Journal of Chemical Ecology (2026) 52:31
https://doi.org/10.1007/s10886-026-01706-6

REVIEW

Harnessing Allelopathic Autotoxicity for Invasive Plant Management: Knowledge Gaps and Future Research Directions

Elizabeth A. Esser[1] · Gary N. Ervin[2] · Rima D. Lucardi[3] · Paul M. Severns[4] · Erika D. Womack-Peoples[5] · Steven H. Bullard[1] · Ashley N. Schulz[1]

Received: 29 January 2026 / Revised: 10 March 2026 / Accepted: 14 March 2026

Abstract

Nuisance species are typically managed using mechanical removal, biological, cultural, or chemical treatments, applied either individually or in combination. Applications of synthetic pesticides may result in significant non-target effects that reduce biodiversity or result in pesticide drift, and target organisms can rapidly develop pesticide resistance. Biological control has less physical impact on ecosystems than mechanical removal, and none of the human health concerns of synthetic pesticides, but relies on coevolved antagonists that are introduced to the invaded environments and can have non-target effects (e.g., outcompeting native species, switching to non-target native organisms, and ineffectively suppressing the target organism). Due to increasing restrictions, it is becoming more difficult to import, propagate, and release new biological control agents. These concerns, in combination with the increased rates of species invasion and economic and ecological costs of existing control methods, necessitate alternative means of nuisance species control. In this review, we examine an alternative control approach based on the principles of allelopathy and autotoxicity. Autotoxins used in this manner exploit secondary metabolites produced by a target species and/or their endosymbionts to inhibit growth or induce mortality with reduced non-target impacts. We synthesized autotoxicity-related literature to compare plant-derived autotoxins to traditional biological and chemical controls and discuss how further autotoxicity research and development can assist with the control of nuisance plant species. Although autotoxins provide a promising new frontier for nuisance species control, further research is necessary to effectively develop, test, and deploy these biochemical controls for species inhibition or mortality.

Keywords Allelopathy · Autotoxicity · Biological control · Invasive species · Secondary metabolites

Introduction

Nuisance non-native species (i.e., invasive species) have been implicated in the extinction and endangerment of species worldwide and were estimated to cost the global economy US$423 billion in damages and management costs in 2019 alone, with this annual cost tripling each decade (Pimentel et al. 2005; Pyšek et al. 2020; Diagne et al. 2021; IPBES, 2023). Despite increased efforts to improve biosecurity, Early Detection Rapid Response (EDRR; Reaser et al. 2020), and attempts to manage invasive populations (Graham et al. 2019), the global spread of invasive species is accelerating (Seebens et al. 2017). Control methods vary by species, but typically include mechanical removal, chemical pesticides, biological control, and cultural approaches (Simberloff 2001; Manning and Miller 2011; Jardine and Sanchirico 2018). Mechanical removal involves physically

✉ Elizabeth A. Esser
eae197@msstate.edu

[1] College of Forest Resources, Mississippi State University, PO Box 9681, Starkville, MS 39762, USA

[2] Department of Biological Sciences, Mississippi State University, PO Box GY, Starkville, MS 39762, USA

[3] USDA Forest Service, Southern Research Station, 320 E Green St, Athens, GA 30602, USA

[4] University of Georgia, 2315 Miller Plant Sciences, 120 Carlton St, Athens, GA 30602, USA

[5] Department of Biochemistry, Nutrition, and Health Promotion, Mississippi State University, Starkville, MS 39762, USA

Published online: 28 March 2026

removing or destroying invasive species in an area through methods such as brush cutting, digging, dredging, girdling, manual pulling, mowing, mulching, soil solarization, tilling, and others (Manning and Miller 2011; Jardine and Sanchirico 2018). Chemical control includes herbicides, fungicides, insecticides, and rodenticides (Pimentel 2014). Classical biological control consists of importing and releasing living organisms (e.g., invertebrates, pathogens, vertebrates) from a target organism's native range in an attempt to exterminate populations of the target invasive species, though other types of biological control can be used, such as conservation biological control, which enhances natural habitat that protects and promotes native natural enemies (Eilenberg et al. 2001; Heimpel and Mills 2017). Cultural controls can consist of prescribed fire, hunting, fishing, or harvesting (Nuñez et al. 2012). Invasive insects and animals can also be controlled through trapping (El-Sayed et al. 2009), while some invasive plants can be suppressed by adjusting planting time and density, cover cropping, planting indigenous plant species, rotating crops, using competitive cultivars, and other methods (Schuster et al. 2018). Typically, invasive species suppression is most effective when multiple control approaches are used in combination, such as with integrated pest management systems (DiTomaso et al. 2017). Although many methods exist for managing invasive species, there are few recorded instances of successful invasive species eradication (Parkes and Panetta 2009). Most successful eradications have occurred for small populations in geographically isolated areas, such as small islands (Mack and Lonsdale 2002; Glen et al. 2013; Moon et al. 2015), indicating that new or multiple control methods may be necessary for successful eradication of more widespread populations.

Although they are one of the most effective invasive species control methods, broad spectrum chemical pesticides (e.g., herbicides, insecticides) are being phased out globally because of their non-target impacts on other flora and fauna, reduced effectiveness due to adaptive resistance, runoff and leaching within soils, and human toxicity through acute and prolonged exposure (Georghiou 1972; van der Werf 1996; Annett et al. 2014; Li and Jennings 2017). Due to this toxicity, individuals who want to apply pesticides are required to hold a pesticide applicator's license or certification, and frequently need specialized personal protective and other equipment (EPA, 2026), which can make pesticides inaccessible and unaffordable to many. Further, many environments require repeated applications of pesticides to successfully control a population of an invasive species, which can make using chemical controls even more cost prohibitive (Pimentel 2005). There are also risks associated with using chemical pesticides within aquatic environments, as well as environmental bioaccumulation (Pérez et al. 2017). Due to these and other limitations and risks associated with chemical controls, the 2022 United Nations Kunming-Montreal Global Biodiversity framework aims to reduce risks from pesticides by 50% by 2030, and there is a trend towards increased pesticide legislation in developed countries (Handford et al. 2015; Möhring et al. 2025).

Other management methods can also have detrimental environmental effects, such as soil disturbance caused by tilling and other mechanical methods (Zuber and Villamil 2016). Soil disturbance can negatively impact ecological communities, for example, by severing networks of beneficial fungi and microfauna in the soil (Helgason et al. 2009), compacting soil enough to reduce water infiltration and increase erosion (Labelle et al. 2022), and creating bare ground for invasive plant colonization (Kyle et al. 2007), as well as impact human health by aerosolizing small particulates that can cause breathing dysfunction (Weeks et al. 2021). There is also a history of non-target effects of biological control agents that have resulted in detrimental ecological impacts (Thomas and Willis 1998; van Driesche and Hoddle 2017), such as introduced biological control agents competing with native predators or parasitoids for native pest species or trophic cascades when keystone species are involved (Simberloff and Stiling 1996), which has made biological control more expensive and time-intensive (Mason et al. 2005). The increased regulation and scrutiny of chemical, mechanical, and biological controls due to negative impacts to human health and/or the environment prompt the need for effective alternative invasive species control methods.

One potential approach to invasive species management is the development and use of allelopathic autotoxicity. Allelopathy is the production and release of compounds by an organism that inhibit the growth, survival, or reproduction of other organisms (Muller 1969; Hierro and Callaway 2021). Allelopathic interactions influence species distribution and competition, and they are a well-known mechanism facilitating plant establishment, including that of rapidly spreading invasive plant species such as knapweeds (*Centaurea* spp. L.) (Muller 1966; Callaway and Aschehoug 2000; Hierro and Callaway 2003). While allelopathic secondary metabolites, in general, serve to harm or prevent the co-occurrence and/or competition of other species (i.e., interspecific impacts), autotoxins are a class of allelopathic secondary metabolites that can kill or inhibit the growth of individuals of the species that produced them (i.e., intraspecific impacts) (Putnam 1985; Miller 1996; Singh et al. 1999). Compared to studies of allelopathic impacts, few studies have investigated the role of autotoxicity in plants (but see Dorning and Cipollini 2006; Ervin and Wetzel 2000; Hu and Zhang 2013). In nature, autotoxicity occurs when leachates from plant parts contaminate soil and act as a toxin to other individuals of the same species, often

by preventing growth and seed germination (Munther and Fairbrothers 1980; Singh et al. 1999; Alías et al., 2006). By reducing or delaying germination, autotoxicity may serve as a method of population regulation, helping to reduce intraspecific competition (Picman and Picman 1984; Perry et al. 2005; Renne et al. 2014). This naturally occurring autotoxicity has both ecological and agricultural implications because it influences plant growth (Singh et al. 1999; Ervin and Wetzel 2000). Autotoxicity of some trees has been identified as being partially responsible for the replant problem in orchards, including in apples (*Malus domestica* [Suckow] Borkh) and pears (*Pyrus* spp. L.) (Singh et al. 1999; Nicola et al. 2016), and autotoxicity of rice prevents fields from being used in successive years (Chou and Lin 1976; Chou et al. 1977; Chou 1995). Some plants avoid autotoxicity by sequestering allelochemicals in specialized structures like trichomes or vacuoles, by producing allelochemicals that are only toxic after modification, by developing detoxifying abilities, or by only producing allelochemicals in deep roots or other plant parts that are far from sexually reproductive propagules, such as seeds (Singh et al. 1999; Sirikantaramas et al. 2008).

