THE INVASION OF GARLIC MUSTARD IN NORTH AMERICA AND CONTROL MEASURES

by

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ABSTRACT

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Key Words: invasive species, biodiversity, garlic mustard, ectomycorrhizal fungi, understory community, ecological invasion, biological control, Arbuscular mycorrhizal fungi

The purpose of this report is to investigate the impact of garlic mustard invasion on forest and control measures. Invasive species often cause harm to local ecosystems. Garlic mustard is an invasive herb native to Europe that was brought to North America in the early 1800s. Its seeds are small and numerous and spread easily. It is one of the most aggressive invasive species in Ontario. Garlic mustard invades undisturbed forests and its main effect is to reduce the abundance of soil and root mycorrhizal fungi, inhibiting the growth of native plants. Garlic mustard alters the diversity and activity of forest soil microorganisms. And studying the complex population dynamics of invasive species can help with planning and management. It is also important to choose appropriate control methods, mechanical control and chemical control (hand pulling, herbicide, etc.) on garlic mustard treatment effect is not obvious. The introduction of natural enemies in biological control is an efficient control method. Four weevil species have great potential in garlic mustard control. The possibility of eradicating invasive plants can be greatly improved by applying population genetics to biological control.

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INTRODUCTION

Biological invasion is a species that is introduced through human activities or natural activities, gains a competitive advantage after the natural obstacles to its proliferation disappear, spreads rapidly in the local area, and conquers new areas in the ecosystem (Valéry et al. 2008). Invasive species can cause obvious damage or impact the local ecosystem or landscape. Species invasions will destroy the local complex ecosystem and reduce biodiversity (O'Sullivan et al. 2019a). Biological invasion is now a global environmental problem that needs to be solved urgently in the world (Rodgers et al. 2008). A comprehensive understanding of biological invasions is helpful for the prediction and control of invasions, as well as for investigating issues such as ecology and evolution (Gurevitch et al. 2011).

Plant invasions have been increasing in forests around the world, with herbaceous invaders forming a single layer of undergrowth, competing for space and nutrients from native plants (Liebhold et al. 2017). Garlic mustard (*Alliaria petiolate*) is a biennial herb native to Europe with rapid adaptability and phenotypic plasticity (Yates and Murphy 2008a) (Figure 1). It was introduced to North America in the mid-1800s and expanded its distribution up to 6,400 square kilometers every year at a rapid rate (O'Sullivan et al. 2019a). It has invaded relatively undisturbed forests in the Midwestern United States and southern Ontario, Canada, and is one of the most aggressive invasive species in North America (DURKA et al. 2005). It has caused great damage to the local forest because it will form a dense single-species forest, replace the dominant native plant community, and greatly reduce the number and diversity of native plant species (Portales-Reyes et al. 2015).

Figure 1 Garlic Mustard (Invader of the month – Garlic Mustard n.d.)

Allelopathy is often regarded as the reason for the successful invasion of some non-native plants (Portales-Reyes et al. 2015). It refers to a plant species that produce toxic secondary compounds, directly or indirectly affecting neighboring plants or soil microorganisms, and destroying the germination and growth of neighboring species (Portales-Reyes et al. 2015; Rodgers et al. 2008). There are many plant secondary compounds in garlic mustard, including glucosamine, flavonoids, and so on (Rodgers et al., 2008). These compounds can affect the growth of native plants, change the activities of the soil group, and prevent the use of herbivores. Most herbivores will not eat this invasive plant because it contains nitrogen and sulfur to help defense itself

(Lewis et al. 2006). Therefore, there is almost no pressure from herbivores in North American garlic mustard (Blossey et al. 2001a). This is also one of the reasons why invasive species successfully invade, that is, there are no natural enemies. In this case, the invasion process of garlic mustard is smoother (O 'Sullivan et al. 2019a). The secondary compounds produced by garlic mustard through allelopathy can destroy the root fungal symbionts in competing species. Roberts and Anderson (2001) believe that "garlic mustard may reduce the competitiveness of native plants by interfering with the formation of the mycorrhizal association and root growth."

