Control Methods for the Invasive Plant Garlic Mustard (*Alliaria petiolata*) within Ontario Natural Areas

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This report has been prepared by The Nature Conservancy of Canada to better define strategic management of the invasive species, Garlic Mustard, within Southern Ontario natural areas. The background information, analysis and strategies identified in this document are based on the best available knowledge and are subject to modification based on new information and revised objectives.

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Cover illustrations: (clockwise from left), Garlic Mustard on NCC's Gibwood property (credit: Heather Arnold), Garlic Mustard seedlings (credit: Gary Fewless) Garlic Mustard 1st year basal rosettes (credit: Gary Fewless), and Garlic Mustard flowering adults (credit: Heather Arnold).

Table of Contents

1.0 Introduction

The Nature Conservancy of Canada (NCC) is a national, non-profit organization dedicated to protecting areas of biodiversity for their intrinsic value and for the benefit of future generations. NCC works with partners to secure and manage important habitats and supporting landscapes as the means of conserving a viable legacy of natural ecosystems. NCC's conservation goal is the long-term survival of native species, communities, and ecological systems through the design and conservation of portfolios of sites within all ecological regions of Canada.

The biennial herb Garlic Mustard (*Alliaria petiolata*) is widely recognized as a serious threat to natural habitats and their biodiversity. Garlic Mustard has invaded many NCC properties, particularly in Southwestern Ontario. This report describes Garlic Mustard's relevant life history traits, its effects on natural systems, and recommends two of eight control treatment options. Information was collected from a variety of sources including: scientific journals, internet resources, and interviews with conservation professionals knowledgeable about Garlic Mustard control.

Although updated data is not available, in 1996 Garlic Mustard was documented in at least 37 national and provincial parks and Areas of Natural and Scientific Interest (ANSIs) in Ontario (Haber 1996). Precise data is not available for the total number of NCC Ontario properties that Garlic Mustard has invaded, however in 2007 the approximate frequency of Garlic Mustard populations on NCC properties was as follows: Southwestern Ontario (all properties and easements, i.e. approximately 30); Northwestern Ontario (no properties); Midwestern Ontario (three properties), Central Ontario (one property) and Eastern Ontario (one property). Given the frequency and severity of Garlic Mustard invasions in Southwestern Ontario, focus is on this region's capacity and constraints for Garlic Mustard management.

2.0 Background

2.1 Species Biology and Ecology

Garlic mustard is a moderately tall (up to 1 m) biennial herb in the mustard family. Native to Europe, it has naturalized in North America, North Africa, India, Sri Lanka and New Zealand (Tunyalee and Martin 2000). North America's first records for Garlic Mustard date back to the mid 19th century (Nuzzo 1993a), but in the last few decades its range has rapidly expanded.

The species has many competitive advantages that account for its status as an aggressive, invasive species. These advantages include: a broad ecological niche, rapid seedling growth (including cool season growth), ability to self-pollinate, ability to re-sprout from roots, prolific seed production, and a relatively short vegetative stage (Czarapata 2005; McCarthy 1997; Blossey et al. 2001). Within its native range, 69 insect species, 7 fungi and several viruses are natural predators on Garlic Mustard (Szentesi 1991, Hinz and Gerber 1998). Within North America natural predators do not appear to substantially impact Garlic Mustard populations (Blossey et al. 2001).

Garlic Mustard populations are comprised of two cohorts (stages), not including seeds. Between February and early May of its first growing year Garlic Mustard seeds germinate and form a basal rosette which continues to grow throughout the summer and the following winter during snow-free, above-freezing days. First year rosettes experience high drought-induced mortality (Meekins 2000) and both survival rates and density are positively correlated with summer precipitation (Slaughter et al. 2007).

In spring of the second growing year the plant produces one or more flower stalks, sets seed between mid June and late September and then senesces. Each second cohort plant produces an average of 22 fruit (Tunyalee and Martin 2000), and between 150 and 850 cylindrical black dormant seeds (Huffman 2006). Because of the dual cohort, population sizes fluctuate widely from year to year with the majority of plants in rosette stage in one year, and flowering stage the next year (Meekins 2000). Populations tend to expand rapidly, on average doubling in size every four years (Nuzzo 1999).

