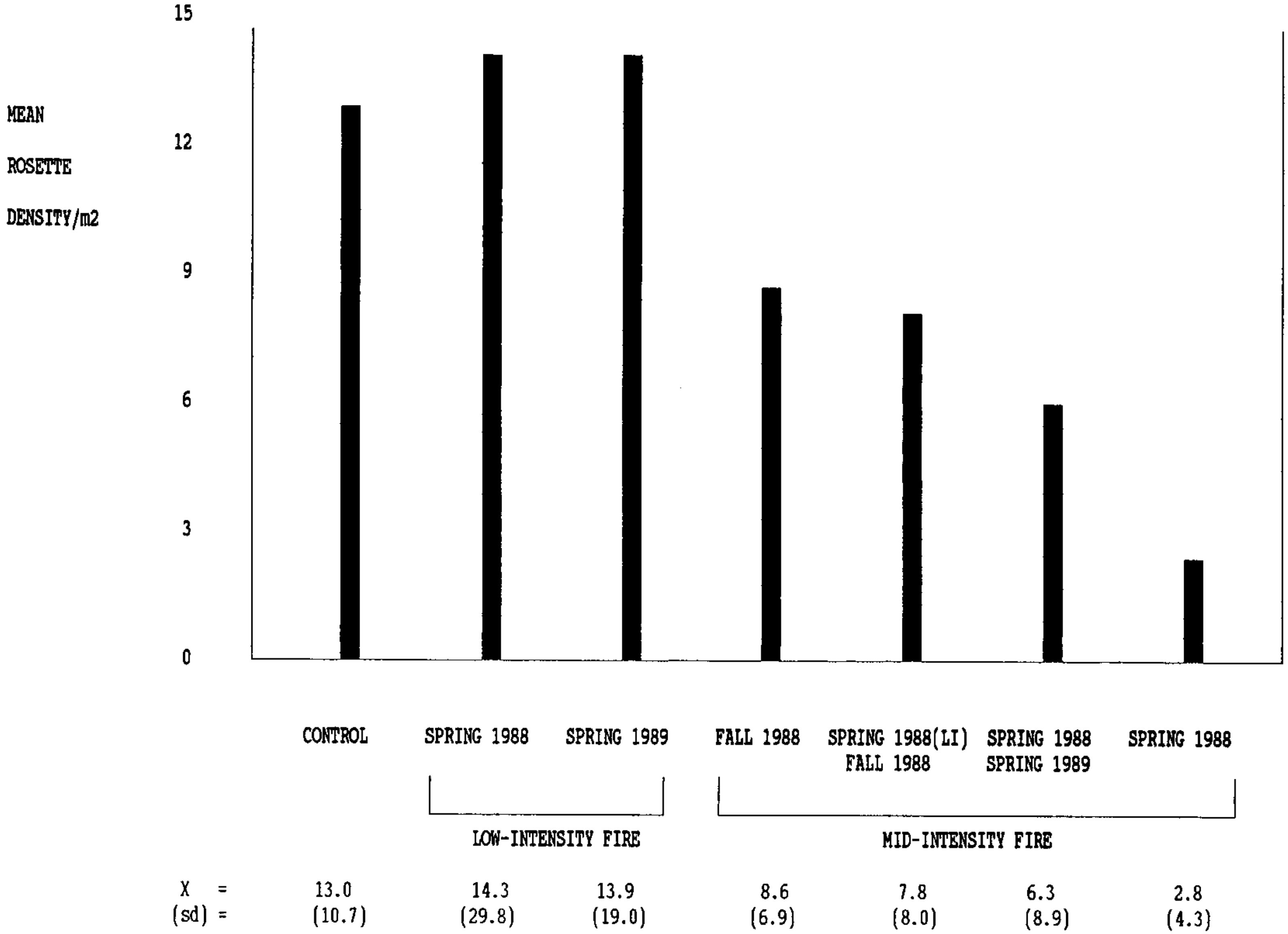
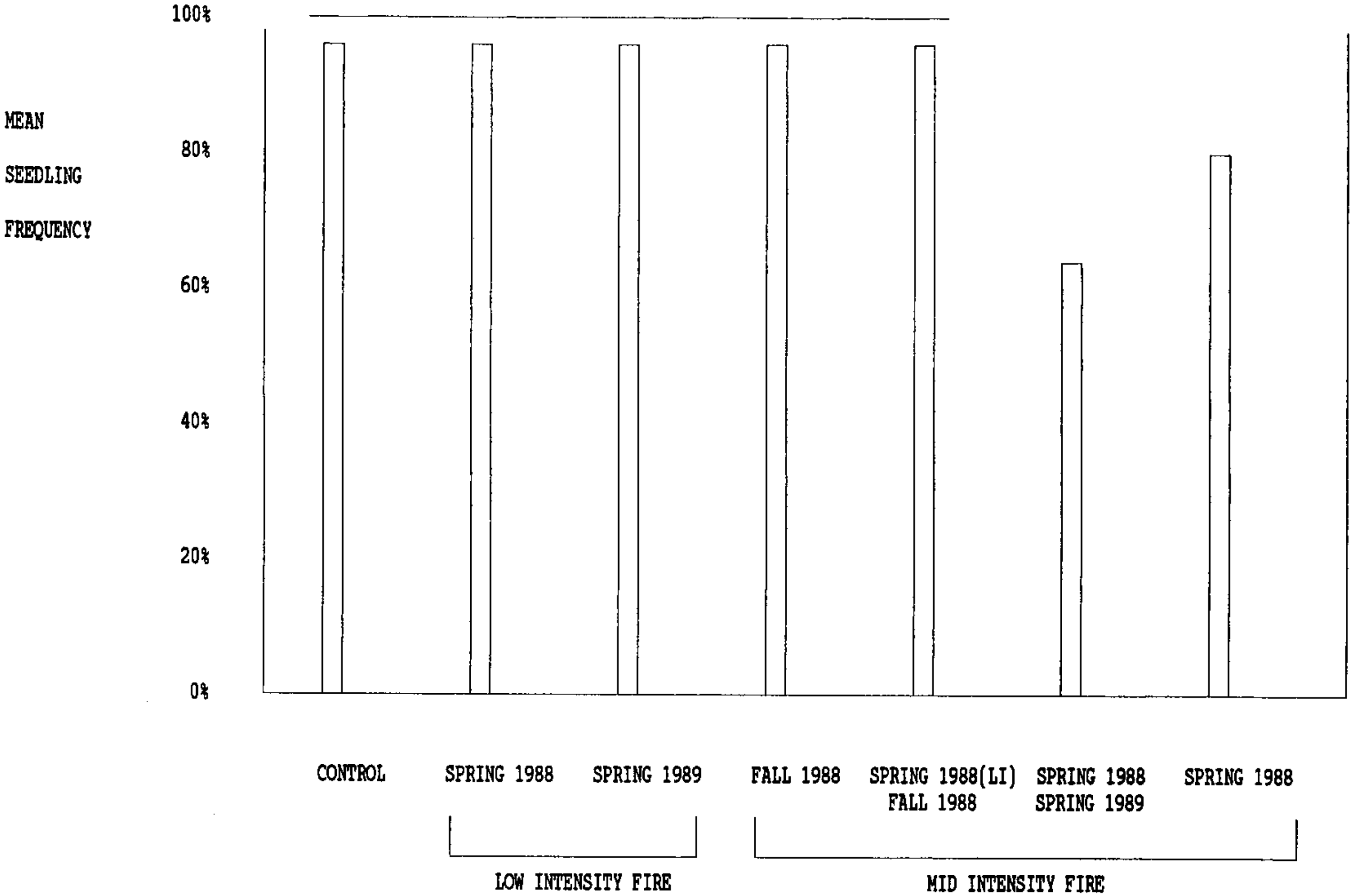
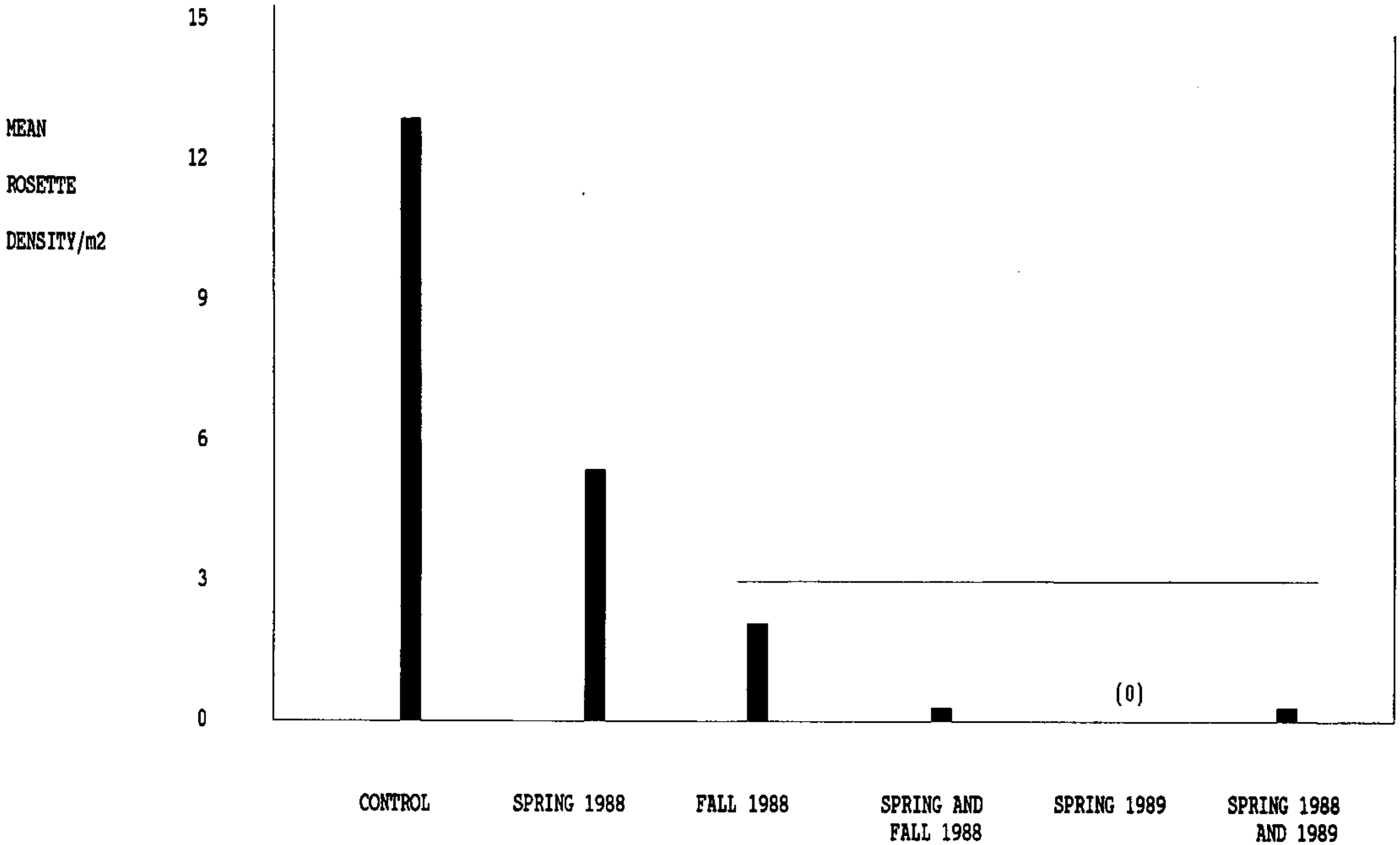


FIGURE 3: MEAN SEEDLING FREQUENCY OF GARLIC MUSTARD (<u>Alliaria officinalis</u>) FOLLOWING SINGLE OR REPEATED FIRES: Data collected June 1989, fires conducted April 1988, November 1988, April 1989 (n=20 quadrats/treatment). Treatments linked by a horizontal bar are not significantly different. Unlinked fire treatments are significantly different from each other and from the linked treatments, $P<0.05$.