Although the study of autotoxicity itself is not new, with studies on the autotoxic origin of human disease dating back to the seventeenth century (Stern 1906), it was not until the last few decades that researchers recognized the potential to harness autotoxicity to potentially manage weeds and pests (Singh et al. 1999).Extensive work has been done studying the potential of using allelochemicals for plant management, but fewer studies have focused on autotoxicity specifically as a potential management method (Weston 1996; Jabran et al. 2015; Khamare et al. 2022). In plants, autotoxins can be classified as a type of biopesticide (i.e., a naturally occurring substance often produced from living organisms that controls typically non-related pests through non-toxic mechanisms; EPA, 2025a), specifically a bioherbicide, as they are derived from the living plants as a byproduct of growth (Bailey 2014). Plants have exhibited autotoxin-dependent responses following decapitation pruning, prolonged seed soaking, and external applications of autotoxins to growth media, seeds, or directly onto the plant (Gog et al. 2005; Xu et al. 2015; Li et al. 2016; Wang et al. 2022; Table S1). Decapitation pruning can increase biosynthesis of autotoxins as a result of induced secondary defense (Li et al. 2010, 2016), while prolonged seed soaking can also extract autotoxins from within the seed and then expose the embryo to high concentrations resulting in decreased germination (Li et al. 2016). Plants can be exposed to autotoxins that leach out of decomposing plant tissues, autotoxins exuded by living plants, or, in experimental settings, autotoxins that have been extracted from plant tissue (Zhang et al. 2016; Mohler et al. 2018; Jahantab et al. 2021; Bonanomi et al. 2022). In many plants, the mechanisms preventing autotoxicity by secondary metabolites can also be overridden by extracting those secondary metabolites, concentrating them, and applying them to the source species (Li et al. 2010, 2016, 2018; Kato-Noguchi et al. 2017; Su et al. 2022). Dosage-dependent responses to autotoxins include morphological changes (e.g., dwarfism, pleiocotyly, disturbed phyllotaxis, lack of secondary roots, and changes in leaf shape), physiological changes (e.g., reduced chlorophyll content, increased cell respiration, increased peroxide and superoxide dismutase activity, increased malondialdehyde, and decreased electron transport), differential gene expression, inhibited growth and reproduction, decreased germination, and death in plants (Singh et al. 1999; Liu et al. 2013; Li et al. 2016; Favaretto et al. 2017; Huang et al. 2019; Zhong et al. 2024; Table S1). Whatever the method of exposure, Li et al. (2016) suggest that most organisms contain or can produce autotoxins. Autotoxic effects have been documented in at least 138 plant species exposed to extracts of their own tissues (Table S1), and autotoxicity has been documented in many other species exposed to autotoxins through methods other than direct extraction (e.g. exposed to decomposing tissue, grown in soil where the species was previously grown) (Zhang et al. 2011; Mazzoleni et al. 2015; Bonanomi et al. 2022). Autotoxicity has also been identified in many invasive plants, and Li et al. (2016) found that none of the 17 invasive plants they tested were able to tolerate autotoxic effects when exposed to their own extracts. A study of giant salvinia (*Salvinia molesta* D. Mitch.) identified a group of autotoxins termed "salvinicides" that may be useful for managing it in the invaded range, demonstrating compelling evidence that autotoxins offer a promising new tool for invasive species management (Li et al. 2018).

While most species tested so far are susceptible to autotoxicity, some autotoxins discovered thus far appear to be species specific (Munther and Fairbrothers 1980; Li et al. 2016). Some studies have demonstrated that the same concentration that was toxic to the producing plant species was not toxic to other species, including those in the same family (e.g., Poaceae) (Munther and Fairbrothers 1980; Li et al. 2016). Though the mechanism and extent of species specificity is currently unknown, the potential specificity of autotoxins could make them a more environmentally friendly method of invasive species management by reducing harm to non-target organisms, with significant implications for ecosystem restoration goals. The purpose of this review is to: (1) compare the potential of plant autotoxins to traditional biological and chemical controls, (2) discuss implications of autotoxin research and development for the potential control of invasive plant species, and (3) outline knowledge gaps and necessary future research to develop,

test, and deploy promising biochemical controls for invasive plant species inhibition or mortality.

Comparing Autotoxins and Traditional Chemical Pesticides: Specificity, Resistance and Environmental Implications

While autotoxins and traditional chemical controls both use chemical compounds to kill invasive pests, autotoxins are naturally occurring chemicals that are produced by the target organism, while traditional chemical controls are not derived from the target organism and are produced synthetically (Singh et al. 1999; Umetsu and Shirai 2020). Traditional chemical controls generally fall under the umbrella of pesticides and include herbicides, insecticides, fungicides, nematicides, and rodenticides (EPA, 2025b). Previous autotoxin research led the United States Environmental Protection Agency to consider a new category of biopesticide classification called "biochemical-like," which contains pesticides that "usually have uncomplicated structures and are commonly present in the environment or the human diet at significant levels or have been widely used for non-pesticidal purposes" (EPA, 1997). In practice, autotoxins are similar to chemical controls in that both use specific chemical compounds to kill organisms through contact and uptake and thus will likely use similar application methods (Table 1). Although the application methods of autotoxins and traditional chemical controls are similar, the two are developed through different processes (Fig. 1). Traditional chemical controls are generally developed synthetically by identifying a biological target within the pest and designing chemical compounds that disrupt the target (Umetsu and Shirai 2020). In contrast, autotoxins are discovered through extraction from the pest itself and further developed by fractionation to determine, rather than create, chemicals

Table 1 Broad comparison of traditional chemical control agents, biological control agents, biopesticides, autocides, and autotoxins

Attribute	FORM OF CONTROL				
	Chemical Control Agents	Biological Control Agents	Biopesticides	Autocides	Autotoxins
Strategy for application	Spray target species	Release organisms for control of target species	Spray target species (most common)	Release of modified target species	Spray target species
Is the form of control living?	No	Yes	Yes (e.g., targeted fungal pathogens) and No (e.g., nanoparticles)	Yes (management occurs through sterilization of target species, for example)	No
Population eradication vs. suppression?	Suppression short term, eradication long term	Suppression most likely, eradication rare	Suppression most likely, eradication rare	Suppression short term, eradication long term	Suppression short term, eradication long term
Control mechanism is sustained after application?	No	Possibly (reproduction and spread of living agents)	Possibly (reproduction and spread of living agents)	Possibly (mutations in offspring)	No
Risk of failure from biotic factors?	No	Yes (natural enemies of the biological control agent)	No	Yes (introduction of non-sterile individuals)	Yes, possibly (microbial modification, dilution effect)
Risk of failure from abiotic factors?	Yes (dilution or erosion of chemicals from precipitation immediately after application)	Yes (biological control agent not adapted to climate)	Yes (living biopesticides not adapted to climate, non-living biopesticides impacted by precipitation)	Yes (mortality of individuals due to environmental disturbances, such as drought, fire, or flooding)	Yes (dilution or erosion of biochemicals from precipitation immediately after application)
Risk of non-target effects?	Yes	Yes, possibly	Yes, possibly	No	Low

