

Impacts and treatment of garlic mustard (*Alliaria petiolata*): application of research to populations in the Portland, Oregon metro area

Garlic mustard (*Alliaria petiolata*) may be the most notorious invasive plant of forest understories in North America. It is thought to spread quickly into undisturbed forests and displace native species, including tree seedlings (Rodgers et al. 2008). Garlic mustard has been managed intensively to avoid impacts on native habitat. Recently, however, some have called into question the magnitude of the threat posed by garlic mustard (e.g. Lankau et al. 2009; Cipollini and Cipollini 2016). The purpose of this review is to summarize prominent research on the invasiveness of garlic mustard and the efficacy of control efforts. The relevance of this research to management in the Portland, Oregon metropolitan region is discussed.

Garlic Mustard Background

Garlic mustard is native to Eurasia, and was originally introduced to North America for culinary uses (Grieve 1959). It was documented on the East Coast of the United States in the 1860s (Rodgers et al 2008). By the 1980s garlic mustard had caught ecologists' attention as a potentially invasive species of forest understories (Becker et al. 2011).

Observations of rapid colonization (Rodgers et al. 2008), as well as life-history traits characteristic of strong invaders (Baker 1974) suggest that garlic mustard may be invasive. It attracts generalist pollinators, can self-pollinate (Cavers 1979; Anderson et al. 1996), and produces numerous seeds (Cavers 1979). It also has a rosette growth form (Cavers 1979), considered by Baker (1974) to be a competitive advantage.

Garlic Mustard Dispersal and Establishment

Garlic mustard spreads exclusively by seed, with no vegetative reproduction (Cavers et al. 1979). Unsurprisingly, Biswas and Wagner (2015) found propagule pressure by seed to be the most important determinant of population spatial structure in garlic mustard. Similarly, Eschtruth and Battles (2009) found propagule pressure to be an important determinant of spatial structure, and determined that spread is dominated by local, not long distance, dispersal.

Though garlic mustard has been observed in relatively "intact" forests, several studies have suggested that disturbance facilitates its establishment. Bartuszevige et al. (2007) found

that establishment was significantly enhanced by removal of leaf litter from the forest floor. Nuzzo et al. (1999) found that total garlic mustard cover remained stable or declined over seven years in plots with no disturbance. Cover increased rapidly in plots with periodic disturbance, suggesting that disturbance may be an important component of garlic mustard spread (Nuzzo et al. 1999). Eschtruth and Battles (2009) found a strong interaction between garlic mustard propagule pressure and canopy disturbance. In their study of Eastern hemlock forests, garlic mustard was most successful in sites with the greatest level of canopy decline, caused by an insect, the woolly adelgid. High propagule pressure magnified the response of garlic mustard to high canopy disturbance. Likewise, canopy disturbance magnified its response to high propagule pressure. The authors concluded that consideration of either propagule pressure or disturbance will be incomplete without consideration of the other (Eschtruth and Battles 2009).

Impacts of Garlic Mustard

Garlic mustard is thought to alter forest vegetation by displacing understory species and tree seedlings (Cavers et al. 1979; Rodgers et al. 2008; Miller 2015). Some observational studies have shown changes in native vegetation concurrent with garlic mustard establishment (e.g. Rose et al. 2015). However, the degree to which the negative correlation between garlic mustard and native species is caused by garlic mustard is unclear, and studies of garlic mustard impacts have shown mixed results (Hochstedler et al. 2007; Rose et al. 2015).

In an eight-year monitoring study, Rose et al. (2015) observed significant changes in forest understory vegetation composition, along with expansion of a garlic mustard population. Species richness increased in all study plots, whether or not garlic mustard was present, but native richness was lower in plots with the highest garlic mustard biomass. The calculated importance values of some native species increased, while they decreased for others. Similarity analysis showed significant changes in composition across the study period, even when garlic mustard data were excluded from analysis, indicating that garlic mustard could not be the only driving force behind community change. The authors concluded that native plant response to garlic mustard is species-specific, and longer-term studies are needed to determine the significance of garlic mustard impacts (Rose et al. 2015). In addition to species specificity, Aylward (2016) found that site specificity is an important determinant of a community's response to garlic mustard. Invaded and non-invaded plots were surveyed in forests across

Massachusetts and New York. In linear models, garlic mustard presence was only a significant predictor for one response variable, native Shannon diversity, which contrary to expectations, was higher in invaded than non-invaded plots. All other response variables, including species evenness, native herbaceous density, and invasive species density, were predicted by forest site or the interaction between site and garlic mustard presence. The author concluded that site-level features must be considered in any attempt to determine garlic mustard impacts (Aylward 2016).