Seeds generally remain dormant for up to 22 months in northern populations (Solis 1998) but have been reported to remain viable for up to four years (Baskin and Baskin 1992) and possibly considerably longer (Nuzzo, personal communication 2006). The seed germination rate is between 12 and 100% (Baskin and Baskin 1992; Byers 1988; Cavers et al. 1979; Anderson et al. 1996 as cited in Nuzzo 2000). Survival rates from seedling to mature plant are low, ranging from 1% (Nuzzo 1993) to 2% - 4% (Cavers et al. 1979).

Garlic Mustard has a white taproot with an S-shaped curve at the top. Axillary buds are produced on the upper surface of the S-curve and on the root crown (Nuzzo 2000). Damage to the flower stem stimulates additional, and often multiple, stem growth from these axillary buds.

Anthropogenic seed dispersal appears to be the primary long distance vector, with wildlife, domesticated animals, humans and vehicles as agents of distribution (Nuzzo 2000). Seeds generally fall only a few meters away from the parent plant. Dispersal by wind and water is likely less common.

Garlic Mustard is a habitat generalist most successful in partial shade and moist soils but able to withstand a wide range of light and moisture conditions. The species increases in biomass the least in full sun or full shade conditions versus partial shade (Dhillion and Anderson 1999) and on acidic soils (Anderson and Kelley 1995). It quickly invades forest edges, hedgerows, shaded roadsides, and urban areas. Garlic Mustard can grow on soils of sand, loam, or clay and substrates of limestone or sandstone.

Garlic Mustard is primarily found in disturbed wooded areas, where disturbance has facilitated: seed dispersal (McCarthy 1997); creation of micro sites with reduced competition (Anderson et al.1996); and mixing of seeds with mineral soil (Nuzzo 1993). Within forests, Garlic Mustard is typically first seen along trails and streams, but within a few years spreads throughout the forest (Baskin and Baskin 1992). It invades densely vegetated areas as readily as sparsely vegetated areas, and species-rich areas more readily than species-poor areas (Nuzzo unpublished data). Once established, ongoing disturbance acts to increase Garlic Mustard reproduction and seed output (Byers and Quinn 1998).

2.2 Ecological Impacts

Garlic Mustard is widely regarded as one of the most prevalent and problematic invasive species within eastern North America's deciduous forest communities. Garlic Mustard's invasion (and in many cases domination) of mature forest understory communities is notable because these mature habitats were previously considered relatively resistant to non native herbaceous plant invasions.

Garlic Mustard initially invades forests along areas of disturbance and then spreads as an advancing front with multiple satellite populations (McCarthy 1997). Populations spread on average 5.4m / year with the greatest increases through previously uninvaded areas (Nuzzo 1999). After a few years of spreading, the front meets the satellite populations and forms an extensive monoculture of Garlic Mustard (Nuzzo 1999). Garlic Mustard has been reported to dominate forest understories within 5 to 7 years of initial introduction (Czarapata 2005). Unlike most invasive species Garlic Mustard populations do not appear to decrease with natural succession of the forest ecosystem (McCarthy 1997).

Sites where Garlic Mustard is dominant are distinct in community structure and composition from non invaded sites. Invaded sites typically have lower cover and diversity of herbaceous native plant species than non invaded sites (Nuzzo 2000). Garlic Mustard has also been linked to: inhibiting recruitment of woody seedlings (Meekins and McCarthy 1999); reducing diversity of native plant species (Anderson et al. 1996, McCarthy1997, Meekins and McCarthy 1999, Slaughter et al. 2004); and reducing habitat suitability for ground nesting bird species (Gibson 2006).

Garlic Mustard's displacement of, and dominance over, native vegetation appears to be weakly explained by direct allelopathic effects (McCarthy and Hanson 1998, Prati and Bossdorf 2004); partially explained by competitive superiority (McCarthy 1997, Meekins and McCarthy 1999, Carlson and Gorchov 2004) and

most conclusively explained by inhibition of mycorrhizal activity (Roberts and Anderson 1998, Vaughn and Berhow 1999, Stinson et al. 2006).