People continue to study various prevention and control measures to cope with the negative impact of garlic mustard on the ecosystem. The control of invasive species includes biological control, chemical control, and mechanical control. Burning garlic mustard, removing it, using herbicides, and introducing natural enemies can all have a certain degree of control effect (Shartell et al. 2012a). Biological control is relatively safe and has broad development prospects, but there are some uncertainties (CHALAK et al. 2011). Among them, weevils can be used as an efficient biological control agent. Its larvae can dig the root cap of garlic mustard, and will feed on the leaves of garlic mustard as adults (Gerber et al. 2008). For chemical control, glyphosate can be used. The use of glyphosate may be more effective in prevention and control, but if glyphosate is used only once, rapid recovery of garlic mustard may occur (Murphy et al. 2007). And as a chemical agent, it may remain in the wild and harm the environment. Manual removal of garlic mustard can effectively reduce the population. As long as the operation is repeated, the seed bank can be exhausted (Chapman et al. 2012).

However, manual plucking also interferes with the soil and increases the relative emergence rate of exotic species. Burning a large area of garlic mustard to different degrees produces completely different results. Low-intensity fire not only does not necessarily reduce the population size but even increases the survival rate of seedlings (Pardini et al. 2009a). Therefore, the management of garlic mustard requires reasonable planning to achieve the best prevention and control effect.

OBJECTIVE

The purpose of this paper is to analyze the influence of garlic mustard allelopathy on soil microorganisms, determine the factors that affect garlic mustard allelopathy, and further explore the best prevention and control measures for garlic mustard.

HYPOTHESIS

(i) Research Question: How does the allelopathy of mustard affect soil microorganisms?

Alternative Hypothesis: The allelopathy of garlic mustard reduces the content of microorganisms in the soil.

Null Hypothesis: The allelopathy of garlic mustard has no effect on the microbial content in the soil.

(ii) Research Question: What is the best control measure for garlic mustard?

Alternative Hypothesis: Compared with chemical control and mechanical control, biological control is the best measure to control garlic mustard.

Null Hypothesis: There is no difference in the treatment effect of chemical control, mechanical control, and biological control.

LITERATURE REVIEW

GARLIC MUSTARD

Biological invasion is second only to habitat loss as a cause of global biodiversity decline (Luque et al., 2014). Garlic mustard, as one of the most aggressive invasive species in North America, has always been a key research object. It was introduced as food and medicine in the beginning, but then it spread wildly at an exponential rate (Colautti et al., 2014). Garlic mustard is often found in places with high air humidity, such as rivers, moist and shady land in forests. From New England to the Midwest, from southern Ontario to Tennessee, these places have been occupied by garlic mustard (Welk et al. 2002a).

O'Sullivan et al. (2019b) believe that garlic mustard poses a threat to native species, but it will not promote the increase of other invasive species, because it can successfully invade disturbed habitats. This shows that garlic mustard is a successful invasive organism. The reasons for the success of garlic mustard invasion of woodland include several aspects, including a self-bred reproduction system, high seed yield, and rapid growth in the second growing season (Anderson et al. 1996). The seeds of garlic mustard are easily spread through a variety of media, including wind, mammals, and currents. Its population is cross-pollinated at a high level and has a lot of genetic variation (Cruden et al. 1996). And every ovule that is pollinated will develop into a viable seed (Cruden et al., 1996). The high viability of the seeds contributed to the success of the garlic mustard invasion. The repeated introduction is also one of the reasons for the success of the invasion because the range of introduction has produced genetic variation and thus increased the evolutionary potential of invasive species (Durka et al. 2005). However, these studies lack consideration of allelopathic effects.

ALLELOPATHY

Some evidence indicates that the reason why invaders can spread and reproduce quickly and inhibit other plants is that they produce new compounds that can fight against native species. This is the new weapon hypothesis (Callaway et al. 2008).

To begin with, these compounds can fight against local animals. Cruciferous plants usually produce irritating compounds, such as toxins and insect repellents (Renwick 2002). The combination of flavonoid glycosides and butenenitrile glycosides in garlic mustard secondary compounds can prevent them from being eaten by insects. In addition, there are also studies that prove that garlic mustard relies on these compounds to create ecological traps for native animals. For example, although native American butterflies can rely on most wild mustard as host plants, they cannot survive on garlic mustard. Garlic mustard allows adults to lay eggs on its leaves, but these larvae cannot survive on its leaves (Renwick et al. 2001). There is increasing evidence that garlic mustard is resistant to the native butterfly *Pieris napi oleracea* and will also greatly reduce the number of white butterflies in West Virginia (Renwick 2002).

In addition, the reason for the strong flavor of garlic mustard is glucosinolates, a sulfur and nitrogen compound extracted from amino acids (Rodgers et al. 2008). For a long time, the fungicidal, bactericidal and allelopathic effects of glucosinolide have attracted much attention (Fahey et al. 2001). Among all the secondary compounds of garlic mustard, glucosinolates play a major role. Glucosinolates belonging to the aliphatic group are the most studied (Fahey et al. 2001). Both glucosinolates and their breakdown products enhance the ability of garlic mustard to compete with native plants after the invasion (Fahey et al. 2001; Rodgers et al. 2008).

