SPECIES: Alliaria petiolata

INTRODUCTORY

SPECIES: Alliaria petiolata

AUTHORSHIP AND CITATION:
Munger, Gregory T. 2001. Alliaria petiolata. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: http://www.fs.fed.us/database/feis/ [2007, September 24].

FEIS ABBREVIATION:
ALLPET

SYNONYMS:
Alliaria officinalis Andrz. ex Bieb. [6,31,68,73]

NRCS PLANT CODE [78]:
ALPE4

COMMON NAMES:
garlic mustard

TAXONOMY:
The scientific name of garlic mustard is *Alliaria petiolata* (Bieb.) Cavara & Grande (Brassicaceae) [26,27,32,48,61,82,86,89].

LIFE FORM:
Forb

FEDERAL LEGAL STATUS:
No special status

OTHER STATUS:
Ranked as a severe threat by the Tennessee Exotic Pest Plant Council [71]

Ranked as a category 1 species (highly invasive) by Vermont Department of Environmental Conservation [81]

Ranked as a moderate threat (species shows invasive behavior, and known to impact native species, or has a wide distribution and statewide abundance) by Minnesota Department of Natural Resources [47]

DISTRIBUTION AND OCCURRENCE

SPECIES: Alliaria petiolata

GENERAL DISTRIBUTION:
Native to Europe [6,15,26,48,68,73,82,87] and Asia [48,82,87], garlic mustard occurs in northern Europe from England across Scandinavia to the western areas of the former Soviet Union, and south to Italy [56]. It was 1st reported in the North America in 1868 on Long Island, New York [50], and has since established throughout much of the Northeast and Midwest. Garlic mustard can be found in Canada from southern Ontario east into the St. Lawrence Valley in Quebec [15,27], as well as around Victoria, British Columbia [15]. In the United States it is established and invasive in deciduous woodlands and disturbed areas from northern New England west to eastern North Dakota, and south to eastern Oklahoma and South Carolina [6,14,17,23,27,32,33,48,56,57,60,61,65,68,73,77,82,89]. Occurrences of garlic mustard have also been recorded in Utah, eastern Colorado, and around Portland, Oregon, Seattle, Washington, and Juneau, Alaska [31,55,75,77,86,87]. The PLANTS database
provides a map of garlic mustard's distribution in the United States.

ECOSYSTEMS [25]:
FRES10 White-red-jack pine
FRES11 Spruce-fir
FRES14 Oak-pine
FRES15 Oak-hickory
FRES17 Elm-ash-cottonwood
FRES18 Maple-beech-birch
FRES19 Aspen-birch
FRES39 Prairie

STATES:

AK	AR	CO	CT	DE	GA	IL
IN	IA	KS	KY	ME	MD	MA
MI	MN	MO	NE	NH	NJ	NY
NC	ND	OH	OK	OR	PA	RI
SC	SD	TN	UT	VT	VA	WA
WV	WI	DC				

BC	ON	PQ

BLM PHYSIOGRAPHIC REGIONS [8]:
None

KUCHLER [38] PLANT ASSOCIATIONS:
K074 Bluestem prairie
K081 Oak savanna
K082 Mosaic of K074 and K100
K098 Northern floodplain forest
K100 Oak-hickory forest
K101 Elm-ash forest
K102 Beech-maple forest
K104 Appalachian oak forest
K106 Northern hardwoods
K107 Northern hardwoods-fir forest
K108 Northern hardwoods-spruce forest

SAF COVER TYPES [22]:
20 White pine-northern red oak-red maple
25 Sugar maple-beech-yellow birch
27 Sugar maple
31 Red spruce-sugar maple-beech
39 Black ash-American elm-red maple
42 Bur oak
50 Black locust
52 White oak-black oak-northern red oak
53 White oak
55 Northern red oak
59 Yellow-poplar-white oak-northern red oak
60 Beech-sugar maple
61 River birch-sycamore
62 Silver maple-American elm
63 Cottonwood
95 Black willow
108 Red maple
110 Black oak
225 Western hemlock-Sitka spruce
235 Cottonwood-willow

SRM (RANGELAND) COVER TYPES [69]:
601 Bluestem prairie

HABITAT TYPES AND PLANT COMMUNITIES:
In the eastern U.S., garlic mustard occurs in the understory of a variety deciduous forests and woodlands. It is rarely reported as being associated with conifers, although Cavers and others [15] state that 7 of 37 tree and shrub species found growing over garlic mustard in eastern Canada were coniferous. While not intended as an exhaustive or definitive list, the following are specific examples of communities in which garlic mustard has been found.

Oak savanna/eastern prairie: In northern Illinois prairie and savanna remnants, garlic mustard is an important herb layer species in areas with greater relative shade. Associated herbs include rue anemone (*Thalictrum thalictroides*), broadleaf enchanter's nightshade (*Circaea lutetiana*), starry false lily-of-the-valley (*Maianthemum stellatum*), jumpseed (*Polygonum virginianum*), Atlantic camas (*Camassia schilloides*), spotted geranium (*Geranium maculatum*), and avens (*Geum* spp.) [11]. Garlic mustard was present along the fringes of a white oak-northern red oak (*Quercus alba*-*Q. rubra*) savanna in northern Illinois [29].

Xeric upland eastern deciduous forest: Garlic mustard is present in black oak (*Q. velutina*)-dominated sand forest in central Illinois, especially in disturbed areas, and along nearby shaded roadsides. Herbaceous associates at 1 site included hog peanut (*Amphicarpa bracteat*a), lambsquarters (*Chenopodium album*), broadleaf enchanter's nightshade, white snakeroot (*Ageratina altissima*), licorice bedstraw (*Galium circaezans*), beggarslice (*Hackelia virginiana*), Carolina leaf-flower (*Phyllanthus caroliniensis*), and feathery false lily-of-the-valley (*Maianthemum racemosum*) [54].

Mesic upland eastern deciduous forest:
Northeast - Garlic mustard occurs in upland oak-hickory (*Quercus*-*Carya* spp.) forest in New Jersey [14], and was present in the herb layer of a sugar maple (*Acer saccharum*)-dominated stand in southwestern Vermont, along with jewelweed (*Impatiens capensis*), ladyfern (*Athyrium filix-femina*), intermediate wood fern (*Dryopteris intermedia*), Christmas fern (*Polystichum acrostichoides*), Canadian white violet (*Viola canadensis*), Jack-in-the-pulpit (*Arisaema triphyllum*), and rosy sedge (*Carex rosea*) [90].

