Monitoring garlic mustard (*Alliaria petiolata*) in anticipation of future biocontrol release (2005-2009)

Report to the Legislative-Citizen Commission on Minnesota Resources

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Executive Summary

Garlic mustard (*Alliaria petiolata* (Bieb.) Cavara & Grande) is a biennial forb that has become invasive in forests in Minnesota and much of the United States. Garlic mustard has been found to negatively impact native biota in the areas it invades. Three species of *Ceutorhynchus* weevils native to Europe are being studied to determine if they can be safe and effective biological control agents for garlic mustard. In 2005, a garlic mustard monitoring program was initiated in Minnesota. Permanent monitoring plots were established at 12 sites throughout Minnesota. One purpose of the program was to provide baseline data on garlic mustard populations which could then be compared with data collected after biological control agent release to determine the effectiveness of garlic mustard control and the response of the native plant community. Additionally, the monitoring program provides information on year to year changes in garlic mustard, the extent of herbivory on garlic mustard in Minnesota, and the relationship between garlic mustard and other plant species and ground cover. In addition to the standard monitoring protocol, data has been collected to better understand how the sites differ in their levels of shading and tree canopy species composition.

The garlic mustard monitoring data from 2005 to 2009 showed that garlic mustard populations can vary considerably from year to year. Multiple years of monitoring are necessary to characterize garlic mustard populations. About half of the sites demonstrate strong cycling in the dominance of one garlic mustard life stage over another. For example, in year one the site is dominated by the seedling (1^{st} year) stage of the garlic mustard, in the next year the adults (2^{nd} year plants) dominate and prevent the establishment of many seedlings. In the 3^{rd} year the site is dominated by seedlings again. These life stage fluctuations will be important to consider if biological control insects are released so that the insects and plants are matched at the correct life stages. Monitoring data has also shown that garlic mustard plants are occurring at high population densities (up to 133 adult plants m^{-2} and 720 seedlings m^{-2} mean densities). Garlic mustard monitoring sites also appear to be heavily impacted by nonnative earthworms as no site had a layer of leaf litter deeper than 2 cm in June 2009. Monitoring data also showed that garlic mustard is currently experiencing very little herbivory in Minnesota. The mean amount of leaf tissue removed due to insects was never over 3% in the 5 years of the study. Low herbivory indicates that garlic mustard is currently not heavily impacted by insects already present in Minnesota.

Site to site differences in garlic mustard populations may be due to a number of factors, such as light availability, tree species composition, land use history, high deer populations, soil properties, and other environmental factors. The amount of light available to plants in the understory of the forest has been found to be a strong driver of the growth of garlic mustard. Garlic mustard populations may differ across sites due to the amount of light they receive. Light availability in the form of photosynthetically active radiation (PAR) was characterized at each of the 12 sites. In general, the sites differed little in the amount of PAR available. When plant community differences are observed among the sites, it is likely that it is factors other than light availability which cause those differences. Tree species making up the canopy were surveyed at each site. The differences and similarities in tree species composition may aid in interpreting the varying population changes and impacts of garlic mustard among the sites.

Chapter 1

Population Biology of Garlic Mustard (*Alliaria petiolata*) in Minnesota Hardwood Forests

2005-2008

See attached journal article

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Chapter 2

Garlic Mustard (*Alliaria petiolata*) Monitoring in Minnesota: 2009 Update

INTRODUCTION

Garlic mustard (*Alliaria petiolata*) is a non-native, biennial, herbaceous plant that has become abundant in wooded areas in Minnesota and the eastern United States (Meekins et al. 2001; Rodgers et al. 2008). Garlic mustard can form dense cover on the forest floor and negatively impact native species (Nuzzo 1999; Blossey et al. 2001; Stinson et al. 2006). In order to better understand garlic mustard populations in Minnesota and to collect baseline data in the event of biological control insect release (Blossey et al 2001), a garlic mustard monitoring was initiated in Minnesota in 2005. The results of the monitoring data collected from 2005 to 2008 are presented in Van Riper et al. 2010. This chapter provides an update to Van Riper et al. 2010 by presenting the data gathered in 2009.

Garlic mustard and associated plant communities were monitored at deciduous forests sites in Minnesota. Garlic mustard populations can fluctuate dramatically from year to year (Meekins and McCarthy 2002; Winterer et al. 2005; Pardini et al. 2009). Multiple years of monitoring are necessary to produce baseline data on garlic mustard populations and to determine the impacts of biological control agents, should they be released (Blossey 1999). It is expected that releasing biological control agents would decrease the population density and cover of garlic mustard and reduce garlic mustard plant height and silique production (Blossey et al. 2001; Davis et al. 2006; Gerber et al. 2007a, b). In this study data were collected on garlic mustard population density, cover, height, and silique production so the current population could be characterized and comparisons could be made should biocontrol agents be released in the future. Additionally, data were collect on the current levels of insect herbivory garlic mustard experiences in Minnesota.

In addition to collecting data on garlic mustard, data were collected on the other species growing with garlic mustard. The relationship between garlic mustard and other species can then be examined. The species composition of the site also indicates how the site is likely to respond to the reduction of garlic mustard. If the site has few native species present, it may need additional restoration actions after garlic mustard is reduced to restore a native plant community.

The composition of the ground layer can impact garlic mustard and other native species. Invasive, nonnative earthworms have damaged many forests in Minnesota and caused large reductions in the depth of the layer of litter generally found in deciduous forests (Bohlen et al. 2004; Hale et al. 2005). Earthworm impacts can create environments that favor invasive species such as garlic mustard and negatively impact native species (Bartuszevige et al. 2007; Blossey et al. 2009). In this study, data were collected on depth of litter layer and ground cover composition to determine the status of the litter layer at the monitoring sites and its relationship with garlic mustard and other species.

Together, the data on garlic mustard populations, native and invasive species, herbivory, and litter depth provide a strong understanding of the current impact and population of dynamics of garlic mustard in Minnesota. These data can be compared with data collected after the release of biological control agents to determine if the agents are effective at reducing garlic mustard and whether the native plant species are able to increase after garlic mustard cover is reduced.

METHODS

Methods follow the standard protocol of the Ecology and Management of Invasive Plants Program developed in 2003 (available at http://www.invasive plants.net) and described in Van Riper et al. 2010. Data were collected from 12 sites throughout Minnesota (Table 1). Each site consisted of 20 permanent 1-m by 0.5-m monitoring plots. Data were collected on garlic mustard population density, estimated visual percent cover, and adult plant heights and numbers of siliques (seed pods). The presence of any type of insect damage was noted and the average amount of leaf removed due to insects was visually estimated for each plot. All other species in the plots were identified and their percent covers were visually estimated. The depth of the layer of leaf litter was measured for each plot. For each plot, the ground cover was visually estimated for the following categories: leaf litter, bare soil, woody debris, rocks. Statistical analyses were performed using Statistix 7 (2000).

Garlic mustard is a biennial plant and can have complicated population dynamics (Pardini et al. 2009). Data were collected on the various life stages of garlic mustard. A garlic mustard seed germinates early in the spring. By the fall monitoring period (October) the seedlings had grown into basal rosettes of leaves. The rosettes over-winter and in the following spring, they bolt to form adult plants. Adult plants flower in April-May. By June they have formed siliques which are counted in the monitoring protocol. Adult plants fully mature and drop seeds and senesce by late July to August. Therefore, in the June monitoring period both seedling and adult stages of garlic mustard are present, but in October only the rosette stage is present.

A few unexpected events occurred during the course of the study. On May 25, 2008 Warner Nature Center was hit by a tornado. A number of trees were knocked down in the area of the garlic mustard monitoring plots. This opened up the canopy to more light than the site had experienced in previous years. At the Luce Line Trail, garlic mustard plants in plots 1-10 and 16-20 were treated with 2% Roundup (glyphosate) herbicide on May 29-30, 2008. At Pine Bend Bluff SNA, in an effort to reduce the amount of *Rhamnus cathartica* L. (common buckthorn) and *Lonicera spp*. (nonnative honeysuckles), those trees were cut down in April 2009 in the area with garlic mustard monitoring plots 1-10 and 16-20. See chapter “Differences in available photosynthetically active radiation among garlic mustard monitoring sites” in this report for more information. The tree clearing resulted in a dramatic increase in light to the plots and a loss of some plots as they were covered in brush piles. Unforeseen events are to be expected in any long-term monitoring project. Having 12 monitoring sites helps dampen the impact of alterations to any 1 monitoring site. We are also able to continue to follow the monitoring sites after these changes and note the impacts on garlic mustard and other plant species.

RESULTS

Fluctuations in garlic mustard populations over time

Garlic mustard populations in Minnesota are highly variable from year to year (Van Riper et al. 2010). Garlic mustard population density in 2009 followed previous years in showing variability (Fig. 1). Warner Nature Center (WN) and Westwood Hills (WH) continued to show strong population cycling with the sites alternating between being dominated by the seedling/rosette 1st year life stage in one year and then dominated by the adult 2nd year life stage the next (Fig 1). Coon Rapids (CR), Cottage Grove (CG), Luce Line (LL), and Nerstrand (NE) had showed population cycling in the first three years of monitoring, but then the pattern became less pronounced. The 2009 data show CR, CG, and LL returning toward a cycling pattern (Fig. 1a), but at NE the pattern was less clear. At NE, rosette density tended to be decreasing, seedling density increasing, and adult density returning to cycling. Previously, the Willmar (WI) rosette population density was increasing each year, but in 2009 the rosette population density decreased (Fig. 1a). However, seedling and adult population densities increased indicating that the garlic mustard population is still increasing at this site (Fig. 1b, c). Pine Bend (PB) had been trending towards decreasing rosette populations, but 2009 saw an increase rosette population (Fig. 1a). The high seedling density and low adult density may indicate that this site is beginning to cycle (Fig. 1b, c). Fort Snelling (FS) and Hilloway Park (HP) had shown relatively stable rosette population densities, but both saw increases in seedling and rosette densities in 2009 while adult population density remained rather stable (Fig. 1). Baker Park (BP) and Plainview (PL) had shown variable rosette population density over time. In 2009, BP had similar seedling and rosette population densities to 2008, but had a marked decrease in adult population density (Fig 1). PL had similar rosette population densities to previous years, a slight increase in seedling population density, and a decrease in adult population density (Fig. 1).

The mean May 2009 to October 2009 mortality for garlic mustard seedlings to the rosette stage, averaged across all sites, was 80%. The mean October 2008 to May 2009 mortality for garlic mustard rosettes over-wintering to become adults, averaged across all sites, was 34%. In previous years, seedling to rosette mortality ranged from 47-77% and rosette to adult mortality ranged from 7-45% (Van Riper et al. 2010). The 2009 seedling to rosette mortality of 80% was similar to the 77% recorded in previous years. The 2009 rosette to adult mortality of 34% fell within the 7-45% range previously recorded. The total mortality from seedling stage in June to adult stage in June of the next year was 89%, 62%, and 70% for 2008-2009, 2007-2008, and 2006-2007, respectively. There can be high mortality from the seedling to adult stage.

The mean total garlic mustard percent cover (seedling cover + adult cover) in the spring of 2009 ranged from 8% cover at LL to 61% cover at WI (Fig. 2). The rosette percent cover in the fall of 2009 ranged from 1% cover at NE to 21% cover at FS (Fig. 2). In the spring, WI, WN, FS, WH, and HP clustered together with total garlic mustard covers ranging from 42-61% (Fig. 2). PL, CR, BP, NE, CG, PB, and LL clustered together with total garlic mustard cover ranging from 8-22% (Fig. 2). Ranges of garlic mustard percent cover in the spring and fall of 2009 were similar to those observed in 2005-2008.

The spring 2008 herbicide treatment at LL appeared to have an impact on garlic mustard cover, but little impact on garlic mustard population density. Data were collected in June 2008 before the herbicide had killed the plants. All data after June 2008 reflect the aftermath of the herbicide treatment. It would be expected that the herbicide treatment would cause a reduction in the rosettes in 2008 and the adults in 2009. However, the population density for rosettes at LL in 2008 was the highest recorded for LL (55 rosettes m^{-2}, Fig. 1a). Adult garlic mustard population density at LL in 2009 was low (10 adults m^{-2}), but the same as that recorded in 2007 (Fig. 1c). The population density data appeared to be following a population cycling pattern with little impact from the herbicide. However, garlic mustard percent cover at LL did decrease after the herbicide treatment. Total (adult + seedling) garlic mustard percent cover in the spring went from 44% in 2006 to 18% in 2007 to 40% in 2008 to 8% in 2009 (Fig. 2). This follows a pattern of population cycling, although the 8% cover in 2009 is the lowest recorded. Fall rosette percent cover did not cycle so strongly, ranging from 3% in 2006 to 7% in 2007 to 9% in 2008 to 3% in 2009 (Fig. 2). While garlic mustard percent cover was somewhat reduced after the herbicide treatment, the cover of garlic mustard was still similar to values recorded in previous years.

Fluctuations in garlic mustard plant height and reproductive output

It is anticipated that biological control agents, if released, would cause a decrease in mean adult garlic mustard stem height (Gerber et al. 2007a, b). Mean garlic mustard stem heights were determined for each site for 2005-2009 (Fig. 3). Mean stem heights ranged from a low of 17 cm tall at LL and BP to a high of 63 cm tall at NE. Mean stem heights vary considerably from year to year (Fig. 3) and variations do not appear to relate to which life stage is dominant at a given site. For example, WN and WH show strong cycling of life stages, but adult plant heights do not cycle. Abiotic factors may have a strong impact on mean adult stem height.