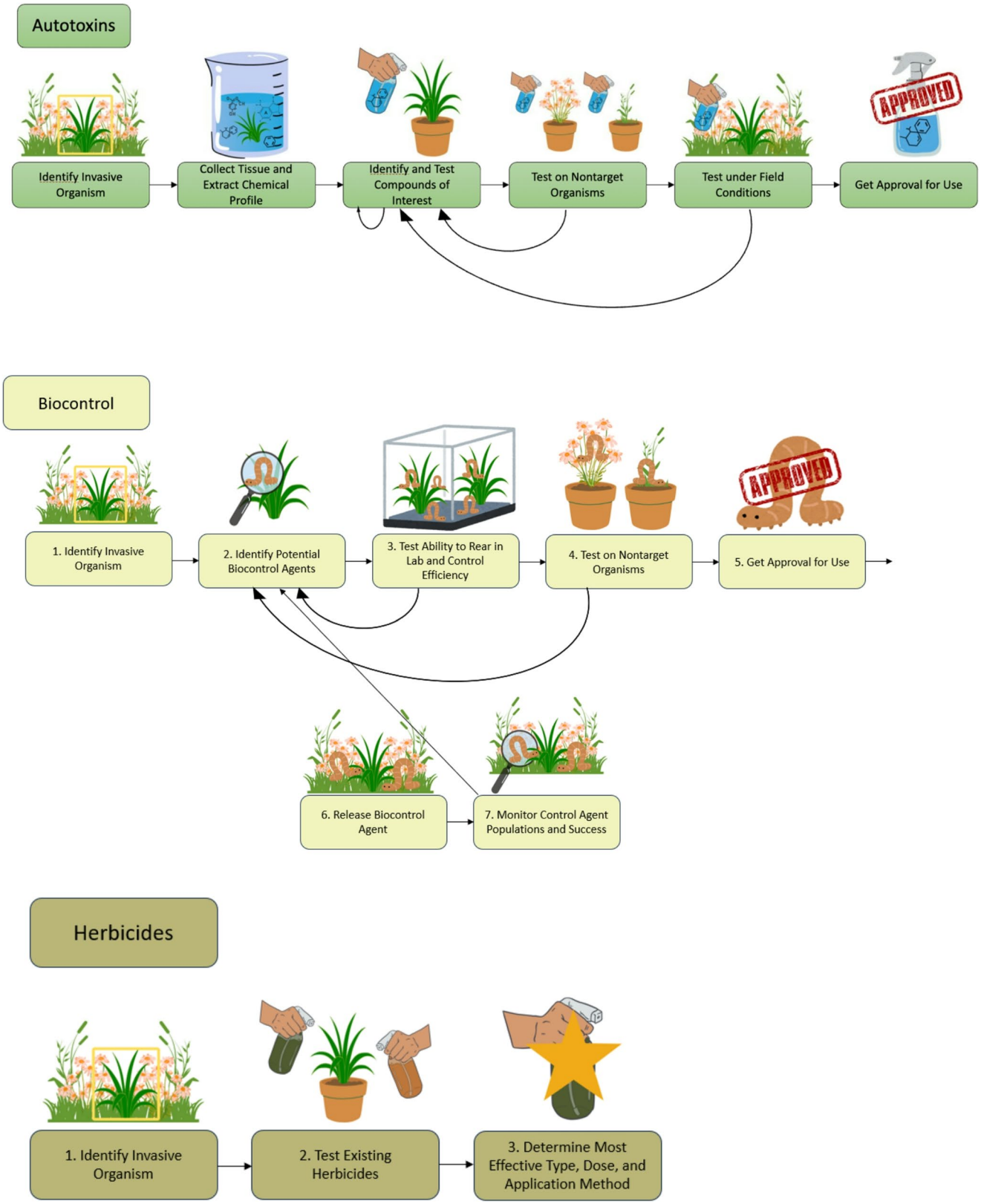

Fig. 1 Comparison of development processes for autotoxins (top), biological control (middle), and herbicides (bottom)

or combinations of chemicals with the largest lethal effect (Kato-Noguchi et al. 2017; Su et al. 2022; Fig. 1). Thus, while traditional chemical controls are developed to target a group of organisms (Umetsu and Shirai 2020), autotoxins are developed on a species-by-species basis. Because of this, it may take longer to develop enough separate autotoxins to control multiple organisms than it would to develop traditional chemical controls for the same number of organisms. For example, to manage three plant pests, we would have to develop three different autotoxins but may only need to develop one herbicide.

Although the development processes for autotoxins and traditional chemical controls differ, both require similar testing and approval in the United States. Both autotoxins and traditional chemical controls are required to be approved by the Environmental Protection Agency in the United States under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA; EPA, 2025a), and approval is contingent on the effectiveness of the product and the potential for it to cause harm to humans and the environment (Bradley et al. 2011; Lee et al. 2024). While the approval process is the same, regulatory approval for autotoxic compounds (e.g., bioherbicides) varies by country and compound, but likely takes less time than approval for traditional chemical controls because autotoxic compounds have reduced regulatory requirements (Hallett et al., 2005; Islam et al. 2024). Autotoxic compounds are classified as "biochemical-like," which require less data and, thus, less testing time for approval (Leahy et al. 2014). The EPA also provides an accelerated approval process for biochemical-like compounds, with an estimated approval timeline for an autotoxin that will not be used on food items of seven months compared to an estimated approval timeline of twelve months for a similar traditional chemical pesticide (Leahy et al. 2014).

Another area in which autotoxins and traditional chemical controls appear to differ is their level of specificity. Traditional chemical controls have a low level of specificity, with the most specific still targeting large groups of organisms, such as broadleaf or grass-specific herbicides (Walker et al. 1988). The degree of specificity depends on the chemical compound and its mode of action. For example, while some herbicides like fluazifop are only toxic to certain types of plants, in this case grasses, (Walker et al. 1988), many non-selective herbicides, like glyphosate, are toxic to all plants (Duke and Powles 2008). Many allelopathic compounds researched for weed management are also toxic to a wide variety of plant species (Khamare et al. 2022). For example, juglone, a compound produced by black walnut (*Juglans nigra* L.) that is commonly studied for weed management, is toxic to trees, field crops, and a variety of weed species (Strugstad and Despotovski 2012). In contrast to the low level of specificity of traditional chemical controls and of allelopathic compounds used for control, some autotoxins have shown the potential to be species specific and have limited or no effect on species other than the producing species (Munther and Fairbrothers 1980; Li et al. 2016). The high level of specificity of some autotoxins could potentially reduce non-target effects and environmental impacts when compared to traditional chemical controls.

One of the other issues with traditional chemical controls is the potential for resistance to develop, creating pests that require higher amounts of pesticide or other methods to manage, and organisms could likely adapt or evolve resistance to autotoxins in similar ways (Hawkins et al. 2019). Thus far, no research has been done regarding how quickly or if organisms can develop resistance to autotoxins, but resistance is well-documented for traditional chemical controls, particularly in agricultural crops and weeds, and there is evidence of evolution by native plants of resistance to allelochemicals produced by invasive plants (Callaway et al. 2005; Bonny 2016). If resistance does occur in organisms treated with autotoxins, it may be easier to combat because of the nature of autotoxin development. If populations of organisms evolve autotoxin resistance, specimens from that population could be collected to derive new, population-specific autotoxins to which the organisms have not yet developed resistance. The metabolites a plant produces vary based on environmental conditions, so different populations of the same species can produce different metabolites, potentially allowing different autotoxins to be sourced from different locations (Moore et al. 2014; Goh et al. 2016; Labarrere et al. 2019). In this way, continual development of new autotoxins potentially could allow researchers and managers to more efficiently address autotoxin resistance than has been possible with traditional herbicide resistance. However, more research needs to be conducted to determine how quickly organisms can or will develop resistance to autotoxins, and whether autotoxin resistance will cause similarly unmanageable populations as traditional chemical control resistance does.

One final major difference between autotoxins and traditional chemical controls is that autotoxins are already present in the environment, while many synthetic chemical compounds are not. Because autotoxins are extracted from the species they are being used to treat, some amount is already present in the environment (Zhang et al. 2016). Research by Li et al. (2016) suggests that each organism may contain the amount of autotoxins needed to kill it. If this is true, the amount of autotoxins being added to the environment through control efforts would be similar to pre-existing levels of autotoxins contained in the pest organisms already present. Plant metabolites also generally persist in the environment for a shorter amount of time than synthetic pesticides (Smith and Perfetti 2020). This could mean that

autotoxins will not have the same problems with accumulation and environmental toxicity as some chemical controls do (Ansari et al. 2024) because no significant amount of persistent new chemicals are being introduced to the environment. Thus, autotoxins may be a new frontier for invasive species management and ecosystem restoration efforts of plants, wildlife, and ecosystem services as compared to traditional chemical controls, as they may result in reduced non-target effects.