Midwest - In southwestern Ohio it is found under sugar maple, white oak, northern red oak, American elm (*Ulmus americana*), and hickory (*Carya* spp.), along with herbaceous associates cutleaf toothwort (*Cardamine concatenata*), stickywilly (*Galium aparine*), Virginia springbeauty (*Claytonia virginica*), toadshade (*Trillium sessile*), Jack-in-the-pulpit, mayapple (*Podophyllum peltatum*), Clayton's sweetroot (*Osmorhiza claytonii*), downy yellow violet (*Viola pubescens*), and touch-me-not (*Impatiens* spp.) [19]. In west-central Ohio, garlic mustard is associated with sugar maple, American beech (*Fagus grandifolia*), hickories, oaks, and slippery elm (*Ulmus rubra*). Herbaceous associates include toadshade, wild blue phlox (*Phlox divaricata*), running strawberry bush (*Euonymus obovata*), common periwinkle (*Vinca minor*), white panicle aster (*Symphyotrichum lanceolatum*), whiteflower leafcup (*Polymnia canadensis*) , wild leek (*Allium tricoccum*), Adam-and-Eve (*Aplectrum hyemale*), and goldenrod (*Solidago* spp.) [24].

In central Indiana native forest remnants in a rural agricultural matrix, garlic mustard occurred across the field-forest ecotone, from open areas into the forest interior. Dominant overstory species were sugar maple and American beech at some sites; other sites also included American basswood (*Tilia americana*), white ash, and several oak and hickory species [12]. Garlic mustard is listed as an understory associate in several sugar maple-basswood and sugar maple-basswood-white ash habitat types in southern Wisconsin. Common ground flora for these similar habitat types include broadleaf enchanter's nightshade, feathery false lily-of-the-valley, spotted geranium (*Geranium maculatum*), white avens (*Geum canadense*), mayapple, Jack-in-the-pulpit, whip-poor-will flower (*Trillium cernuum*), American lopseed (*Phryma leptostachya*), riverbank grape (*Vitis riparia*), Clayton's sweetroot, pointedleaf tick trefoil (*Desmodium glutinosum*), rattlesnake fern (*Botrychium virgianum*), Maryland sanicle (*Sanicula marilandica*), bloodroot (*Sanguinaria canadensis*), blue cohosh

(*Caulophyllum thalictroides*), early meadow-rue (*Thalictrum dioicum*), Shawnee salad (*Hydrophyllum virginianum*), bristly greenbrier (*Smilax tamnoides*), sharplobe hepatica (*Hepatica nobilis*), and Canadian woodnettle (*Laportea canadensis*) [36].

Garlic mustard was invasive in the herb layer of a northern Illinois mesic upland white oak forest, with additional herbaceous layer components consisting of cutleaf toothwort (*Cardamine concatenata*), snow trillium (*Trillium grandiflorum*), bloody butcher (*Trillium recurvatum*), dogtooth violet (*Erythronium americanum*), Shawnee salad, wild leek, rock polypody (*Polypodium virginianum*), mayapple, and whip-poor-will flower [30], and was abundant in a northern Illinois dry-mesic forest with a white oak and black oak overstory [49]. Another northern Illinois location mentioning the presence of garlic mustard included a forested site dominated by a slippery elm, white oak and white ash overstory and nodding wakerobin (*Trillium flexipes*), bloody butcher, spotted geranium and feathery false lily-of-the-valley in the herb layer, as well as a sugar maple, white ash, white oak forest with a variety of herbaceous spring ephemerals [53]. Also in northern Illinois, a large population of garlic mustard was found in a white oak-northern red oak-black walnut (*Juglans nigra*) woodland with a native herbaceous layer of broadleaf enchanter's nightshade, Jack-in-the-pulpit, stickywilly, and spotted geranium [67].

Garlic mustard, Virginia creeper (*Parthenocissus quinquefolia*), and wild grape (*Vitis vulpina*) are common in the understory of a northern Kentucky hardwood forest dominated by white ash (*Fraxinus americana*), black locust (*Robinia pseudoacacia*), and American elm [39]. Another Kentucky forest with an overstory of sugar maple and white ash is dominated by garlic mustard in the herb layer. Downy yellow violet, stickywilly, wild blue phlox, Virginia creeper, Canadian wildginger (*Asarum canadense*), Virginia springbeauty, mayapple, common chickweed (*Stellaria media*), largeleaf waterleaf (*Hydrophyllum macrophyllum*), nodding fescue (*Festuca subverticillata*), bleeding heart (*Dicentra* spp.), and sedge (*Carex* spp.) are associated herbs [41].

Lowland eastern deciduous forest:
Northeast - Garlic mustard is mentioned as an understory herb in a willow-box elder (*Salix* spp.-*Acer negundo*), silver maple (*A. saccharinum*) habitat type on Long Island, New York [28], and was reported as occurring under a dense canopy of silver maple and ash species in a floodplain forest along the Raritan River in New Jersey [14]. Garlic mustard was prevalent in the herb layer of a Maryland Potomac River floodplain forest dominated by American sycamore (*Platanus occidentalis*), common hackberry (*Celtis occidentalis*), and box elder. Common herb layer associates at this location included bluntleaf waterleaf (*Hydrophyllum canadense*), and Canadian woodnettle, along with the exotic ground ivy (*Glecoma hederacea* L.) [60]. A study conducted on 2 upper Allegheny River islands in northwestern Pennsylvania found garlic mustard frequently occurring under a dominant overstory of silver maple and American sycamore, along with groundlayer associates common blue violet (*Viola sororia*), white avens, Canadian clearweed (*Pilea pumila*), fringed loosestrife (*Lysimachia ciliata*), creeping jenny (*Lysimachia nummularia*), white snakeroot (*Ageratina altissima*), narrowleaf bittercress (*Cardamine impatiens*), sensitive fern (*Onoclea sensibilis*), reed canarygrass (*Phalaris arundinacea*), whitegrass (*Leersia virginica*), and hairyfruit sedge (*Carex trichocarpa*) [85].

Midwest - Trimbur [74] studied garlic mustard from 4 floodplain sites in central Ohio. Common overstory associates for these sites were: i) boxelder, sugar maple, and American sycamore; ii) elm, boxelder, eastern cottonwood (*Populus deltoides*), and American sycamore; iii) elm, maple, swamp white oak (*Quercus bicolor*); and iv) ash cherry (*Prunus* spp.), elm, Ohio buckeye (*Aesculus glabra*), honey-locust (*Gleditsia triacanthos*), and black locust. Common herbaceous species for the same sites were: i) violet (*viola* spp.), stinging nettle (*Urtica dioica*), white avens, common cowparsnip (*Heracleum maximum*), jewelweed, and Maryland sanicle; ii) Canadian wildginger, common cowparsnip, Canadian woodnettle, Maryland sanicle, pale touch-me-not, and Canadian honewort (*Cryptotaenia canadensis*); iii) sweetroot spp., white avens, Canadian wildginger, fragrant bedstraw (*Galium triflorum*), whiteflower leafcup (*Polymnia canadensis*), and poison-ivy (*Toxicodendron radicans*); and iv) sweetroot spp., white avens, jewelweed, and Maryland sanicle. Garlic mustard was found in a southwestern Ohio floodplain under sugar maple, black walnut and white ash, along with Canadian wildginger, cutleaf toothwort, clustered blacksnakeroot (*Sanicula odorata*), feathery-false-lily-of-the-valley, longstyle sweetroot (*Osmorhiza longistylis*), jumpseed (*Polygonum virginianum*), wild leek, nodding wakerobin, Canadian clearweed, limestone bittercress (*Cardamine douglassii*), Canadian woodnettle, smooth Solomon's seal (*Polygonatum biflorum*), and touch-me-not [19]. Garlic mustard was also found in the understory of a young red maple (*Acer rubrum*)-silver maple stand in lowland forest in west central Ohio along with herb layer associates jewelweed, Greek valerian (*Polemonium reptans*), nightcaps (*Anemone quinquefolia*), violet, meadow parsnip, sanicle, and sweetroot [24]. Garlic mustard was a common understory component in ravine bottoms in a northern Kentucky hardwood forest dominated by sugar maple, white ash, American sycamore, and box elder. Additional herb layer components included common chickweed, Canadian clearweed, trumpet creeper (*Campsis radicans*), mayapple, hairy wildrye (*Elymus villosus*) and Canadian wildginger [41]. Garlic mustard was present in a black maple (*Acer nigrum*)-American basswood-black walnut-dominated forest with a rich herbaceous cover in the floodplain of the Pecatonica River in northern Illinois [53].