Removal studies are conducted to determine the effect of one species on others in a community. Garlic mustard removal studies have resulted in mixed and sometimes conflicting results. Stinson et al. (2007) found that native species diversity, but not richness, increased two years after garlic mustard removal. Graminoids and tree seedlings increased, but there was no response by shrubs or herbaceous plants. They concluded that garlic mustard may directly impact recruitment of some tree species, while change in graminoid cover was most likely due to other environmental factors. In a similar removal study, Dornbush and Hahn (2013) found no effect of garlic mustard removal on richness or diversity. They also observed no response of target restoration species to garlic mustard removal. In a longer-term study, Hochstedler et al. (2007) found no effect of five years of garlic mustard treatment on native richness or diversity.

Other studies have investigated garlic mustard's competitive abilities. Phenological adaptations may improve its performance in the understory relative to native species. An Illinois study found that garlic mustard is most photosynthetically active in April, before canopy closure and emergence of spring ephemerals. Second-year plants also produce shade-adapted leaves in May that harvest light under the closed canopy. The authors suggested that the ability to take advantage of fluctuating light levels may enable garlic mustard to compete strongly with native species (Myers and Anderson 2003). Smith and Reynolds (2015) attempted to show that this phenology improved the competitive success of garlic mustard over understory natives. In a series of microcosm experiments, they altered light levels, germination time, and species richness. While extended leaf phenology promoted garlic mustard growth, there was no evidence that it led to impacts on native species (Smith and Reynolds 2015).

Several studies have tested the strength of competition between garlic mustard and other species. Meekins and McCarthy (1999) grew three native Ohio species, in monoculture and with garlic mustard. One species had lower harvest biomass when grown with garlic mustard than when grown alone. The two other native species had higher biomass with garlic mustard than

alone. Garlic mustard biomass was lower with these two species than alone. Results indicate that in some cases garlic mustard can be a stronger competitor than its neighbors, but in others it is the weaker competitor (Meekins and McCarthy 1999). A Minnesota study found that garlic mustard performance can be reduced by competition from other species. Woodland herbs were planted in plots at four levels of species richness, and garlic mustard seed was added to each plot. Number of emerged seedlings, survival to rosette stage and adulthood, siliques produced, and biomass were quantified. While there was no measurable impact of native species richness, native cover significantly affected all measures of garlic mustard success. These results support the hypothesis that garlic mustard plants are sensitive to competition, and woodlands lacking native vegetation are most susceptible to garlic mustard invasion (Phillips-Mao et al. 2014).

Allelopathy is often considered to be garlic mustard's most important mechanism of impact. Many species in the mustard family produce sulfur-containing compounds called glucosinolates. Glucosinolates are broken down when plant cells rupture to release products that can be allelopathic (Brown and Mora 1995; Vaughn and Berhow 1999). Sinigrin is the most important glucosinolate produced by garlic mustard. Sinigrin, and one of its breakdown products, allyl isothiocyanate (AITC) are the most frequently tested garlic mustard allelochemicals (Vaughn and Berhow 1999; Cipollini and Cipollini 2016). These compounds may affect other species, both directly by inhibiting seed germination and growth, and indirectly by killing mycorrhizal symbionts (Cipollini and Cipollini 2016).

Many studies have investigated the allelopathic properties of garlic mustard, with variable results. Several have reported germination or growth inhibition in response to garlic mustard extracts or to commercially-produced glucosinolates. Roberts and Anderson (2001) reported reduced mycorrhizal fungal germination and tomato and sorghum root growth in samples treated with garlic mustard leachate. Hale et al. (2016) found that *Maianthemum racemosum* treated with leaf extract had lower root biomass and fungal hyphae abundance than untreated plants. Performance reductions in garlic mustard-treated plants were similar to those in fungicide-treated plants. These results support the hypothesis that disruption of underground mutualisms is the mechanism by which allelochemicals affect plants (Hale et al. 2016).