Recent studies have suggested that Garlic Mustard, by inhibiting arbusccular mycorrhizal fungi (AMF) activity in native plants, has great potential to substantially alter the structure and function of mature deciduous forests. Over three quarters of all native vascular plant species have associations with mycorrhizal fungi that increase the availability of a wide variety of soil resources. Either through root exudates, leaf litter, or damaged root tissue, Garlic Mustard releases phytochemicals into soils that reduce AMF colonization of plant roots (Roberts and Anderson 1998, Stinson 2006), and reduce plant growth (Stinson et al. 2006). The strength of dependency on AMF varies across plants (Klironomos 2003), and accordingly there is variation in growth reductions of native species in contact with Garlic Mustard (Stinson et al. 2006). In 2006, Stinson and colleagues reported that species with coarse roots (typically slow growing woody plants – e.g. Sugar Maple, Black Cherry, Red Maple) tend to have the highest AMF dependency and suffer the highest reductions (i.e. 50-75%) in growth in association with Garlic Mustard. Weedy non-native species (e.g. Chicory, Dandelion, White Clover and Plantain) suffered the least reduction (i.e. 0-20%) in growth. These results suggest that phytochemical suppression of woody competitors, can explain in part Garlic Mustard's successful invasion of mature forested habitats. Moreover by disproportionately repressing regeneration of canopy tree species, and favouring weedy species it has dramatic implications for changing the composition of forest communities. Native species richness has been shown to take years to rebound following removal of Garlic Mustard (McCarthy 1997).

3.0 Management Goals

Recognizing the prevalence of Garlic Mustard across NCC Southwestern Ontario properties and its ability to spread rapidly, reduce native vascular plant growth, alter forest community structure, and threaten the viability of conservation targets, NCC Southwestern Ontario has explicitly identified control of this species as a priority management activity across many properties (NCC 2007a, 2007b, 2007c, 2006a, 2006b, and 2006c). For these properties, the primary Garlic Mustard management goal is to maintain and enhance the condition of conservation targets[1] by controlling invasions of Garlic Mustard. Specific objectives related to the management of Garlic Mustard include:

- Prevent on site Garlic Mustard seed production in order to deplete the seedbank
- Reduce the area infested with Garlic Mustard
- Restore native species diversity, and seedling density
- Reduce dispersal of seeds from other properties, and prevent the spread of Garlic Mustard within the property
- Encourage control of Garlic Mustard on adjacent properties
- Assess effectiveness of management

Management approaches adopted by NCC must reflect both the best available knowledge and organizational implementation capacity. An ideal management approach would have several of the following characteristics: few negative impacts on native species, single treatment / year, wide window of treatment, low investment of time and funds, and long-term, measurable enhancement of conservation targets.

4.0 Prevention and Early Detection

The most effective method of controlling Garlic Mustard is to prevent its initial establishment (Whitman 2006). Seed dispersal can be reduced by minimizing access through natural areas. Erosional disturbance and seed transport can be prevented by restricting motor vehicles, bicycles, horses and other domestic animals from accessing properties where Garlic Mustard is a concern. Such traffic can be controlled by

[1] NCC southwestern Ontario conservation targets that may be impacted by Garlic Mustard invasions include: treed alvars, deciduous forests, swamp forest wetland complexes, and rolling sand plain forest complexes.

eliminating unnecessary access points (e.g. roads and trails). Where vehicles or domestic animals are permitted, they should be restricted to existing pathways and tires should be cleaned before entrance.

Annual monitoring will ensure that new invasions are promptly detected. Property boundaries, in particular those bordering disturbed areas, should be monitored to assess the likelihood of invasion from adjacent properties. Within a property high risk areas include trails, streams and disturbed areas. These dispersal corridors should also be monitored for Garlic Mustard colonization, and where possible decommissioned so as to prevent Garlic Mustard from spreading to the property interior. Trail users and staff can also be encouraged to knock soil and seeds from their footwear before entering a property. Known invasions should be mapped to guide subsequent early detection and eradication efforts.

