

## ELEMENT STEWARDSHIP ABSTRACT

for

*Alliaria petiolata*

(*Alliaria officinalis*)

Garlic Mustard

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## SPECIES CODE

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## SCIENTIFIC NAME

*Alliaria petiolata* (M. Bieb.) Cavara and Grande

*Alliaria petiolata* is the correct name for this species. In American floras this species is often referred to as *Alliaria petiolata* Andrz. Names used in older floras include *Alliaria alliaria* L. (Britton), *Sisymbrium alliaria* Scop., *Sisymbrium officinalis* DC (not *S. officinale*), and *Erysimum alliaria* L.

The genus name *Alliaria* refers to the garlic or *Allium*-like fragrance of the crushed leaves, an unusual odor for the mustard family. The species name *petiolata* refers to the petiolate leaves.

## COMMON NAMES

GARLIC MUSTARD is the most widely and virtually only common name used in North America. Additional common names, used primarily in England and old pharmacopias, include Hedge-garlic, Sauce-alone, Jack-by-the-Hedge, and Poor-man's-mustard, and less frequently Jack-in-the-Bush, Garlic Root, Garlicwort, and Mustard-root (de Bray 1978, Brooks 1983). Common names reference the European use of this plant as a potherb (Fernald et al. 1958), and the edge habitat in which it frequently occurs.

## DESCRIPTION and DIAGNOSTIC CHARACTERISTICS

*Alliaria petiolata* is an obligate biennial herb of the mustard family (Brassicaceae). Seedlings emerge in spring and form basal rosettes by midsummer. Immature plants overwinter as basal rosettes. In the spring of the second year the rosettes (now adult plants) produce flower stalks, set seed, and subsequently die.

Basal leaves are dark-green and kidney-shaped with scalloped edges, 6-10 cm diameter. Stem leaves are alternate, sharply-toothed, triangular or deltoid, and average 3-8 cm long and wide, gradually reducing in size towards the top of the stem. All leaves have pubescent petioles 1-5+ cm long. New leaves produce a distinct garlic odor when crushed. The fragrance fades as leaves age, and is virtually non-existent by fall.

Plants usually produce a single unbranched or few-branched flower stalk, although robust plants have been recorded with up to 12 separate flowering stalks. Flowers are produced in spring (usually April to May) in terminal racemes, and occasionally in short axillary racemes. Some plants produce additional axillary racemes in mid-summer. Flowers are typical of the mustard family, consisting of four white petals that narrow abruptly at the base, and 6 stamens, two short and four long. Flowers average 6-7mm in diameter, with petals 3-6mm long. Fruits are linear siliques, 2.5-6cm long and 2mm wide, held erect on short (5mm), stout, widely divergent pedicels. Individual plants produce an average of 4-16 siliques. Siliques contain an average of 10-20 seeds, arranged alternately on both sides of a papery sinus. Seeds are black, cylindrical (3mm x 1mm) and transversely ridged, and range in weight from 1.62-2.84mg.

Adult plants range in height from 0.05m to 1.9m, and average 1.0m, at the time of flowering.

Immature plants can be confused with other rosette-forming species, especially violets (*Viola* sp.), white avens (*Geum canadense*), and *Cardamine* sp in midwestern and northeastern states, and fringe cup (*Tellima grandiflora*) and piggy-back plant (*Tolmiea menziesii*) in western states. *Alliaria petiolata* can be distinguished from these plants by the strong garlic odor in spring and summer. In fall and winter *Alliaria* can

be distinguished by examining the root system. *Alliaria petiolata* has a slender, white, taproot, with a distinctive "s" curve at the top of the root, just below the root crown (Nuzzo, personal observation). Axillary buds are produced at the root crown and along the upper part of the "s".

Chromosome number of  $2n=36$  has been recorded for European material, and  $2n=24$  for North American and European material (Cavers et al. 1979). An analysis of genetic variation indicated that North American populations may have originated from multiple introductions from Europe, most likely the British Isles, as well as Belgium and The Netherlands (Meekins 2000).

Excellent illustrations are contained in Cavers et al. (1979). Descriptive characteristics derived from Cavers et al. (1979) and Gleason and Cronquist (1991) except where otherwise noted. There is one other species in this genus (Gleason and Cronquist 1991).

#### STEWARDSHIP SUMMARY

*Alliaria petiolata* invades forested communities and edge habitats. The plant has no known natural enemies in North America, is self-fertile, and is difficult to eradicate once established. Thus, the best and most effective control method for *Alliaria petiolata* is to prevent its initial establishment.

In shaded and partially shaded communities lacking *Alliaria petiolata* the preferred method is to monitor annually, and remove all *Alliaria petiolata* plants prior to seed production. Once it is established, the management goal is to prevent seed production until the seed bank is depleted, potentially 2-5 years. Cutting of flowering stems at ground level provides the most effective control with minimal or no side effects, but has a high labor cost. Burning and herbicide application both provide control at a lower labor cost, but each has potential drawbacks: Fire may increase total presence of *Alliaria petiolata*, and may alter ground-layer composition; and herbicides may negatively impact some native ground-layer species. The method of choice depends on the size of infestation, the type of community invaded, and the work-force available. In all cases, control must be continued annually until the seedbank is exhausted. Frequency and abundance of *Alliaria petiolata* in unmanaged sites limit effectiveness of single site management, as seeds are continually imported into the managed site. Once *Alliaria petiolata* is well established, successful control is unlikely without considerable expenditures of labor and money over an extended period of time. Biological control for this species is in development.

#### IMPACTS (THREATS POSED BY THIS SPECIES)

*Alliaria petiolata* is one of the few alien herbaceous species that invades and dominates the understory of forested areas in North America. Its phenology is typical of cool-season European plants, and *Alliaria* grows during early spring and late fall when native species are dormant.