Comparing Autotoxins and Biological Control Agents: Discovery Method and Control Duration

Biological control is the exploitation of living agents to directly or indirectly combat pest organisms using one of four methods depending on whether biological control agents are added for permanent or temporary establishment, such as with classical and augmentative biological control, or native agents are utilized with or without human intervention, such as with conservation and natural biological control (Stenberg et al. 2021). The overall concept of biological control is not particularly novel, as humans have manipulated natural enemies in agricultural systems through trial and error for millenia (Gurr et al. 2000a). As a scientific practice, however, biological control is still a fairly modern development, with "The Classical Era" of biological control beginning around 1880 (van den Bosch et al. 1982; Gurr et al. 2000a). Since then, several forms of biological control have been developed. Classical biological control, also known as traditional or importation biological control, requires identification and collection of natural enemies from the pest species' native range (Hoddle et al. 2021). This form of biological control takes advantage of the coevolved relationship between the natural enemy and target pest species, which drives the natural enemy's purported ability to search for, identify, and attack the target species (assuming the absence of host switches), thus driving biological control success (Eilenberg et al. 2001).

Augmentative biological control is a practice that specifically focuses on the identification and release of natural enemies without the intention of establishment and reproduction of the biological control agent and long-term control of the target species (Eilenberg et al. 2001; Stenberg et al. 2021). Conservation biological control is an approach that is aimed at maximizing the impact of the natural enemy by providing the specific resources necessary to preserve or protect the natural enemy population, with the intent of promoting long-term control (Gurr et al. 2000b). These approaches can be used for the propagation and release of classical biological control agents with a coevolved relationship with the target species, though conservation biological control and natural biological control (Heimpel and Mills 2017; Stenberg et al. 2021), can also be viewed as a method to propagate or promote the natural enemies present in and native to the introduced range of the target species (Eilenberg et al. 2001). Another approach to biological control, coined the "new associations hypothesis" by Pimentel (1963), also considers the propagation and release of natural enemies native to the introduced range or from regions separate from the native and introduced ranges of the target species (Schulz et al. 2019). Though these approaches do not rely on coevolved relationships like classical biological control, they can take advantage of a natural enemy of a species closely related to the target species, which may allow the natural enemy to recognize the target species as a host while the target species may not be able to recognize and actively defend itself against the newly associated natural enemy (Hokkanen and Pimentel 1984).

Eilenberg et al. (2001) distinguishes these biological control strategies from other, newer pest management strategies that encompass biological factors, such as autocidal control and biorational chemical agents. These strategies were largely undeveloped until the 1970s when integrated pest management and genetic engineering began to overlap. Biorational chemical agents, or biopesticides, are a control strategy that makes use of biological materials derived from animals, plants, bacteria, or nanoparticles of biological origin, usually for the control of a pest in a different species (Ayilara et al. 2023) (Table 1). For example, microbial pesticides (e.g., *Bacillus thuringiensis* Berliner for control of spongy moth [*Lymantria dispar dispar* L.]; Reardon et al. 1994) and botanical extracts (e.g., use of neem [*Azadirachta indica* A.Juss] extracts as an insecticide; Regnault-Roger and Philogène 2008) are common biopesticides that can be found on the market for general use. This control strategy often takes advantage of plant defensive compounds, which are individual or cocktails of secondary metabolites which arose as a result of coevolution between plants and their herbivores (Regnault-Roger and Philogène 2008), similar to classical biological control. Autocidal control mechanisms, which use the organism to control itself and result in the release of modified organisms into the environment, have been largely used to combat invasive insect pests of humans or agricultural commodities (Bartlett and Staten 2009) (Table 1). In particular, the species' genome is often altered in a way that would induce mutations and control the species (Gould and Schliekelman 2004), radiation is used to induce sterility in individuals within a species that are then returned to the environment and cannot breed (Bartlett and Staten 2009), or byproducts can be used to eliminate pests (Debnath et al. 2022). These strategies, such as the "sterile insect technique," and Wolbachia-induced "incompatible insect technique," are used to manage pests on an area-wide

basis by reducing their ability to produce viable offspring (Klassen 2005; Marec and Vreysen 2019; Gong et al. 2023).

Autotoxins appear to have some similar, yet different, characteristics compared to traditional biological control agents (Heimpel and Mills 2017), biopesticides (Glare et al. 2012), and autocides (Gould and Schliekelman 2004) (Table 1). While traditional biological control agents and some biopesticides are living organisms capable of reproducing and sustaining control after an initial application or release, autocides consist of the sterilization or manipulation of living organisms that can then pass on genetic mutations to offspring (Heimpel and Mills 2017; Teem et al. 2020; Debnath et al. 2022). Conversely, autotoxins are *non-living* biochemicals that are derived, isolated, and potentially concentrated from living organisms and applied directly to the target living organism to initiate control (Fig. 1). Biopesticides can also include non-living materials (e.g., nanoparticles) or non-living materials that are derived from living organisms. Thus, autotoxins can be considered a type of biopesticide, though they differ because they have intraspecific impacts versus the interspecific impacts of most other biopesticides that have been developed. Like biological control agents and autocides, autotoxins could be impacted by biotic factors, such as microbial modification or degradation of the extract or leachate (Pellerin et al. 2010) or a dilution effect of phytotoxicity in high density populations (Weidenhamer et al. 1989). Like synthetic pesticides and biological control agents, autotoxins may not provide sustained control in situ, requiring reapplication for a desired level of target species control. Though only roughly comparative, past research of autotoxicity in agricultural crops, such as alfalfa (*Medicago sativa* L.), has demonstrated short-term effects of autotoxicity that reduce alfalfa density and yield a few months to a couple of years after killing the previous stand, but density and yield return to expected levels after that time (Chon et al. 2006).

How Species-Specific are Autotoxins?

One of the more enticing aspects of autotoxins is their reported potential for only being toxic to the producing species and possibly, closely-related species, such as congenerics (Li et al. 2016). Control methods that harm only the targeted species are the ideal management option because of their reduced risk to other organisms, but they are difficult to identify and/or develop. Biological control agents and autocides generally have a higher level of species specificity than chemical controls, but non-target effects can still occur and are a concern with biological control (van Driesche and Hoddle 2017). Finding a management method that can target a single species would greatly advance the field and the toolbox for invasive species management.

Current autotoxicity research shows potential for some level of species specificity. Research by Li et al. (2016) showed that autotoxic extracts of six plants were less toxic or non-toxic to non-origin species by applying the extracts to other species at the same dosage or a slightly higher dosage than was toxic to the producing species. *Salvinia molesta*, a water fern, contained autotoxins that were toxic to other plants in the family Salviniaceae (common salvinia [*Salvinia minima* Baker] and eastern mosquito fern [*Azolla caroliniana* Wiild.]), but were not toxic to any other organism tested, including other ferns in the same class (Polypodiosida) (Table 2) (Li et al. 2016). Autotoxins from hogwort (*Croton capitatus* Michx. var. *lindheimeri*) and Brazilian peppertree (*Schinus terebinthifolia* G. Raddi) did not affect any of the other species they were tested on, including those within the same family as their producing species (Li et al. 2016). Munther and Fairbrothers (1980) also found that the autotoxic extracts of interrupted fern (*Osmunda claytoniana* L.), did not affect spore germination in either of the other species tested (hay-scented fern [*Dennstaedtia punctilobula* (Willd.) J.Sm.] and cinnamon fern [*Osmunda cinnamomea* L.]), providing another example of potentially species-specific autotoxins. However, autotoxic extracts of *Dennstaedtia punctilobula* and *Osmunda cinnamomea* reduced spore germination in all three species tested, indicating that these species did not have species-specific autotoxins (Munther and Fairbrothers 1980).