Roche et al. (2021)'s research shows that the symbiosis of plants and mycorrhizas exists in various places, which plays an important role in plant growth and development and community dynamics. Arbuscular mycorrhizal fungi (AMF) can help plants obtain nutrients, especially nitrogen and phosphorus (Cantor et al. 2011). The study of Cantor et al. (2011) showed that garlic mustard releases a substance called allyl isothiocyanate (AITC) that destroys beneficial arbuscular mycorrhizal fungi in the roots of native plants. AITC had a great negative impact on AMF spore germination, and a low concentration of AITC also caused great harm. When the plant-mycorrhizal relationship is disrupted by garlic mustard, it becomes difficult for the plant to obtain nutrients.

Due to the constant release of these toxins from garlic mustard root tissues, garlic mustard can dominate local forest ecosystems (Vaughn and Berhow 1999). In addition, there is also an interaction between garlic mustard and Ectomycorrhizal fungi (EM fungi). The impact of garlic mustard on EM fungi is partly controlled by the composition of the host tree species (Wolfe et al. 2008). Their experiments also showed that the invasion of garlic mustard was related to the decrease in EM fungal colonization level.

Although invasive species pose a threat to biodiversity and ecosystem stability, they have a potential impact on the process of soil nutrient cycling. The presence of garlic mustard can increase the burden of fungal pathogens in the soil, and improve the effective utilization of soil nutrients and soil pH value (Anthony et al. 2019). It can improve the use of soil nutrients and create a nutrient area suitable for its growth (Ehrenfeld 2003). In this case, Rodgers et al. (2008) believe that garlic mustard has both positive and negative effects, but in general, the negative effects outweigh the positive effects.

Mycorrhiza has always played an important role in decomposer in the nutrient cycle. The successful restoration of fungi can make the successful restoration of native plants possible. According to Anthony et al. (2019)'s research, garlic mustard is a huge hazard to the local soil colony. Even with the large-scale eradication of garlic mustard, it is difficult to restore the pre-invasion fungal community (Anthony et al. 2019).

Of course, not all studies concluded that the allelopathy of garlic mustard will have a huge negative impact on other plants. Current studies have also shown that the degree of the negative impact of garlic mustard on symbiotic species depends on the specific characteristics of different species and the source of garlic mustard (Prati and Bossdorf 2004). They believe that although allelopathy contributes to the success of garlic mustard invasion, it needs to be compared with other factors, and the overall effect of allelopathy may be small.

Trezzi et al. (2016) believe that allelopathic effects will be affected by ultraviolet radiation, temperature, moisture, and other factors, and the effect is not static. Kong et al. (2002) have compared the allelopathic potential of *Ageratum conyzoides* under different environmental stress conditions. Under different environments, the production of allelochemicals will change (Meiners et al. 2012). For example, the allelopathy of garlic mustard varies with light conditions (Smith 2015). The more intense the light, the more glucosinolates are released from garlic mustard roots. Smith (2015) proved through experimental investigation that the potential of garlic mustard allelopathy varies with light conditions, not due to genetic variation between garlic mustard populations under different light environments. Allelochemicals enter the soil through a process of adsorption (Kobayashi 2004). Soil conditions include pH, soil water content, and inorganic/organic matter in the soil. When these levels are reduced, the allelochemicals in the soil are also reduced (Kobayashi 2004). Lankau (2010) believes that soil is a complex environment, and allelochemicals may change drastically over time after entering the soil. Microorganisms in the soil can convert allelochemicals into more toxic by-products, such as thiocynates, nitriles, etc.

CONTROL MEASURES

Invasive species have adverse effects on native species and ecosystems. Therefore, the selection of successful long-term management methods for specific species has always been the focus of attention (Blossey et al. 2001b). People need to study the potential invasion process of invasive plants, formulate relevant scientific quarantine regulations and laws based on the characteristics of various invasive plants and control the further spread of invasive plants (Welk et al. 2002b). In recent years, people have been considering various countermeasures to control the invasion of garlic mustard. Pardini et al. (2009b) claim that studying complex population dynamics will help control garlic mustard. They built a stage structure model to evaluate simulation management strategies. This kind of biological population has density dependence at multiple stages. Some researchers also indicated that Inter-simple sequence repeat (ISSR) markers can be used to examine the biogeographical relationship and genetic similarity between the garlic mustard populations introduced in Europe and North America (Meekins et al. 2001). They state that using molecular tools, including chloroplast DNA, can help people fully understand the spread of garlic mustard from Europe to North America. At the same time, managers should use decision-making tools such as the Invasive Plant Management Decision Analysis Tool (IPMDAT) and WeedSearch to assess the feasibility of the project to achieve specific recovery goals (Corbin et al. 2017). Through experiments on the partial and total eradication of garlic mustard, it was found that with the decrease of garlic mustard plots, the local species diversity will increase significantly (Stinson et al. 2007).