MANAGEMENT CONSIDERATIONS

SPECIES: Alliaria petiolata

IMPORTANCE TO LIVESTOCK AND WILDLIFE:
Use of garlic mustard as a forage species by white-tailed deer is unclear [15,55]. White-tailed deer may avoid grazing garlic mustard in favor of native herbaceous plants, although this has not been empirically tested [3,49,55]. It is likely that white-tailed deer graze a variety of understory herb species in areas typically susceptible to garlic mustard invasion, and can have a dramatic negative impact on some native herb populations [1]. Deer grazing of native herbaceous plants may enhance garlic mustard at the expense of native species by providing small-scale soil disturbance and by reducing interspecific competition. White-tailed deer may provide small-scale disturbances suitable for garlic mustard colonization within forested areas by trampling and exposing soil. In addition, selective herbivory may enhance garlic mustard at the expense of the preferred native species [3,49,55].

Garlic mustard may be deleterious to some species of butterfly. Adults of several butterfly species lay eggs on garlic mustard instead of their native plant hosts. Because larval development on garlic mustard is often fatally inhibited, this can result in garlic mustard acting as a population sink for these butterfly species, a particularly perilous problem for rare species such as the West Virginia white butterfly (*Pieris virginiensis*) [10,55,59].

PALATABILITY:
Garlic mustard is apparently palatable to livestock. It is thought to taint the flavor of milk in dairy cattle [15].

NUTRITIONAL VALUE:
No entry

COVER VALUE:
No entry

OTHER USES:

Garlic mustard was historically eaten as a green vegetable by Europeans and is high in vitamins A and C. It was also used as a medicinal herb in Europe [15].

IMPACTS AND CONTROL:

Impacts: The control of garlic mustard may be desirable to mitigate displacement of native herbaceous species, especially in relatively undisturbed deciduous forests of the eastern and midwestern United States and southern Ontario [3,15,17,49,56]. In forested natural areas, garlic mustard has the potential to dominate the herb layer [41,52,55,91]. Invasion of mature eastern deciduous forests by garlic mustard is notable because these habitats were thought to be relatively resistant to nonindigenous plant invasion, particularly by herbaceous species [43,45,55,56]. From the results of a greenhouse study examining the competitive potential of garlic mustard, Meekins and McCarthy [45] postulated that competition for light within dense garlic mustard stands might inhibit oak regeneration in the understory of eastern deciduous woodlands. However, this same study failed to show greater levels of interspecific competition among garlic mustard, jewelweed, and box elder, 2 potential understory associates. McCarthy [43] demonstrated that removal of garlic mustard from a deciduous forest understory resulted in increased richness and abundance of understory species, especially annuals and woody perennials. Garlic mustard may be particularly detrimental to native spring ephemerals in eastern deciduous forest understories [15]. McCarthy [43] failed to demonstrate a link between the magnitude of garlic mustard infestation and native species diversity. Removal experiments, while providing some insight into possible effects of nonindigenous plant invaders, may be inherently limited in their ability to reflect impacts of invasives on preinvasion communities [84]. Limited and conflicting evidence surrounding the assumption that garlic mustard infestation necessarily results in reduced richness and cover of native herbaceous species points out the critical need for more research in this area.

The allelopathic potential of garlic mustard has received some study, with mixed results. McCarthy and Hanson [44] found little evidence of allelopathic effects of garlic mustard on several plant species studied. They attributed the success of garlic mustard invasiveness strictly to its competitive abilities. Other evidence indicates at least the possibility for allelopathic interference between garlic mustard and neighboring herbaceous plants, as well as the possibility for toxicity against mycorrhizal fungi [35,80]. Roberts and Anderson [64] found a significant negative correlation ($r^2 = 0.29$; $P < 0.05$) between garlic mustard density in the field and the mycorrhizal inoculum potential of the soil. McCarthy [43] found garlic mustard inhibited establishment of seedlings of other species, yet no quantitative relationship could be discerned between garlic mustard biomass and native species diversity. This finding suggests that the mere presence of garlic mustard depresses native diversity, perhaps an allelopathic effect. Further research is needed to a) determine what mechanisms, if any, are responsible for garlic mustard allelopathy, and b) sort out the relative effects of allelopathy vs. resource competition in interactions between garlic mustard and native plants.

Control:

The biology of garlic mustard presents significant challenges to its control because it simultaneously possesses characteristics of native forest herbs such as shade tolerance and relatively large seeds, as well as characteristics often ascribed to weeds such as xenogamy and autogamy, and high seed production and germination under a range of environmental conditions. It is also not impacted by its native herbivores and parasites [3,5,17,44]. While garlic mustard invades relatively undisturbed woodlands, invasion may be expedited by natural and anthropogenic disturbance that removes competing native vegetation. Once garlic mustard becomes established, further dispersal and perpetuation within a particular habitat may require little to no further disturbance [46,56].

Deciduous forest fragments that are isolated in an otherwise predominantly agricultural landscape may be more resistant to garlic mustard invasion, due to limited seed sources and inhibitive dispersal distances [12]. However, in areas with large populations of white-tailed deer, even these insular forest remnants may become colonized by garlic mustard.

As with most invasive plants, deterrence is the most effective strategy against garlic mustard. This includes annual monitoring and removal of all invading plants prior to seed production. Garlic mustard is prolific partly because of its ability to self-pollinate. A single individual can produce large numbers of genetically similar but interfertile progeny, which in turn may colonize even small, local microsite disturbances, leading to a potential garlic mustard outbreak. Allaying invasion may require reducing habitat perturbation in susceptible areas and promoting the health of native plant communities [3].