5.0 Control Treatments

Once Garlic Mustard is established, prevention and detection strategies must be augmented with control treatments. The most effective control strategy is to prioritise treatment of new or scattered populations over heavy infestations, and to work from the outside edges of an infestation inward – i.e. from least to most infested areas (Hillmer and Liedtke 2003). This will limit Garlic Mustard's ability to spread past its existing boundaries (Czarapata 2005). Where possible, nearby seed sources should also be managed (Myers and Bazely 2003). All control treatments will require repeated annual treatment until the existing, local, seed bank is depleted (> 5 years). Long term treatment is also required where dispersal from adjacent populations sustains local recruitment (Slaughter et al. 2007).

In Southwest Ontario, single year treatments (herbicide, clipping and pulling) with no follow up treatment, have been shown to increase Garlic Mustard density relative to no treatment, and relative to yearly treatment (Murphy et al. 2007). These findings suggest that no management may yield better outcomes than an unsustainable management regime that also increases soil disturbance and creates a favourable competitive environment for Garlic Mustard.

Garlic Mustard plants can produce viable seed even when they are pulled/cut before their fruit have substantially developed (Solis 1998, Herms et al. 2002) Therefore, where feasible, treated vegetation with maturing to mature seeds should be removed from site. In dense invasions, the collection and removal of all treated vegetation (to reduce additional release of phytochemicals into the soil) should also be considered. When dealing with Garlic Mustard invasions, great care should always be taken to minimize soil disturbance (Czarapata 2005).

The variety of locations and conditions under which Garlic Mustard invades means there is not a universally appropriate control treatment and each case needs individual assessment. The ecological and logistical advantages and disadvantages of eight control treatments are outlined below.

5.1 Manual Plant Removal

Manual plant removal techniques include hand pulling, clipping flower heads, and cutting plants at the base. With all manual techniques, successful control requires that both cohorts (i.e. basal rosettes and flowering stems) are removed. Removing only the flowering stems releases the basal rosettes from density dependent intraspecific competition and allows them to flourish (Winterer et al. 2005, Meekins and McCarthy 2002). Where possible, cut or pulled plant material should be removed from the site.

5.1.1 Hand Pulling

Hand pulling is a low-tech strategy for controlling Garlic Mustard invasions. It is most easily done when the soil is damp. The S-shaped root must be carefully broken from below the first curve to avoid re-sprouting from the root's adventitious buds. Pulling creates soil disturbance which likely facilitates population recovery or expansion from the seed bank (Murphy et al. 2007). Hand pulling requires considerable labour and is therefore only feasible when cover is low and in small patches (Myers and Bazely 2003, McCarthy 1997). Examples of long-term, successful control of Garlic Mustard in large

patches using hand pulling are scarce (although see Murphy et al. 2007), likely because of soil disturbance.

5.1.2 Basal Cutting

Cutting at the base of the stem is the least labour intensive of the manual plant removal strategies, and avoids the soil disturbance that pulling creates. This treatment can be done with a scythe or weed whacker, or with secateurs in small invasions with scattered individuals, and with lawnmowers or other mowers in large open patches. Basal cutting was found to be the most effective manual removal technique at preventing continued seed accumulation in the seed bank and increasing plant mortality (Rebek and O'Neil 2005). Cutting or weed whacking from the flowering head progressively downwards will reduce the likelihood of seeds ripening even when the stem is severed (Adair personal communication 2007)

Cutting often encourages vigorous resprouting (Czarapata 2005) likely because it does not remove the upper portion of the root. If cut precisely after flowering and before seed maturation (when the stem becomes tough and fibrous), resprouting is less likely (Czarapata 2005, Murphy 2006, Nuzzo 2006). In order to minimise re-sprouting, stems should be cut when most of the root reserves have been allocated to flowering/fruiting. Because flowering is often staggered within a population, two passes are required as late flowering individuals are cut before flowering and will resprout (Nuzzo personal communication 2006). Before cutting, the site should be evaluated to determine where native species should be avoided. Where Garlic Mustard co-occurs with native species, this strategy becomes more labour intensive.