Regarding the management and control effects of garlic mustard, people can consider from the following perspectives, including the reduction in the number of garlic mustard seedlings, the impact on the diversity and regeneration of other plants under the forest (Shartell et al. 2012b; Stinson et al. 2007). Shartell et al. (2012b) compare several methods of removing garlic mustard. They concluded that neither a single herbicide application nor manual pulling had a significant effect on garlic mustard control. Manual plucking of garlic mustard may also interfere with native vegetation, which in turn may promote the invasion of garlic mustard. If the native forest is in a healthy and lush state, it will reduce the abundance of garlic mustard to a certain extent (Bauer et al. 2010).

Nuzzo et al. (1996) conducted an experiment in a sand forest in central Illinois to investigate whether repeated fires could control the invasion of garlic mustard. They believe that using fire to control garlic mustard has two sides. Although persistent fires cannot completely eradicate garlic mustard, their expansion can be controlled. However, a single fire treatment is likely to promote the spread and reproduction of garlic mustard. Therefore, there are limitations in using fire to control garlic mustard.

When applying chemicals to remove garlic mustard, it is necessary to consider whether it will affect other native plants (Frey et al. 2007). Frey et al. (2007)'s research shows that applying glyphosate at low temperatures can effectively control garlic mustard without damaging local herbs. Carlson and Gorchov (2004)'s survey also proved that the herbicide (glyphosate) reduces the density of allium plants without negatively affecting native plants. After the density of allium plants decreased, the native species responded positively. Nuzzo (1991) found that the use of chemical and mechanical control methods in different seasons will have different results. The use of glyphosate in spring can reduce its adult density and seedling frequency, but its use in autumn only reduces the density of rosettes.

As the problem of invasive species becomes more serious, biological control is the only solution that can guarantee safety, economic benefits and meet environmental sustainability at the same time (McFadyen 1998). And McFadyen (1998) believes that traditional biological control is the main method of weed biological control. In the biological control of weeds, it is very important to find effective natural enemies that only target invasive species and do not harm other species (Rauth et al. 2011, Goolsby et al. 2006).

In 1998, a study on the biological control of garlic mustard found that 70 herbivores and 7 fungi in Europe would feed on garlic mustard, but lacked host specificity (Blossey et al. 2001a). Some glucosinolates are present in the host plant of the weevil and act as feeding irritants (Fahey et al. 2001). Generally, only five weevil species from the genus *Ceutorhynchus* can be used as a biological control agent (Blossey et al. 2001a) (Figure 2). Some other candidates for the management of invasive species have been found in southwestern Ontario, Canada, namely stem-picking weevil, diamondback moth, and meadow moth. Assuming that these organisms recognize garlic mustard as a host, they can be considered as natural enemies of garlic mustard (Yates and Murphy 2008b). Rauth et al. (2011) also found that the application of population genetics tools to biological control agents has great potential to facilitate control before release.

Figure 2 Ceutorhynchus scrobicollis (Kaldari 2021)

METHODS AND MATERIALS

SPECIES DESCRIPTION

Garlic mustard (*Alliaria petiolate*), is an aggressive biennial herb native to Europe (Wolfe et al. 2008) (Figure 3 and 4). Garlic mustard is now widely distributed throughout the United States and Canada, it is one of the most aggressive invasive species in North American forests (Rauth 2011) (Figure 5).