In plots that had garlic mustard present, the mean number of siliques present per m^2 was determined (Fig. 4a). This gives an indication of the seed rain density experienced in these plots. In 2009, the mean number of siliques per m^2 ranged from 8 siliques m^{-2} at CG to 348 siliques m^{-2} at WI. Studies have consistently shown that garlic mustard plants average been 14 and 16 seeds per silique (Nuzzo 1999; Susko and Lovett-Doust 1999; Evans and Landis 2007). This means that the plots with the highest density of siliques in 2009 could be producing from 4872 to 5568 seeds m^{-2}.

The mean number of siliques per stem indicates the fecundity of individual plants. It is expected that biological control agents will reduce the number of siliques per stem (Gerber et al. 2007a, b). In 2009, the mean number of siliques $stem^{-1}$ ranged from 1 silique $stem^{-1}$ at LL to 14 siliques $stem^{-1}$ at NE (Fig. 4b). While wide year to year variations in siliques $stem^{-1}$ were found at several sites (eg. WN and FS), other sites were more consistent in the number of siliques $stem^{-1}$ from year to year (eg. NE and PB) (Fig. 4b). The most fecund plant in 2009 was found at HP; it measured 112 cm tall and had 52 siliques. The tallest plant measured in 2009 was from WH and was 130 cm tall with 30 siliques.

To further characterize the fecundity of garlic mustard plants at the sites, the percent of stems without siliques present was calculated (the total number of sterile stems recorded at the site / total number of stems at the sites x 100%). It is anticipated that biological control agents, if released, will increase the percentage of garlic mustard plants without siliques. In previous years, at most sites, more than 95% of the adult stems produced siliques (Fig. 4c). A high percentage of stems without siliques were observed at HP in 2006 due to herbicide drift from early season *Rhamnus cathartica* control. In contrast with previous years, in 2009 there were a number of sites with more than 5% barren stems (Fig. 4c). CG, HP, PL, and WH had from 10-16% adult garlic mustard plants with barren stems. At LL 24% of adult stems (22 plants of 98) were barren. The herbicide applied to seedlings in May 2008 likely resulted in stunted adult plants in 2009 causing the increase in barren stems. BP also had a high percentage of barren stems (27%). It is unclear why the number was so high, but it should be noted that there were very few adult plants at BP, so the high percentage is the result of 6 barren plants out of 22 total adults recorded for the site in 2009).

Site species richness and species composition

Sites varied in their species richness. Species richness for each 0.5m^2 plot was determined and the mean species richness per plot was calculated for each site (Fig. 5). Species richness did not include garlic mustard, but did include native species, nonnative species, species that could not be identified, and moss. PB and WI were the most species rich sites, averaging 8 species per 0.5m^2 plot. FS and LL were the least species rich with between 1.1 and 2.5 species per 0.5m^2 plot. For most sites, mean species richness was very similar between June and October (Fig 5). At PL and CG, species richness decreased from June to October (5.1 to 2.6 and 5.1 to 3.5 species per 0.5m^2 plot, respectively). There was no correlation between total spring garlic mustard cover (adult + seedling) and richness or cover of other (non-garlic mustard) species (Pearson correlations, P=0.91, 0.81).

To characterize the species composition of the sites, lists were made of the 8 most frequent species to occur in the monitoring plots at the 12 sites (Tables 2, 3). Tree seedlings were a common component of the vegetation in the monitoring plots. The invasive tree species *R. cathartica* was one of the 8 most frequent species for 8 of the 12 sites (Table 2). It was the most frequently encountered species at FS, LL, and PB. NE, PL, WN, and WI had no nonnative species among their 8 most frequent species, while BP had 3, CR, FS, LL, and PB had 2, and CG, HP, and WH had 1. CR, FS, LL, and PB all had a nonnative species as their most frequent species. Species such as *Hydrophyllum virginianum, Sanguinaria canadensis*, *Desmodium glutinosum*, *Geranium maculatum*, *Osmorhiza claytonii*, *Ageratina altissimia* var. *altissima*, *Athyrium filix-femina*, and *Amphicarpaea bracteata* are important species that indicate mesic hardwood forest native plant communities (MN DNR 2005). Other common species in mesic hardwood forest and floodplain forest native plant communities include *Phryma leptostachya*, *Parthenocissus sp.*, *Circaea lutetiana*, *Laportea canadensis*, *Impatiens sp.*, and *Galium aparine* (MN DNR 2005). WN and WI each had 3 of the important native species in their top 8 most frequent list, indicating that they are higher quality sites than some of the others. CR, CG, NE, PB, PL, and WH all had one species from the important native species list in their most frequent species list. *G. aparine*, *C. lutetiana*, and

Parthenocissus vitacea were extremely common, occurring in the list of top 8 most frequent species lists for 10, 9, and 6 of the 12 sites, respectively. The species lists indicate that CG, NE, PL, WN, and WI tend to be the highest quality sites while the others are more degraded.

Garlic mustard and leaf litter

All sites had layers of leaf litter that were very low (Fig. 6a). Low depth of litter layer has been associated with invasion of non-native earthworms. In Minnesota, earthworm invasion has caused litter layers to decrease from 10 cm to 0 cm (Hale et al. 2005). In spring 2009, all monitoring sites had layers of leaf litter that were less than 2 cm deep (Fig. 6a). Litter depth was lowest at BP (0.20 cm) and PB (0.36 cm) and highest at CG (1.7cm). The low range of litter depths among the sites makes it difficult to examine the relationship between litter depth and garlic mustard cover and density.

To further characterize ground cover at the sites, the ground cover was visually estimated for each plot into the following categories: leaf litter, bare soil, woody debris, rocks. The ground cover at most sites in spring 2009 was composed mainly of leaf litter (Fig. 6b). With the exceptions of BP and PB, all other sites the ground was at least 60% covered by leaf litter. BP, which had the lowest depth of litter layer, had ground that was 20% covered by leaf litter and 65% composed of exposed bare soil. PB, which is on a steep slope, had ground that was 38% covered by leaf litter and 40% composed of exposed bare soil. High amounts of bare soil indicate disturbed sites which may especially favorable to garlic mustard instead of native species.

Depth of the litter layer and percent of bare soil did not relate to garlic mustard cover or the cover of other species at the site level. Linear regressions showed no significant relationship between spring 2009 depth of litter layer and total cover (adult + seedling) of garlic mustard (P=0.35) or 2009 percent bare soil and total cover of garlic mustard (P=0.15). Depth of litter layer and percent bare soil also did not relate to the percent cover of non-garlic mustard species found at the site (P=0.75, 0.82).

Garlic mustard herbivory levels

Garlic mustard herbivory in 2009 was similar to herbivory levels in 2005-2008 (Table 4). Edge feeding and holes in the leaves were present in almost all (89-97%) of the plots that contained garlic mustard in 2009 (Table 4). Leaf mining and windowpane feeding occurred in the spring, but they occurred in fewer than 8% of the plots with garlic mustard. Across all sites and plots in 2009, the mean amount of leaf removed due to insects was 1.4% in the spring and 2.4% in the fall. All insect herbivory data fell within the range of values seen in 2005-2008.

Plots at three of the sites (FS, NE, and WH) had garlic mustard plants with visible colonies of aphids at their apex (Fig. 6). Additionally, aphids were observed at CG and WN (pers. obs. and pers. comm. Laura Phillips-Mao). Plants with large quantities of aphids showed a twisted morphology in their siliques (Fig. 7). Across all sites, only 3% of plots with garlic mustard had aphids present. Aphids collected in Minnesota by Laura Phillips-Mao were identified by Doris Lagos of the University of Illinois as *Lipaphis brassicae* (pers. comm. Laura Phillips-Mao). Additional information is needed on the potential impacts of this aphid species on garlic mustard.

DISCUSSION

Garlic mustard populations at several of the sites continued to show strong cycling of life stages in 2009. Cycling continued to be strong at WN, WH, CR, CG, and LL. If biological control agents are released, extra care should be taken at the WN, WH, CR, CG, and LL sites to ensure the life stage of the insects match up with the dominant garlic mustard life stage at that time. Garlic mustard population density and percent cover in 2009 were generally similar to the ranges recorded in previous years. In 2009, WN, WH, WI, FS, HP and PL recorded their highest seedling population densities during the 5 year study. The variable nature of garlic mustard populations continues to reinforce the need for multi-year population monitoring (Blossey 1999; Pardini et al. 2009). If biological control agents are released, it will take several years to separate out normal population fluctuations from long-term change in garlic mustard population density and cover.

The year to year variations in garlic mustard height and silique production also indicate that it will take several years to determine if biological control agents are in fact causing a decrease in stem height and seed production. Mean garlic mustard stem heights tended to be shorter with fewer siliques in 2009. Many of the sites were in a year where the seedling stage was more abundant than the adult stage and this may account for the decreases in silique density and the increase in the percentage of plants with no siliques present. Abiotic factors can also play a role in the growth and reproductive success of garlic mustard plants in a given year (Susko and Lovett-Doust 1999; Hochstedler and Gorchov 2007).

Information on species richness, species composition, and litter depth at the sites helps predict which sites may need additional restoration efforts after garlic mustard cover is decreased and which are likely to have a stronger native plant community that may be able to recover on its own. Sites such as Cottage Grove, Nerstrand, Plainview, Warner Nature Center, and Willmar appear to have the strongest native species components of the monitoring sites. These sites may recover more easily than others if garlic mustard is reduced. Sites such as Baker Park, Fort Snelling, Hilloway Park, and Luce Line which have low species richness and few high quality native forest species will likely need additional restoration if garlic mustard cover is reduced. All sites are at risk for continued degradation due to their low depths of the litter layer which indicate that the sites are impacted by nonnative earthworms (Bohlen et al. 2004; Hale et al. 2005; Nuzzo et al. 2009).

Garlic mustard plants in Minnesota are currently experiencing little herbivory from insects already present in Minnesota. This indicates that the release of biological control insects could impact garlic mustard populations. Laboratory testing of potential biological control agents shows promise for these biological control agents to reduce garlic mustard populations (Davis et al. 2006; Gerber et al. 2007a, b).

LITERATURE CITED

Bartuszevige, A. M., R. L. Hrenko, and D. L. Gorchov. 2007. Effects of leaf litter on establishment, growth and survival of invasive plant seedlings in a deciduous forest. Am. Midl. Nat. 158:472-477.

Blossey, B. 1999. Before, during and after: the need for long-term monitoring in invasive plant species management. Biol. Invasions 1:301-311.

Blossey, B., V. A. Nuzzo, H. L. Hinz, and E. Gerber. 2001. Developing biological control of *Alliaria petiolata* (M. Bieb.) Cavara and Grande (garlic mustard). Nat. Areas J. 21:357-367.

Bohlen, P. J., P. M. Groffman, T. J. Fahey, M. C. Fisk, E. Suarez, D. M. Pelletier, and R. T. Fahey. 2004. Ecosystem consequences of exotic earthworm invasion of north temperate forests. Ecosystems 7:1-12.

Davis, A. S., D. A. Landis, V. A. Nuzzo, B. Blossey, E. Gerber, and H. L. Hinz. 2006. Demographic models inform selection of biocontrol agents for garlic mustard (*Alliaria petiolata*). Ecol. Appl. 16:2399-2410.

Evans, J. A., and D. A. Landis. 2007. Pre-release monitoring of *Alliaria petiolata* (garlic mustard) invasions and the impacts of extant natural enemies in southern Michigan forests. Biol. Control 42:300-307.

Gerber, E., H. L. Hinz, and B. Blossey. 2007a. Interaction of specialist root and shoot herbivores of *Alliaria petiolata* and their impact on plant performance and reproduction. Ecol. Entomol. 32:357-365.

Gerber, E., H. L. Hinz, and B. Blossey. 2007b. Impact of the belowground herbivore and potential biological control agent, *Ceutorhynchus scrobicollis*, on *Alliaria petiolata* performance. Biol. Control 42:355-364.

Hale, C. M., L. E. Frelich, and P. B. Reich. 2005. Exotic European earthworm invasion dynamics in northern hardwood forests of Minnesota, USA. Ecol. Appl. 15:848-860.

Hochstedler, W. W., and D. L. Gorchov. 2007. The effects of June precipitation on *Alliaria petioiata* (garlic mustard) growth, density and survival. Ohio J. Sci. 107:26-31.

Meekins, J. F., H. E. Ballard, and B. C. McCarthy. 2001. Genetic variation and molecular biogeography of a North American invasive plant species (*Alliaria petiolata*, Brassicaceae). Int. J. of Plant Sci. 162:161-169.

MN DNR (Minnesota Department of Natural Resources). 2005. Field guide to the native plant communities of Minnesota: the Eastern Broadleaf Forest Province. Ecological Land Classification Program, Minnesota County Biological Survey, and Natural Heritage and Nongame Research Program, Minnesota Department of Natural Resources, St. Paul, Minnesota.

Nuzzo, V. A. 1999. Invasion pattern of the herb garlic mustard (Alliaria petiolata) in high quality forests. Biol. Invasions 1:169-179.

Nuzzo, V. A., J. C. Maerz, and B. Blossey. 2009. Earthworm invasion as the driving force behind plant invasion and community change in northeastern North American forests. Conserv. Biol. 23:966-974

Pardini, E. A., J. M. Drake, J. M. Chase, and T. M. Knight. 2009. Complex population dynamics and control of the invasive biennial *Alliaria petiolata* (garlic mustard). Ecol. Appl. 19:387-397.