*Alliaria petiolata* dominated sites frequently have low native herbaceous richness and cover, and it has been implicated as the cause of this low diversity (Anderson et al. 1996, McCarthy 1997, White et al. 1993). However, little research has been conducted to document this assumption. In a laboratory experiment Meekins and McCarthy (1999) documented that *Alliaria petiolata* outcompeted seedlings of chestnut oak (*Quercus prinus*) but was in turn outcompeted by seedlings of boxelder (*Acer negundo*) and the annual jewelweed (*Impatiens capensis*). In a field experiment, McCarthy (1997) found that removing garlic mustard resulted in greater relative cover of annual species, although actual percent cover of annuals was equal or greater in plots with garlic mustard. Nuzzo (unpublished) conducted an 8-year monitoring study in Illinois and found that in areas with garlic mustard, cover of native perennial herbaceous species declined significantly but species richness did not change. In Ohio, McCarthy (1987) found no correlation between species diversity and *Alliaria petiolata* biomass, and determined that species richness was similar in plots

with and without *Alliaria petiolata*.

Garlic mustard may threaten some butterfly species. Adults of several native butterfly species (*Pieris napi oleracea*, *P.n. marginata*, *P. virginensis*) lay eggs on garlic mustard, but many or all of the larvae die before completing development (Bowden 1971). Thus, garlic mustard serves as a population sink for these species.

This is of particular concern with the rare West Virginia White Butterfly (*Pieris virginensis*) which lays eggs on garlic mustard in the absence of the related native host plant, *Dentaria* [*Cardamine*] *diphylla* (Porter 1994).

*Alliaria petiolata* is most widespread in the midwestern and northeastern United States and in southern Ontario. Canada lists *Alliaria petiolata* as one of four principal invasive aliens in upland habitats (White et al. 1993). Connecticut, Illinois, Indiana, Missouri, and Wisconsin have developed vegetation management guidelines for *Alliaria petiolata* (Brunelle 1996, Nuzzo et al. 1990, Smith 1993). Vermont ranks *Alliaria petiolata* as a category 1 species ("highly invasive") (Vermont DEC 1998), and Minnesota ranks *Alliaria petiolata* as a "moderate" threat ("species shows invasive behavior, and known to impact native species, or has a wide distribution and statewide abundance") (Minnesota DNR 1991).

*Alliaria petiolata* appears to alter habitat suitability for native birds, mammals, and amphibians, and may affect populations of these species. No studies have been conducted of the interaction between *Alliaria petiolata* and these native animals, however. *Alliaria petiolata* is avoided as a food plant by white-tailed deer in Illinois (Nuzzo personal observation), but may be consumed by deer in Ontario (Cavers et al. 1979). White-tailed deer may enhance spread of this species by distributing seed short distances, by exposing bare soil through hoof action, and by consuming native herbaceous species, thereby reducing native competition and increasing available habitat for *Alliaria petiolata*. No deer-*Alliaria petiolata* studies have been conducted to substantiate these observations.

## GLOBAL RANGE

*Alliaria petiolata* is native "throughout Europe from about 68° north southwards, but less common in the extreme south" (Tutin et al. 1964), occurring from England (Martin 1982) east to Czechoslovakia (Lhotska 1975), and from Sweden and Germany south to Italy, but is noticeably absent from Iceland, the Azores, Sardinia and Spitsbergen (Tutin et al. 1964). *Alliaria petiolata* also occurs in North Africa, India, Sri Lanka (Cavers et al. 1979), and has spread to New Zealand (Bangerter 1985) and North America (Cavers et al. 1979, Gleason and Cronquist 1991, Nuzzo 1993a).

The North American range extends from British Columbia (Cavers et al. 1979, White et al. 1993), Washington, and Oregon in the west, and in the east from New England (Gleason and Cronquist 1991), and Ontario (Cavers et al. 1979) to Tennessee (Nuzzo 1993a), Georgia (B. Blossey, p.c.) and westward to Arkansas, Kansas and South Dakota (herbarium specimens). *Alliaria petiolata* was first recorded in North America in 1868 on Long Island NY, and by 2000 had spread to 34 states and 4 Canadian provinces. This plant has spread exponentially since introduction (Nuzzo 1992b, Nuzzo 1993a).

In the United States *Alliaria petiolata* is most abundant in the New England and Midwestern states, but also has populations established as far west as North Dakota and Kansas, and south to Georgia and Arkansas. Infrequent collections from mountain states indicate the plant may be a sporadic rather than established component of the regional flora, and/or in the process of becoming established in Utah (1971, 1983, 1984) and eastern Colorado (1952, 1958, 1966) (dates of herbarium collections). In the western states, *Alliaria petiolata* is established in Portland, Oregon, and several locations in Seattle WA.

In Canada *Alliaria petiolata* is well established in Victoria and Vancouver, British Columbia (Cavers et al.

1979, White et al. 1993), and in the St. Lawrence Valley from Point Pelee in Ontario to Quebec City in Quebec (Cavers et al. 1979). *Alliaria petiolata* is especially abundant in southwestern Ontario, and near Toronto and Ottawa (White et al. 1993). White et al. (1993) recorded the plant as common in deciduous woods on the Canadian Shield, although 25 years earlier Cavers et al. (1979) stated the plant was noticeably absent from the region.

## HABITAT

In its native Europe, *Alliaria petiolata* is an edge species, growing in hedges and fencerows (Fitter et al. 1974, Martin 1982) and in open woods (Wilmanns and Bogenrieder 1988). It is disturbance adapted, and is frequently a component of ruderal communities (Swies and Kucharczyk 1982), including open, highly disturbed forests (Klauck 1986) in Europe.

In North America, *Alliaria petiolata* is most common in deciduous forest (Cavers et al. 1979, Nuzzo 1992, 1993a, Trimbur 1973, Byers and Quinn 1998), and also occurs in the partial shade characteristic of oak savanna, forest edges, hedgerows, shaded roadsides, and urban areas, and occasionally in full sun (Nuzzo 1991). It grows best in partial or filtered light; Dhillion and Anderson (1999) found that both biomass and photosynthetic rates increase as light levels increase, except that at full light photosynthesis declines. Thus, *Alliaria petiolata* is less successful in full sun and full shade than in partial shade (Dhillion and Anderson 1999). Garlic mustard is common in low-quality forests (Hawkes and Abrahamson 1994, Schwartz and Heim 1996) and less frequent in isolated woodlots (forest 'islands' surrounded by crop 'oceans') (Brothers and Springarn 1992). It is rarely found under coniferous trees in the Midwest, but has been reported from under seven species of coniferous trees in Ontario (Cavers et al. 1979).