Others have found no significant response of plants to glucosinolate or garlic mustard extract. McCarthy and Hanson (1998) tested the effects of multiple concentrations of garlic mustard root and shoot extracts on the germination and growth of four species. They selected

target species representing different life history strategies and potential sensitivities: radish (*Raphanus sativus* var. scarlet), winter rye (*Secale cereale*), hairy vetch (*Vicia villosa*), and lettuce (*Lactuca sativa* var. black-seeded simpson). Germination was largely unaffected by the extracts, with only radish seeds showing depressed germination rates in response to one concentration. Similarly, only rye biomass showed a response to one concentration. The authors concluded that, overall, results provided little evidence that allelopathy is a primary mechanism of interference with other plant species (McCarthy and Hanson 1998). Several other studies have failed to find significant effects of garlic mustard allelochemicals on native species. In a greenhouse study, Barto and Cipollini (2009) found no effect of glucosinolates on *Impatiens pallida* growth. Portales-Reyes et al. (2015) hypothesized that rhizobia are affected by garlic mustard allelochemicals, potentially reducing the growth of legume species. While some of their glucosinolate mixtures reduced nodulation, biomass, and seed production, the addition of garlic mustard extract had no affect (Portales-Reyes et al. 2015).

Some question has been raised about the relevance of lab and greenhouse chemical addition studies. Cantor et al. (2011) measured sinigrin and AITC in the field, and concluded that most chemical addition studies use much higher concentrations than are actually present in garlic mustard populations. They did find that AITC reduced fungal spore germination when added at concentrations measured in the field. However, impacts *in situ* were less clear; in garlic mustard populations hyphal length was reduced, but not to a statistically significant level. The authors also found that AITC is present sporadically throughout July and August when adults are senescing, and that it has low residence times in the soil (Cantor et al. 2011). The sporadic nature of AITC release combined with quick degradation rates suggest that any allelopathic effects are highly variable throughout the season (Cipollini and Cipollini 2016).

Soil conditioning studies test for allelopathy under perhaps more ecologically realistic conditions. Native species are planted in soil that was previously used to grow garlic mustard. Stinson et al. (2006) found that three tree species had lower mycorrhizal colonization rates and reduced growth in garlic mustard soil than in control soil. In a similar study, Davis et al. (2012) found no effects of garlic mustard soil on germination of four tree species, although it did reveal a nearly significant effect ($p < 0.06$) on growth of one species. Another soil conditioning study considered competition as well as allelopathy. Native species and garlic mustard were grown together and alone, in soil with and without garlic mustard history. In control soil, there was

evidence of competition between garlic mustard and the native species. However, in soil with garlic mustard history, the competitive effect of garlic mustard on other species was significantly reduced. Garlic mustard was most reduced in garlic mustard history soil, perhaps because of nutrient depletion. With the negative impact of garlic mustard soil history on garlic mustard growth, the authors suggested that garlic mustard's impact during invasion may be weaker than previously expected (Poon and Maherali 2015). After a comprehensive literature review on garlic mustard allelopathy, Cipollini and Cipollini (2016) observed that evidence of benefits of allelopathy to garlic mustard fitness are still lacking. They concluded that garlic mustard could be allelopathic in some circumstances, but generally other types of plant interactions, such as nutrient competition, are likely more important (Cipollini and Cipollini 2016).

Is Garlic Mustard a Main Driver of Change?

With so many studies on garlic mustard impacts yielding mixed results, several researchers have proposed that the plant is not usually a driver ecosystem change, but a consequence of other environmental changes. Some studies suggested that population growth of deer and exotic earthworms are major drivers of change in forests, allowing garlic mustard to establish. One study looked at plots in forests with high and low earthworm density, in areas with and without garlic mustard. Deer were excluded from half of the plots. Survival of seeded native species was highest in plots with low earthworm abundance and deer exclusion fencing. Garlic mustard had a neutral effect on native species, not differing from effects of native species in the plots. The authors concluded that deer and earthworms were the main drivers of native species loss in these forests, with garlic mustard having no measurable effect (Dávalos et al. 2015). In another study, garlic mustard abundance increased 30% annually when deer were present, but declined 12% annually when deer were excluded. Native species increased in abundance as well when deer were excluded. The authors concluded that garlic mustard abundance is linked with an overabundant deer population (Kalisz et al. 2014).

