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The impact of exotic species on native organisms is widely acknowledged, but poorly understood. Very few studies have empirically investigated how invading plants may alter delicate ecological interactions among resident species in the invaded range. We present novel evidence that antifungal phytochemistry of the invasive plant, Alliaria petiolata, a European invader of North American forests, suppresses native plant growth by disrupting mutualistic associations between native canopy tree seedlings and belowground arbuscular mycorrhizal fungi. Our results elucidate an indirect mechanism by which invasive plants can impact native flora, and may help explain how this plant successfully invades relatively undisturbed forest habitat.

Introduction

Widespread anthropogenic dispersal of exotic organisms has raised growing concern over their devastating ecological impacts, and has prompted decades of research on the ecology of invasive species [1–3]. Exotic plants may become aggressive invaders outside their home ranges for a number of reasons, including release from native, specialized antagonists [4], higher relative performance in a new site [5], direct chemical (allelopathic) interference with native plant performance [6], and variability in the responses and resistance of native systems to invasion [7,8]. Thus, successful invasion in many cases appears to involve the fact that invasive species are not at equilibrium, and are either freed of long-standing biotic interactions with their enemies in the home range, and/or disrupt interactions among the suite of native organisms they encounter in a new range [9]. Nevertheless, experimental data on species-level impacts of exotic plants are still limited [10]. One particularly understudied area is the potential for invasive plants to disrupt existing ecological associations within native communities [6,10]. Many exotic and native plants alike depend upon mutualisms with native insects, birds, or mammals for pollination and seed dispersal [11], and with soil microbes for symbiotic nutrient exchange [12]. Thus, when an introduced species encounters a new suite of resident organisms, it is likely to alter closely interlinked ecological relationships, many of which have co-evolved within native systems [6,11].

One such relationship is that between plants and mycorrhizal fungi [12]. Most vascular plants form mycorrhizal associations with arbuscular mycorrhizal fungi (AMF) [12], and many plants are highly dependent on this association for their growth and survival [12], particularly woody perennials and others found in late-successional communities [13]. In contrast, many weedy plants, in particular non-mycotrophic plants, can be negatively affected by AMF [14–16]. Naturalized exotic plants have been found to be poorer hosts and depend less on native AMF than native plants [17]. They often colonize areas that have been disturbed [2], and disturbances to soil have been shown to negatively impact AMF functioning [18]. Furthermore, it has been proposed that the proliferation of plants with low mycorrhizal dependency may degrade AMF densities in the soil [17]. However, a few invasive plants proliferate in the understory of mature temperate forests [2], where AMF density is typically high [19]. The existing mycelial network in mature forest soils may facilitate the establishment of exotic, mycorrhizal-dependent, recruits [20,21], but this should not be the case for non-mycorrhizal invaders. If non-mycorrhizal invasive plants establish and degrade AMF in mature forests, then the effects on certain resident native plants could be substantial.

One of the most problematic invaders of mesic temperate forests in North America is Alliaria petiolata (garlic mustard; Brassicaceae), a non-mycorrhizal, shade-tolerant, Eurasian biennial herb which, like most other mustards, primarily occupies disturbed areas. Garlic mustard is abundant in temperate forests [2], and disturbances to soil have been shown to negatively impact AMF function [18]. Furthermore, it has been proposed that the proliferation of plants with low mycorrhizal dependency may degrade AMF densities in the soil [17]. However, a few invasive plants proliferate in the understory of mature temperate forests [2], where AMF density is typically high [19]. The existing mycelial network in mature forest soils may facilitate the establishment of exotic, mycorrhizal-dependent, recruits [20,21], but this should not be the case for non-mycorrhizal invaders. If non-mycorrhizal invasive plants establish and degrade AMF in mature forests, then the effects on certain resident native plants could be substantial.

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Results/Discussion

We first tested whether native tree seedlings were less able to form mycorrhizal associations when grown in forest understory soils with a history of garlic mustard invasion than when grown in soils that had not experienced invasions (Experiment 1). We found that dominant native hardwood tree species of northeastern temperate forests, *Acer saccharum* (sugar maple), *A. rubrum* (red maple), and *Fagus grandifolia* (white ash), showed significantly less AMF colonization of roots (Figure 1A) and slower growth (Figure 1B) when grown in soil that had been invaded by garlic mustard. AMF colonization was almost undetectable in soil that had been invaded by garlic mustard. These reductions were similar to those observed when seedlings were grown in sterilized soil from both garlic mustard–invaded and garlic mustard–free sites (Figure 1B), strongly suggesting that the mechanism by which garlic mustard suppresses the growth of native tree species is microbially-mediated, and not the result of soil differences or direct allelopathy.