Garlic mustard population densities may oscillate widely from year to year [55]. Its biennial nature and its seed banking propensity can lead to occasions in which dense stands of garlic mustard appear where none were apparent the year before, and then seemingly disappear the following year only to reappear yet again in subsequent seasons. Further, in years where rosettes are apparently sparse and may evade detection, those monitoring such sites may easily but falsely conclude that garlic mustard is absent. In previously infested areas or areas of suspected susceptibility, careful annual monitoring may be the only way to ensure that garlic mustard is indeed absent from the site.

Once garlic mustard appears within an area, management activities should focus on preventing seed production. While most seeds of garlic mustard tend to germinate during the 1st or 2nd spring following their production, a small number of seeds remain within the seed bank and may germinate over the next several years. Because garlic mustard seed banks may remain viable for up to 6 years, long-term control for a particular stand requires vigilant attention for several consecutive seasons [3,7,14,49]. Even after successful management leads to the apparent absence of garlic mustard, continued periodic monitoring is prudent. A method for destroying seeds of garlic mustard in the soil that would not harm seeds of other species has not been determined [7].

Because of the biennial life-history strategy of garlic mustard, eradication treatments conducted during spring, after seedlings have germinated and before adults can produce viable seed, have the advantage of affecting 2 generations simultaneously [49]. Ideally, this maximizes the kill of new germinants and seedlings, as well as prevents seed production in adults. Since natural mortality is greatest at the seedling stage garlic mustard may be most vulnerable to control efforts during this time [20]. One potential downside to this strategy is that delaying treatment too late into spring risks unwanted effects on native spring emergents.

An alternative approach is to delay management activities until after the 1st growing season to take advantage of significant natural mortality of rosettes. First year garlic mustard mortality at a site in northern Illinois was estimated at greater than 95% between April and November [51]. This strategy may be especially prudent when the control method requires intensive labor, such as cutting or hand-pulling plants, if minimizing quantities of applied chemicals is desired, or simply if costs of more intensive management activities are prohibitive.

Control of garlic mustard has been tested using several different methods. Since a single control method is rarely 100% effective, a combination of more than 1 may often be a useful strategy. Regardless of methodology, treatments for eradication of garlic mustard must be applied over the entire area of infestation to prevent seed production.

Manual or Mechanical Removal: Pulling entire plants may be an effective method for control of garlic mustard. Care should be taken to remove as much of the root system as possible, to reduce resprouting potential. Pulling can cause soil disturbance and redistribute seeds stored within the upper soil horizons. This problem may be mitigated by thoroughly tamping disturbed soil after pulling. Generally speaking, cutting results in fewer disturbances than pulling. However, pulling may be done at any time during the plant lifecycle, while cutting must be performed during the 2nd growing season while the flowering stem is elongating. Due to the labor-intensive nature of cutting and pulling plants, these practices may only be practical in small or lightly infested areas, especially where burning or herbicide application is inadvisable [49,55]. Hand removal may be most useful for preventing establishment of new garlic mustard colonies in previously uninfested areas [43].

Control may be accomplished by cutting flowering stems, i.e. using sickles, clippers, or string trimmers, prior to seed production and dissemination. Cutting as close to ground level as possible appears to be most effective. Nuzzo [49] found that cutting at ground level killed 99% of plants and resulted in virtually no seed production, while cutting at 4 inches (10 cm) resulted in 71% mortality and 98% lower total seed production. Mortality was 6% in control plants during the 3-month study period. Cutting plants prior to full flowering or the onset of seed development may result in production of additional flowering stems from buds located on the root crown [55]. However, waiting until after plants have finished flowering risks dissemination of viable seed. Cut or pulled plant material should consequently be removed from the site and destroyed whenever possible to minimize the risk of inadvertently distributing viable seed [55,70].

Mowing may be similar in effect to cutting, but with more possible negative consequences. Mowing of flowering plants may result in regrowth of new flowering shoots, although this response reportedly diminishes as the season progresses [15]. While mowing may be convenient in large, relatively open areas of infestation such as roadsides, this practice may be more problematic than cutting, as described above. Mowing may promote seed dispersal and is more likely to be indiscriminate regarding which plant species are destroyed. Mowing equipment may also create more disturbed habitat that is likely to be recolonized by garlic mustard [55].

Prescribed Fire: In areas with a fire-tolerant native flora, frequent prescribed burning may deter garlic mustard invasion by both directly killing invading plants, and perhaps in some areas by enhancing growth of native herbaceous competitors and thereby reducing habitat for garlic mustard colonization [49,88]. For more information about using prescribed fire as a management tool to control garlic mustard, please see the Fire Management Considerations section of the Fire Effects section of this summary.

Chemical Control: Chemical control of invasive plants such as garlic mustard can be effective, particularly against large areas of infestation or dense monotypic colonies, and especially when considered within the context of an integrated management plan [47,49]. This report briefly examines the effectiveness of selected chemicals for controlling garlic mustard, some issues involved in the timing of application, and potential effects on native plant communities. Use of herbicides in natural areas should be cautiously considered, and appropriate education and training should be sought before proceeding. Particular caution should be exercised with the use of Bentazon or Acifluorfen. Bentazon is very soluble in water and does not bind to soil well, leading to potential groundwater contamination problems. Acifluorfen is toxic to fish, is moderately persistent in soil and kills native grasses and herbs, and can cause serious eye injury [79]. For further information regarding the use of herbicides in natural areas for control of this and other invasive plant species, see the Weed Control Methods Handbook [76].

The effectiveness of 2,4-D against garlic mustard is questionable [55]. Use of 2,4-D in mixtures with other chemicals may improve its effectiveness, but scant evidence is available [15,55].

Application of 1% and 2% glyphosate during the dormant season significantly ($p < 0.05$) reduced adult garlic mustard cover and density in mesic and dry-mesic upland forest and mesic floodplain forest in northern Illinois, but also damaged other species that were green at the time, especially sedges and white avens [53]. Treatment with foliar applied glyphosate also significantly ($p < 0.05$) reduced adult densities of garlic mustard, regardless of spring or fall application, in northern Illinois oak woodland. Seedling frequency in these same plots was significantly ($p < 0.001$) reduced by spring application [49].

Dormant-season application of bentazon was less effective at controlling garlic mustard in northern Illinois mesic deciduous forest, but showed none of the nontarget kill associated with glyphosate. At these same sites, application of acifluorfen during dormant season was highly effective against garlic mustard, but also killed most native herbaceous vegetation, which was mainly dormant at the time of application [53].

Use of systemic, nonselective herbicides during the growing season may not be practical in some areas due to deleterious effects on native ground-layer competitors. In these cases, dormant season application may be preferable in order to maintain viable populations of native competitors [49]. Nuzzo [49] found no difference in effect between single herbicide application and twice applied treatment to the same generation of plants (spring and fall of the same year, fall and the following spring, or 2 consecutive springs). It was suggested that management efforts focus on single applications to successive generations of plants. Fall herbicide application may be a prudent option when risk of negatively affecting native spring-emergent herbs exists. Higher garlic mustard rosette densities in fall may require higher volumes of applied herbicide to be effective [51].