In a Wisconsin study, Rooney and Rogers (2011) revisited forested sites that had been surveyed in 1951. Since the original survey, garlic mustard had established in half of the sites. The goal of the study was to determine if changes in the native vegetation could be correlated with the arrival of garlic mustard. While there was a significant loss of native vegetation, this loss was not correlated with the arrival of garlic mustard. While results do not show that garlic

mustard has no impact on native vegetation, the authors concluded that they are consistent with the idea of invasive species as passengers, not drivers of change (Rooney and Rogers 2011).

Garlic Mustard Control

Garlic mustard has been targeted for management by municipalities in United States for several years, and some studies have examined treatment efficacy and native species responses. Many of these studies, as well as anecdotal reports, suggest that eradication is extremely difficult and time-intensive. The two-point life cycle of garlic mustard (Davis et al. 2014) makes treatment particularly difficult. First-year rosettes compete with adult plants, and treatment of adults can improve rosette survival (Slaughter et al. 2007; Herold et al. 2011). Shartell et al. (2012) found that a single year of treatment, either with herbicide or by hand pulling, led to a population increase the following year, not a decrease. Treatment must happen year after year, and be highly effective at removing adults. Herold et al. (2011) concluded that treatment should only happen for small populations that can receive this dedicated treatment. Even with yearly treatment and successful adult removal, they estimated that it would take five years for differences in community composition to be observed (Herold et al. 2011).

A study of garlic mustard control on a New York roadside found that one year of herbicide plus five years of hand pulling did not result in eradication or suppression. The population was monitored each year, and two digital weed management tools were retrospectively applied after six years of treatment. These tools use population data and detection probability to generate treatment recommendations. Monitoring results showed that adult density increased over the six treatment years. The weed management tools indicated that 12 years of treatment would be required for eradication with a 100% success rate each year. If 10% of adults escaped treatment, eradication would take more than 50 years (Corbin et al. 2016).

The soil seed bank is often targeted in weed treatment, with the hope that depletion will lead to eventual eradication of the population (Davis 2006). However, the role of the seed bank in garlic mustard population dynamics, and its importance in treatment are unclear. Slaughter et al. (2007) found that five years of glyphosate treatment did not reduce the seed bank, and consequently, the number of rosettes emerging each year. Germination trials have shown that seed survival beyond two years is low (Roberts and Boddrell 1983), and the authors concluded that the maintenance of the rosette population must be due to continual seed input from outside

the population (Slaughter et al. 2007). Davis (2006) used population models to determine when targeting the seed bank is effective. Biennial garlic mustard, two annual species, and one perennial species were used in the model. Targeting the seed bank was determined to be effective only for the two annual species. The seed bank was only important for garlic mustard when fewer plants survived treatment than is typical for most treatment regimes. These results suggest that targeting the seed bank may not be an effective strategy (Davis 2006).

Garlic mustard in the Portland, Oregon metropolitan region

Garlic mustard was first documented in Oregon in 1959 (Ornduff 1959), although its initial arrival was likely earlier than that. In the Portland metropolitan area, aggressive treatment in parks, natural areas, and roadsides began between 2005 and 2011 in different parts of the region. While many populations have decreased in size, others have been less responsive to treatment (Delepine, personal communication). There is still uncertainty about the distribution of garlic mustard across the region, with new patches found every year (WeedWise 2015).

At this time, no studies on garlic mustard in the Pacific Northwest have been published in the peer-reviewed literature. Risk assessments and management plans have relied on studies from the eastern United States (e.g. Miller 2015), although it is unclear if garlic mustard behaves the same way, in terms of life-history strategy, competition, or allelopathy in this region. The Pacific Northwest differs substantially from the Midwest and East Coast in soil type, temperature and precipitation patterns, and dominant forest vegetation. All of these factors likely affect garlic mustard population dynamics and its impact on other species. There have been anecdotal accounts of native species declining in forests as garlic mustard populations expand, but no studies to determine the degree to which garlic mustard may be causing native decline.

Some observations suggest that garlic mustard behaves differently here than eastern North America. While garlic mustard has been described as a strict biennial on the east coast of North America (Byers and Quinn 1998), managers in the Portland region have reported the plant sometimes behaving like an annual (Bixby, personal communication). Garlic mustard is described as a winter annual or biennial in its native European range (Cavers et al. 1979), so it is possible that it shows flexibility in strategy here as well. An understanding of growth strategy is important for determining both impacts and effective treatment. Annual plants may be at a

competitive disadvantage, and less likely to be problematic (Baker 1974). Meanwhile, the seed bank may play a more important role in its population dynamics and treatment (Davis 2006).