Figure 3 Garlic mustard rosette (CAREN WHITE 2019)

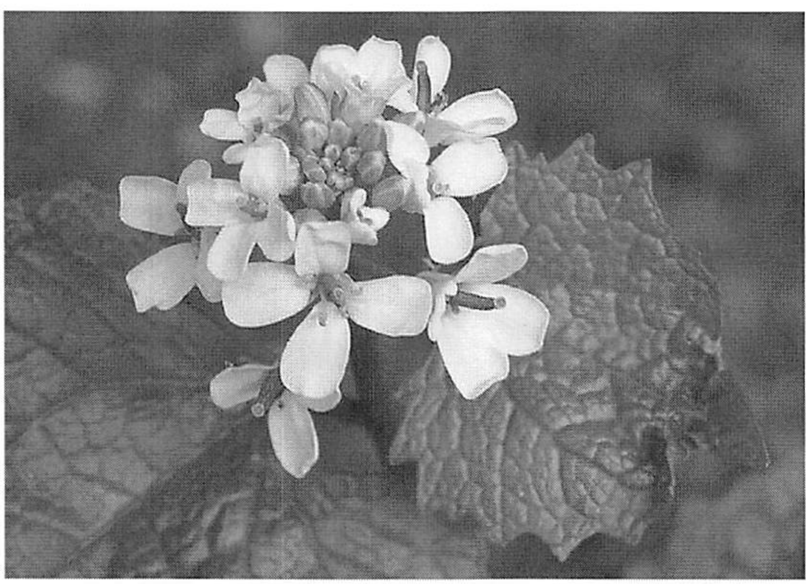

Figure 4 Garlic mustard flower (The Ontario Invasive Plant Council 2021)

Figure 5 Distribution of garlic mustard (EDD Maps 2021)

SEARCH CRITERIA

Keywords: Among the above research questions, the most important keywords are Garlic mustard, allelopathy, invasive species, control measures.

Expand the scope of the above keywords and determine the relevant words. It contains synonyms, different forms of words, etc. The following are search words.

Garlic mustard: *Alliaria petiolata*

Invasive species: invader, invasion

Allelopathy: biochemical inhibition, interaction

Control measures: biological control/biological prevention, chemical control/chemical prevention

Use the above keywords singly or in combination to search in Google scholar and library, and avoid repeated invalid searches.

Data source: All data used in the study are from Lakehead University Library and Google scholar. The databases used include: SpringerLINK Journals, ScienceDirect, Wiley Online Library, Gale virtual reference library, ProQuest search, JSTOR

LITERATURE SELECTION CRITERIA:

All selected journals are subject to peer review. These journals come from academic databases, written by experts, and reviewed by other experts to ensure the accuracy of the research results.

From a wide range of relevant knowledge to gradually narrow the scope to the specific problem studied. In the literature search, I first searched with biological invasion as a keyword. The top-ranked literature has a comprehensive discussion on the background knowledge of biological invasion. This part can be used to introduce the background knowledge. Subsequently, garlic mustard and its Latin name Alliaria petiolate were searched in the library. From this, I can get background knowledge of garlic mustard, including the history of garlic mustard invasion, reasons, and effects. Some of the literature focuses on the relationship between garlic mustard and parasitic wasp colonies, or the application of molecular markers in the study of genetic variation information of garlic mustard. These are irrelevant to the subject or have little to do with them, so they are discarded. Pieces of literature related to the allelopathic effect of garlic mustard and soil microorganisms were screened out, especially the literature on the changes of arbuscular mycorrhizal fungi and endomycorrhizal fungi after the invasion of garlic mustard. In addition, it is necessary to screen out the literature related to the prevention and treatment of garlic mustard. Some literature studies are not based on prevention and control methods, but on theories applied in prevention and control measures, such as demographics, population models, population genetics, etc. This kind of literature is irrelevant to the subject and can be discarded. The literature on the comparison of different prevention and control methods (mechanical control, chemical control, biological control) was analyzed.

ORGANIZATION OF SELECTED LITERATURE

After completing the literature search, read the searched literature repeatedly to figure out the principles of the design experiment and the author's point of view. The selected literature was divided into two categories: allelopathy and preventive measures.

When researching the first category of literature, is divided into two parts: the result of garlic mustard allelopathy on soil microorganisms and the factors that affect the intensity of allelopathic effects.

Summarize the relevant or consistent parts of the conclusion, and summarize the experimental methods and innovations of each study. For the inconsistent conclusions, comparative analysis, summed up the cause of the difference.

When researching the second category of literature, is classified according to different prevention methods—biological control, chemical control, and physical control. The experimental methods selected by different research institutes and experimental locations are different. These studies are collated and compared, and the advantages and disadvantages of various prevention and control measures are analyzed.

By comparing various prevention and control effects, analyze whether biological control can be the most effective prevention and control measure.

RESULTS

SOIL MICROORGANISM

The invasion of garlic mustard has been studied throughout North America for the past two decades, focusing on the abundance and diversity of AM fungi (Table 1).