Mid-summer application of bentazon reduced garlic mustard cover by 94-96% in previously dense stands of garlic mustard rosettes in northern Illinois. Similar applications of acifluoren were less effective, but still significantly reduced garlic mustard cover by 30-46%. Mortality in control plots over the same period was 15%, and not statistically significant. Chemical control activities conducted during the growing season, as above, might be justified when target species densities overwhelm the native flora [52].

Biological Control: Biological control methods for garlic mustard are not yet developed, but investigations are under way. Several insects that are associated with garlic mustard in its native European habitats are being tested to examine their potential effectiveness as control agents [55]. Fungal pathogens may also have some potential use against garlic mustard. For instance, garlic mustard has shown susceptibility to a fusarium root rot (*Fusarium solani*) [16].

BOTANICAL AND ECOLOGICAL CHARACTERISTICS

SPECIES: Alliaria petiolata

- GENERAL BOTANICAL CHARACTERISTICS
- RAUNKIAER LIFE FORM
- REGENERATION PROCESSES
- SITE CHARACTERISTICS
- SUCCESSIONAL STATUS
- SEASONAL DEVELOPMENT

GENERAL BOTANICAL CHARACTERISTICS:
Garlic mustard is an established, cool-season, monocarpic, taprooted, herbaceous biennial [6,15,26,31,49,61] or occasional winter annual [15,31,61]. The common name is derived from the scent of garlic, which is noticeably exuded by its aboveground plant parts, especially foliage [15,31,73,82,86].

Seedlings develop into rosettes 0.8-4 inches (2-10 cm) in diameter during the 1st growing season. Mature plants produce erect flowering stems up to 4.13 feet (1.25 m) high [15]. Each rosette usually produces a single flowering stem, although multiple stems from a single rosette occur occasionally [41]. Flowers are borne in racemes, with fully expanded corollas 0.12-0.48 inches (3-12 mm) across [6,15,17,26,27,61,68,73,74,82,86]. Average plant biomass is quite variable within a habitat, between habitats, or between generations within the same habitat, and is strongly influenced by light. Plants grown under higher irradiance levels typically produce greater biomass per plant [3].

Seeds are produced in pods (siliques) up to 6 inches (15 cm) in length [15,27,31,74,82]. Fully developed siliques typically contain 12-19 seeds, and the number of siliques per plant can vary greatly from 1 to more than 200 [74]. Seeds are oblong to nearly cylindrical [15,61] and about 0.12 inch (3 mm) long [27,31,61].

RAUNKIAER [62] LIFE FORM:
Hemicryptophyte
Therophyte

REGENERATION PROCESSES:

Pollination: Garlic mustard is capable of self-pollinization, as well as cross-fertilization [3,15,17]: both seem equivalent in effectiveness. Self-pollination often takes place before flowers open [3], although variation in this ability may exist between populations [3,17]. Cross-pollination has been observed to occur via generalist insect pollinators, providing a high likelihood of pollination wherever garlic mustard occurs [3,15,17].

Seed production:
Because a large percentage of flowers typically set fruit, and most ovules develop seeds, garlic mustard is a prodigious seed producer [17]. Seed production varies between and within sites and between years, but under shaded, moist (apparently favorable) conditions, dense stands may produce > 100,000 seeds/m^2 [14,15]. Seed production in Ohio ranged from 165 to 868 seeds/plant, depending on habitat and population density [74]. The number of seeds per silique in a southern Ontario study varied from 6 to 22 with an average of 16. The number of siliques varied greatly, from 1 or 2 on small plants to up to 150 per plant [15]. Seed production in several states was as follows:

Estimated Seed Production (seeds/m^2)	Location
15,000	Central Illinois [3]
19,060 - 38,025	Ohio [74]
19,800 - 107,580	Southern Ontario [15]
30,689 - 45,018	New Jersey [14]
10,000	Northern Illinois [49]

Seed dispersal:
In forested areas, garlic mustard is typically 1st seen along trails and streams, and can quickly spread via seeds throughout the forest within a few generations [7]. Seeds generally fall within a few meters of the plant [50,74], and may be ballistically dispelled from siliques [49]. Wind dispersal is doubtful. Seeds stick together when damp and adhere readily to small soil clusters [15]. Seed dispersal rates may accelerate along river corridors [46,50], although there are conflicting reports regarding the ability of seeds to float [15,74]. Humans may also spread seeds. Garlic mustard often invades natural areas along roads and trails, purportedly via seed transport on muddy boots or pant cuffs. Seed dispersal may also be facilitated by roadside mowing, as well as on mud-encrusted automobile tires [50]. Animals, especially white-tailed deer, may promote seed dispersal and spread of garlic mustard. Deer are thought to provide an important seed dispersal vector over short distances by transporting seeds in their fur, although this has not been tested as of this writing [3,15]. Foraging deer may create microsite disturbances favorable to garlic mustard dispersal by mixing mineral soil and garlic mustard seeds [49].

Germination:
Seeds of garlic mustard require cold stratification before they can germinate, with 1 season's overwintering usually sufficient to break dormancy at most North American locations [7]. An additional year of dormancy was reportedly required prior to germination in southern Ontario [15], and this lengthier dormancy period may be required in other northern locations [56,70]. Germination often occurs in early spring and can occur at temperatures approaching 32 degrees Fahrenheit (0 °C) [7,63]. Low-temperature germination is ecologically important because garlic mustard seedlings incur a competitive advantage by being the 1st germinants of the season [7,45].

Seed banking:
Garlic mustard produces small but potentially important seed banks. Seed viability has been shown to drop off substantially after the 1st growing season following stratification, indicating seed banks of garlic mustard are relatively short lived [7,63]. In a study of garlic mustard seed biology, roughly 88% of seeds that germinated did so during the 1st spring following production [7]. In a study comparing garlic mustard populations from

contrasting habitats in New Jersey, 3 out of 4 populations were found to maintain a seed bank. The 4th population was located in a seasonal floodplain where flooding actions were thought to either remove the seedbank or produce a patchy distribution that was difficult to sample [14].

A small percentage of seeds may remain viable for 4-6 years [7,15,63]. Because garlic mustard is a prodigious seed producer, elimination of a single season's crop may not suffice to eradicate the species from an area because germination and survival of only a few individuals in subsequent years may quickly lead to repopulation at or near previous levels [7].

Seedling establishment/growth:
Garlic mustard seedlings emerge in early spring, just before or simultaneous with germination of native spring ephemerals [49]. They establish during periods of relatively high light availability in the forest understory prior to canopy leaf-out, typically with reduced interspecific competition and drought potential [7,15,45]. Greatest mortality rates occur in spring during the seedling stage [15]. Seedling mortality can vary substantially, often depending on moisture availability [14]. Initial seedling density may be very high (20,000 seedlings/m^2) [49,74]. In reports where natural spring seedling densities were approximately 3,100 to 5,600/m^2, only about 1% to 16% survived to produce flowers the following year [14,15]. Two consecutive cohorts retained similar numbers of mature flowering plants during their 2nd spring, despite having initial seedling densities differing by more than 100% [3].