Observational and experimental studies of garlic mustard in the Pacific Northwest should be conducted to shed light on its impacts on other species and on treatment efficacy.

Demographic studies (e.g. Byers and Quinn 1998) and plant phenology studies (e.g. Myers and Anderson 2003; Smith and Reynolds 2015) would help determine the patterns and rates of spread, importance of different life stages, and responses to environmental factors. Competition studies (e.g. Meekins and McCarthy 1999; Phillips-Mao et al. 2014) are necessary to determine how garlic mustard interacts with other species and if it might contribute to their decline.

Studies of response to disturbance (e.g. Dávalos et al. 2015; Kalisz et al. 2014) are particularly important for determining how garlic mustard behaves in the metropolitan area, compared to less-disturbed forests.

Conclusions

Garlic mustard studies from the East Coast and Midwest have not painted a clear picture of its effects in that region. While some studies have found reduced native richness and Shannon diversity in the presence of garlic mustard (Rose et al. 2015, Stinson et al. 2007), others have found either no relationship, or a positive correlation between garlic mustard and native diversity metrics (e.g. Aylward 2016; Dornbush and Hahn 2013). Some studies have shown detrimental effects of garlic mustard allelochemicals (Roberts and Anderson 2001; Hale et al. 2016; Stinson et al. 2006), though field studies have failed to link loss of native species to garlic mustard (e.g. Rooney and Rogers 2011; Dávalos 2015). Even more questions remain about the true impact of garlic mustard in the Pacific Northwest. Research efforts should be undertaken to determine the effects of garlic mustard on other species in the region. Meanwhile, managers must decide if the uncertain impact of this species warrants the expense of the year after year treatment that control will require. Garlic mustard management decisions should be framed within broader habitat management goals and carefully consider the plant composition of the target community.

Christa von Behren
Invasive Species Program
Bureau of Environmental Services
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References

- Anderson, R.C., S.S. Dhillon, and T.M. Kelley. 1996. Aspects of the ecology of an invasion plant, garlic mustard (*Alliaria petiolata*), in Central Illinois. *Restoration Ecology* 4:181-191.
- Aylward, J. 2016. Understory plant community structure in forests invaded by garlic mustard (*Alliaria petiolata*). Masters Theses May 2014 – current. Paper 366.
- Baker, H.G. 1974. The evolution of weeds. *Annual Review of Ecology and Systematics* 5:1-24.
- Barto, E.L. and D. Cipollini. 2009. Density-dependent phytotoxicity of *Impatiens pallida* plants exposed to extracts of *Alliaria petiolata*. *Journal of Chemical Ecology* 35:495-504.
- 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. *The American Midland Naturalist* 158:472-477.
- Becker, R.L., E.J.S. Katovich, H.L. Hinz, E. Gerber, D.W. Ragsdale, R.C. Venette, D.N. McDougall, R. Reardon, L.C. Van Riper, L.C. Skinner, and D.A. Landis. 2011. The garlic mustard (*Alliaria petiolata*) case, what makes a good biological target: The intersection of science, perspectives, policy, and regulation. XIII International Symposium on Biological Control of Weeds, Session 8 Social and Economic Assessments of Biological Control:332-229.
- Biswas, S.R. and H.H. Wagner. 2015. Spatial structure in invasive *Alliaria petiolata*. *Biological Invasions* 17:3211-3223.
- Brown, P.D. and M.J. Morra. 1995. Glucosinolate-containing plant tissues as bioherbicides. *Journal of Agriculture and Food Chemistry* 43:3070-3074.
- Byers, D.L. and J.A. Quinn. 1998. Demographic variation in *Alliaria petiolata* (Brassicaceae) in four contrasting habitats. *The Journal of the Torrey Botanical Society* 125:138-149.
- Cantor, A., A. Hale, A. Justin, M.B. Traw, and S. Kalisz. 2011. Low allelochemical concentrations detected in garlic mustard-invaded forest soils inhibit fungal growth and AMF spore germination. *Biological Invasions* 13:3015-3025.
- Cavers, P.B., Heagy, M.I., Kokron, R.F. 1979. The biology of Canadian weeds. 35. *Alliaria petiolata* (M. Bieb.) Cavara and Grande. *Canadian Journal of Plant Science* 59:217-229.
- Cipollini, D. and K. Cipollini. 2016. A review of garlic mustard (*Alliaria petiolata*, Brassicaceae) as an allelopathic plant. *The Journal of the Torrey Botanical Society* 339-348.
- Corbin, J.D., M. Wolford, C.L. Zimmerman, and B. Quirion. 2016. Assessing feasibility in invasive plant management: a retrospective analysis of garlic mustard (*Alliaria petiolata*) control. *Restoration Ecology*: online.