Rodgers, V. L., K. A. Stinson, and A. C. Finzi. 2008. Ready or not, garlic mustard is moving in: *Alliaria petiolata* as a member of eastern North American forests. BioScience 58:426-436.

Statistix 7. 2000. Statistix version 7.0. Tallahassee, FL: Analytical Software.

Stinson, K. A., S. A. Campbell, J. R. Powell, B. E. Wolfe, R. M. Callaway, G. C. Thelen, S. G. Hallett, D. Prati, and J. N. Klironomos. 2006. Invasive plant suppresses the growth of native tree seedlings by disrupting belowground mutualisms. PLoS Biol 4:e140.

Susko, D. J., and L. Lovett-Doust. 1999. Effects of resource availability, and fruit and ovule position on components of fecundity in *Alliaria petiolata* (Brassicaceae). New Phytol. 144:295-306.

Van Riper, L. C., R. L. Becker, L. C. Skinner. 2010. Population biology of garlic mustard (*Alliaria petiolata*) in Minnesota hardwood forests. Invasive Plant Sci. Manage. *In press.*

Winterer, J., M. C. Walsh, M. Poddar, J. W. Brennan, and S. M. Primak. 2005. Spatial and temporal segregation of juvenile and mature garlic mustard plants (*Alliaria petiolata*) in a Central Pennsylvania woodland. Am. Midl. Nat. 153:209-216.

TABLES

Table 1. Garlic mustard monitoring sites in Minnesota, USA. The ID column lists the abbreviation for that site as found in the figures (from Van Riper et al. 2010).

Site no.	ID	Site Name	City	County	Habitat type	Latitude Longitude
1	BP	Baker Park Preserve*	Maple Plain	Hennepin	Upland	45° 02.427’ 93° 37.195’
2	CR	Coon Rapids Dam Regional Park	Coon Rapids	Anoka	Floodplain	45° 07.975’ 93° 17.841’
3	CG	Cottage Grove Ravine Regional Park	Cottage Grove	Washington	Upland	44° 48.480’ 92° 53.960’
4	FS	Fort Snelling State Park*	Saint Paul	Ramsey	Floodplain	44° 52.373’ 93° 11.634’
5	HP	Hilloway Park	Minnetonka	Hennepin	Upland	44° 57.552’ 93° 26.098’
6	LL	Luce Line	Long Lake	Hennepin	Upland	44° 58.441’ 93° 35.137’
7	NE	Nerstrand State Park, Prairie Creek SNA*	Nerstrand	Rice	Upland	44° 21.527’ 93° 05.809’
8	PB	Pine Bend Bluffs SNA*	Inver Grove Heights	Dakota	Upland	44° 47.076’ 93° 01.732’
9	PL	Plainview – private land	Plainview	Winona	Upland	44° 06.600’ 92° 03.821’
10	WN	Warner Nature Center*	Marine on St. Croix	Washington	Upland	45° 10.853’ 92° 49.641’
11	WH	Westwood Hills Nature Center	St. Louis Park	Hennepin	Upland	44° 58.301’ 93° 23.692’
12	WI	Willmar - private land	Willmar	Kandiyohi	Upland	45° 19.356’ 94° 59.667’

*= one of five sites established in time for spring 2005 data collection

Table 2. Species composition of garlic mustard monitoring plots by site for June 2009. Species listed are the 8 most frequent species (occur in the most plots) for each site, listed in declining order of frequency, with the most frequent species at the top of the list. Tree species listed occurred as tree seedlings in the plots. Nomenclature follows the Integrated Taxonomic Information System (http://www.itis.gov) accessed 22 February 2010 (see Table 3 for authorities and common names).

Baker Park	**Coon Rapids**	**Cottage Grove**	**Fort Snelling**	**Hilloway Park**	**Luce Line**
Fraxinus pennsylvanica^T	*Gleochoma hederacea**	*Galium aparine*	*Rhamnus cathartica**^{T}	*Pinus strobus*^{T}	*Rhamnus cathartica**^{T}
Geum canadense	*Galium aparine*	*Circaea lutetiana*	*Circaea lutetiana*	*Galium aparine*	*Circaea lutetiana*
*Taraxacum officinale**	*Rhamnus cathartica**^{T}	*Osmorhiza claytonii*	*Partheno-cissus vitacea*	*Arisaema triphyllum*	*Geum canadense*
Galium aparine	*Laportea canadensis*	*Rhamnus cathartica**^{T}	*Impatiens sp.*	*Prunus serotina*^{T}	*Fraxinus pennsylvanica*^{T}
Solidago canadensis var. *scabra*	*Ageratina altissima* var. *altissima*	*Maianthemum canadense*	*Fraxinus pennsylvanica*^{T}	*Ulmus sp.* ^{T}	*Galium aparine*
*Rhamnus cathartica**^{T}	*Impatiens sp.*	*Ostrya virginiana*^{T}	*Solanum dulcamara**	*Rhamnus cathartica**^{T}	*Solanum dulcamara**
*Solanum dulcamara**	*Fraxinus pennsylvanica*^{T}	*Rubus sp.*	*Celtis occidentalis*^{T}	*Pilea pumila*	*Parthenocissus vitacea*
Partheno-cissus vitacea	*Geum canadense*	*Anemone quinquefolia*	*Teucrium canadense*	*Acer negundo*^{T}	*Ribes sp.*

Nerstrand	**Pine Bend**	**Plainview**	**Warner Nature**	**Westwood Hills**	**Willmar**
Galium aparine	*Rhamnus cathartica**^{T}	*Circaea lutetiana*	*Prunus serotina*^{T}	*Fraxinus pennsylvanica*^{T}	*Osmorhiza claytonii*
Laportea canadensis	*Ageratina altissima* var. *altissima*	*Ribes sp.*	*Circaea lutetiana*	*Circaea lutetiana*	*Galium aparine*
Viola sp.	*Circaea lutetiana*	*Parthenocissus vitacea*	*Rubus sp.*	*Amphicarpaea bracteata*	*Circaea lutetiana*
Circaea lutetiana	*Celtis occidentalis*^{T}	*Arisaema triphyllum*	*Amphicarpaea bracteata*	*Rhamnus cathartica**^{T}	*Hydrophyllum virginianum*
Carya cordiformis^T	*Prunus sp.* ^{T}	*Geum canadense*	*Desmodium glutinosum*	*Geum canadense*	*Phryma leptostachya*
Carex sp.	*Partheno-cissus vitacea*	*Athyrium filix-femina*	*Acer rubrum*^{T}	*Galium aparine*	*Sanguinaria canadensis*
Geranium maculatum	*Galium aparine*	*Rubus sp.*	*Athyrium filix-femina*	*Acer negundo*^{T}	*Uvularia perfoliata*
Geum canadense	*Leonurus cardiaca**	*Vitis riparia*	*Galium aparine*	*Solanum dulcamara*	*Fraxinus pennsylvanica*^{T}

* = nonnative (Nativity follows Minnesota Department of Natural Resources Vascular Plants of Minnesota -- September 25, 2002 (http://files.dnr.state.mn.us/eco/plant_list9-25-02.pdf) accessed 22 Feb 2010.)

^{T} = tree species

Table 3. List of the species from Table 2 with authority and common name. Nomenclature follows the Integrated Taxonomic Information System (http://www.itis.gov) accessed 22 February 2010.

Scientific name	**Authority**	**Common name**
Acer negundo	L.	box elder
Acer rubrum	L.	red maple
Ageratina altissima var. *altissima*	(L.) King & H.E. Robins.	white snakeroot
Amphicarpaea bracteata	(L.) Fern.	hog peanut
Anemone quinquefolia	L.	wood anemone
Arisaema triphyllum	(L.) Schott	jack-in-the-pulpit
Athyrium filix-femina	(L.) Roth	lady fern
Carex sp.	L.	sedge
Carya cordiformis	(Wangenh.) K. Koch	bitternut hickory
Celtis occidentalis	L.	hackberry
Circaea lutetiana	L.	common enchanter's nightshade
Desmodium glutinosum	(Muhl. ex Willd.) Wood	pointed-leaved tick trefoil
Fraxinus pennsylvanica	Marsh	green ash
Galium aparine	L.	cleavers
Geranium maculatum	L.	wild geranium
Geum canadense	Jacq.	white avens
Gleochoma hederacea	L.	creeping charlie
Hydrophyllum virginianum	L.	Virginia waterleaf
Impatiens sp.	L.	touch-me-not
Laportea canadensis	(L.) Weddell.	wood nettle
Leonurus cardiaca	L.	motherwort
Maianthemum canadense	Desf.	Canada mayflower
Osmorhiza claytonii	(Michx.) C.B. Clarke	Clayton's sweet cicely
Ostrya virginiana	(P. Mill.) K. Koch	ironwood
Parthenocissus vitacea	(Knerr.) A.S. Hitchc.	woodbine
Phryma leptostachya	L.	lopseed
Pilea pumila	(L.) Gray	clearweed
Pinus strobus	L.	white pine
Prunus serotina	Ehrh.	black cherry
Prunus sp.	L.	cherry
Rhamnus cathartica	L.	common buckthorn
Ribes sp.	L.	gooseberry
Rubus sp.	L.	blackberry
Sanguinaria canadensis	L.	bloodroot
Solanum dulcamara	L.	bittersweet nightshade
Solidago canadensis var. *scabra*	Torr. & Gray	Canada goldenrod
Taraxacum officinale	G.H. Weber ex Wiggers	dandelion
Teucrium canadense	L.	germander
Ulmus sp.	L.	elm
Uvularia perfoliata	L.	perfoliate bellwort
Viola sp.	L.	violet
Vitis riparia	Michx.	wild grape

Table 4. Garlic mustard presence and types of insect feeding at 12 sites in Minnesota, USA, 2005 to 2009 (modified from Van Riper et al. 2010). The percentage of plots with garlic mustard present out of the 20 plots at each of 12 study sites in Minnesota over 4 years are presented (5 study sites in spring 2005, 12 study sites for all other dates). Of the plots with garlic mustard present, the percentages of those plots with various types of visual leaf damage estimates are listed by the type of feeding damage.

	Plots with garlic mustard	Plots with feeding by this insect type (of plots with garlic mustard present)				
Time	mustard present	Edge feeding	Holes	Leaf miner	Windowpane feeding	Mean leaf removal
	----------------------------------	%	----------------------------------			
Spring 2005	100	96	98	31	4	1.6
Fall 2005	87	99	98	1	1	1.5
Spring 2006	98	96	97	31	9	1.5
Fall 2006	84	97	98	<1	<1	2.0
Spring 2007	99	100	100	33	0	1.8
Fall 2007	88	97	96	1	0	2.4
Spring 2008	99	100	98	12	4	2.3
Fall 2008	63	97	91	0	<1	3.0
Spring 2009	99	97	98	8	<1	1.4
Fall 2009	78	95	89	0	0	2.4

FIGURES

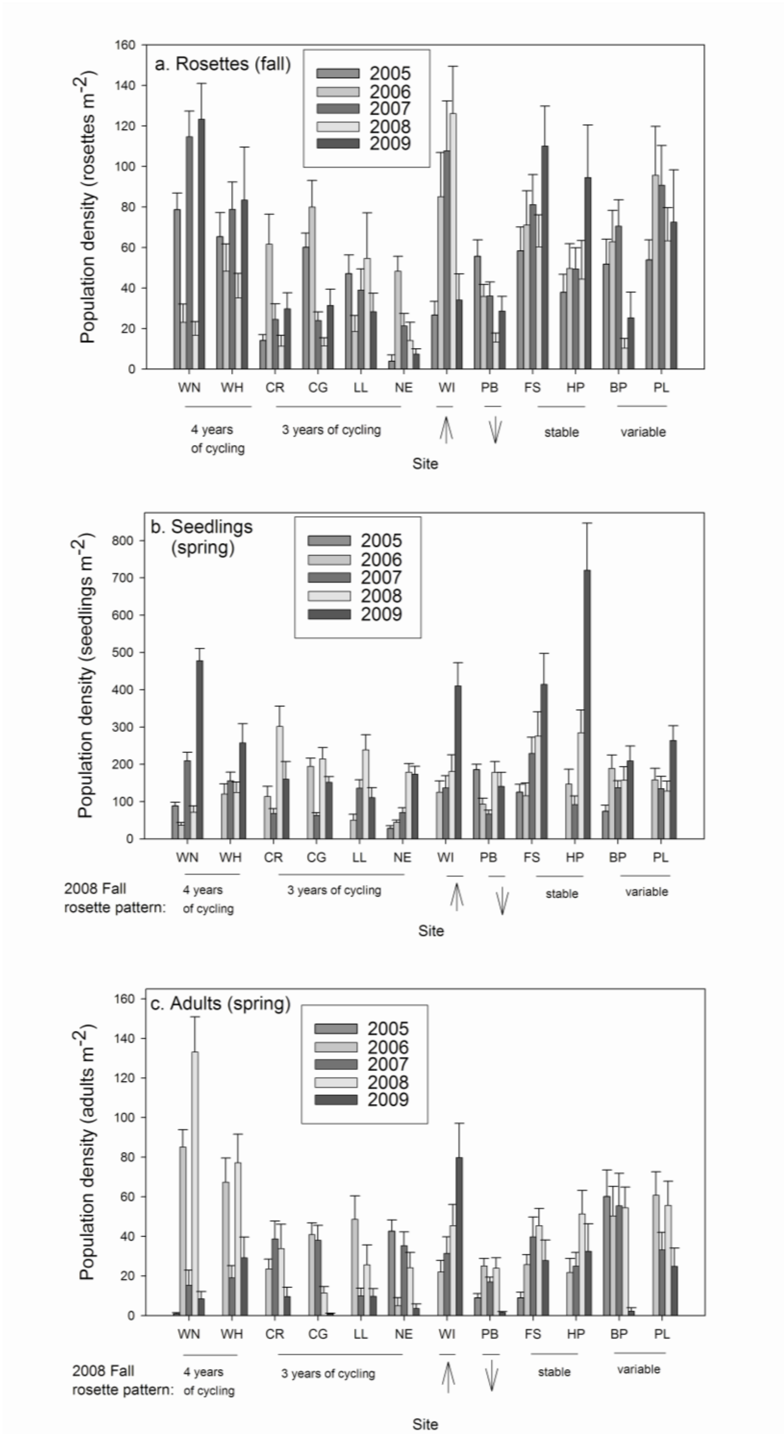


Figure 1. Mean garlic mustard population density (± SE) of rosettes (a), seedlings (b), and adults (c) from 2005-2009 at 12 garlic mustard monitoring sites in Minnesota. Plots are grouped according to the population cycling patterns they exhibited as of fall 2008 (as presented in Van Riper et al. 2010). Note that the y-axes vary.

BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

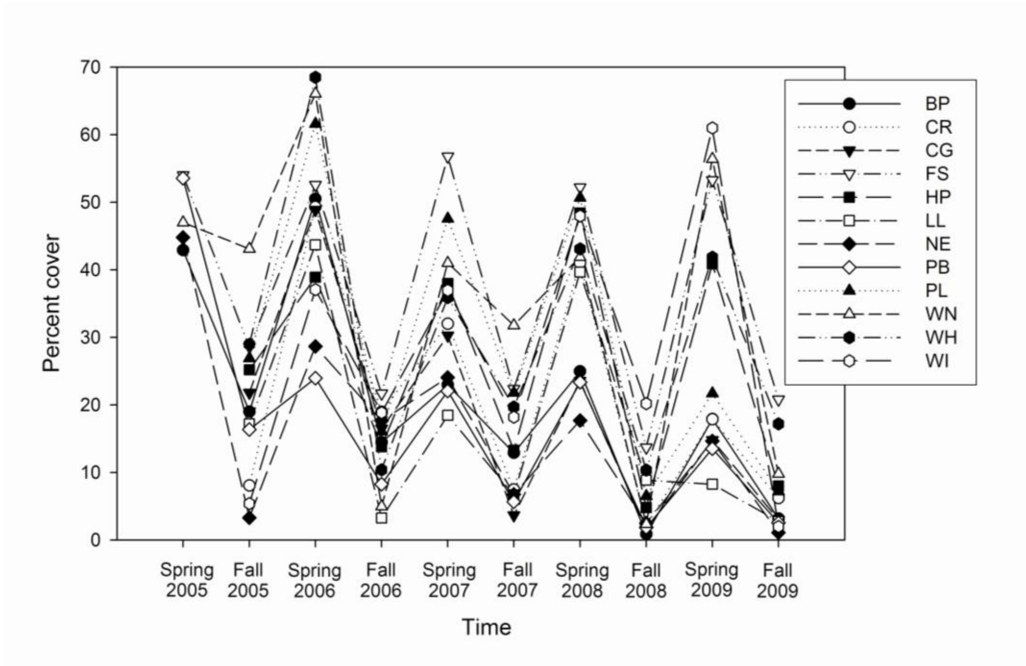


Figure 2. Mean visual percent cover of garlic mustard at each garlic mustard monitoring site from 2005-2009. Spring cover is the total cover of adult + seedling garlic mustard plants in June. Fall cover is the cover of rosettes in October.
BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

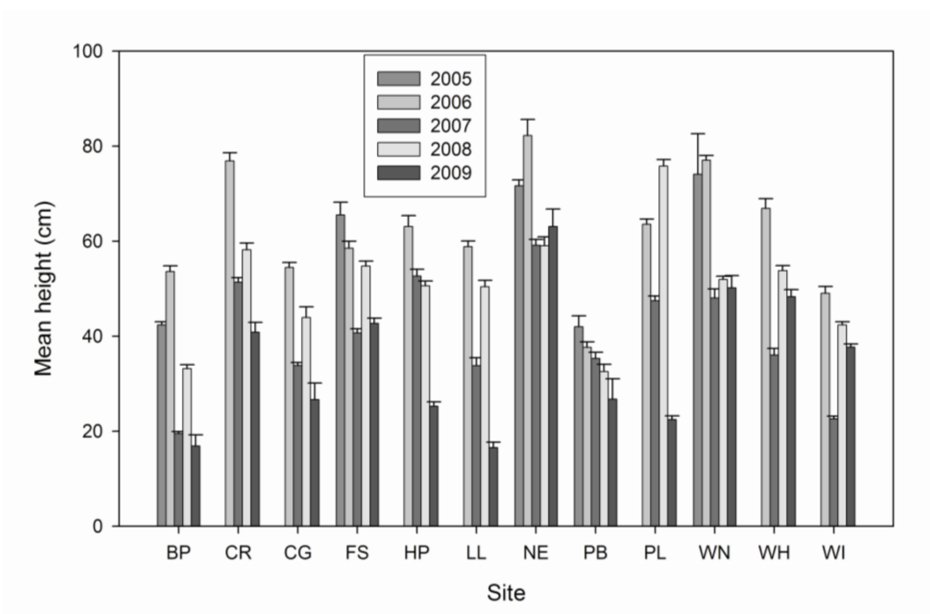


Figure 3. Mean adult garlic mustard stem heights (± SE) by site as measured in June of 2005-2009. BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

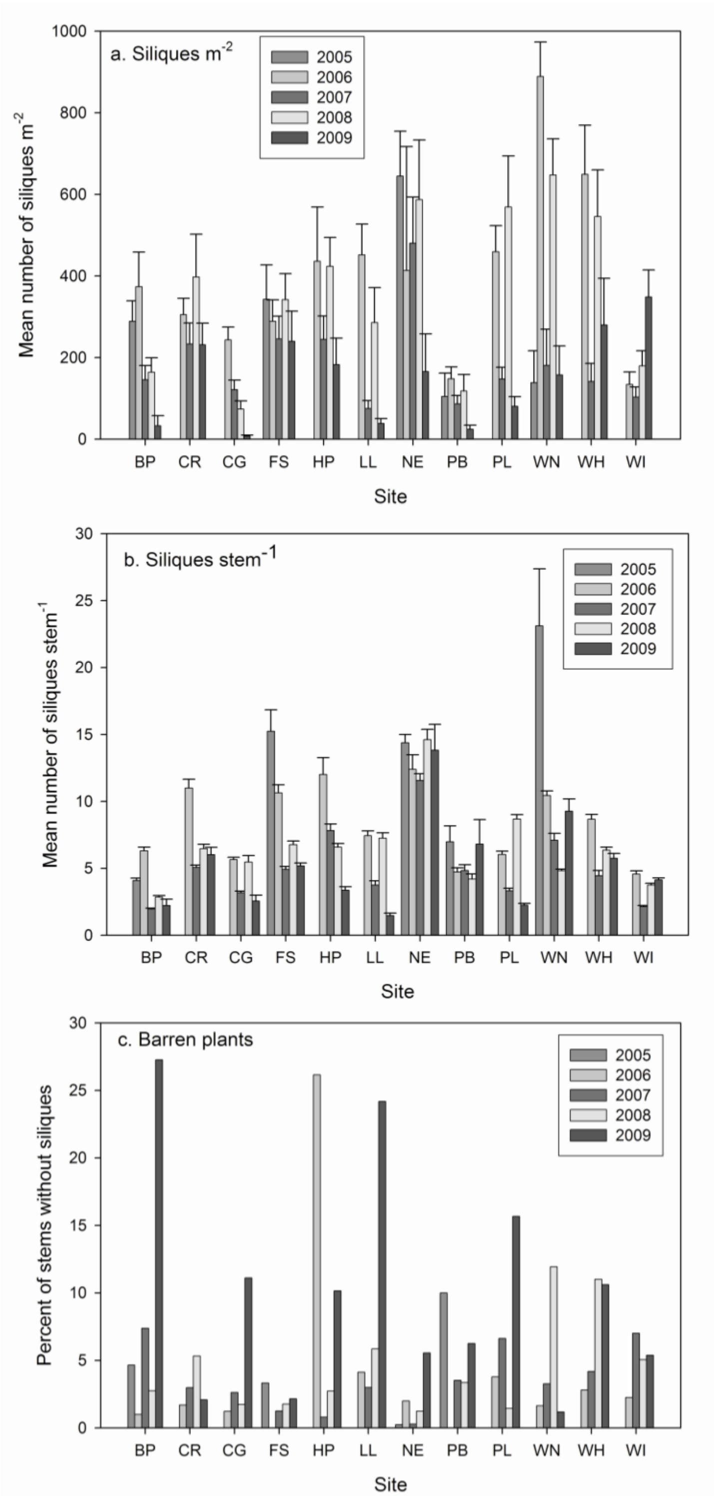


Figure 4. (a) The mean number of siliques per m^2 (± SE) of plots with adult garlic mustard present, (b) mean number of siliques per adult stem, and (c) percent of stems without siliques present (the total number of sterile stems recorded at the site / total number of stems at the sites x 100%). BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

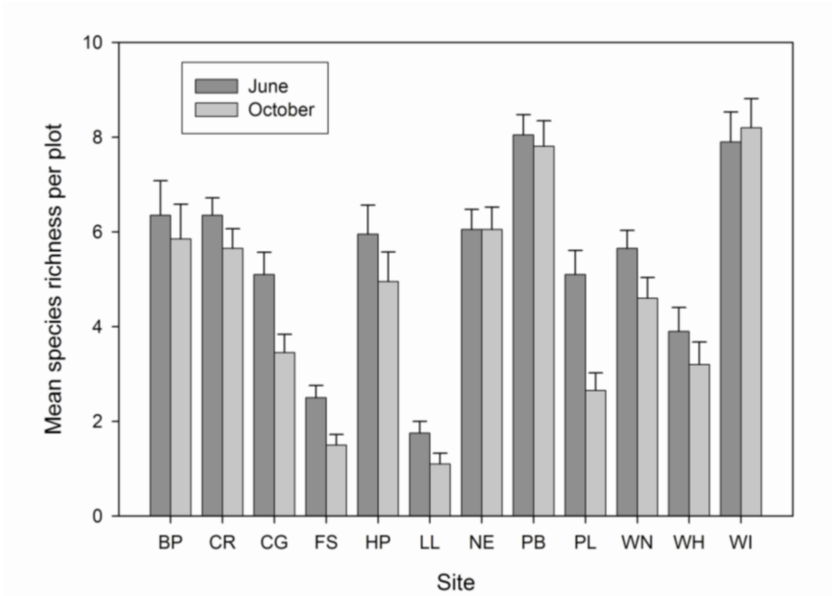


Figure 5. Mean species richness per 0.5m^2 plot (± SE) in June and October 2009.
BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

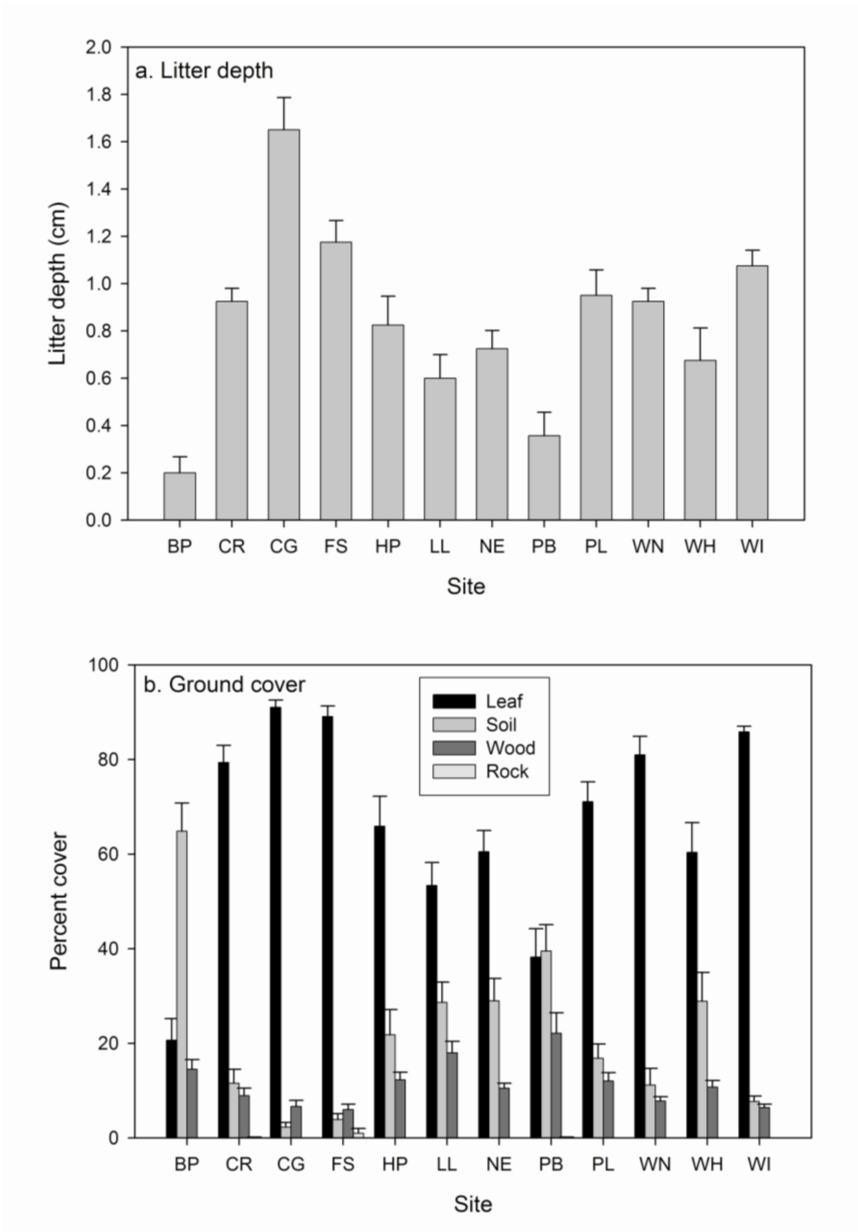


Figure 6. Mean litter depth (cm) (± SE) of each site in June 2009. The mean percent cover (± SE) of various types of ground cover (leaf litter, bare soil, woody debris, or rocks) of each site in June 2009.

BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

Figure 7. Closeup of aphid colony.

Figure 8. Garlic mustard plant with aphid colony present. Note the twisted siliques.

Chapter 3

Differences in Available Photosynthetically Active Radiation among Garlic Mustard (*Alliaria petiolata*) Monitoring Sites

Updated and modified from Van Riper et al. 2010.

INTRODUCTION

Garlic mustard (*Alliaria petiolata*) is a nonnative, herbaceous, biennial plant that is invasive in forests in the United States and can negatively impact native biota (Nuzzo 1999; Blossey et al. 2001; Meekins et al. 2001; Rodgers et al. 2008). In 2005, a monitoring program was initiated in Minnesota to examine the population biology of garlic mustard and its associated species in anticipation of the potential release of biological control insects (Van Riper et al. 2010). Permanent monitoring plots were established at 12 sites throughout Minnesota. Sites vary in aspects such as slope, species composition, latitude and longitude, and potentially light availability.

Garlic mustard populations may be influenced by the amount of light available at a site. Studies have shown that higher light sites can have garlic mustard plants with greater biomass and seed production than lower light sites (Meekins and McCarthy 2000; Myers et al. 2005). The differing amount of light available among sites may drive differences in garlic mustard population density and cover (Eschtruth and Battles 2009). Additionally, when adult garlic mustard plants grow densely they may shade out garlic mustard seedlings germinating under the adult garlic mustard stand. This can contribute to the effect of having populations in which one garlic mustard life stage (adults or rosettes) dominates in any given year (Meekins and McCarthy 2002; Winterer et al. 2005; Pardini et al. 2009; Van Riper et al. 2010).

The purpose of this study was to collect light availability information for the 12 Minnesota garlic mustard monitoring sites. The study attempted to determine whether light availability differs significantly among the 12 sites and if so, which sites tended to have high and low light availability. These data can then be used to determine the relationship between light availability and garlic mustard populations.

METHODS

Twelve garlic mustard monitoring sites, each with 20 permanent 1-m by 0.5-m plots were established in Minnesota in 2005 (Van Riper et al. 2010). To determine light availability we measured the amount of photosynthetically active radiation (PAR, 400 to 700nm) penetrating the forest canopy. Light measurements were taken between August 11 and September 9 in 2008 and between May 12 and June 3 in 2009 (Table 1). Additional measurements were taken at Pine Bend Bluffs on August 27, 2009 since many trees had been cut at the site since the measurements taken in August 2008. All measurements were taken within two hours of solar noon. In August and September

2008 and 2009, tree leaves had not begun to change color or senesce. In May 2009, trees were in early leaf-out, but had not yet reached full leaf-out.

PAR measurement methods follow Van Riper et al. 2010. A LI-190SA point quantum light sensor with a LI-1000 data logger was placed in an area of full sun to measure full sun PAR levels. The data logger sampled PAR levels every 5 seconds and recorded the average PAR level for one minute intervals. While the point sensor recorded full-sun data, a 1-meter LI-191SA line quantum light sensor and a LI-189 visual display were used to take PAR measurements in plots under the forest canopy, placing the line sensor along the center of the 1-m long axis of each plot. PAR readings were taken at 1 meter above the soil surface (equivalent to what an adult garlic mustard plant would receive) and at the soil surface (where seedling and rosette garlic mustard plants would receive light). For each plot, the amount of PAR and the time of each reading were recorded. The percent of full sun PAR incident at 1-m and the soil surface was determined by dividing by the PAR reading under the canopy by the PAR reading in full sun at the time of the plot reading. In 2008, all measurements were taken on days with full sun and no clouds. In 2009, there were not 12 days of full sun in May. Measurements were either taken on days with no clouds or overcast days with an even, full cover of clouds (Table 1).

To determine if sites differed in percent of available PAR, one-way ANOVAs were conducted (Statistix 7 2000). To account for the impact of varying sky conditions and tree leaf-out in spring 2009, a mixed model ANOVA was performed (Oehlert and Bingham 2005). All multiple comparison tests used Tukey's hsd.

RESULTS AND DISCUSSION

Percent of available photosynthetically active radiation in 2008 and 2009

Light has the potential to explain site to site differences in garlic mustard cover and plant species composition. When sites were at full leaf out in August and September of 2008, they showed no significant differences in the percent of available PAR at either the top of the garlic mustard canopy (1 m height) or at the soil surface (one-way ANOVA at 1m P=0.08, $F_{11,228}$=1.69; at soil surface P=0.07, $F_{11,228}$=1.72). The percent of incident PAR was generally low with a mean 6% ±0.7 at the top of the garlic mustard canopy and 3% ±0.4 at the soil surface. Mean percent of full sun PAR incident at 1-m ranged from 2% at Cottage Grove to 13% at Warner Nature Center and from 1% at Luce Line and Cottage Grove to 8% at Warner Nature Center at the soil surface (Fig. 1a). Warner Nature Center was hit by a tornado on May 25, 2008 which caused a number of trees to fall. It is not surprising that Warner would have some of the highest amounts of light availability. Large standard errors were present in the graphs of the mean percent incident PAR because the sites usually had a few plots that occurred in canopy openings which allowed high amounts of light to pass through to the forest floor.

In contrast to the August-September 2008 readings, the sites did show site to site differences in the May-June 2009 readings (one-way ANOVA for percent PAR at 1m P<0.00001, $F_{11,224}$=9.63; at soil surface P<0.00001, $F_{11,224}$=9.7). In May 2009 the sites generally had higher levels of percent of PAR incident at the top of the garlic mustard canopy (1 m height, mean of 15% ±1) or at the soil surface (mean of 12% ±1) than in

Aug-Sep 2008 (Fig. 1b). This difference likely reflects that trees were in full leaf-out in Aug-Sept, but not in May. Mean percent of full sun PAR incident at the 1-meter level ranged from 4% at Luce Line to 30% at Pine Bend, and at ground level ranged from 3% at Willmar to 23% at Pine Bend. Pairwise comparisons (Tukey's hsd) of the sites based on 2009 PAR measures showed that Pine Bend, Warner Nature Center, Coon Rapids, and Westwood Hills tended to have high PAR availability, while Luce Line, Willmar, and Plainview tended to have low PAR availability (Table 2).

The amount (not percent) of available incident PAR penetrating to 1 m and the soil surface is presented in Fig. 2. These data are not directly comparable from site to site to as day to day differences in strength of PAR are not directly comparable. However, these data are included to reinforce the percent PAR data by showing that sites received less PAR in Aug-Sep 2008 than in May-June 2009. The amount of PAR can also be used to compare the results of this study with other studies that examine the impact of available PAR. Note that in 2009, some measurements were taken on overcast days while others were taken on clear days (Table 1).

The May-June 2009 light data are somewhat limited in usefulness as the data are confounded by relationships with date (as time went on sites became more heavily leafed out) and overcast vs. clear sky conditions. The mean percent light reaching 1m above the soil surface was not equal for the group of sites measured on clear sky days versus the group of sites measured on overcast sky days (unequal variances, t=-2.58, df=229.2, P=0.03). Sites measured on clear days had a lower mean percent PAR at 1m (13% ± 1 SE) versus sites measured on overcast days (mean = 17% ± 1 SE). However, this pattern did not hold for the percent PAR reaching the soil surface (unequal variances, t=-1.10, df=216, P=0.27) with sites measured on clear days having similar mean percent available PAR as those measured on overcast days (clear = 11% ± 1 SE, overcast mean = 13% ± 1 SE). The later in the year (the more leaves), the lower the percent PAR at 1m and soil surface (regressions are significant P<0.00001, with low R^2 = 0.08 and 0.12 respectively).

To address the impact of sky conditions and date in 2009 on the PAR measures at 1m, we performed a mixed model ANOVA (Oehlert and Bingham 2005). The dependent variable was the percent of PAR available at 1m and the explanatory variables were date of reading (continuous variable, ordinal date), sky conditions (categorical: overcast or clear), and site. All explanatory variables were significant: date ($F_{1,224}$=27.6, P<0.00001), sky conditions ($F_{1,224}$=6.5, P=0.01), and site ($F_{9,224}$=8.0 P<0.00001). Pairwise comparisons (Tukey's hsd) among sites indicated that Luce Line and Nerstrand differed significantly form Pine Bend. Luce Line and Nerstrand tended to have low levels of PAR while Pine Bend had the highest levels.

Relationship between garlic mustard cover and percent PAR at the site level

Garlic mustard has been shown to have a strong relationship with light. The mean percent available PAR at each of the 12 sites was regressed against the mean garlic mustard cover for the sites to determine if there was a linear relationship (Fig. 3). In August-September 2008, there was a negative relationship between light and garlic mustard as shown in the regression of the cover of garlic mustard seedlings against percent of PAR penetrating to the soil surface (P=0.01, R^2=0.49). Relationships with PAR and adult cover (P=0.12, R^2=0.22, trending positive) and rosette cover (P=0.32, R^2=0.10, trending negative) were non-significant (Fig. 3a). Regressions of garlic mustard cover against PAR at 1 m above soil surface were similar to those at the soil surface for seedlings (P=0.01, R^2=0.48), adults (P=0.13, R^2=0.21), and rosettes (P=0.25, R^2=0.13). There was little evidence for a relationship between garlic mustard cover and light in the May-June 2009 measurements. Regressions of mean garlic mustard percent cover per site against mean percent PAR penetrating to the soil surface were not significant (Fig. 3b, adult: P=0.92, R^2<0.00001, seedling: P=0.45, R^2=0.06, rosette: P=0.23, R^2=0.14) nor were regressions against mean percent PAR penetrating to 1m above the soil surface (adult: P=0.95, R^2=0.0004, seedling: P=0.38, R^2=0.08, rosette: P=0.28, R^2=0.12).

According to the August-September 2008 data, the seedling stage appeared to be most sensitive to the amount of available light (Van Riper et al. 2010). Adult garlic mustard plants showed the expected greater percent cover in sites with higher available PAR (Meekins and McCarthy 2000; Myers et al. 2005), but cover of seedlings and rosettes showed a negative relationship. When adult plants grow tall in relationship with increased light, they may in turn shade out seedlings, causing seedlings to show a negative relationship with light. The pattern of lower cover of seedlings likely persisted as the seedlings grew into rosettes. In the May-June 2009 data there was little evidence of a relationship of percent available PAR and garlic mustard cover. There may truly be no relationship or the analysis of the PAR measurements may be confounded by the effects of increased tree leaf out over the course of the month and the necessity of measuring some sites on clear days and other sites on overcast days.

Relationship between garlic mustard cover and percent PAR at the plot level

In addition to looking at the relationship between garlic mustard cover and percent available PAR at the site level, we also examined the relationship at the plot level. The percent available PAR at each plot was regressed against the garlic mustard cover in that plot. When the garlic mustard cover data for the 240 plots were regressed against the amount of incident PAR there were no strong relationships. Regressions of 2008 garlic mustard cover versus the amount of incident PAR at the soil surface and 1 m in 2008 showed no relationship with seedlings and rosettes (all P>0.05). There was a weak positive relationship with adults at the soil surface (P=0.003, R^2=0.03) and 1 m levels (P=0.01, R^2=0.03). For the 2009 data, all regressions of garlic mustard percent cover per plot against percent PAR penetrating to the soil surface and 1m were not significant (all P>0.05), except for the percent of PAR penetrating to soil surface by the percent cover of adult garlic mustard plants (P=0.009), but the R^2 value was very low (R^2=0.03). At the plot level, light does not appear to be a strong driver of garlic mustard cover.

Impact of tree clearing at Pine Bend

In April of 2009, in an effort to decrease cover of nonnative common buckthorn (*Rhamnus cathartica*) and nonnative honeysuckles (*Lonicera spp.*) at Pine Bend Bluffs SNA, work was completed to cut and apply herbicide stump treatments to these species in an area that overlapped with some of the garlic mustard monitoring plots. Since there had been a dramatic change in tree canopy from the light measurements taken in August 2008, light measures were retaken in August 2009. Figure 4 shows the percent of incident PAR at Pine Bend at each plot in August 2008 and 2009. Many plots experienced a dramatic increase in available light (ex. 4% to 100% for plot 3 and 14% to

97% for plot 18, Fig. 4a). This large increase in available light will likely change the species composition and cover of plots at this site.

CONCLUSION

In general, sites generally showed little difference in the amount of light available. This indicates that differences between sites in garlic mustard population density, garlic mustard cover, and the cover of other species is likely not determined mainly by differences in light availability. It is likely that density-dependence of garlic mustard (Pardini et al. 2009) and other site differences (land-use history, deer population, earthworm invasion, etc.) are the main drivers of garlic mustard and other species differences among sites.