Asexual regeneration:
Garlic mustard spreads exclusively by seeds, with no reports of vegetative reproduction [15,74].

SITE CHARACTERISTICS:
Garlic mustard has a wide tolerance of environmental conditions for growth and reproduction, including moisture regimes ranging from periodically flooded areas to dry sand forest [15,42], light environments ranging from open fields to shaded forest interior [12,14], and a range of various soil characteristics including texture [14,15,57], nutrient level [14], organic matter content [14,15], and pH [4,14]. It is apparently not found on acid soils in Indiana, Kentucky, Massachusetts, or the Canadian Shield region [15], and is absent from undrained peat and muck soils [49]. Garlic mustard may be less competitive in areas with low soil pH, as evidenced by an experiment demonstrating a significant positive correlation ($r = 0.98$; $p < 0.001$) between plant dry weight and soil pH. This has been hypothesized as a contributing factor in the limited colonization of garlic mustard in the southern third of Illinois, where soils are more acidic than in the more heavily colonized central and northern sections of the state [4]. Inhibition of garlic mustard by acidic soils may explain its apparent absence from conifer-dominated communities [66].

Garlic mustard appears to favor shaded sites [50], and is often found in dense groups of nearly pure stands, sometimes covering large areas, particularly under moist shaded conditions such as mature eastern deciduous woodlands. In drier or more open areas plants increase allocation to fruit production, perhaps in response to observed declines in seed weight, seed germination, and seedling survivorship [14,46]. While biomass production may be greatest under full sun [15], and garlic mustard plants can also be found under dense shade, they are most commonly found in woodland understories with partial shade and are probably less invasive under extreme conditions of light or shade [49]. Nuzzo [50] describes typical habitat in Illinois as mesic upland or floodplain forest, usually shaded, and often associated with some type of disturbance. Despite its apparent affinity for moist shaded environments, garlic mustard is not tolerant of growing season inundation, which may limit its ability to invade wetland communities [49].

Most populations of garlic mustard appear to be connected to some form of disturbance [14,49]. Garlic mustard is often associated with anthropogenic disturbance such as trails, roads, or railroads [49,50], and less commonly, in farm fields and gardens [50]. Garlic mustard is sometimes linked to naturally disturbed habitats such as floodplains and riverbanks, where the combination of flooding as a dispersal agent and moist, shaded conditions may promote invasion [46]. Garlic mustard was invasive in relatively undisturbed woodlands in central Illinois. Establishment was thought to occur where small-scale anthropogenic and natural disturbance removed competing vegetation, such as areas browsed by white-tailed deer [3]. Experiments examining mechanisms that link disturbance and garlic mustard occurrence and spread are scarce. One study showed that disturbance of soil in a young hardwood forest in northern Kentucky resulted in lowered garlic mustard densities compared to undisturbed plots [39]. An experiment in a southwestern Ohio deciduous forest examined the effects of small-scale litter disturbance on garlic mustard invasiveness. There were no differences ($p = 0.7184$) in garlic mustard germination, rosette survival, growth, or reproduction among total litter removal, partial litter removal, and control treatments, indicating that forest floor disturbance alone may not be a prerequisite for invasion [46]. More research is needed to help understand factors that influence garlic mustard invasiveness and habitat invasibility, particularly for the role of disturbance. In particular, questions involving which life history traits are affected by disturbance seem most appropriate. Experiments that separate disturbance-mediated dispersal from other interactions between disturbance and garlic mustard invasiveness might provide important insights leading to more effective management prescriptions.

SUCCESSIONAL STATUS:
Garlic mustard occurs in communities that represent a wide range of successional stages, from prairie openings to understories of mature, shade-tolerant eastern hardwood forests. While garlic mustard colonizes a variety of sites, it is often mentioned with particular concern to invasiveness in the herb layer of mature eastern deciduous forests, since these communities were thought to be somewhat resistant to invasion by nonindigenous plants (see "Impacts and Control" in the "Management Considerations" section of this summary). In some areas of eastern deciduous forest, dense garlic mustard stands may inhibit recruitment of woody seedlings, perhaps altering successional trajectories [45].

The ability of garlic mustard to invade and compete in habitats with light environments ranging from partial to deep shade may be due to its ability to acclimate to variation in irradiance [2,15]. Despite substantial plasticity in photosynthetic response to variation in irradiance, photosynthetic rates of garlic mustard at high light levels lag behind those of species typically found in unshaded environments, inhibiting the competitiveness of garlic mustard under these conditions [20]. Nevertheless, the ability of the species to acclimate to a wide range of light environments almost certainly contributes to its ubiquitous and invasive nature [2].

Garlic mustard is often mentioned in association with oak savannah communities which, when viewed from the context of fire as the determinant of successional trajectory, represent a transitional state between grassland and forest. For example, garlic mustard was present mainly in areas of lower ambient light levels in a northern Illinois oak savanna remnant, invading where reduced fire frequency resulted in increased tree canopy cover [11]. Because the presence of garlic mustard may inhibit the ability of a forest understory to carry surface fire [49], invasion of garlic mustard could potentially accelerate succession in these oak savannas by further suppressing fire.

SEASONAL DEVELOPMENT:
Garlic mustard seedlings almost always emerge in early spring. In shaded areas growth is rapid until deciduous trees form leaves, after which growth slows. Garlic mustard growing in more open areas may continue steady production of new leaves into summer [74]. Germination usually occurs in February or March, depending on conditions and location [3,15,63,74]. There are reports of germination being triggered by the 1st warm rains of the season [49].

Seedlings develop into rosettes early during the 1st growing season. In central Illinois, garlic mustard leaf area increased into early June, then declined slightly or remained nearly constant until the following spring [3]. Rosettes overwinter and may retain considerable green leaf tissue. They are capable of winter growth during periods of above-freezing temperatures and no snow cover [15,74], although some leaf tissue may be destroyed by extended periods of subfreezing temperatures [3]. Anderson and others [3] observed that new leaf growth was initiated when temperatures warmed to greater than 37-41 degrees Fahrenheit (3-5 °C) for several hours per day. Substantial winter mortality is possible. Nearly 80% mortality was recorded from November 1989 to May 1990 in a northern Illinois dry-mesic upland forest [51]. Fall and winter growth varies by season and location, but by late winter rosettes have leaf primordia surrounding 1 or more terminal flowerbuds [74].

Garlic mustard plants that survive winter undergo rapid bolt growth early in the 2nd spring (March in many areas) [14,15,74]. Reinitiation of growth during this period includes increases in leaf production and elongation of flowering stems, and all surviving plants bolt [15,74]. In central Illinois, plants bolted in March, growing quickly to a maximum leaf area by late April or early May. Stem growth was also rapid during this period, elongating at an average rate of 0.76 inch/day (1.9 cm/day) between April 18 and May 13. Following this period of rapid growth, leaf area quickly declined. Nearly all 2-year-old plants were devoid of green leaves by early July [3]. The fact that bolting occurs very early in spring may contribute to garlic mustard's competitive ability by limiting light and space resources that might otherwise be available to native herbs [45].