*Alliaria petiolata* grows on sand, loam, and clay soils, and on both limestone and sandstone substrates, and is rarely found on peat or muck soils. It frequently grows in well-fertilized sites (Cavers et al. 1979), and is described as a nitrophile by Passarge (1976) and Wilmanns and Bogenrieder (1988). In Europe, *Alliaria petiolata* increased in cover with deposition of air-borne industrial emissions, which increased soil nitrogen, nitrate, phosphorous and pH (Wilmanns et al. 1986, Wilmanns and Bogenrieder 1988). In the British Isles, *Alliaria petiolata* is associated with calcareous soils (Clapham et al. 1962). In the U.S., it has been recorded growing on soils with pH 5.0 to 7.2 (Byers and Quinn 1998, Anderson and Kelley 1995), and may be less common on soils of lower pH (Anderson and Kelley 1995, Grime et al. 1988). Under laboratory conditions, *Alliaria petiolata* biomass increased as pH increased from 4.2 to 6.3 (Anderson and Kelley 1995).

*Alliaria petiolata* is common in river-associated habitat, particularly in the Northeast (Nuzzo 1993a). It may preferentially invade drier forest communities in the Midwest than it does in the northeast (Nuzzo 1993a). This is supported by the higher presence along railroads in the Midwest (Nuzzo 1993a), which are generally indicative of drier habitats. Byers and Quinn (1987) reported that *Alliaria petiolata*, once considered a plant of floodplains and moist woods in New Jersey, had become common in a wider range of habitats. In the Great Plains garlic mustard is most frequently recorded from moist, usually riverine, habitat and waste ground (Kansas and Oklahoma), while on the eastern edge of the Rocky Mountains it has been recorded along hiking trails (Utah), and on the grounds of a hotel and around a beaver pond (Colorado).

## BIOLOGY-ECOLOGY

*Alliaria petiolata* seeds germinate in early spring, beginning in late February or early March, and concluding by mid May in northern states and Canada (Cavers et al. 1979, Roberts and Boddrell 1983). In northern Illinois, germination coincides with emergence of spring beauty (*Claytonia virginica*) and false mermaid weed (*Floerkea proserpinacoides*).

Seedling density in heavily infested forests was recorded at 5,080/m<sup>2</sup> at the cotyledon stage, and 2,235/m<sup>2</sup> at the 2-3 leaf stage, in northern Illinois (Nuzzo unpublished), at 830-1800/m<sup>2</sup> in central Illinois (Anderson et al., 1996), and approximated at 20,000/m<sup>2</sup> in Ohio (Trimbur 1973). Seedlings undergo high mortality, declining by 30% to more than 50% (Trimbur 1973, Cavers et al. 1979, Byers and Quinn 1998) by late spring.

By June seedlings develop the characteristic rosette of first year plants. First year rosettes are sensitive to summer drought (Byers and Quinn 1998, MacKenzie 1995) and 60-90% die by fall (Byers and Quinn 1998, Anderson et al. 1996). By mid-fall rosettes average 4-10 cm diameter (range 1-15 cm) and are dark green to purplish in color. The rosettes continue to grow in winter during snow-free periods when temperatures are above freezing (Cavers et al. 1979, Anderson et al. 1996). Natural mortality continues through winter: in northern Illinois rosette density in November averaged 186.4/m<sup>2</sup> (range 50-466/m<sup>2</sup>), and declined significantly to an average of 39.9/m<sup>2</sup> (range 4-102/m<sup>2</sup>) by the following spring (Nuzzo 1993b).

Total survival rate from seedling to adult stage varies from 1.4% to 42.3% (Meekins 2000, Anderson et al. 1996, Byers and Quinn 1998, Cavers et al. 1979) and is strongly influenced by weather, with lower survival in years with dry summers (Meekins 2000).

*Alliaria petiolata* is an obligate biennial: all plants that survive the winter produce flowers in their second year, regardless of size, and subsequently die (Cavers et al. 1979, Byers and Quinn 1998, Bloom et al. 1990, Meekins 2000). Plants only 5cm tall, with 3-4 leaves, have been observed with flowers and seeds. The majority of plants are taller, averaging 0.7 to 1.0 meters when in flower. Plant height is influenced by available light; plants in deep shade averaged 46 cm tall while plants in partial shade averaged 77.5 cm tall (Meekins 2000). Maximum growth occurs at 50% of full light (Meekins 2000). Flower stalks begin to elongate in March or April, growing at the rate of 1.9cm/day (Anderson et al. 1996), and flowers open early April through May. Stem elongation and flowering activity are presumably temperature-related; in England, long-term studies have documented that *Alliaria petiolata* flowers open 4 to 6.6 days earlier with each 1 degree C increase in temperature (Fitter et al. 1995, Sparks and Yates 1997). *Alliaria petiolata* flowering period occurs some 6-10 weeks after new seedlings germinate; in established populations in northern locations generations overlap, and two cohorts can be seen from March through June. Most flowers open by 1100 hr (Cruden et al. 1996). Flowers remain open for 2 (3) days, but nectar production and insect visitation occur primarily on the first day of flowering (Cruden et al. 1996). *Alliaria petiolata* flowers can be self- or cross-pollinated (Cavers et al. 1979, Babonjo et al. 1990, Anderson et al. 1996). Flowers that are not insect pollinated automatically self-pollinate (Cruden et al. 1996). Pollinators include medium and small sized solitary bees (primarily Andrenidae and Halictidae), medium sized flies (primarily Syrphidae) and rarely a honey bee or bumblebee (Cruden et al. 1996). Midges visit flowers and may effect pollination (Cavers et al. 1979). Seed production is similar for both self-pollinated and cross-pollinated flowers (Anderson et al. 1996). Whether in-bred or out-bred, *Alliaria petiolata* plants maintain substantial genetic variation within populations (Byers 1988). Because *Alliaria petiolata* is self fertile, a single individual is sufficient to populate or repopulate a site.

Plants usually produce 1-2 flowering stems, although a single individual may produce up to 12 separate stems. Damage to the primary flower stem stimulates growth of additional stems (Cavers et al. 1979) from axillary buds at the stem base and along the root crown, although such damage is not a prerequisite for development of multi-stem plants (Nuzzo personal observation). Some plants continue to produce flowers through August in small axillary inflorescences. Plants with large rosettes produce flowers earlier and for a longer time period, and consequently produce significantly more seeds, than plants with small rosettes (Byers 1988).