While some autotoxicity studies show a promising level of species-specificity, many others have not found similar levels of species-specificity. Though many autotoxicity studies only test for non-target effects on a few species, most of these studies have shown negative effects of autotoxins to both the producing species and other species (Table S1). In some cases, the negative effects observed in other species were smaller than in the producing species. Ervin and Wetzel (2000) demonstrated that while common rush (*Juncus effusus* L.) extracts decreased seedling mass, chlorophyll content, and shoot development intraspecifically to *Juncus effusus*, these extracts also decreased chlorophyll content but did not impact seedling mass in blunt spikerush (*Eleocharis obtusa* [Willd.] Schult.). In other studies, similar effects are seen on both the producing plant and on other species (Chou and Lin 1976; Baldwin and Callahan 1993; Li et al. 2010). For example, Baldwin and Callahan (1993) observed a similar reduction in photosynthetic capacity under hydroponic exposure to nicotine in both plants that produce nicotine (flowering tobacco [*Nicotiana sylvestris* Speg. & Comes] and tree tobacco [*Nicotiana glauca* Graham]) and those that do not (jimsonweed [*Datura stramonium* L.] and tomato [*Lycopersicon esculentum* L.]), though the plants that did

Table 2 List of autotoxic plant extracts tested on other taxa. Only studies that demonstrated autotoxicity and tested the biologically active autotoxic extracts on other taxa were included. If extracts were tested on a congener, the congeners were not included in the "Family" column; only taxa that are in the same family but not congeners were included. Growth impacts include both decreased and increased growth in response to extracts, the letters detail which specimens experience impacts (C = congeners, F = specimen in the same family, E = extra-familial taxon), and numbers detail how many taxa in each category experienced impacts. For more details on taxa tested, methods, and growth impacts, see Table S1

Plant Taxa (as listed in the corresponding Citation)	Family	Congeners Tested?	Family Tested?	Extra-familial Tested?	Growth impacts?	Citation
Actinidia deliciosa (Chev.) Liang & Ferguson	Actinidiaceae	No	No	Yes (6)	Yes (6E)	Okada and Kato-Noguchi 2021
Amygdalus scoparia Spach	Rosaceae	No	No	Yes (5)	Yes (5E)	Jahantab et al. 2021
Amaranthus palmeri S.Wats.	Amaranthaceae	No	No	Yes (2)	No	Li et al. 2016
Ambrosia artemisiifolia L.	Asteraceae	Yes (1)	No	No	Yes (1 C)	Su et al. 2022
Ambrosia trifida L.	Asteraceae	Yes (1)	No	No	Yes (1 C)	Su et al. 2022
Anastatica hierochuntica L.	Brassicaceae	No	Yes (2)	Yes (3)	Yes (2 F, 3E)	Hegazy et al. 1990
Asparagus officinalis L.	Asparagaceae	No	No	Yes (6)	Yes (6E)	Kato-Noguchi et al. 2017
Atriplex canescens (Pursh) Nutt.	Amaranthaceae	No	No	Yes (5)	Yes (5E)	Jahantab et al. 2021
Brachiaria mutica (Forssk.) Stapf	Poaceae	No	Yes (2)	Yes (1)	Yes (1 F, 1E)	Chou 1989
Camptotheca acuminata Decne.	Nyssaceae	No	No	Yes (1)	Yes (1E)	Li et al. 2010
Celosia argentea L.	Amaranthaceae	No	No	Yes (3)	Yes (3E)	Liang et al. 2018
Cistus albidus L.	Cistaceae	No	No	Yes (1)	Yes (2E)	Robles et al. 1999
Citrullus lanatus (Thunb.) Matsum. & Nakai	Cucurbitaceae	No	Yes (1)	No	Yes (1 F)	Yu et al. 2000
Croton capitatus Michx.	Euphorbiaceae	No	Yes (1)	Yes (2)	No	Li et al. 2016
Dennstaedtia punctilobula (Willd.) J.Sm.	Dennstaedtiaceae	No	No	Yes (2)	Yes (2E)	Munther and Fairbrothers 1980
Digitaria decumbens Stent	Poaceae	No	Yes (3)	Yes (1)	Yes (2 F, 1E)	Chou 1989
Humulus lupulus L.	Cannabaceae	No	No	Yes (3)	Yes (3E)	Zhang et al. 2011
Hyptis suaveolens (L.) Poit.	Lamiaceae	No	No	Yes (2)	Yes (2E)	Kumari and Prasad 2018
Jacobaea vulgaris Gaertn.	Asteraceae	No	Yes (2)	Yes (7)	Yes (2 F, 7E)	Mohler et al. 2018
Juncus effusus L.	Juncaceae	No	No	Yes (2)	Yes (1E)	Ervin and Wetzel 2000
Lilium brownii F.E.Br. ex Miellez	Liliaceae	No	No	Yes (1)	Yes (1E)	Zhong et al. 2024
Medicago sativa L.	Fabaceae	Yes (1)	No	No	Yes (1 C)	Wang et al. 2022
Medicago truncatula Gaertn.	Fabaceae	Yes (1)	No	No	Yes (1 C)	Wang et al. 2022
Nicotiana glauca Graham	Solanaceae	Yes (1)	Yes (2)	No	Yes (1 C, 2 F)	Baldwin and Callahan 1993
Nicotiana sylvestris Speg. & Comes	Solanaceae	Yes (1)	Yes (2)	No	Yes (1 C, 2 F)	Baldwin and Callahan 1993
Oryza sativa L.	Poaceae	No	No	Yes (2)	Yes (2E)	Chou and Lin 1976
Osmunda cinnamomea L.	Osmundaceae	Yes (1)	No	Yes (1)	Yes (1 C, 1E)	Munther and Fairbrothers 1980
Osmunda claytoniana L.	Osmundaceae	Yes (1)	No	Yes (1)	No	Munther and Fairbrothers 1980
Parthenium hysterophorus L.	Asteraceae	No	No	Yes (2)	Yes (2E)	Kumari and Prasad 2018
Picea schrenkiana Fisch. & C.A.Mey	Pinaceae	No	No	Yes (5)	Yes (5E)	Ruan et al. 2011
Quercus shumardii Buckland	Fagaceae	Yes (1)	No	No	Yes (1 C)	Li et al. 2016
Saccharum spp. L.	Poaceae	No	Yes (2)	Yes (2)	Yes (2 F, 1E)	Viator et al. 2006
Salvinia molesta D.Mitch.	Salviniaceae	Yes (1)	Yes (1)	Yes (15)	Yes (1 C, 1 F)	Li et al. 2016
Schinus terebinthifolia G. Raddi	Anacardiaceae	No	Yes (1)	Yes (2)	No	Li et al. 2016
Scutellaria baicalensis Georgi	Lamiaceae	No	No	Yes (3)	Yes (3E)	Zhang et al. 2010
Senna uniflora (Mill.) H.S.Irwin & Barneby	Fabaceae	No	No	Yes (1)	Yes (1E)	Kumari and Prasad 2018
Solidago canadensis L.	Asteraceae	Yes (2)	No	Yes (1)	Yes (2 C, 1E)	Karpavičienė et al. 2019
Triadica sebifera (L.) Small	Euphorbiaceae	No	No	Yes (3)	No	Li et al. 2016

produce nicotine exhibited a larger decrease in biomass than non-producing plants did. Even in studies that do not directly test the autotoxic compounds on other species, some of the identified autotoxic compounds have been shown to have negative effects on other species. Of the six compounds that were identified as being autotoxic to patchouli (*Pogostemon cablin* [Blanco] Benth.), four have been identified as common allelopathic chemicals in other plants (Bachheti et al. 2020). It is unclear if some methods, such as those used by Li et al. (2016), are more successful at isolating species-specific compounds than other autotoxicity studies, if only some plants produce species-specific autotoxins, or if studies showing species-specificity happened to test species combinations that were not toxic to each other. Further research is needed to confirm the species-specificity seen by Li et al. (2016) and to determine why species-specific autotoxic compounds are less common in the broader literature.

Further research is also needed to determine if there is a mechanism of species specificity, as there are many types of compounds that could be autotoxic that may all have different modes of action. Denyer (1990) hypothesized that autotoxic impacts may be the result of physiochemical interaction or reaction with microbial structures or biological molecules, or some disturbance of metabolic processes. Autotoxins, like most substances, follow the notion of the Paracelsus Axiom and have a dosage-dependent mode of action in which they cause no effects at low levels but cause stress or death at higher levels (Wu et al. 2015; Hickman et al. 2021; Jahantab et al. 2021). Species that produce a given autotoxic compound already contain a base amount of that autotoxin, so a smaller amount of exogenous autotoxin is needed to reach toxic levels. Many species have mechanisms of avoiding autotoxicity, including storage in special compartments (e.g., vacuoles, trichomes, etc.) and modifying or metabolizing the autotoxin (Wink 1993; Inderjit and Duke 2003; Li et al. 2021). However, the uptake of extra autotoxins in addition to those already produced by and contained in the plant could overwhelm these toxicity avoidance mechanisms. In species that do not produce a given autotoxin, higher doses need to be applied for the total autotoxin amount to reach the level at which it is toxic or at which toxicity avoidance mechanisms are overwhelmed. This dosage dependency hints at a mode of action and could potentially explain the species-specificity seen for some autotoxins (Li et al. 2016).