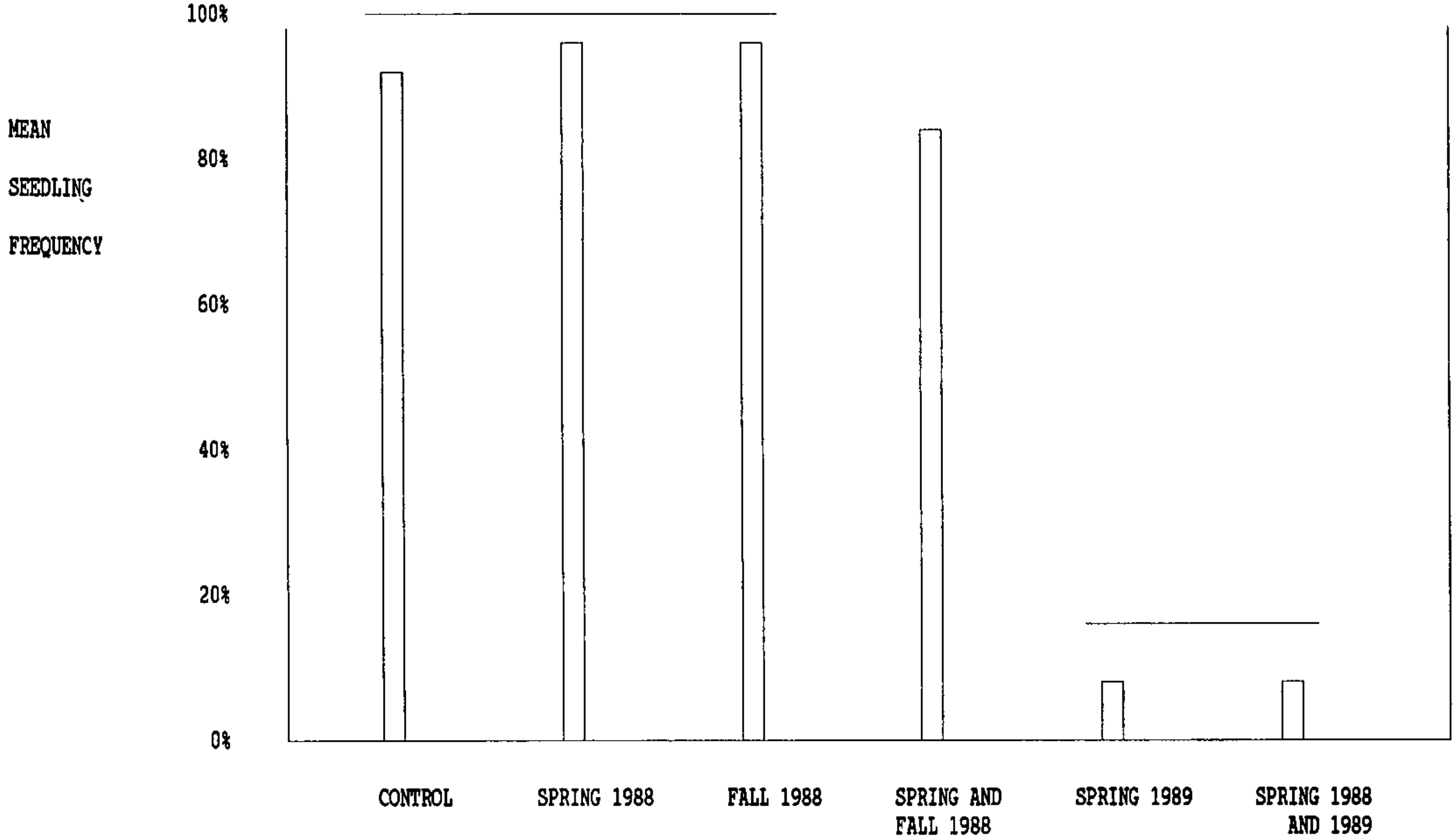
X =	97.1	96.0	97.4	98.3	96.1	66.3	80.4
(sd) =	(4.0)	(11.1)	(4.7)	(7.1)	(4.9)	(28.9)	(20.7)

FIGURE 4: MEAN ROSETTE DENSITY/M² OF GARLIC MUSTARD (Alliaria officinalis) FOLLOWING SINGLE AND REPEATED APPLICATIONS OF GLYPHOSATE: Date 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 treatment, $P<0.05$.



	CONTROL	SPRING 1988	FALL 1988	SPRING AND FALL 1988	SPRING 1989	SPRING 1988 AND 1989
X =	13.1	5.5	1.9	0.2	0.0	0.2
(sd) =	(11.2)	(6.3)	(3.1)	(0.6)		(0.6)

FIGURE 5: MEAN SEEDLING FREQUENCY OF GARLIC MUSTARD (Alliaria officinalis) 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, $P<0.05$.



	CONTROL	SPRING 1988	FALL 1988	SPRING AND FALL 1988	SPRING 1989	SPRING 1988 AND 1989
X =	92.6	96.1	97.7	83.4	13.8	14.4
(sd) =	(12.5)	(7.8)	(5.8)	(15.0)	(10.4)	(6.9)