We then conducted additional experiments to confirm that garlic mustard specifically caused AMF decline in the native soils (Experiment 2–4). We grew seedlings of the same three native tree species used in Experiment 1 in uninvaded forest soils that were conditioned for 3 mo with either garlic mustard plants or with one of the three native tree species. All three tree species demonstrated significantly lower AMF colonization in soils conditioned by *A. petiolaris* (0%–10%) than in soils conditioned by the native plants (20%–65%; Figure 2A). AMF colonization was similar in unconditioned (control) soils and soils conditioned with native plants. In addition, growth of the tree seedlings was the lowest in soils conditioned by garlic mustard (Figure 2B), confirming that garlic mustard plants reduce native plant performance by interfering with the formation of mycorrhizal associations.

We investigated whether there is a phytochemical basis to garlic mustard’s observed antifungal effects on AMF in Experiments 3–4. In an earlier study, Vaughn and Berthow [31] isolated the phytotoxic glucosinolates hydrolysis products allyl isothiocyanate, benzyl isothiocyanate, and glucotropaeolin from extracts of *A. petiolaris* root tissues and found evidence for their allelopathic effects on certain plants in the absence of mycorrhizas. These phytochemicals could have direct effects on plant growth through allelopathy as well as indirect effects via disruption of AMF. To experimentally establish that garlic mustard’s effect on AMF is phytochemically based, we grew native tree seedlings on uninvaded soils to which we added individual aqueous extracts of garlic
mustard or each of the native trees species (Experiment 3).

We found that garlic mustard extract was just as effective as the living plant at reducing AMF colonization (Figure 3A) and growth (Figure 3B) of the native plants. Moreover, exposing AMF spores to extract of garlic mustard severely and significantly reduced germination rates of those spores (Experiment 4; Figure 3C). Collectively, our results clearly demonstrate that garlic mustard, probably through phytochemical inhibition, disrupts the formation of mycorrhizal associations. Our results thus reveal a powerful, indirect mechanism by which an invasive species can suppress the growth of native flora.

Because plants vary in their dependency on AMF [32], garlic mustard’s disruption of native plant-fungal mutualisms should not inhibit the growth of all plants equally, but rather should correlate strongly with the mycorrhizal dependency of species encountered in the invaded range. Specifically, courser root production, which impedes the nutrient uptake of typically slow-growing, woody plants such as tree seedlings, may explain the stronger AMF dependency of certain species [19,33]. To test whether garlic mustard’s effects correlate with AMF dependency, and whether garlic mustard has stronger negative effects on forest tree seedlings than on other plants, we conducted another experiment (Experiment 5) using 16 plant species for which we determined AMF dependency [19,33] by exposing AMF spores to extract of garlic mustard severely and drastically impairing the growth of native canopy species. It is currently unclear precisely which phytochemicals produced by garlic mustard have the observed antifungal properties, whether and how they interact with other soil microbes, and whether these anti-fungal effects extend to other functionally important forest soil fungi such as ectomycorrhizal fungi and saprotrophic fungi. In addition, within the home range, it is not known if evolutionary natural resistance of co-occurring European neighbors may buffer the effects of garlic mustard’s antifungal properties [34–36]. Further research in these directions is needed to better understand the effects of this invader on natural ecosystems and the mechanisms involved. In North America; however, the disruption of native tree seedling–AMF mutualisms may facilitate garlic mustard’s invasion into mature forest under-
story and have particularly negative effects on the growth, survival, and recruitment of native trees, and the composition of forest communities.

Materials and Methods

Experiment 1. Using a 15-cm-wide corer, we collected soil from garlic mustard-invaded and nearby garlic mustard–free locations at each of five forested areas dominated by Fraxinus americana L. (white ash), Acer rubrum (maple), or white ash in a completely randomized design with ten replicates of each treatment combination. The initial wet biomass of each seedling was recorded prior to planting, and dry weights were estimated using a dry-weight regression calculated from twenty extra seedlings. Pots were randomly placed on a greenhouse bench. Plants were watered (400 ml) once per week. Fertilizer was not added. After 4 mo of growth, shoots and roots were harvested, dried at 60 °C for 48 h, and weighed to determine biomass. An approximately 1-g subsample of roots from each seedling was extracted, stained with Chlorazol Black E [37] and analyzed for mycorrhizal colonization by AMF [38]. Biomass and percent mycorrhizal colonization data were analyzed using analysis of variance (ANOVA) for two fixed effects (soil type and species) and their interaction, followed by the Ryan–Einot–Gabriel–Welsch (REGW) multiple-range test.