5.1.3 Clipping Flower Heads

Manual attempts to remove Garlic Mustard also include cutting of just the flower heads. Although this does not disturb the soil; prohibits seed production; and may avoid impacting low growing native species, it encourages growth of new flower heads and repeat treatments can become prohibitively labour intensive (Whitman 2006).

5.2 Herbicide Application

While NCC does not have a policy with respect to application of herbicides, within NCC Southwestern Ontario properties, herbicides will only be considered when they are: unlikely to spread offsite through air or water; non toxic to people or non-target organisms; and not persistent in the environment (Hillmer and Liedtke 2003). While several herbicides may effectively kill Garlic Mustard (e.g. Bentazon, 2,4-D and Aciflourfen; Nuzzo 1996 and 2000), their non target effects, ability to spread offsite through water, and/ or residual life time make them unsuitable for use.

Glyphosate is widely considered the most appropriate herbicide for use on conservation lands. It has very low acute toxicity to mammals and birds and is inactivated once in contact with soil. It rarely reaches the water table or causes other known lasting negative environmental effects. The readily available form of Glyphosate, Roundup®, is only intended for terrestrial use. Because it is water soluble, when it enters waterbodies it may have toxic effects on fish (Pesticide Action Network 1996) and amphibians (Relyea 2005). Treatment using Roundup® should therefore not be employed when rainfall events are expected, and/ or along water bodies. Although not currently available in Canada, Aquamaster, Accord, Rodeo AquaNeat, and Glypro are Glyphosate products that can be used near water as they rapidly dissipate by adsorption to suspended particles and bottom sediments (Czarapata 2005).

Judiciously applied Roundup®[2] at 1 – 3% concentrations to dormant rosettes in late fall or early spring (when temperatures are above freezing, and on snow free days) would meet the standards for herbicide use within NCC Southwestern Ontario properties. A fall application kills first year plants, reducing the next year's seed bearing cohort and reduces the risk of impacting early germinating spring ephemerals. A spring application, if timed to avoid spring ephemerals, could have the added benefit of killing those basal rosettes that have already germinated. Dense litter cover can reduce the success of both spring and fall treatments. Roundup® sprayed in the summer would target both cohorts, but can also kill native vegetation and is therefore only appropriate in Garlic Mustard monocultures.

Fall applications of Roundup® have been shown to reduce Garlic Mustard adult cover by 93-95% (Nuzzo 1991, 1996), 87-100% (Frey et al. 2002), and 44-85% (Carlson and Gorchov 2004). In one experiment, five years of fall spraying reduced adult cover from 8% to 1% but did not reduce rosette cover, likely because of seed rain from adjacent, unsprayed areas (Slaughter et al. 2007).

Roundup® is a non-selective herbicide, however if applied while native species are dormant, its documented effects appear to be restricted to the physiologically active Garlic Mustard and a few native evergreen species (Nuzzo 1996, Carlson and Gorchov 2004). Little data is available on community level responses to Garlic Mustard control. Slaughter and Gorchov (2004) report an increase of spring perennials, but not summer perennials or annuals, following 3 years of fall herbiciding. Five years of Roundup® treatment within an Ohio forest revealed no significant effects on the richness or diversity of non-target native plants (Hochstedler et al. in press).

Herbicide application has several advantages over manual removal of Garlic Mustard. When judiciously applied it greatly reduces the risks of re-sprouting, soil disturbance, and non target species impacts; has a more flexible window of time for application; and is less labour intensive for large scale invasions. In the vicinity of species at risk, Roundup® should be applied using a wick applicator to prevent drift. Where Garlic Mustard density is high, spot spraying with a back pack sprayer will be more efficient.