Flowering occurs in spring of the 2nd season, usually from early April to early June, depending upon location and season [3,15]. In central Illinois lower flowerbuds appeared in early April, and reached the maximum number per plant about 2 weeks later. Flowering, and the presence of green fruit, peaked around mid-May. Fruit dehiscence began in late May or early June, and by late June no green fruits remained [3]. Damage to terminal flowerbuds can initiate flower production via axillary buds, sometimes occurring well into summer, but these late-season blooms rarely produce viable fruit [3,74].

Typically, seeds are ripe and begin to shed by mid-June and continue to drop throughout summer and into autumn. Seeds have mostly all dropped by early November [3,15]. Once mature plants have produced fruit they senesce and die [74]. Some variability exists regarding the timing of senescence, which is probably related to environmental conditions such as irradiance levels or moisture availability [3].

FIRE ECOLOGY

SPECIES: Alliaria petiolata

- FIRE ECOLOGY OR ADAPTATIONS
- POSTFIRE REGENERATION STRATEGY

FIRE ECOLOGY OR ADAPTATIONS:

Fire Adaptations:

Although garlic mustard plants are readily top-killed when exposed to fire, they may ultimately survive by sprouting from the root crown [53,54]. Ecological conditions that permit sprouting are not well understood and it is unclear to what extent resprouted plants are capable of producing viable seed (see Fire Effects section of this summary).

At the population level, garlic mustard may be adapted to perpetuate itself in mixed-severity or low-severity surface fire regimes, although this has not been quantified. Even though individual plants may be killed by fire, postfire conditions may be favorable for rapid population expansion because of increases in the area of disturbed habitat and, depending on the extant community, temporary reductions in interspecific competition. Additionally, garlic mustard seed banks may facilitate rapid recolonization of disturbed areas [14]. For example, 3 consecutive years of prescribed burning in a central Illinois black oak forest, which were described as "hot and fast" with flame lengths to 4 ft. (1.2 m), failed to eradicate garlic mustard populations. This was attributable, in part, to the protection afforded a small number of plants by refugia such as the lee of a downed log or an area of damp litter [54]. The ability of individual plants to escape mortality will depend upon fire severity and the heterogeneity of the fire landscape.

Fire Regimes:

Garlic mustard may be found within understory surface, stand-replacement, mixed-severity fire, and nonfire regimes [13]. Because garlic mustard has become established only relatively recently in most areas in North

America, and because natural fire regimes have been substantially altered in many of these areas, predicting the response of garlic mustard to any particular fire regime is speculative. In some areas colonized by garlic mustard, estimated mean fire return intervals may be longer than the time in which garlic mustard has been present. As natural areas and preserve managers reintroduce fire into locations where natural and anthropogenic fire has been suppressed in recent times, the response of this and many other species may become better understood. Those who intend to reintroduce fire where it has been absent for a substantial period are encouraged to plan and implement research and monitoring programs and share their findings.

Fire regimes of some of the plant communities in which garlic mustard occurs are summarized below. For further information, see the FEIS summaries of the dominant species listed below.

Community or Ecosystem	Dominant Species	Fire Return Interval Range (years)
maple-beech-birch	*Acer-Fagus-Betula*	> 1000
silver maple-American elm	*A. saccharinum-Ulmus americana*	< 35 to 200
sugar maple	*A. saccharinum*	> 1000
sugar maple-basswood	*A. saccharinum-Tilia americana*	> 1000 [83]
bluestem prairie	*Andropogon gerardii* var. *gerardii-Schizachyrium scoparium*	< 10 [37,58]
sugarberry-America elm-green ash	*Celtis laevigata-U. americana- Fraxinus pennsylvanica*	< 35 to 200
beech-sugar maple	*Fagus* spp.-*A. saccharum*	> 1000
black ash	*Fraxinus nigra*	< 35 to 200 [83]
tamarack	*Larix laricina*	35-200 [58]
yellow-poplar	*Liriodendron tulipifera*	< 35
eastern white pine-northern red oak-red maple	*Pinus strobus-Quercus rubra-A. rubrum*	35-200
Virginia pine-oak	*P. virginiana-Quercus* spp.	10 to < 35
sycamore-sweetgum-American elm	*Platanus occidentalis-Liquidambar styraciflua-U. americana*	< 35 to 200 [83]
eastern cottonwood	*Populus deltoides*	< 35 to 200 [58]
aspen-birch	*P. tremuloides-Betula papyrifera*	35-200 [21,83]
black cherry-sugar maple	*Prunus serotina-A. saccharum*	> 1000
oak-hickory	*Quercus-Carya* spp.	< 35
northeastern oak-pine	*Quercus-Pinus* spp.	10 to < 35
southeastern oak-pine	*Quercus-Pinus* spp.	< 10
white oak-black oak-northern red oak	*Q. alba-Q. velutina-Q. rubra*	< 35
northern pin oak	*Q. ellipsoidalis*	< 35
bur oak	*Q. macrocarpa*	< 10 [83]
oak savanna	*Q. macrocarpa/Andropogon gerardii-Schizachyrium scoparium*	2-14 [58,83]
chestnut oak	*Q. prinus*	3-8

northern red oak	*Q. rubra*	10 to < 35
post oak-blackjack oak	*Q. stellata-Q. marilandica*	< 10
black oak	*Q. velutina*	< 35 [83]
elm-ash-cottonwood	*Ulmus-Fraxinus-Populus* spp.	< 35 to 200 [21,83]

POSTFIRE REGENERATION STRATEGY [72]:
Caudex/herbaceous root crown, growing points in soil
Ground residual colonizer (on-site, initial community)
Initial off-site colonizer (off-site, initial community)
Secondary colonizer (on-site or off-site seed sources)

FIRE EFFECTS

SPECIES: Alliaria petiolata

- IMMEDIATE FIRE EFFECT ON PLANT
- DISCUSSION AND QUALIFICATION OF FIRE EFFECT
- PLANT RESPONSE TO FIRE
- DISCUSSION AND QUALIFICATION OF PLANT RESPONSE
- FIRE MANAGEMENT CONSIDERATIONS

IMMEDIATE FIRE EFFECT ON PLANT:
Garlic mustard is often top-killed when exposed to fire. A prescribed burn in the understory of a northern Illinois hardwood forest removed all aboveground garlic mustard biomass [30]. Prescribed burns in a central Illinois black oak forest conducted both in the fall and in mid-spring removed nearly all garlic mustard rosettes [54]. Although there was no immediate postfire survey of plants mentioned in the article, Luken and Shea [41] suggest that garlic mustard "plants are readily killed by mid-intensity dormant season fires". Emergent seedlings may also be killed by fire [54].