LITERATURE CITED

Blossey, B., V. A. Nuzzo, H. L. Hinz, and E. Gerber. 2001. Developing biological control of *Alliaria petiolata* (M. Bieb.) Cavara and Grande (garlic mustard). Nat. Areas J. 21:357-367.

Eschtruth, A. K. and J. J. Battles. 2009. Assessing the relative importance of disturbance, herbivory, diversity, and propagule pressure in exotic plant invasion. Ecol. Monogr. 79:265-280.

Meekins, J. F. and B. C. McCarthy. 2000. Responses of the biennial forest herb *Alliaria petiolata* to variation in population density, nutrient addition and light availability. J. Ecol. 88:447-463.

Meekins, J. F., H. E. Ballard, and B. C. McCarthy. 2001. Genetic variation and molecular biogeography of a North American invasive plant species (*Alliaria petiolata*, Brassicaceae). Int. J. of Plant Sci. 162:161-169.

Myers, C. V., R. C. Anderson, and D. L. Byers. 2005. Influence of shading on the growth and leaf photosynthesis of the invasive non-indigenous plant garlic mustard [*Alliaria petiolata* (M. Bieb) Cavara and Grande] grown under simulated late-winter to mid-spring conditions. J.Torrey Bot. Soc. 132:1-10.

Nuzzo, V. A. 1999. Invasion pattern of the herb garlic mustard (Alliaria petiolata) in high quality forests. Biol. Invasions 1:169-179.

Oehlert, G. W. and C. Bingham. 2005. MacAnova 5.05. University of Minnesota. http://www.stat.umn.edu/macanova

Pardini, E. A., J. M. Drake, J. M. Chase, and T. M. Knight. 2009. Complex population dynamics and control of the invasive biennial *Alliaria petiolata* (garlic mustard). Ecol. Appl. 19:387-397.

Rodgers, V. L., K. A. Stinson, and A. C. Finzi. 2008. Ready or not, garlic mustard is moving in: *Alliaria petiolata* as a member of eastern North American forests. BioScience 58:426-436.

Statistix 7. 2000. Statistix version 7.0. Tallahassee, FL: Analytical Software.

Van Riper, L. C., R. L. Becker, L. C. Skinner. 2010. Population biology of garlic mustard (*Alliaria petiolata*) in Minnesota hardwood forests. Invasive Plant Sci. Manage. *In press.*

Winterer, J., M. C. Walsh, M. Poddar, J. W. Brennan, and S. M. Primak. 2005. Spatial and temporal segregation of juvenile and mature garlic mustard plants (*Alliaria petiolata*) in a Central Pennsylvania woodland. Am. Midl. Nat. 153:209-216.

TABLES

Table 1. Monitoring sites in order of dates of data collection for May and June 2009 along with sky conditions. All sites are located in Minnesota, USA between 44°6.600’ and 45°19.356’N and 92°3.821’ and 94°56.667’W.

Site	**Site ID**	**2009 Date**	**2009 Sky Conditions**	**2008 Date**	**2008 Sky Conditions**
Westwood Hills Nature Center	WH	5-12	overcast	8-19	clear
Coon Rapids Dam Regional Park	CR	5-13	overcast	8-18	clear
Fort Snelling State Park	FS	5-14	clear	8-15	clear
Warner Nature Center	WN	5-15	clear	8-11	clear
Baker Park Preserve	BP	5-18	clear	8-29	clear
Cottage Grove Ravine Regional Park	CG	5-19	clear	9-05	clear
Hilloway Park	HP	5-26	overcast	8-19	clear
Luce Line Trail	LL	5-26	overcast	9-8	clear
Nerstrand State Park, Prairie Creek SNA	NE	5-27	overcast	9-3	clear
Pine Bend Bluffs SNA	PB	5-27	overcast	8-26	clear
Plainview – private land	PL	6-03	clear	8-28	clear
Willmar – private land	WI	6-08	clear	8-25	clear

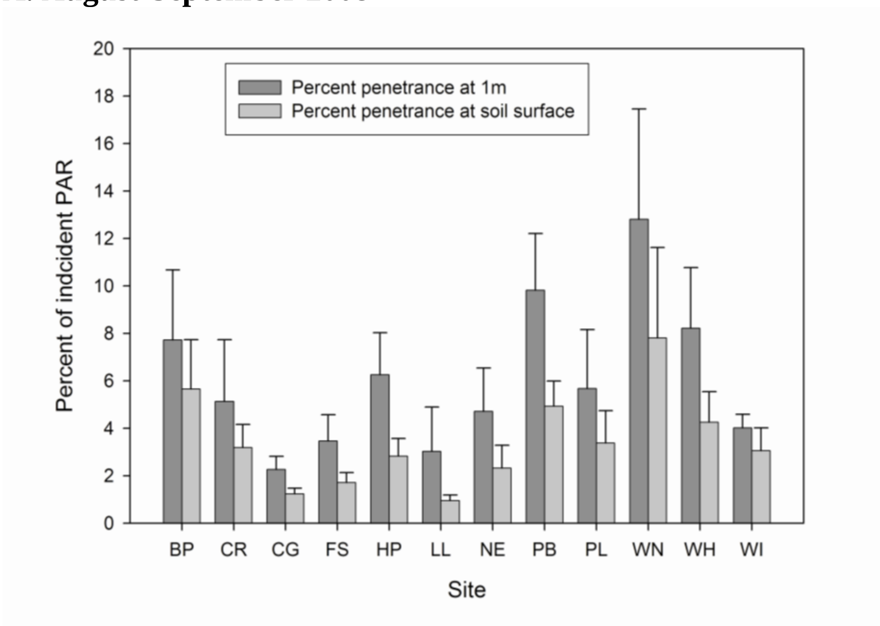
Table 2. Percent PAR reaching the soil surface and 1m above soil surface from highest percent to lowest. Group = sites that are not statistically different from one another according to multiple comparison tests. Date order = order in which data were taken (ex. 1=first site to have data collected, 12=last site). Sky = sky conditions on date of data collection.

Site	% PAR	SE	Group	Date order	Sky
By percent of PAR reaching soil surface					
PB	22.9	4.3	a	10	overcast
WN	22.2	3.9	a	4	clear
CR	17.5	1.1	ab	2	overcast
WH	16.8	1.6	ab	1	overcast
BP	16.7	3.4	ab	5	clear
HP	16.6	1.5	ab	7	overcast
CG	15.6	3.8	ab	6	clear
FS	7.4	1.8	bc	3	clear
NE	4.0	0.4	c	9	overcast
PL	3.4	2.4	c	11	clear
LL	3.3	0.4	c	8	overcast
WI	2.9	0.9	c	12	Clear
By percent of PAR reaching 1m above soil surface					
PB	29.7	4.4	a	10	overcast
WN	24.2	4.9	ab	4	clear
WH	22.2	1.7	ab	1	overcast
CR	21.2	1.5	abc	2	overcast
HP	21.0	2.4	abc	7	overcast
BP	16.0	3.2	bcd	5	clear
CG	15.6	2.9	bcde	6	clear
NE	9.4	1.3	cde	9	overcast
FS	9.4	1.9	cde	3	clear
WI	6.8	1.8	de	12	clear
PL	5.4	2.7	de	11	clear
LL	3.8	0.5	e	8	overcast

BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

FIGURES

A. August-September 2008



B. May-June 2009

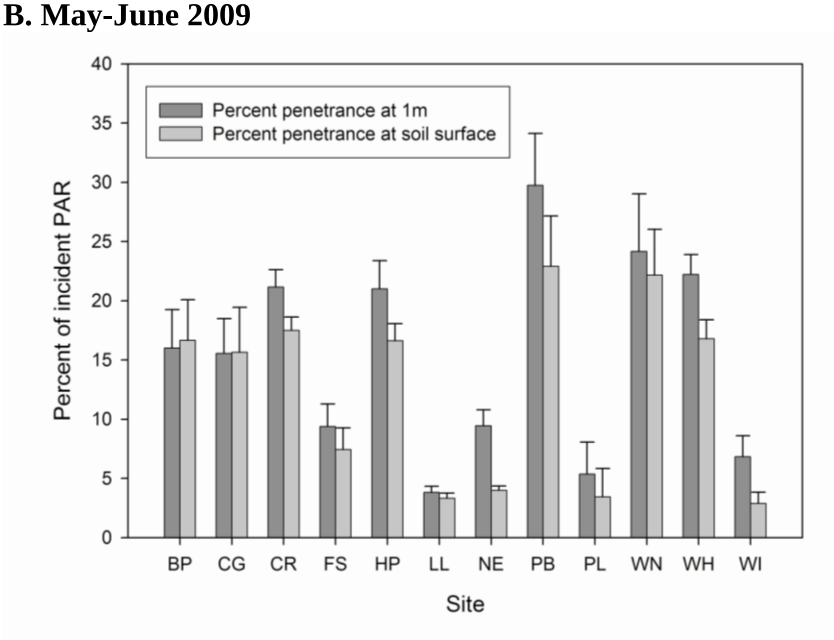
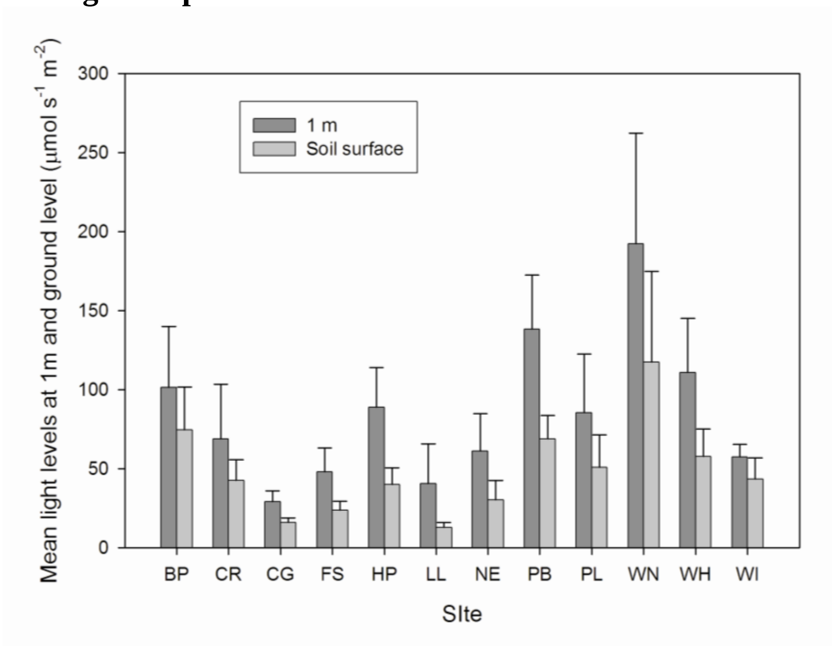


Figure 1. The mean percent of incident photosynthetically active radiation (PAR) penetrating to 1 meter above the soil surface and at the soil surface (± SE) in 2008 (A) and 2009 (B). Measurements were taken in August and September 2008 and May and June 2009 within 2 hours of solar noon at 12 sites in Minnesota, USA. Note that y-axes differ.

BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

A. August-September 2008



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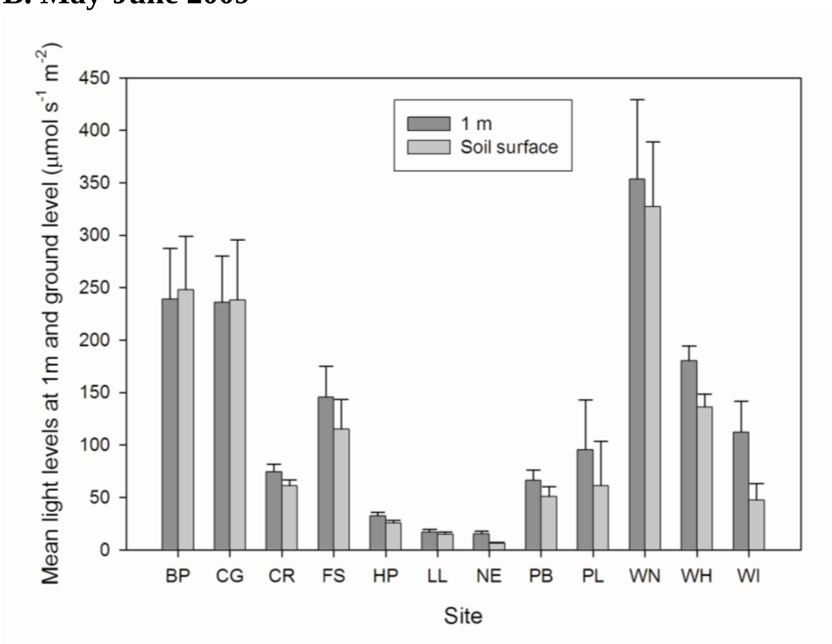
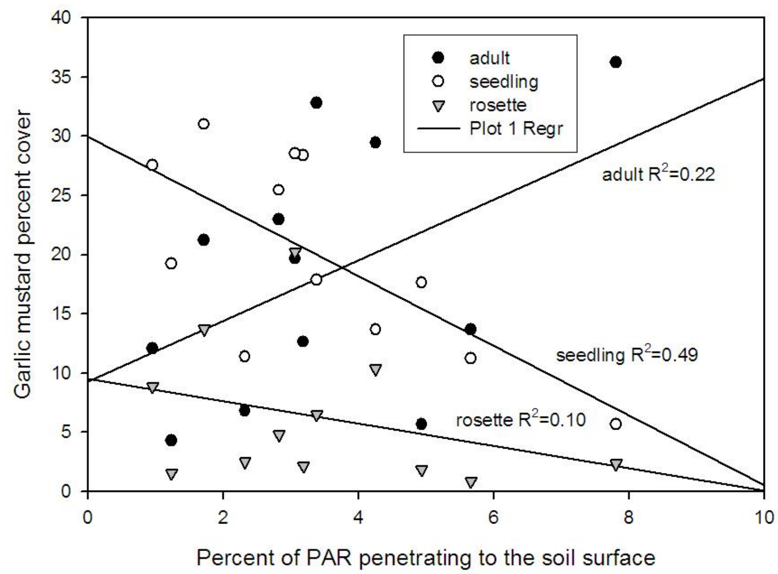


Figure 2. The mean amount of incident photosynthetically active radiation (PAR) penetrating to 1 meter above the soil surface and at the soil surface (± SE) in 2008 (A) and 2009 (B). Measurements were taken in August and September 2008 and May and June 2009 within 2 hours of solar noon at 12 sites in Minnesota, USA. Note that y-axes differ.

BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

A. PAR from August-September 2008



B. PAR from May-June 2009

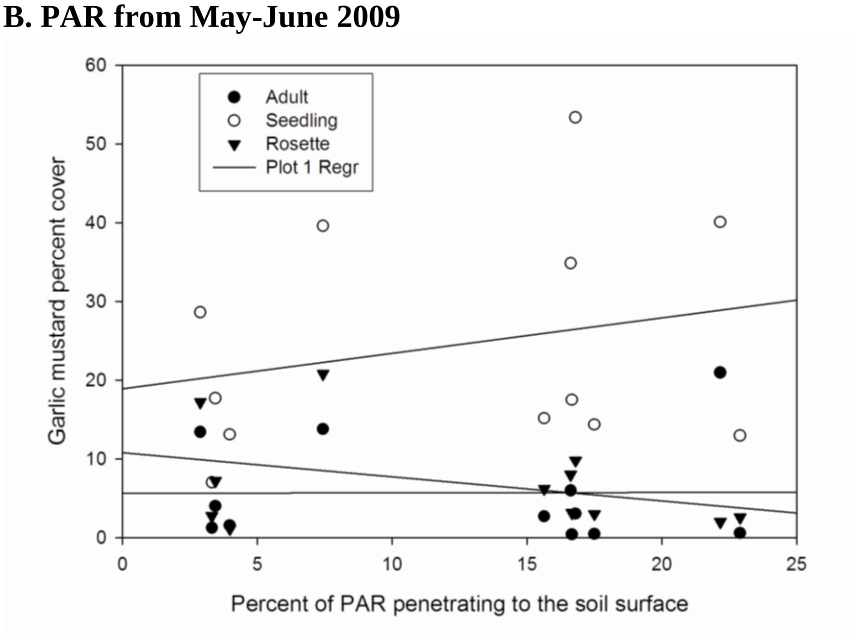


Figure 3. Linear regressions of mean percent cover of garlic mustard and mean percent PAR reaching the soil surface of the 12 monitoring sites, Minnesota, USA in 2008 (A) and 2009 (B). In 2009, all R^2 measures were <0.15. PAR measurements were taken during August and September 2008 and May and June 2009 within 2 hours of solar noon. Adult and seedling garlic mustard covers were measured in June of each year. Rosette cover was measured in October of each year. Note that y-axes differ.

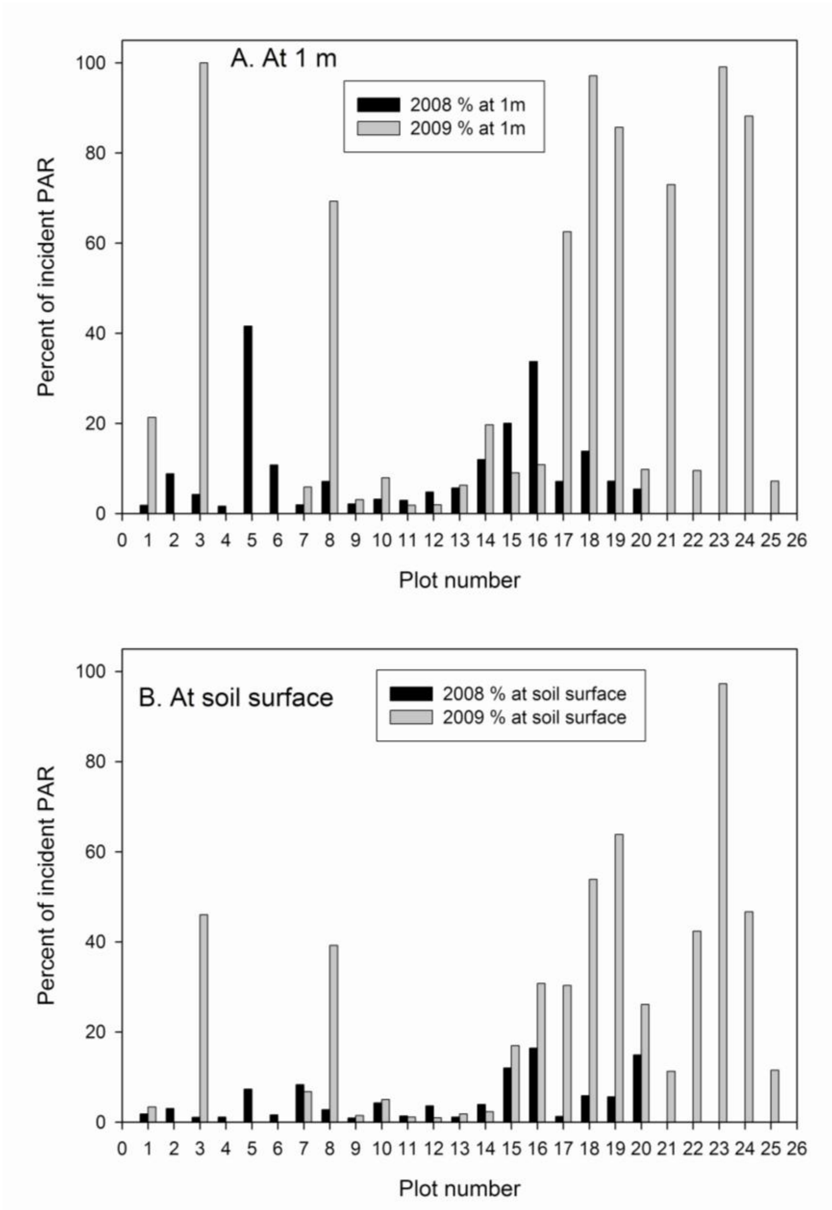


Figure 4. The percent of incident PAR penetrating 1 meter above the soil surface (A) and to the soil surface (B) and as measured in August 2008 and 2009 within 2 hours of solar noon at Pine Bend Bluffs Scientific and Natural Area, Minnesota, USA. In 2008 readings were taken at plots 1-20. In early spring 2009, a large number of trees were removed and piled up. Plots 2, 4, 5, and 6 were covered by brush piles, so there are no measurements for these plots in 2009. Plots 21-25 were established in June 2009 to replace the lost plots (consequently there are no May 2009 readings for plots 21-25). Plots 1-10 and 16-25 are in the area where trees were cleared. No trees were cleared in the area where plots 11-15 were located.

Chapter 4

Tree Canopy Differences among Garlic Mustard (*Alliaria petiolata*) Monitoring Sites

INTRODUCTION

Garlic mustard (*Alliaria petiolata*) in an invasive forb which can have negative ecological impacts on the communities which it invades ((Nuzzo 1999; Blossey et al. 2001; Rodgers et al. 2008). To characterize Minnesota garlic mustard populations and to collect pre-release data in the event of the release of biological control agents, a garlic mustard monitoring program was initiated in Minnesota (Van Riper et al. 2010). The monitoring protocol used is a standard protocol developed by the Ecology and Management of Invasive Plants Program (http://www.invasiveplants.net) to facilitate standardized data collection across states and data collectors. The monitoring protocol focuses on collecting species data on forest floor species and does not address the tree canopy. In order to better describe the 12 garlic mustard monitoring sites, data was collected on the tree species present at the sites. A sample of trees in the understory and canopy were identified and their diameters at breast height (dbh) measured.

METHODS

Each garlic mustard monitoring site has 20 permanent 0.5 m by 1.0 m monitoring plots. In these plots data are recorded on the plant species composition of the forest floor. There is not a standard protocol component for describing the tree canopy. In order to give quantitative descriptions of the tree compositions of the 12 sites, each site was surveyed. The 20 monitoring plots are laid out along four transects, with the plots 10 m apart from one other. In order to survey the tree species, four transects of 40 m each were laid out next to the permanent monitoring plots. Any trees with a dbh greater than 2 cm found within 0.5 m of either side of the transect were recorded. The tree was identified, its position along the transect was recorded, dbh was recorded, and it was noted whether the top of the tree was part of the canopy (no other trees above it) or in the understory (the top of the tree did not reach full sun). For each site, a total area of 160 m^2 was surveyed (40m transect x 1m wide x 4 transects). Sites were surveyed in August and September of 2008. At this time slope and aspect were visually estimated for each site. Tree canopy data was summarized using Statistix 7 (2000). Tree species scientific names, authorities, common names, and native/nonnative status are listed in the Appendix.

RESULTS

Twenty-three different tree species were recorded among the 12 monitoring sites. *Ulmus rubra*, *Acer negundo,* and *Quercus rubra* were the most frequent native species as they were found at 6 or more of the sites (Table 1). The invasive tree, *Rhamnus cathartica* was present in 5 of the sites. However it should be noted that *Rhamnus cathartica* is present at almost all of sites, but several have done work to control adult plants, so there are fewer tree-sized individuals at those sites. The native species *Celtis occidentalis, Franxinus pennsylvanica, Tilia americana, Acer saccharum, Ostrya virginiana,* and *Prunus serotina* were found at 3 or 4 of the sites. The remaining 13 species were only found at 1 or 2 of the sites.

The number of each species of tree present at each site shows some of the variation among sites. *Ostyra virginiana* was only present at 3 sites, but was very frequent at the Cottage Grove and Willmar sites (Table 1). *Ulmus rubra* was the most frequent tree at Coon Rapids, Luce Line, and Plainview while *Acer negundo* was the most frequent tree at Baker Park and Fort Snelling. Hilloway Park showed the legacy of planted *Pinus strobus* with that species slightly more frequent than *Ulmus rubra*. Nerstrand had the largest number of *Acer saccharum*. The invasive tree, *Rhamnus cathartica* was the most frequent tree at Pine Bend Bluffs. At Warner Nature Center, *Prunus serotina* and *Quercus alba* were the most frequent trees. *Fraxinus pennsylvanica* was the most frequent tree at Westwood Hills. The variations in frequencies and species that are unique to individual sites, highlight the differences among sites.

Species diversity and total number of trees further distinguish the sites from one another. The most diverse sites were Plainview (8 species), Nerstrand (7), Cottage Grove (6), Luce Line (6), Pine Bend (6), and Westwood Hills (6) (Table 1). Baker Park was the least diverse with only 3 species found in the survey area. Nerstrand had 4 species that were not present at any of the other sites (Table 1). Cottage Grove, Willmar, Luce Line, and Plainview all had the highest total number of trees present (Table 1). Warner Nature Center had the fewest number of trees present, but it should be noted that the sites was hit by a tornado on May 25, 2008 causing trees to fall. Baker Park, Fort Snelling, and Westwood Hills also had relatively fewer trees than other sites.

To further clarify similarities and differences among the sites, a cluster analysis was run on PC-ORD (McCune and Mefford 1999). Data on the number of each species present in each site was used to perform a cluster analysis using the Sorensen (Bray-Curtis) distance measure and the group average linkage method. The cluster analysis (Fig. 1) showed that Cottage Grove and Willmar were the most similar sites (both had high numbers of *Ostrya virginiana* and had similar numbers of *Acer negundo*). Luce Line, Plainview, and Coon Rapids were very similar in their high numbers of *Ulmus rubra*. Additionally, Luce Line and Plainview had similar numbers of *Quercus rubra* and *Acer saccharum*. Fort Snelling and Westwood Hills were somewhat similar in their abundance of *Acer negundo* and *Fraxinus pennsylvanica* and they were the only sites with *Populus deltoides*. Baker Park's common species and low diversity made it somewhat similar to the cluster of Coon Rapids, Luce Line, Plainview, Fort Snelling, and Westwood Hills. Hilloway Park and Warner Nature Center were somewhat similar to each other in that each had *Ulmus rubra, Acer negundo,* and *Prunus serotina*. Pine Bend with its high number of *Rhamnus cathartica* and 2 unique species and Nerstrand with its high number of *Acer saccharum* and 4 unique species were the two sites that were least similar to any of the sites.

Sites varied in slope from nearly level to extreme slopes (Table 3). Slope and aspect may impact the tree species composition at a site. In the cluster analysis (Fig. 1), Pine Bend and Nerstrand were the most unlike the other sites and those two sites had the steepest slopes. Cottage Grove and Willmar were similar to one another and both were on strong to moderate slopes. Hilloway Park and Warner Nature Center grouped together and both were on very gentle slopes. With the exception of Plainview, all the sites in the Baker Park, Coon Rapids, Luce Line, Plainview, Fort Snelling, and Westwood Hills group had level to very gentle slopes.