5.3 Biological Control

Due to the long term investment and only gradual success that has been observed controlling Garlic Mustard by manual removal or herbicides, researchers are investigating more efficient and effective treatments. Biological control, which uses living organisms to control unwanted plant species, has been under investigation since 1998. Four weevils are being studied including *Ceutorhynchus alliariae* and *Ceutorhynchus roberti* both of which mine Garlic Mustard stems; *Ceutorhynchus scrobicollis* which mines Garlic Mustard roots; and *Ceutorhynchus constrictus* which develops inside Garlic Mustard seeds. *C. scobicollis* has been found to be the most damaging to Garlic Mustard and is being tested under quarantine in the USA (Coombs et al. 2004).

Currently biological control methods for Garlic Mustard are unavailable for use on NCC properties as they are still in the research stage and have unknown levels of risk and effectiveness. Staff treating Garlic Mustard should maintain awareness of research developments and consider adopting biological control if it appears to be an improvement over existing practices.

5.4 Corn Gluten

Experiments with corn gluten applied to the soil where seeds have dispersed have shown some success in killing seedlings (Czarapata 2005). Corn gluten prevents seedlings from developing secondary roots thereby depriving them of moisture and nutrients (Whitman 2006). Corn gluten is not appropriate for use

[2] Roundup® should be applied under growing conditions (i.e. leaves must be green). Do not apply if rainfall is forecast immediately after application or if winds are strong. Spray coverage should be uniform and complete and directed with the nozzle tip close to the leaves (do not spray weed foliage to the point of runoff). Foliage should be dry before spraying. Use a water soluble dye to delineate sprayed areas. Hand wicking should be used for scattered populations, or in the vicinity of species at risk (Monsanto Canada 2002, Hillmer and Liedtke 2003).

in natural areas because it is non-selective and halts germination of all seeds (Toronto Master Gardeners 2004).

5.5 Intensive Planting

A method of Garlic Mustard control that is currently being tested by the Iowa Native Plant Society is to intensively over-plant Garlic Mustard infested areas with common, fast-growing, shade-tolerant native plants (Whitman 2006). A one year transplant study showed that transplanting 9 or 11 ramets/ m^2 of Bloodroot in Garlic Mustard invasions greatly reduced the number of Garlic Mustard basal rosettes (Murphy 2005). Further, long-term, research is required to justify intensive planting as a control strategy. This strategy's value may be greatest in combination with other control methods.

5.6 Light Alteration

Alteration of light conditions, (e.g. by removing trees and increasing sun exposure) was found to be an ineffective control method due to Garlic Mustard's ability to survive in a wide range of light conditions (Myers et al. 2005).

5.7 Controlled Burning

Controlled burning has been reported to be both effective (Myers & Bazely 2003, Nuzzo et al. 1996) and ineffective (Tunyalee and Martin 2000, Luken and Shea) in reducing Garlic Mustard populations. A slow hot fire is needed to burn through the litter layer, kill the root crown, and prevent resprouting (Nuzzo et al. 1996). In the short term, burning off leaf litter can improve growing conditions for Garlic Mustard (McCarthy 1997, Luken and Shea 2000). Therefore, long term success requires burning every year until the seedbank has been depleted (Nuzzo personal communication 2006). In Southwestern Ontario, dense Garlic Mustard stands have been observed to extinguish a controlled burn, suggesting burning is not an appropriate regional solution (Duncan personal communication 2006). Burning should only be undertaken where it is appropriate to the historic disturbance regime.

5.8 Passive Treatment

Taking no action to control Garlic Mustard would be appropriate if: Garlic Mustard had no adverse ecological effects; populations diminish naturally over time; alternative solutions pose greater ecological risks than benefits; or there are no known or feasible solutions. Research and the experiences of conservation professionals have confirmed that Garlic Mustard populations strongly impact native communities and do not wane in size over time. Preliminary research also indicates that available control methods can be applied with minimal impacts on non target species. It could be argued that areas with extremely dense Garlic Mustard populations may take 10+ years to control and that the required investment is prohibitively expensive. However, where the viability of conservation targets is compromised, a long term, incremental, control strategy is strongly recommended over allowing invasions to continue spreading