Alternatively, the methods that autotoxin-producing plants use to avoid autotoxicity may not be able to deal with externally applied autotoxins, as these plants more commonly encounter the autotoxins endogenously (Gog et al. 2005; Li et al. 2016). For example, plants commonly avoid autotoxicity by storing toxic compounds in specialized structures, such as trichomes or oil glands (Singh et al. 1999). Li et al. (2018) found that releasing autotoxins from trichomes onto the surface of the plant led to damage in *Salvinia molesta*, showing that the plant surface was vulnerable to autotoxins. Gog et al. (2005) similarly found that wild parsnip (*Pastinaca sativa* L.), parsley (*Petroselinum crispum* [Mill.] Fuss), and rough lemon (*Citrus jambhiri* Lush.) experienced cell damage when they were exposed to autotoxins either by slicing open the oil tubes where the autotoxins were sequestered or by dropping the autotoxins into a pinprick in the leaf. This indicates that while plants are able to limit toxicity by sequestering the autotoxins they produce, toxicity can still occur when these compounds are applied exogenously or released from sequestration. Recent studies have also investigated the effect of autotoxins on plant roots, suggesting that roots may be more sensitive to autotoxins than other plant parts (Xin et al. 2019; Zhang et al. 2020). Plants that do not produce a given autotoxin but commonly encounter that autotoxin exogenously may have evolved methods for dealing with externally encountered autotoxins, leading to reduced toxicity.

In addition to not having effective methods of dealing with externally applied autotoxins, producing species may also be more vulnerable to autotoxins because their cell membranes and/or cell walls may be more permeable to the autotoxin, allowing it to quickly travel through cells of the producing organism and cause damage in tissues that are already saturated with the autotoxic compounds (Li et al. 2016). Species that produce and use a given autotoxin generally have mechanisms to internally transport the autotoxin, and the presence of these transport mechanisms may lead to more swift damage when autotoxins are applied externally, especially if the autotoxins are present in high enough levels to overwhelm sequestration or detoxification mechanisms. For example, Chi et al. (2013) found that several genes in rice (*Oryza sativa* L.) were upregulated in response to exposure to ferulic acid, an endogenously produced autotoxin that generates reactive oxygen species. However, these genes did not upregulate in response to juglone, an allelochemical that also generates reactive oxygen species but is not produced by rice. These results provide some support for the hypothesis of differential reaction to endogenously produced and externally encountered compounds. After more autotoxic compounds have been identified, more research should be conducted to determine their mechanism of toxicity to the producing species and how other species avoid toxicity.

While some autotoxins seem to show a level of species specificity, the potential for non-target effects has not been tested thoroughly or in a manner similar to other control methods. Many studies have not tested autotoxins for species-specificity, and those that have only did so on a few species (Table 2, S1). Some autotoxicity studies have tested

the effects of autotoxins on co-occurring species (e.g., Ervin and Wetzel 2000; Zhang et al. 2011), but these tests are generally done on a small number of species, if they are done at all (Table S1). In some cases, only species of agricultural importance are tested (e.g., Chou and Lin 1976; Li et al. 2010). Few studies have tested autotoxins on congeners or species in the same family, so if species specificity does exist, it is unclear how closely related species can be before effects are seen (Table 2). Because invasive organisms can co-occur with a wide range of species based on the specific area of invasion, it is crucial that autotoxins undergo thorough testing to determine if they are harmful to species other than the producer. Direct effects on non-target organisms could include growth reduction, reduced reproductive capacity (e.g., producing no or fewer seeds), or mortality of a species. Indirect effects could include promotion of other invasive species as a result of reducing populations of the target species, thus opening a niche for other invaders to fill. Future testing of the potential non-target effects of autotoxins should be more comprehensive, potentially following the framework used for testing biological control agents or herbicides.

Identification and quarantine testing of biological control agents considers how easy it is to collect and rear the biological control agent, as well as the ability of the agent to suppress the target pest with little to no other impacts to non-target species (Meurisse et al. 2022). Non-target species risks that are assessed may include direct and indirect effects to non-target species, changed relationships between an agent and a native species as a result of environmental changes, or human-assisted or self-dispersal of the agent to a new area (Simberloff 2012). Using a similar framework to test non-target effects of autotoxins may help prevent unforeseen consequences. Other factors related to biological control agent testing, such as phenology matching between biological control agents and the target and non-target species, may not be directly relevant to autotoxin applications, though it would potentially be important to determine which season(s) or environmental conditions would be most ideal for autotoxin application given the phenology of the target species. This is to be expected as chemical pesticide applications also often rely on a prescription of timing for the most impactful reduction of the target invasive/nonnative.

Though they are rarer or typically only focus on non-target impacts on a single desirable species (e.g., agricultural studies aimed at maximizing yield of a single species while killing all other species), studies of the non-target impacts of herbicides could also be valuable to understand some of the direct and indirect effects of autotoxins (Smith et al. 2006). For example, some herbicides have been documented to also be toxic to terrestrial and aquatic animals, causing behavioral changes, reproductive disorders, and immunological responses, as well as toxic to plants, fungi, bacteria, and other naturally occurring, living organisms within an environment (Bamal et al. 2024). Though autotoxins likely do not have the same active ingredients as synthetic herbicides, studies of the impacts of autotoxins on living organisms that could get exposed to the autotoxin after application, as well as how the autotoxin moves through an ecosystem, will likely be necessary to approve use of autotoxins for the control of invasive species. Autotoxins will primarily be spread via human application, though there is a potential for residual autotoxin to drift, run off, or volatilize and impact adjacent areas. These same processes also affect herbicides, so it could be useful to model autotoxin testing after herbicide testing.

Knowledge Gaps and Challenges for Future Research

Current research suggests that there is a great potential for autotoxins to be used in invasive species management. However, there are still many knowledge gaps that need to be addressed before autotoxins are actively used in management efforts, and there are some challenges for future research and development of autotoxins. Below, we outline some of the knowledge gaps and challenges related to: (1) sources of autotoxins, (2) resistance and tolerance to autotoxins, (3) environmental effects, (4) species specificity, (5) ethical and regulatory considerations, and (6) production and cost of autotoxins.

Sources of Autotoxins One of the knowledge gaps surrounding autotoxins is whether all species produce autotoxins. Autotoxicity can benefit species by preventing intraspecific competition (Singh et al. 1999), and can be regulated so the toxin is only produced in response to an environmental stimulus (Newman 1978) and at a quantity that results in a beneficial effect. For example, Picman and Picman (1984) and Duke et al. (1987) documented that autotoxins can inhibit germination to reduce competition within Santa Maria feverfew (*Parthenium hysterophorus* L.) and annual wormwood (*Artemisia annua* L.), respectively. Given these benefits, it could be hypothesized that all plants should be capable of producing autotoxins (Li et al. 2016), but that natural checks and balances exist to prevent production of strong autotoxins that would result in significant species mortality (Paramanik et al., 2008; Colautti and Antunes 2025). In the context of invasive plants, the novel weapons hypothesis was developed to support the idea that invasive species have novel biochemical weapons that can help them overcome interspecific competition in the novel range (Callaway and Ridenour 2004). For invasive plants to develop

more potent allelopathic chemicals, they would also have to evolve low energetic production costs and adaptations to the allelopathic toxin (Colautti and Antunes 2025). Whether invasive plants are producing autotoxins or allelopathic toxins to overcome intraspecific or interspecific competition, these toxins could potentially be harnessed to turn back on the invasive plant in need of control. However, it is unclear (1) which species produce autotoxins, (2) the mechanisms for extracting and amplifying the toxins, and (3) the dosage that would be necessary to effectively induce growth reduction or mortality. Paramanik et al. (2008) and Li et al. (2018) are just two examples of studies that have found that high concentrations of an autotoxin can effectively reduce growth and/or induce mortality of plant species, though more research needs to be conducted to fully explore the sources of and mechanisms behind autotoxins. It may be difficult to discover autotoxins in organisms that only produce them under certain conditions, as preliminary extracts may not contain any autotoxin depending on environmental conditions. Organisms that only produce autotoxins under certain conditions may also require higher doses of autotoxins to reach toxic levels if the organisms being treated are not already producing the autotoxin themselves. If autotoxins are only produced under certain conditions, this could make the discovery and use process of autotoxins more complicated.