- Dávalos, A., V. Nuzzo, and B. Blossey. 2015. Interactive effects of deer, earthworms, and non-native plants on rare forest plant recruitment. *Biological Conservation* 187:173-181.
- Davis, A.S. 2006. When does it make sense to target the weed seed bank? *Weed Science* 54:558-565.
- Davis, M.A., A. Colehour, J. Daney, E. Foster, C. Macmillen, E. Merrill, J. O'Neil, M. Pearson, M. Whitney, M.D. Anderson, and J.J. Dosch. 2012. The population dynamics and ecological effects of garlic mustard, *Alliaria petiolata*, in a Minnesota oak woodland. *The American Midland Naturalist* 168:364-374.
- Davis, M.A., C. MacMillen, M. LeFevre-Levy, C. Dallavalle, N. Kriegel, S. Tyndel, Y. Martinez, M.D. Anderson, and J.J. Dosch. 2014. Population and plant community dynamics involving garlic mustard (*Alliaria petiolata*) in a Minnesota oak woodland: a four year study. *The Journal of the Torrey Botanical Society* 141:205-216.
- Dornbush, M.E. and P.G. Hahn. 2013. Consumers and establishment limitations contribute more than competitive interactions in sustaining dominance of the exotic herb garlic mustard in a Wisconsin, USA forest. *Biological Invasions* 15:2691-2706.
- Eschtruth, A.K. and J.J. Battles. 2009. Assessing the relative importance of disturbance, herbivory, diversity, and propagule pressure in exotic plant invasion. *Ecological Monographs* 79:265-280.
- Hale, A.N., L. Lapointe, and S. Kalisz. 2016. Invader disruption of belowground plant mutualisms reduces carbon acquisition and alters allocation patterns in a native forest herb. *New Phytologist* 209:542-549.
- Grieve, M. 1959. *A modern herbal*, vol. 2. New York, Hafner.
- Herold, J., R.M. Anderson, J.T. Bauer, B. Borowicz, and R.C. Anderson. 2011. Comparison of the effect of early and late removal of second-year garlic mustard (*Alliaria petiolata*) on first-year plants and deciduous forest spring and summer dominant herbaceous groundlayer species in central Illinois, USA. *Ecological Restoration* 29:225-233.
- Hochstedler, W.W., B.S. Slaughter, D.L. Gorchov, L.P. Saunders, and M.H.H. Stevens. 2007. Forest floor plant community response to experimental control of the invasive biennial, *Alliaria petiolata* (garlic mustard). *The Journal of the Torrey Botanical Society* 134:155-165.
- Kalisz, S., R.B. Spigler, and C.C. Horvitz. 2014. In a long-term experimental demography study, excluding ungulates reduced invader's explosive population growth rate and restored natives. *PNAS* 111:4501-4506.
- Lankau, R.A., V. Nuzzo, G. Spyreas, and A.S. Davis. 2009. Evolutionary limits ameliorate the negative impact of an invasive plant. *PNAS* 106:15362-15367.