6.0 Control Method Summary and Recommendations

In Southwestern Ontario NCC requires a Garlic Mustard control strategy that is effective and efficient in the long term. Property managers should aim to treat Garlic Mustard as soon after detection as possible to minimise further invasion and long term damage to ecosystem structure and function. Given Garlic Mustard's prevalence in Southwestern Ontario, its seed bank longevity, and its impact on AMF, immediate extermination of the species and restoration of native species diversity should not be expected. Incremental, statistically significant progress (i.e. reduction in flowering Garlic Mustard stem density, and increased density of native species) however should be achievable within 3-5 years of concerted treatment (McCarthy 1997). Long term commitment and funding for treatment is essential, as aborted treatment may prove to be worse than doing nothing.

In areas where Garlic Mustard is known to occur, NCC properties should be monitored annually for new invasions. High risk areas include disturbed areas, trails, and along waterbodies. Where possible these areas should be protected from invasions, for example by closing trails.

As this report has shown, there is no single solution for controlling Garlic Mustard. The costs and potential risks of any one method must be compared with the alternative, inaction, and allowing Garlic Mustard to continue invading natural areas. Manual removal (basal cutting) and Roundup® application (1 - 3% solution) are the only approaches that currently have demonstrated quantitative success in reducing Garlic Mustard populations with minimal impacts on non target species. Both approaches have distinct advantages.

Basal cutting is recommended where: Garlic Mustard population density is low, native species are sparse, waterbodies are nearby, leaf litter smothers winter basal rosettes, and a labour force is readily available to act immediately and repeatedly before seeds begin to mature.

Roundup® application is widely regarded by conservation professionals as the most effective and efficient control, and is recommended where: Garlic Mustard populations are dense and extensive, evergreen native species are sparse, non evergreen native species are dense, basal rosettes are not smothered by leaf litter, and a labour force is more constrained in availability.

An aggressive control approach (that aims to remove 75 – 100% of live Garlic Mustard individuals/ year and that tolerates some non-target mortality) is likely to more significantly reduce Garlic Mustard populations and allow for ecosystem recovery than a conservative treatment (i.e. removal of 25%, with no tolerance for non-target mortality). Conservative treatment (e.g. wick application of herbicide or manual cutting) is appropriate where species at risk or other species of conservation significance occur.

Where capacity allows, combining multiple approaches is likely to accelerate the success of Garlic Mustard control (Myers and Bazely 2003, Nuzzo personal communication 2006, Hochstedler et al. in press) and reduce the likelihood of long term selection for resistance to single treatment approaches. A fall herbicide will kill 2nd cohort individuals. This can be followed by a spring herbicide (if spring ephemerals have not yet emerged) to kill 1st cohort individuals and / or a summer basal cutting to kill remaining 2nd cohorts before they set seed. Because Garlic Mustard density increases with precipitation, management efforts should be intensified following a wet summer (Hochstedler et al. in press)

When many properties are simultaneously invaded by Garlic Mustard, such as is occurring in Southwestern Ontario, and capacity is limited, land managers must prioritize their efforts to control Garlic Mustard. Sites with the greatest perceived conservation value and the smallest Garlic Mustard populations should be addressed first. Smaller populations have a greater chance of successful control and the required investment is low relative to the potential benefits. Small invasions have the highest increase in population density and are very likely to become large and much more challenging to manage if not treated in a timely manner.

Whether an infestation is eliminated, contained, or allowed to expand depends largely upon the speed and effectiveness of management while the infestation is still small. Large scale invasions should be considered a secondary priority, but should be treated as soon as capacity allows to prevent further accumulation of Garlic Mustard in the seed bank. Staff should actively engage adjacent landowners throughout treatment and encourage complementary treatment on their properties. Without Garlic Mustard treatment on these adjacent properties, natural area populations will be maintained by these external seed sources.

The ability of plant communities to re-colonize once Garlic Mustard is removed is unclear from available research. Because of the AMF-inhibiting phytochemicals released by Garlic Mustard, re-planting may eventually be needed to ensure that re-growth includes native species and not just other weedy species which may take this opportunity to invade.