The dbh measures give an indication of tree size at the monitoring sites. Canopy trees had very similar dbhs among the sites with the exception of Fort Snelling and Pine Bend Bluffs (Fig. 2a). Fort Snelling had several very large *Populus deltoides* which increased its average dbh. The canopy trees Pine Bend Bluffs tended to be small. Average dbh among the understory trees varied more greatly (Fig. 2b). Understory trees were largest at Hilloway Park and Westwood Hills. Cottage Grove, Luce Line, Pine Bend, and Willmar had the smallest average dbhs of their understory trees. The sum of all the dbh values for the trees at a site indicates which sites have the most tree biomass (Table 2). Willmar, Hilloway Park, and Coon Rapids had the highest amount of tree biomass while Pine Bend Bluffs and Luce Line had the lowest (Table 2). Trees with the highest average dbh were found at Warner Nature Center (26.8 cm) and Hilloway Park (25.8 cm), while Pine Bend Bluffs (8.6 cm) and Luce Line (9.0 cm) had the lowest (Table 2). Warner Nature Center had the fewest trees (12), but they were large (26.8 cm) while Cottage Grove had the highest number of trees (39), but they were small (9.4 cm) (Table 2).

DISCUSSION

The variability in tree species composition, number, and size indicates that the 12 garlic mustard monitoring sites vary in their site history (historic natural community, logging/farming history, other disturbances, etc.) and/or environmental factors (soil pH, soil nutrients, slope (Table 3), latitude, etc.). Garlic mustard, garlic mustard biological control agents, and other plant species may have different impacts among the sites. Understanding site differences will aid in interpreting the impacts of garlic mustard and their biocontrol agents.

LITERATURE CITED

Blossey, B., V. A. Nuzzo, H. L. Hinz, and E. Gerber. 2001. Developing biological control of *Alliaria petiolata* (M. Bieb.) Cavara and Grande (garlic mustard). Nat. Areas J. 21:357-367.

McCune, B. and M. J. Mefford. 1999. PC-ORD - Multivariate Analysis of Ecological Data, Version 4.25, MjM Software, Gleneden Beach, Oregon, U.S.A.

Nuzzo, V. A. 1999. Invasion pattern of the herb garlic mustard (Alliaria petiolata) in high quality forests. Biol. Invasions 1:169-179.

Rodgers, V. L., K. A. Stinson, and A. C. Finzi. 2008. Ready or not, garlic mustard is moving in: *Alliaria petiolata* as a member of eastern North American forests. BioScience 58:426-436.

Van Riper, L. C., R. L. Becker, L. C. Skinner. 2010. Population biology of garlic mustard (*Alliaria petiolata*) in Minnesota hardwood forests. Invasive Plant Sci. Manage. *In press.*

Statistix 7. 2000. Statistix version 7.0. Tallahassee, FL: Analytical Software.

TABLES

Table 1. The tree species present at each site. Tree species are listed in order of frequency, with the species found at the most sites listed first. The table shows the number of individuals of that species found within the 160 m^2 survey area.

Tree species	BP	CR	CG	FS	HP	LL	NE	PB	PL	WN	WH	WI	Total	# of sites
Ulmus rubra	3	10	1		6	13	1	1	11	1	1		48	**10**
Acer negundo	12	4	2	6	1				6	2	2	3	38	**9**
Quercus rubra			4			1		3	1	2	1		12	**6**
Rhamnus cathartica		2	1	4		4		19					30	**5**
Celtis occidentalis			1	1				5	1				8	**4**
Fraxinus pennsylvanica		7		4		2					12		25	**4**
Tilia americana	2								2		1	5	10	**4**
Acer saccharum						7	12		4				23	**3**
Ostrya virginiana			30				1					21	52	**3**
Prunus serotina					2				1	4			7	**3**
Populus deltoides				2							1		3	**2**
Carya cordiformis							1						1	**1**
Crataegus sp.							1						1	**1**
Fraxinus nigra							2						2	**1**
Juglans cinerea								1					1	**1**
Malus sp.									1				1	**1**
Pinus strobus					7								7	**1**
Populus granidentata							1						1	**1**
Quercus alba										3			3	**1**
Quercus bicolor												3	3	**1**
Quercus macrocarpa								2					2	**1**
Robinia pseudoacacia					3								3	**1**
Zanthoxylum americanum						1							1	**1**
Total # of trees	17	23	39	17	19	28	19	31	27	12	18	32	282	
Total # of species	3	4	6	5	5	6	7	6	8	5	6	4		

BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

Table 2. Summary of diameter at breast height data (cm) for the 12 garlic mustard monitoring sites. “Sum of all the dbhs” sums the dbhs of all the trees at the site to show which sites have the greatest biomass of wood). “Mean dbh” indicates the mean dbh of trees at the site (showing which sites have the largest trees). Sites are listed in descending order of the sum of dbhs.

Site	**Total # of trees**	**Sum of all dbhs (cm)**	**Mean dbh (cm)**	**S.E. of Mean**
Willmar	32	491.2	15.4	2.4
Hilloway Park	19	489.9	25.8	2.3
Coon Rapids	23	445.7	19.4	3.0
Nerstrand	19	421.1	22.2	3.4
Westwood Hills	18	417.6	23.2	3.5
Baker Park	17	399.2	23.5	4.0
Fort Snelling	17	375.8	22.1	6.8
Cottage Grove	39	365.5	9.4	1.6
Plainview	27	354.6	13.1	1.7
Warner Nature	12	321.3	26.8	4.2
Pine Bend	31	265.8	8.6	1.6
Luce Line	28	251.8	9.0	1.7
For all sites	282	4599.5	16.3	0.9

Table 3. Slope differences among the garlic mustard monitoring sites.

Site	**Primary slope at site**	**Degrees of slope**	**Direction the slope faces**
Coon Rapids	nearly level	0.3-1.1	not applicable
Luce Line	nearly level	0.3-1.1	not applicable
Westwood Hills	nearly level	0.3-1.1	not applicable
Fort Snelling	very gentle	1.1-3	north & south
Hilloway Park	very gentle	1.1-3	east
Warner Nature	very gentle	1.1-3	north & south
Baker Park	gentle	3-5	south
Willmar	moderate	5-8.5	north
Cottage Grove	strong	8.5-16.5	east
Plainview	strong	8.5-16.5	west
Nerstrand	extreme	24-35	south
Pine Bend	extreme	24-35	south-southeast

FIGURES

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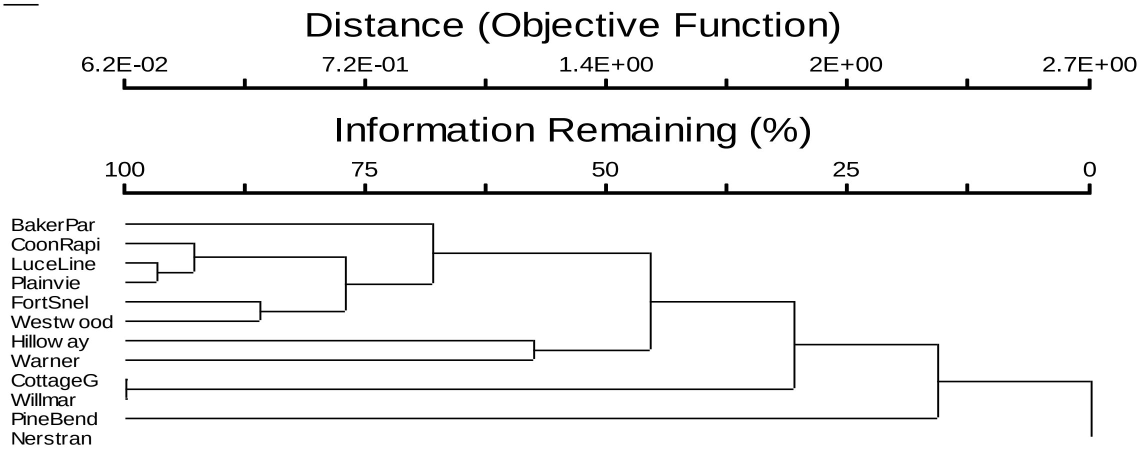

Figure 1. Cluster analysis using the Sorensen (Bray-Curtis) distance measure and the group average linkage method.

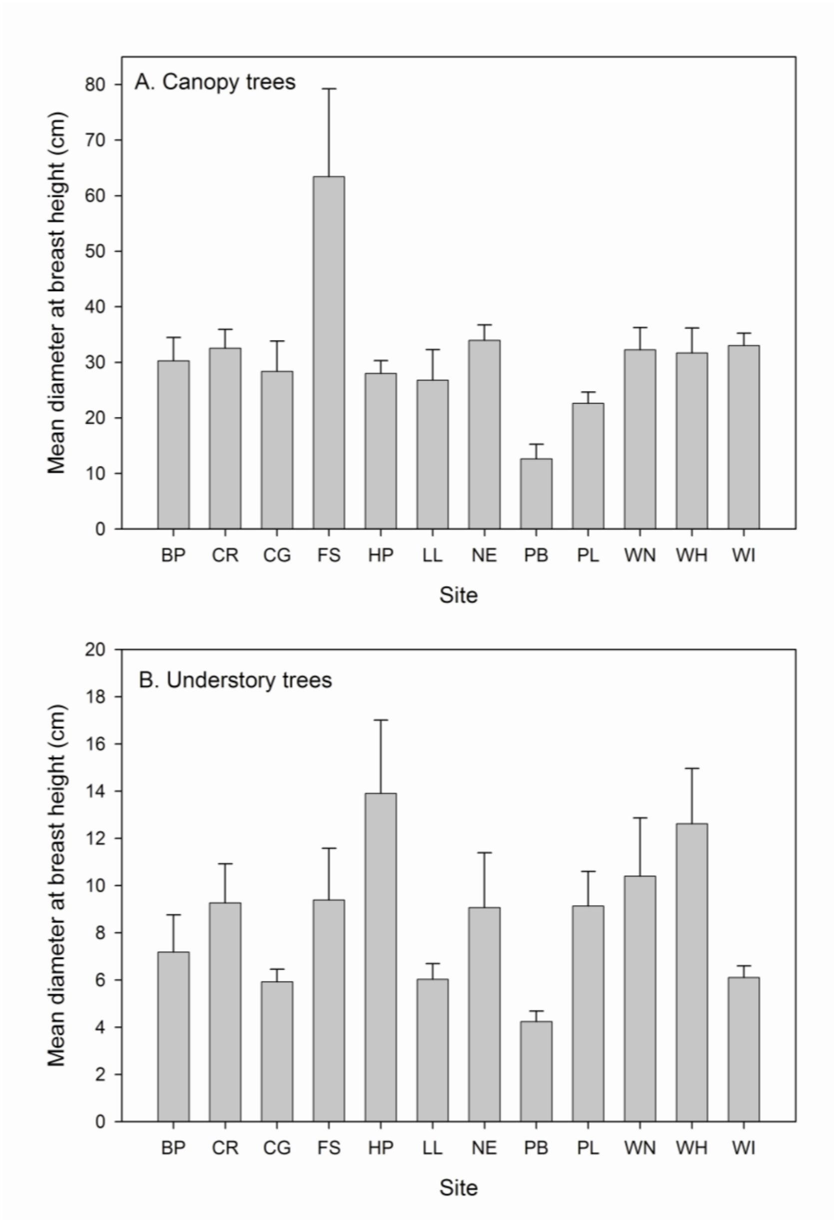

Figure 2. Mean diameter at breast height (dbh) of canopy trees (A) and understory trees (B) at 12 garlic mustard monitoring sites in Minnesota. Note that the y-axes vary.
BP=Baker Park, CR=Coon Rapids, CG=Cottage Grove, FS=Fort Snelling, HP=Hilloway Park, LL=Luce Line, NE=Nerstrand, PB=Pine Bend, PL=Plainview, WN=Warner Nature, WH=Westwood Hills, WI=Willmar

APPENDIX

Appendix 1. Species names, authority, and nativity status in Minnesota. Taxonomy follows the Integrated Taxonomic Information System (http://www.itis.gov/) accessed 4 Feb 2010. Nativity follows Minnesota Department of Natural Resources Vascular Plants of Minnesota -- September 25, 2002 (http://files.dnr.state.mn.us/eco/plant_list9-25-02.pdf) accessed 4 Feb 2010.

Species	**Authority**	**Common name**	**Native/Nonnative**
Acer negundo	L.	box elder	native
Acer saccharum	Marsh.	sugar maple	native
Carya cordiformis	(Wangenh.) K. Koch	bitternut hickory	native
Celtis occidentalis	L.	hackberry	native
Crataegus sp.	L.	hawthorn	native
Fraxinus nigra	Marsh.	black ash	native
Fraxinus pennsylvanica	Marsh.	green ash	native
Juglans cinerea	L.	butternut	native
Malus sp.	P. Mill.	apple	needs to be identified to species
Ostrya virginiana	(P. Mill.) K. Koch	ironwood	native
Pinus strobus	L.	white pine	native
Populus deltoides	Bartr. ex Marsh.	cottonwood	native
Populus granidentata	Michx.	bigtooth aspen	native
Prunus serotina	Ehrh.	black cherry	native
Quercus alba	L.	white oak	native
Quercus bicolor	Willd.	swamp white oak	native
Quercus macrocarpa	Michx.	bur oak	native
Quercus rubra	L.	northern red oak	native
Rhamnus cathartica	L.	common buckthorn	nonnative
Robinia pseudoacacia	L.	black locust	nonnative
Tilia americana	L.	basswood	native
Ulmus rubra	Muhl.	slippery elm	native
Zanthoxylum americanum	P. Mill.	prickly ash	native