Seeds develop in a linear silique, with siliques forming on the lower part of the inflorescence while flowers

are still opening on the upper part. Seeds ripen and disperse between mid-June and late September (Cavers et al. 1979). Seed production varies by site and year (Trimbur 1973, Byers and Quinn 1998, Meekins 2000). *Alliaria* produces an average of 11.5-19.5 seeds/silique (range 3 to 28), and 8.9-18.8 siliques/plant (range 2 to 422)(Trimbur 1973, Nuzzo 1991, Nuzzo 1999, Cruden et al. 1996, Byers and Quinn 1998, Susko and Lovett-Doust 1998, Cavers et al. 1979). Actual production varies significantly within and between communities, with plants in drier communities tending to produce fewer seeds than plants in mesic and wet communities (Byers and Quinn 1998), and isolated plants producing more seeds than plants growing in high densities (Meekins 2000). Plants produce an average of 136-295 seeds (Byers and Quinn 1998, Nuzzo 1999, Trimbur 1973), and up to 2421 seeds under lab conditions (Meekins 2000). Maximum production per plant is estimated at 7,900 seeds on a plant with 12 stems, while minimum production is 14 seeds on a plant with 2 siliques (Nuzzo unpublished). Seed production is density dependent, with each plant producing fewer seeds as density increases, but total seed production increasing with increasing density (Trimbur 1973, Meekins 2000). Seed production within dense patches of *Alliaria* ranges from 3,607/m<sup>2</sup> to 45,018/m<sup>2</sup> (Nuzzo unpublished, Anderson et al. 1996, Byers and Quinn 1998, Trimbur 1973) and has been estimated as high as 107,580/m<sup>2</sup> (Cavers et al. 1979). At low density, *Alliaria* seed production varies from 168-8034/m<sup>2</sup> (Meekins 2000).

Seeds are dormant at maturity and require 50 to 105 days of cold stratification to come out of dormancy (Byers 1988, Lhotska 1975, Baskin and Baskin 1992, Meekins and McCarthy 1999). The dormancy period lasts eight months in southern locales (Baskin and Baskin 1992, Byers 1988) and eight to 22 months in northern areas (Cavers et al. 1979, Solis 1998). *Alliaria* seeds break dormancy more rapidly when exposed to low temperatures that fluctuate around freezing (0.5 to 10 C, as occurs in central states such as Kentucky) than under a constant temperature regime well below freezing (as occurs in northern states and Canada). This is likely a physiological rather than genetic response, as Ontario seed germinated at 20% and 50% in 3 months when moist stratified at 5 and 2 degrees C, respectively (Cavers et al. 1979).

Unlike some forest crucifers that fail to germinate under leaf cover, *Alliaria petiolata* seeds germinate in both light and dark after dormancy is broken (Bloom et al. 1990, Byers 1988). Light alone will not stimulate germination during cold stratification (Byers 1988). Germination rates of 12-100% have been reported (Baskin and Baskin 1992, Byers 1988, Cavers et al. 1979, Anderson et al. 1996, Roberts and Boddrell 1983), but rates vary greatly within and between populations and habitats (Byers 1988, Cavers et al. 1979). Interestingly, substrate affects germination rate: Baskin and Baskin (1992) reported lower germination on sand substrates than on finer soils, as seeds on sand failed to afterripen (possibly due to water relations at the seed:soil interface). The majority of seeds germinate as soon as dormancy is broken (Roberts and Boddrell 1983, Baskin and Baskin 1992). A small percentage of seed remains viable in the seed bank for up to four years (Roberts and Boddrell 1983, Baskin and Baskin 1992). In a three years study, Meekins (2000) determined that *Alliaria petiolata* stands produce numerous viable seeds but relatively few seedlings germinate, and speculated that the majority of seeds in the seedbank never germinate.

In 4 sites in Ohio the seedbank averaged 936 seeds/m<sup>2</sup> (range 305-1780) in the top 10 cm of soil (Byers and Quinn 1998). Byers (1998) determined that seeds were concentrated in the upper 5cm of soil, and that three of four populations maintained a seed bank after germination. The fourth population, located in a floodplain, lacked a seedbank due to flooding and scouring of the surface, but was expected to gain new seeds during flood deposition.

*Alliaria petiolata* spreads exclusively by seed (Cavers et al. 1979). Seeds typically fall within a few meters radius of the plant. Wind dispersal is limited, and seeds purportedly do not float well, although seeds readily attach to moist surfaces (Cavers et al. 1979). Anthropogenic distribution appears to be the primary dispersal mechanism (Lhotska 1975, Nuzzo 1992, 1993a). Seeds are transported by natural area visitors on boots and in pant cuffs, pockets and hair, and by roadside mowing, automobiles and trains (Nuzzo 1992). Seeds are

widely dispersed in floodwaters. Seeds may be dispersed by rodents or birds; isolated plants are frequently found at the bases of large trees in forest interiors. Seeds may possibly be distributed directly or indirectly by white-tailed deer (*Odocoileus virginianus*).

In southern locales *Alliaria petiolata* populations are even-aged, alternating annually between immature plants and adult plants (Baskin and Baskin 1992), probably due to the 8 month seed dormancy. In northern climates, garlic mustard populations can be even-aged in early stages of invasion, and then become multi-aged as the seed bank builds up. In many stands *Alliaria petiolata* cycles between large populations in one year and small populations the next, often with the majority of plants in the rosette stage one year and the flowering stage the next year (Meekins 2000, Nuzzo 1999, Nuzzo et al. 1996). Meekins (2000) speculated this may be due to establishment of two subpopulations from two or more separate colonization events occurring in different years.

*Alliaria petiolata* is disturbance adapted, and is frequent in sites subjected to continued or repeated disturbance, such as floodplains (Pyle 1995, Byers and Quinn 1998), and in early successional or low quality communities (Hawkes and Abrahamson 1994, Luken et al. 1997). The greatest increases in presence occur in sites subjected to large-scale natural disturbances (Nuzzo 1999). Byers and Quinn (1998) found that *Alliaria petiolata* resource (biomass) allocation to reproduction was greatest in the most disturbed site. By implication, continued disturbance promotes greater seed production which in turn promotes larger populations. Once garlic mustard enters a forest it becomes a permanent part of the community, increasing in presence each year (Nuzzo 1999). In the absence of disturbance, *Alliaria petiolata* gradually declines to a low stable level. This strategy of increased presence and low but continuous abundance allows garlic mustard to rapidly expand when disturbance occurs (Nuzzo 1999).