- McCarthy, B.C. and S.L. Hanson. 1998. An assessment of the allelopathic potential of the invasive weed *Alliaria petiolata* (Brassicaceae). *Castanea* 63:68-73.
- Meekins, J.F. and B.C. McCarthy. 1999. Competitive ability of *Alliaria petiolata* (garlic mustard, Brassicaceae), and invasive, nonindigenous forest herb. *International Journal of Plant Sciences* 160:743-752.
- Miller, G. 2015. Oregon Department of Agriculture noxious weed pest risk assessment for garlic mustard *Alliaria petiolata* Brassicaceae. <http://www.oregon.gov/ODA/shared/Documents/Publications/Weeds/GarlicMustardPlantPestRiskAssessment.pdf>.
- Myers, C.V. and R.C. Anderson. 2003. Seasonal variation in photosynthetic rates influences success of an invasive plant, garlic mustard, (*Alliaria petiolata*). *The American Midland Naturalist* 2:231-245.
- Nuzzo, V. 1999. Invasion pattern of herb garlic mustard (*Alliaria petiolata*) in high quality forests. *Biological Invasions* 1:169-179.
- Ornduff, R. 1959. *Alliaria officinalis* Andr. in Oregon. *Madroño* 15:96.
- Peterson, K.J. 2007. Garlic mustard control: is success a possibility? Strategy and potential impact. *In: Meeting the challenge: Invasive plants in Pacific Northwest ecosystems. General Technical Report PNW-GTR 694. U.S. Forest Service Pacific Northwest Research Station. p. 59-62.*
- Phillips-Mao, L., D.L. Larson, and N.R. Jordan. 2014. Effects of native herbs and light on garlic mustard (*Alliaria petiolata*) invasion. *Invasive Plant Science and Management* 7:257-268.
- Poon, G.T. and H. Maherali. 2015. Competitive interactions between a nonmycorrhizal invasive plant, *Alliaria petiolata*, and a suite of mycorrhizal grassland, old field, and forest species. *PeerJ* 3:e1090.
- Portales-Reyes, C., T.V. Doornik, E.H. Schultheis, and T. Suwa. 2015. A novel impact of a novel weapon: allelochemicals in *Alliaria petiolata*. *Biological Invasions* 17:2779-2791.
- Roberts, K.J. and R.C. Anderson. 2001. Effect of garlic mustard (*Alliaria petiolata* (Bieb. Cavara & Grande)) extracts on plants and arbuscular mycorrhizal (AM) fungi. *The American Midland Naturalist* 146:146-152.
- Roberts, H.A. and J.E. Boddrell. 1983. Seed survival and periodicity of seedling emergence in eight species of Cruciferae. *Annals of Applied Biology* 103:301-309.
- Rodgers, V.L., K. 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.

Rooney, T.P. and D.A. Rogers. 2011. Colonization and effects of garlic mustard (*Alliaria petiolata*), European buckthorn (*Rhamnus cathartica*), and Bell's honeysuckle (*Lonicera x bella*) on understory plants after five decades in southern Wisconsin forests. *Invasive Plant Science and Management* 4:317-325.

Rose, S.D., A.G. Endress, P.J. Frank, M.C. Kwit, and J.C. Helge. 2015. Increasing invasion of *Alliaria petiolata* and change in the understory community across eight years in a fragmented Illinois woodland. *Biodiversity Management and Forestry* 2013.

Shartell, L.M., L.M. Nagel, and A.J. Storer. 2012. Efficacy of treatments against garlic mustard (*Alliaria petiolata*) and effects on forest understory plant diversity. *Forests* 3:605-613.

Slaughter, B.S., W.W. Hochstedler, D.L. Gorchov, and A.M. Carlson. 2007. Response of *Alliaria petiolata* (garlic mustard) to five years of fall herbicide application in a southern Ohio deciduous forest. *The Journal of the Torrey Botanical Society* 134:18-26.

Smith, L.M. and H.L. Reynolds. 2015. Extended leaf phenology, allelopathy, and inter-population variation influence invasion success of an understory forest herb. *Biological Invasions* 17:2299-2313.

Stinson, K., S. Kaufman, L. Durbin, and F. Lowenstein. 2007. Impacts of garlic mustard invasion on a forest understory community. *Northeastern Naturalist* 14:73-88.

USDA-APHIS 2016. Guidelines for the USDA-APHIS-PPQ weed risk assessment process. Plant Epidemiology and Risk Analysis Laboratory.
https://www.aphis.usda.gov/plant_health/plant_pest_info/weeds/downloads/wra/wra-guidelines.pdf.

WeedWise. 2015. Garlic Mustard 2015 Report. Clackamas Soil and Water Conservation District.

Vaughn, S.F. and M.A. Berhow. 1999. Allelochemicals isolated from tissues of the invasive weed garlic mustard (*Alliaria petiolata*). *Journal of Chemical Ecology* 25:2495-2504.