Year	Location	Purpose	Major local species	Main soil microorganism	Iimpact	Primary technology	Remark
2006 - 2016	Trillium Trail Nature Reserve in Fox Chapel, Pennsylvania, USA	the effects of garlic mustard on mycorrhizal community composition and diversity	Maianthemum racemosum	/	Community evenness decreased.	beta distribution	/
2006-2007	Holden Arboretum in northeastern Ohio	Effects of litter on soil microorganisms	Beech, maple, wild leek, bedweed	/	The effect of litter on soil microbial abundance was relatively weak	TRFLP analysis, non-metric multidimensional	Focus on total bacterial abundance
2007	Guelph, Canada	compare the effects of garlic mustard and foreign AM fungi on local AM fungi	/	AM Fungi	Garlic mustard inhibited the growth of AM fungi, but had little effect on the diversity.	PCR, ROC and TRFLP analysis	Controlled greenhouse conditions
2007	Allegheny County, Pennsylvania, USA	Comparison of root colonization and community structure of garlic mustard plants with and without	White oak, sugar maple, jack-in-the-pulpit, False solomon's seal	AM Fungi	Selective inhibition of AMF	TRFLP analysis、PCR	Field conditions
2014-2015	Five stands in the Midwest of the United States	Effects of garlic mustard on soil food webs	Oak	AM, ECM, SAF	Mycelial density decreased and fungal composition	Illumina MiSeq、PCR	Manipulative Mesocosm Experimen
2015、2017	eight temperate, deciduous forests in southern New England, USA	Restoration of soil fungi after the eradication of garlic mustard	Maple, oak, ash, geranium, Canadian Mayflower	AM fungi, EM fungi	Soil microbes cannot recover	PLFA analysis	Remove by hand pulling

Table 1 Experiments on the effects of garlic mustard invasions on soil microorganisms across North America (Roche et al. 2021; Burke and Chan 2010; Koch et al. 2011; Burke 2008; McCary and Wise 2019; Anthony et al. 2019)

Different plots had different main species, but the invasion of garlic mustard caused a decrease in soil microbial content, especially AM fungi. The number of AM fungi declined, as did the number of mycorrhizal plants.

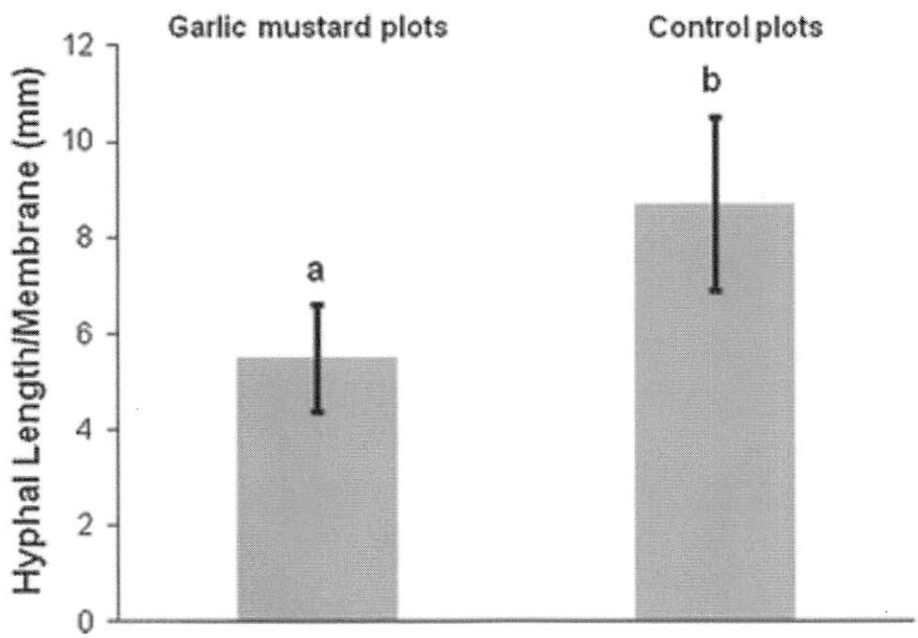

Figure 6 Fungal hyphae lengths with and without garlic mustard (Cantor et al. 2011)

Figure 6 above shows that the average length of fungal hyphae was significantly lower in areas where garlic mustard survived than in areas without garlic mustard.