Along with the knowledge gaps that still exist regarding autotoxin sources and mechanisms, there are also many challenges that could hamper eventual use of autotoxins for invasive species control. The first challenge is that autotoxins are reactionary by nature. Specifically, autotoxins will have to be sourced *after* a species is an identified problem or management priority, and this lag time for autotoxin development could allow species to gain a stronger foothold in the introduced range, making them more difficult to manage later on. Thus, while autotoxins are a promising frontier for invasive species control, their reactive rather than proactive nature may mean that they are more useful for managing established invasions rather than preventing new ones. However, if used in a holistic paradigm of concurrent prevention and intervention, invasive species management may succeed in some areas where extant approaches with chemical intervention are currently failing.

Resistance and Tolerance to Autotoxins In addition to the knowledge gaps associated with sources and mechanisms of autotoxins, there are knowledge gaps regarding what adaptations the species have to resist or grow tolerant to autotoxins or allelopathic toxins. It is hypothesized that many organisms that contain autotoxic compounds have evolved ways to avoid autotoxicity (Newman 1978; Singh et al. 1999). Autotoxicity can be avoided by sequestering autotoxic compounds in specialized organelles, producing them in small amounts, or through detoxification pathways (Sirikantaramas et al. 2008). Picman and Picman (1984) found that water soluble autotoxins can inhibit germination in *Parthenium hysterophorus*, but germination and growth reductions were only temporary, potentially due to leaching of the water soluble autotoxins or tolerance to the autotoxins. While external application of high concentrations of autotoxins seems to overcome pathways preventing autotoxicity (Paramanik et al., 2008), there is likely variation in how quickly some populations could evolve a tolerance to externally applied autotoxins. Lankau (2011) demonstrated that garlic mustard (*Alliaria petiolata* [M.Bieb.] Cavara & Grande) reduced investment in allelopathic compounds and soil microbial communities adapted resistance to the compounds over time. Such interactions and feedbacks with endophytes or soil or plant microbiomes could also lead to autotoxin tolerance over time that may only be observed in natural settings and are more difficult to test for in a controlled environment. Organisms being treated with autotoxins will need to be monitored to determine if organisms can develop autotoxin tolerance, and how quickly this occurs.

Environmental Effects Even if autotoxins are extremely specific, it is unclear if autotoxins will have other non-target effects. The specificity of autotoxins could make people less concerned about strictly applying autotoxins only to the target species, potentially opening the door for increased non-target effects. As with other chemicals, there could be potential for accumulation in the environment. There is also potential for bioaccumulation to occur after prolonged autotoxin use, as seen in pesticides such as dichlorodiphenyltrichloroethane (DDT) (Kesic et al. 2021). Autotoxins that are species-specific at low doses may be toxic to a wider range of organisms at high doses, and bioaccumulation could lead to organisms experiencing these high doses of autotoxins even if they are applied in low doses (Isensee 2024). Bioaccumulation potential should be investigated in autotoxins, and the amount of autotoxin required for toxicity in off-target species should be identified, even if this amount is well above the dose required for target species toxicity.

Depending on their chemistry, autotoxins could also linger in water or soils, potentially altering ecosystem chemistry. For example, many autotoxins identified thus far are acids (e.g., P-coumaric acid, salicylic acid, malonic acid, cinnamic acid, and benzoic acid) and adding large amounts of acidic autotoxins into the environment could change soil chemistry (Table S1). Soil acidity affects what plants can grow, what microbes are present, and nutrient cycling (Robson 1989). Thus, autotoxins could have indirect off-target

effects on the environment by modifying soil chemistry rather than through direct toxicity.

Autotoxins can be varying types of biological molecules, from lipids to water-soluble compounds, so it is imperative to be cognizant of the types and stereochemistry ratios of molecules in autotoxins and how they will interact with the environment. Abiotic factors such as salt stress, cold, and drought cause changes in the types and amounts of secondary metabolites that plants produce (Akula and Ravishankar 2011), and infections or insect damage can also alter or induce the production of some secondary metabolites (Bennett and Wallsgrove 1994). If autotoxins are being directly extracted from plants rather than synthesized in a laboratory, all of the different compounds and stereochemistry ratios present in extracts should be studied for off-target effects.

Species Specificity One of the major knowledge gaps is how species-specific autotoxins are compared to other controls. Thus far, some autotoxins have shown no toxic effects on other species (Munther and Fairbrothers 1980; Li et al. 2016), but the majority of autotoxins tested on other species have shown some negative effects (Table 2). Autotoxins of some species seem to only affect congeners or species in the same family (e.g., *Salvinia molesta*), but most autotoxins have negative effects on plants both within and outside their family (Table 2). Extensive research will be needed to determine the specificity of autotoxins, especially those being developed for use in management of invasive organisms that are spread across a variety of habitats. For example, autotoxins developed to control cogongrass (*Imperata cylindrica* [L.] P. Beauv.), an invasive grass that is now present on six continents (MacDonald 2004), would need to be tested extensively to determine whether these autotoxins would impact any of the other organisms found near cogongrass invasions, especially other grasses in Poaceae. Most autotoxins have been tested only on plants outside the family of the producing species, and tests on congeners have been done for autotoxins produced by only ten species (Table 2). How closely related a species can be before being negatively affected by autotoxins remains an important knowledge gap, as some non-native species have native congeners in the introduced range (e.g., native coral honeysuckle [*Lonicera sempervirens* L.] and non-native Japanese honeysuckle [*Lonicera japonica* Thunb.] both occur in the southeastern United States). Examining autotoxin impacts based on phylogenetic relatedness should be considered during research and testing.

Ethical and Regulatory Considerations If all organisms produce autotoxins, there could be ethical questions that arise regarding how far researchers should go when utilizing autotoxins to combat invasive species. If autotoxin production extends beyond plants, there is potential for them to be developed and used as biological weapons to destroy agricultural crops or other living commodities that humans and other animals rely on for survival. Once there is more knowledge of the capabilities of autotoxins, regulations may be required to limit their development beyond invasive species control. Research and development of autotoxins should have a defined scope that is specific and within the approvals of appropriate governing bodies.

Autotoxins may also be met with the same skepticism faced by herbicides. Though autotoxins are naturally derived, their similarities to better-known and more infamous herbicides may lead to public distrust of their safety, or lead to increased regulation that stymies their development. To prevent public distrust, autotoxins will need to be thoroughly tested, and researchers should be open with governing and regulating bodies, stakeholders, and the public during the development process to ensure maximal adoption of this new approach with advancing technology.

On the other side of the coin, autotoxins may also face skepticism over their efficacy, which could slow uptake (Cordeau et al. 2016). Natural pesticides, including bioherbicides and autotoxins, are often viewed as less effective than synthetic pesticides, which have a more extensive record of success (Fusar Poli et al. 2025). Bioherbicide effectiveness is often more dependent on environmental conditions and the quality of the source of the compounds than synthetic herbicides are, and some bioherbicides that demonstrate sufficient toxicity under laboratory conditions have inconsistent toxicity when applied in the field (Cordeau et al. 2016). In order to reduce skepticism and ensure efficacy, autotoxins will need to be tested extensively in the field under a variety of conditions.

Production and Cost of Autotoxins Another challenge of using autotoxins in management is that they may not be cost effective to produce or use. Few bioherbicides are currently on the market, and even fewer are derived from plant compounds, partially due to inconsistent control under field conditions (Cordeau et al. 2016). Because autotoxins are intended to be species-specific, it may not be cost effective to mass produce them. Furthermore, there is speculation that specific autotoxins may only be effective on certain genotypes, meaning that autotoxins would have to be developed separately for different populations. While this small-scale, tailored approach will be useful in limiting non-target effects, it would also make it difficult to scale up autotoxin production (Ash 2010). The more specific autotoxins are, the more it may cost to develop and produce them, reducing their cost-effectiveness. Some autotoxins may also be more difficult to extract and purify than others, which could

increase production costs. For example, ailantone is an allelochemical produced by tree of heaven (*Ailanthus altissima* (Mill.) Swingle) that is toxic to many plants, but it has not been adopted as a bioherbicide partially because of how expensive it is to produce (Khamare et al. 2022). It is possible that autotoxins will not turn into a marketable product, which could slow their uptake and accessibility for managers.