At any given site *Alliaria petiolata* cover and density fluctuate annually, reflecting the biennial nature of the plant (Byers 1988, Nuzzo 1999). These annual fluctuations are deceptive, as *Alliaria petiolata* consistently occurs with increasing frequency through time, on average doubling in four years and tripling in eight years (Nuzzo 1999). Garlic mustard is frequently overlooked at low density levels. In many sites it can be present for a number of years before appearing to "explode" in favorable years. Once it reaches this level of abundance control is difficult to achieve. *Alliaria petiolata* invades densely vegetated quadrats as readily as sparsely vegetated quadrats, and species-rich quadrats more readily than species-poor quadrats (Nuzzo unpublished).

McCarthy (1997) observed that *Alliaria petiolata* spreads in a demic pattern, i.e.; through establishment of multiple small populations. Within 7 Illinois forests, garlic mustard spread at an average rate of 5.4 m/year, although in any given site rate-of-spread varied substantially, increasing up to 36 m and decreasing as much as 18 m between years (Nuzzo 1999). This "advance-retreat" pattern is typical of garlic mustard, and explains the "sudden" appearance of a dense garlic mustard stands in a forest where few plants were seen the year before. The general pattern of spread is a ragged advancing front, supplemented by establishment of satellite populations 6-30m ahead of the front. After a few years, the front coalesces with the satellite populations to form an extensive area of garlic mustard (Nuzzo 1999).

Because sites dominated by *Alliaria petiolata* frequently have lower species diversity than similar uninvaded sites, and invaded sites often appear to lose species diversity, the assumption has been made that garlic mustard outcompetes native groundlayer flora (McCarthy 1997, Anderson et al. 1996, White et al. 1993.). Meekins and McCarthy (1999) experimentally demonstrated that seedlings of chestnut oak (*Quercus prinus*) had reduced growth when grown with *Alliaria petiolata*, while jewelweed (*Impatiens capensis*) and boxelder (*Acer negundo*) had increased growth; i.e.; *Alliaria petiolata* was competitively superior to *Q. prinus*, but *I. capensis* and *A. negundo* were competitively superior to *Alliaria petiolata*. McCarthy (1997) found that

annual species had higher relative cover in quadrats where garlic mustard was removed than in paired quadrats containing garlic mustard, and concluded that garlic mustard outcompeted annual species (although, actual cover of annual species was similar or greater in plots with garlic mustard).

*Alliaria petiolata* produces several phytotoxic chemicals that may interfere with native plant species (Vaughn and Berhow 1999). The roots contain sinigrin (and its breakdown product allyl isothiocyanate (AITC)), and glucotopaeolin (and its breakdown product benzyl isothiocyanate (BzITC)) (Vaughn and Berhow 1999).

*Alliaria petiolata* may also inhibit mycorrhizal activity in native plants (Roberts and Anderson 1998, Vaughn and Berhow 1999). Under field conditions, density of garlic mustard was significantly negatively correlated with soil mycorrhizal potential (Roberts and Anderson 1998). Like other members of the Brassicaceae, *Alliaria petiolata* is nonmycorrhizal, while some 75% of native groundlayer plants are mycorrhizal (Harley 1969). AITC and BzITC are known to restrict growth of mycorrhizal fungi (Gamliel and Stapleton 1993), and water leachates of *Alliaria petiolata* prevented germination of a mycorrhizal fungi (Roberts and Anderson 1998).

*Alliaria petiolata* is rarely if ever browsed by deer or other large herbivores in the U.S., although Cavers et al. (1979) reported occasional browsing by deer. Garlic mustard is occasionally browsed by slugs and snails, which remove small amounts of leaf tissue (Nuzzo, personal observation), and sometimes attacked by an unidentified flea beetle (B. Blossey, personal observation).

In Europe *Alliaria petiolata* is fed upon by 69 species of insects, including at least 5 that are monophagous (feed exclusively upon *Alliaria*) (Szentesi 1991, Hinz and Gerber 1998). In its native range, *Alliaria petiolata* is a preferred host plant for Pieridae butterflies (Forsberg and Wiklund 1989, Courtney and Duggan 1983, Remorov 1987, Kuijken 1987). In the Netherlands *Alliaria petiolata* is targeted by the orange-tip butterfly *Anthocharis cardamines* (Pieridae) when the preferred host species *Arabis glabra* is unavailable (Kuijken 1987). In eastern Europe *Alliaria petiolata* is utilized by butterflies that feed on commercial crucifers (Remorov 1987) and thus may be a threat to commercial production of cabbage. However, macerates of *Alliaria petiolata* leaves sprayed on cauliflower deterred oviposition by the garden pebble moth (Jones and Finch 1987). s

At least one native butterfly (spring azure: *Celastrina ladon*) uses *Alliaria petiolata* as a nectar source in Pennsylvania (Yahner 1998). Three native butterflies (including *Pieris virginiensis* and *Pieris napa oleracea*) sometimes use *Alliaria petiolata* for ovipositing, but the larvae rarely survive (Bowden 1971, Huang et al. 1995, Courant et al. 1994). *Pieris virginiensis*, a rare butterfly specific to toothwort (*Dentaria* [*Cardamine*] *diphylla* and *D. laciniata*), is stimulated to oviposit on *Alliaria petiolata* because it is chemically similar to the native toothworts; all contain the glucosinolate sinigrin, a strong attractant that the native butterflies use to cue in on the appropriate host plant (Huang et al. 1995). Larvae of these native butterflies feed on *Alliaria petiolata* leaves, but most die by the 4<sup>th</sup> instar (Haribal and Renwick 1998). Courant et al. (1994) speculate that some *P.n. oleracea* may be adapting to *Alliaria petiolata*, as 14 of 34 larvae raised on this plant developed into adults. In general, garlic mustard serves as a population sink for native butterflies (Bowden 1971, Huang et al. 1995). It is taller than the native *Dentaria* (the sole plant host of *P. virginiensis*), has a longer growing season, and is often more abundant than the native *Dentaria*; thus, native butterflies presumably have difficulty locating the native host when both plant species are present, and confuse *Alliaria petiolata* for *Dentaria* based on the chemical similarity (Huang et al. 1995, Porter 1994).