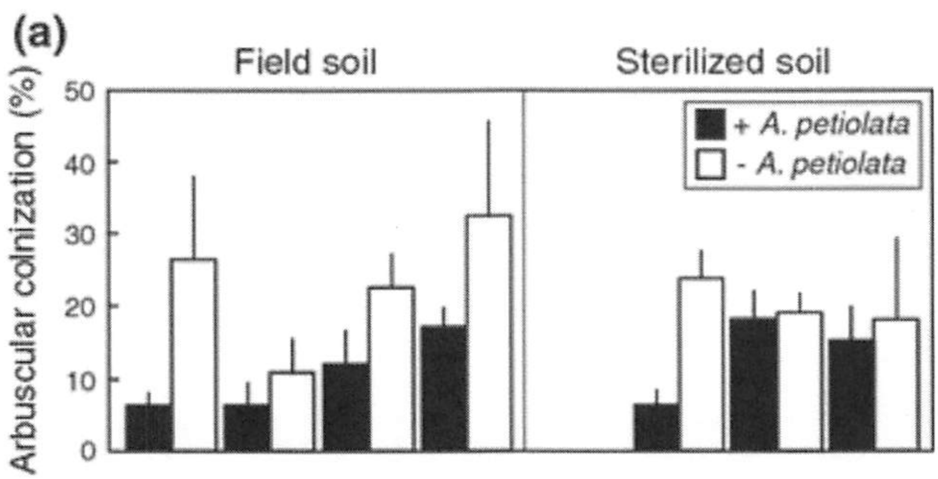

Figure 7 Comparison of field and sterile soil with and without garlic mustard (Koch et al. 2011)

Figure 7 shows that arbuscular colnization is reduced by the presence of garlic mustard in both field and sterile soil.

CONTROL METHODS

Control measure	Form/Materials used	Advantages	Disadvantage	Remark
Mechanical control	Fire	Convenient	Harm other native plants	Control of seeds and seedlings is limited
	Hand-pull	Accurate remove	Large amount of labor、Soil disturbance	/
Chemical control	Glyphosate	Convenient and cheap	Harm other native plants	Control of seeds and seedlings is limited
Biological control	Four weevils	safe and effective	Uncertainty	Host-specific

Table 2 Comparison of control methods (Rodgers et al., 2008; Blossey et al. 2001a; Shartell et al. 2012b)

Each control method can reduce the density of garlic mustard to some extent, but there are advantages and disadvantages.

DISCUSSION

SOIL MICROORGANISM

Through the analysis of literature on the relationship between allelopathy of garlic mustard and soil microorganisms, it can be seen that the invasion of garlic mustard has a great impact on the local soil microorganisms. Most studies have concluded that the invasion of garlic mustard can affect the normal activity of soil microbes.

Firstly, AM fungi were the main important microorganisms affected, followed by EMF. AM fungi play a major role in plant growth by helping to attenuate negative effects around plants. These negative effects include heavy metal stress, salt stress, and so on (Miransari, 2010). Once the abundance and diversity of AM fungi decline, it means that the symbiotic relationship of plants is destroyed. Native plants may die under environmental stress, which provides more space and resources for garlic mustard to survive. But not all plants will be badly affected. Non-mycorrhizal plants do not have many symbiotic relationships with fungi, so the number of species does not vary much (Roche et al. 2021).

Glucosinolate and AITC released by allelopathy of garlic mustard are the main reasons for the difficulty of AMF spore germination (Cantor et al. 2011). Besides, the allelopathic effect of garlic mustard on soil microorganisms will change according to some factors. July to August is the senescence season for adult garlic mustard when allelochemicals in the soil tend to be the highest of the year (Cantor et al. 2011). According to the experiment of Burke and Chan (2010), the abundance of soil microorganisms in April was significantly higher than that in August.

For the effects of garlic mustard on soil microorganisms, the researchers focused on the abundance and diversity of microorganisms. The density and composition of mycelia of AMF fungi will be greatly affected (Cantor et al. 2011). In controlled trials, total fungal abundance was the lowest in areas where garlic mustard was grown (McCary and Wise 2019). The effect is different depending on the density of garlic mustard per unit area (McCary and Wise 2019). The higher the density of garlic mustard per unit area, the more allelopathic secondary compounds it secretes, so the greater the impact on soil microorganisms.

In addition, the effects of garlic mustard on soil microbes are long-lasting. Once garlic mustard has successfully invaded and formed dense rosettes, it is difficult for the soil microbial community to return to its previous state, even if garlic mustard is removed by hand. Anthony et al. (2019)'s research showed that three years after the removal of garlic mustard, the fungus in the soil had not recovered. Although the soil microbial community is difficult to recover, the abundance of mycorrhizal plant species will increase.