DISCUSSION AND QUALIFICATION OF FIRE EFFECT:
It has been suggested that dense stands of garlic mustard may be able to resist low-severity fire, such that "abundant green garlic mustard plants"...may "literally extinguish fires" [49], but detailed descriptions of the direct effects of fire on garlic mustard plants (or visa versa) are scarce. Such observations may be confounded by the inherently patchy nature of mixed-severity fire regimes in many eastern deciduous forests where garlic mustard may commonly be found. For more information see the "Fire Ecology" section of this summary.

PLANT RESPONSE TO FIRE:
Garlic mustard has at least some ability to sprout from the root crown following damage by fire. By excavating charred rosettes, Nuzzo and others [54] found that adult plants resprouted from adventitious buds on the root crown located just below the soil surface following a mid-spring burn. In a northern Illinois oak woodland, garlic mustard reportedly resprouted several weeks following complete top removal by a prescribed fire conducted in late March [30]. Repeated fall burning (2-3 annual burns) did not reduce abundance or relative importance of garlic mustard in an eastern mesophytic forest understory in Kentucky [41].

DISCUSSION AND QUALIFICATION OF PLANT RESPONSE:
There is some indication that garlic mustard is capable of sprouting following fire, but several questions remain. To what extent is postfire sprouting in garlic mustard influenced by fire severity? What, if any, physiological conditions promote or constrain postfire root crown sprouting? To what extent are resprouting plants successful at producing seed?

Nuzzo and others [53] reported that a fall burn in a central Illinois black oak forest removed 79% of the litter layer, and very few adult garlic mustard plants were encountered in these plots the following spring. Conversely, many garlic mustard plants resprouted following a mid-spring burn at the same site that resulted in removal of only 32% of the litter layer. Spring burn plots retained a damp 0.4- to 0.8-inch (1-2 cm) layer of litter which seems to have protected the root crowns of top-killed plants, fostering survival via sprouting of multiple secondary shoots from adventitious buds located just below the soil surface [54].

Hintz [30] conducted a late-March prescribed burn in a mesic upland oak-hickory forest in northern Illinois. Garlic mustard established following the fire, although it is unclear whether these were sprouting burned plants or new spring seedlings. The burn was conducted near the time when seedling emergence might be expected, leaving some question as to which life-cycle stage was observed to be "sprouting". There is reference to "very little" garlic mustard producing seed that summer, intimating that at least some adult plants were present both prior to and after the fire.

Luken and Shea [41] conducted a prescribed fire experiment in a northern Kentucky mesic deciduous forest in which they showed that garlic mustard plants could be removed by a fall burn. Yet it was also apparent from this experiment that populations can persist following even repeated burns. Garlic mustard remained the dominant species in the herb layer of both burned and unburned plots through 3 seasons of fall burning, and beyond. The authors proposed 3 possible explanations. First, persistence of individual garlic mustard plants immediately following fire may result from the patchy nature of many understory or mixed-severity burns. Under such conditions some extant plants may escape damage, and because of its ability to self-pollinate [3,15,17], the survival of a single plant may be sufficient to perpetuate a population. Second, the data of Luken and Shea [41] showed that burning resulted in higher densities of flowering stems compared with control plots. They speculated this as being due to either resprouting or release from competition. No observations of sprouting were reported. Third, even if all plants are killed, the existing seed bank may remain viable for several years [7,14], requiring subsequent annual burns to completely eradicate the population.

FIRE MANAGEMENT CONSIDERATIONS:
Control of invasive garlic mustard populations using prescribed fire, especially as a single management tool, appears to be difficult. Some temporary control is likely, but difficulties sustaining long-term control are confounded by a) the patchiness of understory and mixed-severity fires, b) the biennial nature of the species, c) the moderately persistent seed bank, and d) garlic mustard's propensity for rapid population increase (see section on Biological and Ecological characteristics) [41,54,67].

It may be possible to substantially diminish the number of individuals in a garlic mustard population with repeated burn treatments. But prescribed burning, especially during the growing season, could actually increase the relative importance of garlic mustard [3,41,54]. A prescribed burn conducted in May in a northern Illinois dry-mesic upland deciduous forest effectively reduced cover of garlic mustard, from a pre-burn 29.4% cover to 2.3% cover, postfire year 1. But May burning also damaged the native forb community, where total stem density of major herbs and small shrubs was reduced by 32% and average number of species per plot was reduced by 35%, postfire year 1. Although native plants subsequently showed gradual recovery, these effects were detectable for 3 years, most notably for Jack-in-the-pulpit and stickywilly. Garlic mustard recovery was more rapid. Within three years following burning garlic mustard had rebounded to 17.3% cover compared with a pre-burn level of 29.4% [67].

Dormant-season burns, while less likely to have negative effects on indigenous flora, also appear to be less effective at killing garlic mustard rosettes. After 3 years following a March prescribed burn at the above location, both garlic mustard and native herb cover had returned to approximate pre-burn levels [67].

It has been suggested that a narrow window of time exists during early spring in some areas and in some years, during which garlic mustard may be more effectively controlled by fire without damaging native plants. This hypothesis remains untested as of this writing [67]. Also, spring burns may increase seedling survival. Fires of insufficient severity may spare a sizable fraction of seedlings protected by the unburned portion of the litter layer. Additionally, a spring burn timed too early may permit survival of garlic mustard seedlings that germinate after treatment. In addition to greater initial seedling survival, removal of a portion of the litter layer may also provide a more favorable environment for growth and development of garlic mustard rosettes [54].

Apparently not all fires are equally effective at top-killing garlic mustard. The effectiveness of prescribed spring and fall burn treatments in reducing garlic mustard populations in an oak (*Quercus* spp.)-dominated dry-mesic upland forest in northern Illinois was directly related to fire "intensity". "Low-intensity" burns, with flame lengths up to 1.2 inches (3 cm), were patchy and frequently extinguished within plots. These "low intensity" burns had little to no effect on garlic mustard plants, whether seedlings or adults, regardless of season of burning. It was suggested that abundant green garlic mustard plants frequently extinguished the "low intensity" fires. "Mid-intensity" burns, with flame lengths up to 3 inches (15 cm), burned through most of the plots and significantly reduced the presence of garlic mustard. Adult plant densities were reduced by both spring and fall burns, as well as repeated fires, although single spring burns were most effective [49].

In areas with long fire-return intervals where favorable conditions for conducting effective prescribed burns may be rare to nonexistent, especially repeated annual burns, or where fire-sensitive native species exist, prescribed fire may be unsuitable as a management tool. Nevertheless, in areas with a fire-tolerant native flora, frequent prescribed burning may deter garlic mustard invasion by both directly killing invading plants, and perhaps in some areas by enhancing growth of native herbaceous competitors and thereby reducing habitat for garlic mustard colonization [49,88]. It is highly likely that managers who use fire to control garlic mustard may need to augment burn treatments with 1 or more additional control methods, such as pulling or herbicide use to achieve acceptable levels of control (see Management Considerations section for more information on other control methods).

Alliaria petiolata: References

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