In Illinois a root rot (*Fusarium solani*) has been observed to kill 80-90% of *Alliaria petiolata* in laboratory conditions (Chen 1996). In Ontario an unidentified virus (or several viruses) has been observed to kill flowering plants and prevent them from ripening viable seeds (Cavers personal communication 1989).

*Alliaria petiolata* is frequently infected with a strain of turnip mosaic virus (TuMV-A1) in both Ontario and Europe, with infected plants developing a mosaic leaf pattern (Stobbs and Van Schagen 1987). The virus does not affect total seed production or seed germination, but does reduce diameter of individual seeds and average silique length (Stobbs and Van Schagen 1987). Although closely related to TuMV-Br, a virus that infects crops in the Brassicaceae, the two viruses are mutually exclusive: the *Alliaria* virus is not transmissible to commercial Brassicaceae species, specifically rutabagas and canola, nor does TuMV-Br infect *Alliaria petiolata* (Stobbs and Van Schagen 1987). In Europe *Alliaria petiolata* is a host plant for seven fungi (Hinz and Gerber 1998) and a number of viruses, including cucumber mosaic virus (CMV) and turnip mosaic virus (TuMV), that infect commercially propagated crucifers (Polak 1985). *Alliaria* is host for an isolate of turnip yellow mosaic virus (TYMV-A) that induces systemic infection in broccoli, turnip, and other crucifers grown in Europe (Pelikanova et al. 1990). This was the first finding of TYMV-A virus in wild growing vegetation in the former Czechoslovakia (Pelikanova 1990).

Garlic mustard was historically eaten as a potherb, particularly in winter and early spring when few greens were unavailable (Georgia 1920). There is no direct evidence that *Alliaria petiolata* was specifically imported for garden or medicinal use, although Fernald et al. (1958) state that this "old fashioned garden plant...has spread somewhat to roadsides and borders of groves", and cite earlier authors who describe the use of garlic mustard as a salad plant. Zennie and Ogzewalla (1977) promote eating garlic mustard for its high Vitamin A content (8,600 units/100g in young leaves, 19,000 in basal leaves) and Vitamin C content (190mg/100g in young leaves), both substantially higher than levels in commercially grown fruits and vegetables.

*Alliaria petiolata* is an ingredient in several 'gourmet' recipes (Shufer 1999, Couplan 1999). This has prompted a warning by editors of HORTIDEAS newsletter to "avoid planting this herb" (Hortideas, 1999). At least one U.S. seed company (Canterbury Farms) offers *Alliaria petiolata* seeds for sale (\$1.00/package).

## RECOVERY POTENTIAL

Recovery potential of areas cleared of *Alliaria petiolata* has not been determined. Communities in good natural quality should recover well and without assistance if *Alliaria petiolata* is removed before a large population develops. Few native species occur in dense garlic mustard infestation, and recovery of heavily infested communities may require replanting. Allelopathic chemicals, if present, may inhibit growth of some native species. Low quality forests, which lack many native species and community structure, will require replanting regardless of the impact of *Alliaria petiolata*.

Luken et al. (1997) removed Amur honeysuckle (*Lonicera maackii*) from an early successional forest, and found that *Alliaria petiolata* rapidly increased in abundance, becoming the dominant plant species in the resulting gaps. They caution that management for one nonindigenous species may result in an increased abundance of another nonindigenous species. McCarthy (1997) experimentally removed *Alliaria petiolata* and found that species richness did not change over a three year period.

## MONITORING REQUIREMENTS

### Qualitative:

Monitor once or twice annually for *Alliaria petiolata* presence in a site: Monitor in late fall or very early spring for immature rosettes, and in early to mid spring for flowering adults. The purpose of this type of monitoring is to locate and remove plants before seeds are produced. Once *Alliaria petiolata* is established in a natural area, efforts should be made to eradicate, or at least to contain, the plant rather than just monitor its spread. Walk through potential habitat: parking lot edges, trails, riverbanks, floodplains, and streamsides.

If time allows monitor all forest perimeters (*Alliaria petiolata* usually enters along disturbed edges), edge communities, and dry-mesic and floodplain forest interiors (*Alliaria petiolata* occasionally enters at the bases of large trees). Look for basal rosettes in late summer through very early spring; look for flowering plants in mid to late spring. Flowering plants are easier to locate, but must be removed as soon as seen. Basal rosettes are less noticeable, but may be removed at any time prior to flowering.

#### Quantitative:

Monitor annually for presence/absence, frequency, cover, density, and seed production on a square meter basis, as appropriate for meeting management objectives. Use a quadrat size and shape that minimizes variance in abundance between quadrats within a given management area or treatment plot.

### MONITORING PROGRAMS

A monitoring protocol is being developed to assess growth of *Alliaria petiolata* in the U.S. and Europe, with and without natural enemies (V.Nuzzo and B. Blossey).

### MANAGEMENT

*Alliaria petiolata* should be removed from natural areas before it sets seed, as one plant can populate or repopulate a site. It appears to threaten the structure of forest communities, and should be given high management priority as soon as it is observed in or near a preserve.

The goal of *Alliaria petiolata* management is to prevent seed production. The primary management objective in areas lacking this plant is to prevent establishment, by annually monitoring for and removing all *Alliaria petiolata* plants. The primary management objective in infested sites is to prevent seed production. Cutting flowerstalks is effective in small populations. Fire and herbicide may be useful for larger populations but both have potential side effects. No method provides 100% control.

Growing season mortality reduces *Alliaria petiolata* seedling populations by 80%-90% between spring and late fall (Anderson et al. 1996, Byers and Quinn 1998); hence, control is most economical when undertaken in late fall or early spring prior to flower production. Late fall is usually the preferred season for control, as native plants are dormant and management can be conducted until snow covers the ground. If weather is unfavorable in fall, control can still be conducted in early spring. Delaying control until spring can be risky, as native herbs may begin growth earlier than anticipated, and weather may limit or prevent management activities.

Management priority should be given to small populations of *Alliaria petiolata*, and to high quality natural areas. Low quality natural areas, and sites with established large *Alliaria petiolata* populations, have low management priority.