CONTROL METHODS

According to the above results, I can find that traditional methods (i.e. herbicide, hand pulling, and fire) can remove garlic mustard to a certain extent, but each method has advantages and disadvantages. And biological control has great potential.

Firstly, glyphosate is usually chosen as the control agent in the chemical control of garlic mustard. The main concern with glyphosate is its possible effects on other plants (Carlson and Gorchov 2004). Glyphosate is generally more effective in removing garlic mustard in the spring (Shartell et al. 2012b). But because glyphosate is a non-selective pesticide, the use of the herbicide in the spring can reduce the diversity of other native species. A single application of the herbicide to garlic mustard in the fall can reduce its density. But when garlic mustard is not completely eradicated, native species richness does not improve significantly (Carlson and Gorchov 2004).

Secondly, the prescribed fire can control the growth and development of garlic mustard to a certain extent. A fire in a certain area may clear a large area of adult garlic mustard rosettes, but the root crowns are not completely burned and have a chance to germinate in the spring (Nuzzo 1991). Use fires later in the spring to reduce rosettes and seedlings more. And while the fire is going on, the survival of other native plants will be affected by the fire. These burned logs will provide some protection for the underlying garlic mustard, reducing the chance of fire (Nuzzo et al. 1996). Nuzzo et al.(1996)'s experiments showed that after three fires, garlic mustard seed banks began to decline. But in the following five years, the population of garlic mustard increased again, indicating its strong vitality and reproductive ability. Continuous fires control the spread of garlic mustard, but intermittent fires do not, and garlic mustard doubles over two years (Nuzzo et al. 1996).

The hand-pulled method does remove garlic mustard with precision, but it requires a lot of labor (Nuzzo 1991). The rapidly-multiplying nature of garlic mustard means that the area it occupies is often very large, and pulling it by hand is time-consuming and laborious. In addition, large-scale hand pulling can disturb the soil and affect soil microbes (Rodgers et al., 2008). The hand-pull is suitable for small areas. For example, for garlic mustard found accidentally on the street, we can quickly remove it by hand and report it to relevant departments, to reduce the spread of garlic mustard as much as possible.

Both mechanical and chemical treatments significantly reduced the adult population of garlic mustard but did not suppress the spread of garlic mustard due to the large number of seeds stored in seed banks and the presence of many seedlings in the undergrowth (Nuzzo 1991). In particular, glyphosate and fire can damage other plants and reduce native species diversity to some extent. In addition, garlic mustard is highly resistant to stress, allowing it to regenerate even after severe damage (Bassdorf et al., 2004). Controlling garlic mustard is a long-term project in order to deplete the seed bank.

In this case, biological control is the most promising form of control. So far there are 69 species of insects that eat garlic mustard (Rodgers et al., 2008). Most studies have focused on four species of weevils, including *C. scrobicollis, C. Roberti, C. Alliariae,* and *C. constrictus*. These four weevil species can eliminate both root crowns and leaf and seed yields. Excessive seed production is responsible for the widespread of garlic mustard and for garlic mustard that is otherwise difficult to remove. And the seed production of garlic mustard will be greatly reduced at high concentrations of weevils (Gerber et al., 2008). The two weevils in the same ecological niche cause the same damage, and their combined effect is the superposition of their respective effects (Gerber et al., 2008). Another benefit of biological control is specificity (Carlson and

Gorchov 2004). These weevils only target garlic mustard, and they do not affect other species while damaging garlic mustard.

CONCLUSION

In general, the invasion of garlic mustard is a cause for concern. The secondary compounds released during allelopathy can seriously affect the survival of soil microorganisms. Among them, AM fungi are more seriously affected. In this case, the symbiotic relationship of native plants is disrupted and growth and development are inhibited by environmental stresses. The effects of garlic mustard on soil microbes are profound and long-lasting, even if the garlic mustard is removed. The abundance of garlic mustard seeds hampers control efforts. Traditional control methods, including chemical control and mechanical control, cannot completely remove garlic mustard due to ineffective control of garlic mustard seedlings and seeds. Biological control has a promising future in the management of garlic mustard. The host specificity of the four weevil species and their consumption of garlic mustard seeds and seedlings complement the traditional control methods. In terms of the degree of impact on the surrounding native plants and the effect on the removal of garlic mustard seed seedlings, biological control is the best control. Future research can be carried out in the direction of comprehensive governance, combining short-term and long-term effective methods, to achieve the best control effect.

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