7.0 Effectiveness Monitoring

Quantitative, annual, long-term monitoring of Garlic Mustard and native species will allow managers to assess the effectiveness of control strategies, and the need for adaptive management. Baseline data should be collected before treatment begins, and annually thereafter. Summer monitoring is recommended to capture the greatest diversity of native vegetation and both Garlic Mustard cohorts. Because Garlic Mustard populations alternate annually between high and low density, several years of data is required to determine an actual increase or decrease in Garlic Mustard populations (Myers and Bazely 2003). Effectiveness monitoring programs should be designed to be cost-efficient so that resources available for control are not unreasonably depleted.

Quantitative effectiveness monitoring can be undertaken using permanent 1 x 2 m plots (systematically located along transects) within the area where management will or has occurred, and just beyond, to track changes in Garlic Mustard and native species populations over time. A minimum of two transects is recommended, with sampling plots separated by 5-10 m, yielding a minimum total of 12 plots for each control technique. Plots corner/s should be identified with permanent markers (e.g. 30-50 cm rebar, plastic or aluminum conduit driven into the ground). Where environmental parameters vary greatly, additional plots should be monitored. Monitoring transects should situated so as to be protected from other uses that might confound the management impacts (e.g. burning, trails, vandalism etc). Where possible, the perimeters of an invasion should be marked and georeferenced annually.

Parameters that should be recorded include: species frequency, cover, and density (Nuzzo 2000). Separate data should be collected for each Garlic Mustard cohort (i.e. basal rosettes and flowering adults). Coarse environmental parameters (i.e. ELC, canopy cover, % cover of bare ground, litter cover, wood and rock) should also be referenced to each plot. Clear records of control approach (e.g. fall spray 2% Roundup, July basal cutting 75% of adults cut pre seed development) should be maintained across the monitoring plots. Care should be taken while monitoring to avoid trampling vegetation in and near the quadrat. See Table 1 for a sample monitoring form.

Table 1.Sample Garlic Mustard Monitoring Form

Property Name:	Observer/s:	Monitoring Date (dd/mm//yy):	
Plot Code:	UTM coordinates NAD83	N:	E:
ENVIRONMENTAL DATA			
% Cover Rock:	% Cover Litter:	% Cover Wood:	
% Cover Bare Ground:	ELC type:	Control History:	
% Canopy Cover:	Notes:		
SPECIES PERCENT COVER (in 5% increments)			
Species Name	**% Cover**	**Species Name**	**% Cover**
Adult Garlic Mustard			
Seedling Garlic Mustard			

8.0 Conclusion

Garlic mustard (*Alliaria petiolata*) is an invasive herbaceous biennial herb that poses a serious threat to the ecological diversity of natural areas in Southwestern Ontario. This report emphasises the importance of invasion prevention through annual monitoring of properties, and where possible creating dispersal barriers. Where Garlic Mustard populations have already established, management should prioritise controlling those with the greatest threat to conservation targets, tackling new and scattered populations before heavy infestations, from the outside edges inward.

Two main control methods are recommended in this report. The first is manual cutting of entire populations of Garlic Mustard at the base before seed maturation and disposing of the cut material off site. The second recommended method is chemical treatment using a 1 to 3 % solution of glyphosate applied during the dormant season of native species. Wick application is recommended for populations within the vicinity of species at risk, and spray application is otherwise recommended. Manual treatment is appropriate for small invasions, or large invasions with few native species. Glyphosate treatment is recommended for large invasions with many native species. For accelerated results, both chemical and manual treatment can be undertaken.

All treatment methods require repeated treatment for at least 5 years as Garlic Mustard seeds may remain viable in the seed bank for this length of time and single, one-off, treatments may exacerbate the invasion. Monitoring data should be used to determine the success of the methods, and the plan of action should remain flexible to accommodate unexpected outcomes.

This document should be reviewed and adapted where new information becomes available. When Garlic Mustard invasion is listed as a threat in any property management plan, this report can be used to help determine the most appropriate management strategies.

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