### BIOLOGICAL CONTROL

Biological weed control — the use of a plant's specialized "natural enemies" to control a nonnative plant — may be the only effective way to reduce large infestations *Alliaria petiolata* in North America. B. Blossey of Cornell University is coordinating a program to investigate the potential for biological control of *Alliaria*. At least 69 phytophagous insect species and seven fungi are associated with *Alliaria petiolata* in Europe (Hinz and Gerber 1998). Of these, four monophagous weevils (two shoot-miners, one seed-feeder, and one root feeder; all *Ceutorhynchus* species) are being investigated as potential biocontrols. *Ceutorhynchus alliariae* and *C. robertii* are sibling species that mine shoots and petioles of rosettes and bolting plants of garlic mustard; heavily attacked plants die without producing seeds (Hinz and Gerber 1998). *C. constrictus*

larvae develop in *Alliaria petiolata* seeds; each larva destroys one-two seeds (Hinz and Gerber 1998). *C. scrobicollis* larvae feed in the root crown and occasionally the lower parts of shoots; heavily attacked plants die without producing seeds (Hinz and Gerber 1999). Adults of all 4 *Ceutorhynchus* species feed on *Alliaria petiolata* leaves and cause some damage, but the majority of damage is caused by the larvae (Hinz and Gerber 1999). A fifth species, the flea beetle *Phyllotreta ochripes*, preferentially feeds on *Alliaria petiolata*, but adults have been found on other Cruciferae, including *Rorippa*, *Brassica*, and *Sinapsis* species (Hinz and Gerber 1999). All five insects will be studied for several years in Europe to document their impact on *Alliaria petiolata*, and to verify that *Alliaria petiolata* is their exclusive food source. If one or more insects pass all safety and specificity tests required by the USDA, they will be brought to North America for field releases.

An unidentified virus (or several viruses) can kill a flowering plant and prevent it from ripening viable seeds in Ontario (Cavers personal communication 1989), and may provide some control. *Alliaria petiolata* developed severe mosaic symptoms when infected with CMV and TuMV, but only when grown in ruderal soil; plants in a natural environment had mostly symptomless infection (Polak 1985).

## BURNING

Prescribed burning provides inconsistent management results; *Alliaria petiolata* populations may remain stable, decrease, or increase following one or more fires. In Kentucky, *Alliaria petiolata* populations had no significant change following three years of repeated dormant season burns (Luken and Shea 2000). In Illinois, *Alliaria petiolata* populations were maintained at a low level when fires burned completely through the affected area, and were conducted for at least two consecutive years (Nuzzo 1991, Nuzzo et al. 1996, Schwartz and Heim 1996). Fires that left a thin litter layer (1-2 cm) did not kill *Alliaria petiolata* root crowns, which subsequently produced multiple flower stalks from axillary buds (Nuzzo et al. 1996). Fires that removed the litter layer may enhance survival of seedlings that germinate after burning (Nuzzo et al. 1996). Thus, after a single fire, total *Alliaria petiolata* cover can increase due to survival of adult plants, and/or to enhanced seedling survival.

Spring and fall fires are equally successful in reducing cover of *Alliaria petiolata* rosettes (Nuzzo 1991, Nuzzo et al. 1996). Spring fires also reduce seedling presence if conducted during the germination period (Nuzzo 1991), although native herbaceous species are damaged by a growing season burn (Schwartz and Heim 1996).

Use of fire as a management tool should be tailored to the specific community. Removal of the litter layer may facilitate invasion by disturbance adapted species, including *Alliaria petiolata*, particularly if there is little native ground-layer present at the site. Fires should only be conducted when at least two or more consecutive fires can be scheduled; burning only once may increase *Alliaria petiolata* abundance. Impact of consecutive fires on the community should be considered, including changes in ground-layer composition. While fire can maintain *Alliaria petiolata* at low abundance, it does not eliminate this plant (Nuzzo et al. 1996).

## CHEMICAL

Dormant season herbicide application can provide effective control of *Alliaria petiolata*, but poses a potential threat to native herbaceous and graminoid species. Glyphosate (Roundup, Rodeo, Accord) produces a high degree of control, but results in some native herb loss and significantly reduces graminoid cover. Bentazon (Basagran SG, Basagran T/O) produces nearly equal control, with much lower impact on graminoid species, and little or no impact on native herbs. Glyphosate is suitable for use in forest communities that have few semi-evergreen herbaceous or graminoid species. Bentazon appears suitable for use in many forest

communities, but should be subjected to further tests before widespread use. The effectiveness of chemical control is dependent on the chemical contacting all plants; under field conditions this rarely or never happens.

#### Glyphosate (Roundup, Rodeo, Accord)

Glyphosate (Roundup) applied at 1%, 2%, and 3% concentrations to dormant rosettes in late fall or early spring reduced adult cover by >95% (Nuzzo 1991, 1996). Control was slightly greater with higher glyphosate concentrations. Seedlings that germinate after application are not affected by the herbicide because glyphosate is inactivated when it contacts soil. Glyphosate applied after germination will significantly reduce seedling populations (Nuzzo 1991).

Glyphosate is a non-selective herbicide and will kill native species, particularly when applied in spring. At the community level, glyphosate did not affect mean species richness or total mean herbaceous cover, but did significantly reduce cover of both sedges and grasses, at both 0.5% and 1% concentrations (Nuzzo 1996).

#### 2,4-D (sold under many brand names)

2,4-D is not recommended for control of *Alliaria petiolata*. An ester formulation of 2,4-D applied during the growing season reduced *Alliaria petiolata* cover by 10% at 0.25 lb/acre, 70% at 0.50 lb /acre, and 45% at 1.0 lb /acre. Dormant season application at very low concentration had no effect on *Alliaria petiolata* (Nuzzo unpublished). Ortho Weed-B-Gone (a 2,4-D formulation available at many hardware and garden stores) at 0.4% had no effect on *Alliaria petiolata* adult plants (Rich Dunbar personal communication 1990).

Mixing 2,4-D with other chemicals provides a more effective kill, based on visual assessment. A 1% solution of Mecamine (2,4-D plus Dicamba) reduced *Alliaria petiolata* (Bill McClain personal communication 1990). Treatment with Kilmore (2,4-D, MCPP and Dicamba) applied at the rate of 1.1 liter/hectare killed all flowering *Alliaria petiolata* (R.H. Brown personal communication in Cavers et al. 1979).