Experiment 2. Using field soil without a history of garlic mustard invasion (see Experiment 1), we grew garlic mustard, sugar maple, red maple, and white ash seedlings in separate 6-in pots (n = 10) to condition the soil to each plant species. After 3 mo of conditioning, shoots and roots were removed. Unconditioned soil served as a control to the the four plant-conditioning treatments. We added one seedling of each of the three tree species to each of the five soil treatments. Pots were randomly placed on a greenhouse bench. Plants were watered (400 ml) once per week, without fertilizer. After 4 mo of growth, plants were harvested, biomass was determined, and percent mycorrhizal colonization of roots was assessed as in Experiment 1. Data were analyzed using two-factor ANOVA followed by the REGW multiple-range test.

Experiment 3. To 6-in pots containing field soil without a history of garlic mustard (see Experiment 1), we added a one-time, 100-ml aqueous extract [27] of whole plants of either garlic mustard, sugar maple, red maple, or white ash. A water control was included to give five treatments. Whole-plant extract was used to account for secondary compounds exuded through roots and leaf litter. After 1 wk of exposure to the extract, seedlings of each tree species were planted in each of these five treatments to give a full factorial design (extract source x tree species) with ten replicates of each treatment combination. Plants were watered (40 ml) every week, without fertilizer. After 4 mo of growth, plants were harvested, biomass was determined, and roots were assayed for mycorrhizal colonization as in Experiment 1. Data were analyzed by two-factor ANOVA.

Experiment 4. Spores from AMF native to the forest sites were obtained using trap cultures (as described in [39]), but with a mix of native plants) of soil samples from the uninvaded locations. We visually collected and separated spores of Glomus and Acaulosporae from these cultures, and compared germination rates of each genus in five treatments: a water agar control and water agar amended with an aqueous extract from each of the four plants, as above. Ten randomly drawn spores were added into each plate, which was then incubated at 18 °C for 10 d. Ten replicate plates were prepared for each of the ten treatment combinations (two AMF genera × five extracts). Plates were monitored microscopically for spore germination. Percent germination data were analyzed using ANOVA for two fixed effects (extract source and AMF genus), and because of a significant interaction, each AMF genus was then analyzed separately using single-factor ANOVA followed by the REGW multiple-range test.

Experiment 5. We investigated the effects of garlic mustard on woody and herbaceous plants using the following 16 native plant species: Cichorium intybus L., Trifolium repens, Plantago major, and Taraxacum officinale (dominant herbaceous colonizers of forest edges and bare ground); Soldago canadensis, Chrysanthemum leucanthemum, Daucus carota, and Asclepias syriaca (dominant herbaceous edge and gap species); Jacquemourtia virginiana, Populus deltoids, Morus alba, and Prunus virginiana (dominant woody colonizers of forest edges and gaps); and Prunus serotina (dominant tree species of mature forest). Seedlings of each plant were transplanted into 8-in pots. For each species, growth was compared under the following soil treatments: (1) soil without a history of garlic mustard and inoculated with AMF, (2) soil without a history of garlic mustard, without AMF, (3) soil with a history of garlic mustard, without AMF, and (4) soil with a history of garlic mustard, inoculated with AMF. Experimental soil was collected within a mature-canopy maple forest location with and without garlic mustard. Soils from each location type were then mixed, cleared of
all coarse roots and debris, autoclaved, and added to the pots as a 1:1 mix of soil and silica sand. AMF spores were extracted from soil collected from sites representing the four different habitats, and pooled. The AMF-inoculation treatment consisted of adding 200 randomly picked spores to each pot, 2 cm below the surface, and beneath the newly transplanted seedlings. Plants were watered (500 ml) once per week, without fertilizer. They were harvested after 4 mo of growth, dried at 60 °C for 36 h, and weighed to determine biomass.

AMF dependency of each plant species was determined by computing the difference in plant growth in the presence and absence of AMF, i.e., contrast of treatments (1) and (2) [32]. The effects of garlic mustard on plant growth and percent colonization of each plant were determined by contrasting treatments (1) and (3). To ask whether any relationships existed among mycorrhizal dependency, life form, and garlic mustard effects, we performed two regressions: percent reduction in AMF colonization by garlic mustard on AMF dependency and percent reduction in plant biomass by garlic mustard on AMF dependency.

References

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Author contributions. KAS, RMC, and JNK conceived and designed the experiments. KAS and JNK performed the experiments. KAS, SAC, JRP, BEW, RMC, GCT, SGH, DP, and JNK analyzed the data. JNK contributed reagents/materials/analysis tools. All authors wrote the paper.

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