#### Triclopyr (Garlon 3A, Garlon4, Pathfinder)

A spring application of triclopyr amine (Garlon 3A ) mixed at 7oz/5gallon water (just over 1%) killed 92% of *Alliaria petiolata* rosettes in a limited test (Rich Dunbar personal communication 1990).

#### Bentazon (Basagran SG and Basagran T/O)

Growing season application of Bentazon (Basagran) at 0.50-1.0 lb /acre reduced *Alliaria petiolata* rosette cover by 90-95% (Nuzzo 1994). Impacts of dormant season application could not be determined by this study, as severe drought killed rosettes in both control and treatment plots (Nuzzo 1996). Bentazon did not affect species richness or herb cover, and had minimal effect on graminoid cover (Nuzzo 1996). *Alliaria petiolata* seedlings were not affected by treatment (Nuzzo 1996). Bentazon is a post-emergent contact herbicide that kills dicots (broadleaf plants) and some sedges but will not kill most grasses. It is used to control mustards in agricultural fields and is primarily a contact herbicide, meaning it kills or injures portions of the plant that it lands on and little else. It blocks photosynthesis by binding with the D1 protein of the photosystem II complex. This stops CO<sub>2</sub> fixation and production of ATP and NADPH<sub>2</sub> which are needed for plant maintenance and growth. In most cases, however, the plants are actually killed because the blockage in the photosystem promotes formation of oxidized molecules that cause chain reactions destroying chlorophyll, carotenoids and cellular membranes. Bentazon's biggest drawback appears to be that it is very soluble in water and does not bind to soil particles which suggests a high potential for groundwater contamination. It has a short half life and breaks down rapidly in soil (average half-life 20 days), however, and estimates based

on an EPA survey indicate it is found in about 0.1% of rural drinking water wells nationwide although it is widely used. It was not detected in any US community water systems nor was it detected at concentrations above 0.02 mg/L in any well. Bentazon is rapidly broken down in non-susceptible plants and has little effect on germinating seeds. The brands Basagran SG and Basagran T/O are registered for use in non-crops sites, roadways and other rights of way and thus can be legally used in natural areas in at least some states. The labels state that this herbicide should not be applied under sycamores or rhododendrons and that it may kill trees and shrubs if applied to soil beneath their canopies.

#### Acifluorfen (Blazer)

Acifluorfen is not recommended for control of *Alliaria petiolata*. Like Bentazon, Acifluorfen is used to control mustards in agricultural fields. Warm-season application of Acifluorfen (Blazer) at 0.25, 0.37 and 0.5 lb /acre reduced *Alliaria petiolata* cover by 30-40% (Nuzzo 1994). Dormant season treatment eliminated *Alliaria petiolata* rosettes, and prevented seedling germination the next spring (no seedlings were observed 7 months after fall treatment, and 2 months after spring treatment) (Nuzzo 1996). Acifluorfen reduced species richness and graminoid cover, and significantly reduced herbaceous cover in treated plots (Nuzzo 1996). Acifluorfen has a soil residual, and treated plots had low herbaceous cover through the first growing season after treatment (Nuzzo 1996).

#### Mecoprop (Mecomec, many other brand names)

*Alliaria petiolata* was heavily damaged by aerial application of 2.4 kg /acre of mecoprop (Birnie 1984).

#### CUTTING

Cutting flowering *Alliaria petiolata* plants at ground level results in 99% mortality, and eliminates seed production. Cutting at 10 cm above ground level results in 71% mortality and reduces seed production by 98% (Nuzzo 1991). Cutting is most effective when plants are in full bloom and/or have developed siliques; plants cut earlier in the flowering period may have sufficient resources to produce additional flowerstems from buds on the root crown (Nuzzo, personal observation).

Cut flower stems may form viable seed. Solis (1998) pulled *Alliaria petiolata* plants at four flowering stages (flowerbud, flowering, newly formed siliques, well-formed siliques) and piled each flowering stage in a separate fenced plot; the following spring *Alliaria petiolata* seedlings were abundant in all plots and absent from the empty control plot, indicating that pulled (and by implication, cut) *Alliaria petiolata* flower stems produce viable seed. Cavers et al. (1979) suggested that vivipary (germination of seeds while still in the silique) does not occur, although all seeds remained viable during the observation period. Until more information is available, cut or pulled stems should be removed from the site whenever feasible.

Cutting with a weed whip provides quick removal of flowering stems, but may remove other desirable species. Some native species, such as Trillium, are severely impacted if cut. Most other species are not substantially damaged, and the benefits of removing *Alliaria petiolata* should be weighed against the temporary reduction in growth and reproduction of native groundcover species. Cutting with a weed whip may distribute cut stems (and hence seeds) across the site; care should be taken to collect and remove cut material whenever possible.

#### GRAZING, DREDGING, AND DRAINING

Not tested.

## MANIPULATION OF WATER LEVEL AND SALINITY

Not tested. Short-term growing season inundation does not harm *Alliaria petiolata* rosettes (Byers and Quinn 1998). Extended mid summer flooding resulted in 100% mortality of immature rosettes, but also distributed *Alliaria petiolata* seeds across the floodplain (Nuzzo 1999).

## MOWING, DISCING AND PULLING

Mowing may have an effect comparable to cutting, but the equipment could severely disturb soil and native vegetation. Mowing would be useful in full sun situations such as roadsides, but may distribute seeds. In forested locations a weed whip is more practical and less damaging. Discing is not an acceptable method of control due to the destruction of the community. Root-cutting is a very effective although labor intensive means of control.

Pulling is very labor intensive but effective if the upper half of the root is removed. *Alliaria petiolata* frequently snaps off at or just below the root crown when the flower stalk is pulled, leaving adventitious buds which send up new flower stalks. Pulling can result in substantial soil disturbance, damaging desirable species and bringing up *Alliaria petiolata* seeds from the seedbank. Soil should be thoroughly tamped after pulling to minimize chances for re-establishment of garlic mustard or other weedy species. In general, cutting is a less destructive method of control than pulling but is effective only when the flower stalk is elongating, whereas pulling can be conducted throughout the growing season.

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