Conclusions

Existing research shows some potential of autotoxins to act as a more species-specific tool in the fight against invasive plants, but much more research is needed before autotoxin use becomes a reality. Though autotoxins have been investigated preliminarily for a variety of plants, more research is needed to determine how many target organisms can produce and are susceptible to autotoxins, and how specific autotoxins will be (i.e., ensure no non-target effects). Because autotoxins have similar production methods and use as current chemical and biological control methods, frameworks for testing chemical and biological controls can be used to thoroughly test for non-target effects of autotoxins. Future testing of autotoxins should focus not only on refining the development process, but also on elucidating the full range of potential non-target effects, including those on closely related and co-occurring species, sublethal impacts, and effects on humans and other animals. With thorough research, autotoxins could become an important tool in invasive species management efforts.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10886-026-01706-6.

Acknowledgements We thank Dr. David Giannasi for sharing his insights on plant biochemistry and biochemical-like controls for non-native plant species.

Author contributions Elizabeth A. Esser: Conceptualization, Writing – original draft, Writing – review & editing. Gary N. Ervin: Conceptualization, Writing – review & editing. Rima D. Lucardi: Conceptualization, Writing – review & editing. Paul M. Severns: Conceptualization, Writing – original draft. Erika D. Womack-Peoples: Conceptualization, Funding Acquisition, Writing – review & editing. Steven H. Bullard: Conceptualization, Writing – review & editing. Ashley N. Schulz: Conceptualization, Funding Acquisition, Supervision, Writing – original draft, Writing – review & editing. All authors read and approved the final manuscript.

Funding This review was developed from research supported by USDA Forest Service, Southern Research Station (23JV11330160055 and 24JV11330101010), as well as the United States Department of Agriculture National Institute of Food and Agriculture McIntire-Stennis project MISZ-069550 through the Forest and Wildlife Research Center at Mississippi State University. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Literature Cited

Akula R, Ravishankar GA (2011) Influence of abiotic stress signals on secondary metabolites in plants. Plant Signal Behav 6(11):1720–1731

Alías JC, Sosa T, Escudero JC, Chaves N (2006) Autotoxicity against germination and seedling emergence in *Cistus ladanifer* L. Plant Soil 282:327–332

Annett R, Habibi HR, Hontela A (2014) Impact of glyphosate and glyphosate-based herbicides on the freshwater environment. J Appl Toxicol 34(5):458–479

Ansari I, El-Kady MM, Mahmoud AED, Arora C, Verma A, Rajarathinam R, Singh P, Verma DK, Mittal J (2024) Persistent pesticides: accumulation, health risk assessment, management and remediation: an overview. Desalination Water Treat 317:100274

Ash GJ (2010) The science, art and business of successful bioherbicides. Biol Control 52(3):230–240

Ayilara MS, Adeleke BS, Akinola SA, Fayose CA, Adeyemi UT, Gbadegesin LA, Omole RK, Johnson RM, Uthman QO, Babalola OO (2023) Biopesticides as a promising alternative to synthetic pesticides: a case for microbial pesticides, phytopesticides, and nanobiopesticides. Front Microbiol 14:1040901

Bachheti A, Sharma A, Bachheti RK, Husen A, Pandey DP (2020) Plant allelochemicals and their various applications. In: Merillon JM, Ramawat KG (eds) Co-evolution of secondary metabolites. Springer, Cham, pp 1–25

Bailey KL (2014) The bioherbicide approach to weed control using plant pathogens. In: Abrol DP (ed) Integrated Pest Management: Current Concepts and Ecological Perspective. Academic Press, pp 245–266

Baldwin IT, Callahan P (1993) Autotoxicity and chemical defense: nicotine accumulation and carbon gain in solanaceous plants. Oecologia 94(4):534–541

Bamal D, Duhan A, Pal A, Beniwal RK, Kumawat P, Dhanda S, Goyat A, Hooda VS, Yadav R (2024) Herbicide risks to non-target species and the environment: A review. Environ Chem Lett 22:2977–3032

Bartlett AC, Staten RT (2009) The sterile insect release method and other genetic control strategies. In: Radcliffe EB, Hutchison WD, Cancelado RE (eds) [eds.], Radcliffe's IPM World Textbook. University of Minnesota, St. Paul, MN, URL. https://ipmworld.umn.edu

Bennett RN, Wallsgrove RM (1994) Secondary metabolites in plant defence mechanisms. New Phytol 127(4):617–633

Bonanomi G, Zotti M, Idbella M, Termolino P, De Micco V, Mazzoleni S (2022) Field evidence for litter and self-DNA inhibitory effects on *Alnus glutinosa* roots. New Phytol 236(2):399–412

Bonny S (2016) Genetically modified herbicide-tolerant crops, weeds, and herbicides: Overview and impact. Environ Manage 57(1):31–48

Bradley G, McGinley H, Hermsen N (2011) A global perspective on autotoxins regulatory issues. In Offshore Technology Conference (pp. OTC-21806). OTC

Callaway RM, Aschehoug ET (2000) Invasive Plants Versus Their New and Old Neighbors: A Mechanism for Exotic Invasion. Science 290:521–523

Callaway RM, Ridenour WM (2004) Novel weapons: invasive success and the evolution of increased competitive ability. Front Ecol Environ 2(8):436–443

Callaway RM, Ridenour WM, Laboski T, Weir T, Vivanco JM (2005) Natural Selection for Resistance to the Allelopathic Effects of Invasive Plants. J Ecol 93(3):576–583. http://www.jstor.org/stable/3599423

Chi WC, Chen YA, Hsiung YC, Fu SF, Chou CH, Trinh NN, Chen YC, Huang HJ (2013) Autotoxicity mechanism of *Oryza sativa*: transcriptome response in rice roots exposed to ferulic acid. BMC Genomics 14:1–18

Chon SU, Jennings JA, Nelson CJ (2006) Alfalfa (*Medicago sativa* L.) autotoxicity: current status. Allelopathy J 18(1):57

Chou CH (1989) Comparative phytotoxic nature of leachate from four subtropical grasses. J Chem Ecol 15(7):2149–2159

Chou CH (1995) Allelopathy and sustainable agriculture. In: Allelopathy: Organisms, Processes and Applications. pp. 211–223. Inderjit, Dakshini, K.M.M. and Einhellig, F.A., Eds., ACS Symposium Series No. 582, American Chemical Society, Washington, DC

Chou CH, Lin HJ (1976) Autointoxication mechanism of *Oryza sativa* I. phytotoxic effects of decomposing rice residues in soil. J Chem Ecol 2(3):353–367

Chou CH, Lin TJ, Kao CI (1977) Phytotoxins produced during decomposition of rice stubbles in paddy soil and their effect on leachable nitrogen. Bot Bull Acad Sin 18:45–60

Colautti RI, Antunes PM (2025) A critical reassessment of the novel weapons hypothesis and allelopathy as an adaptive strategy that facilitates plant invasion. New Phytol 248(2):507–516

Cordeau S, Triolet M, Wayman S, Steinberg C, Guillemin JP (2016) Bioherbicides: dead in the water? A review of the existing products for integrated weed management. Crop Prot 87:44–49

Debnath D, Samal I, Mohapatra C, Routray S, Kesawat MS, Labanya R (2022) Chitosan: an autocidal molecule of plant pathogenic fungus. Life 12(11):1908

Denyer SP (1990) Mechanisms of action of autotoxins. Int Biodeterior 26(2–4):89–100

Diagne C, Leroy B, Vaissière AC, Gozlan RE, Roiz D, Jarić I, Salles JM, Bradshaw CJ, Courchamp F (2021) High and rising economic costs of biological invasions worldwide. Nature 592(7855):571–576. https://doi.org/10.1038/s41586-021-03405-6

DiTomaso JM, Van Steenwyk RA, Nowierski RM, Vollmer JL, Lane E, Chilton E, Burch PL, Cowan PE, Zimmerman K, Dionigi CP (2017) Enhancing the effectiveness of biological control programs of invasive species through a more comprehensive pest management approach. Pest Manag Sci 73(1):9–13

Dorning M, Cipollini D (2006) Leaf and root extracts of the invasive shrub, *Lonicera maackii*, inhibit seed germination of three herbs with no autotoxic effects. Plant Ecol 184(2):287–296

Duke SO, Powles SB (2008) Glyphosate: a once-in-a-century herbicide. Pest Manage Science: Former Pesticide Sci 64(4):319–325

Duke SO, Vaughn KC, Croom EM, ElSohly HN (1987) Artemisinin, a constituent of annual wormwood (*Artemisia annua*), is a selective phytotoxin. Weed Sci 35:499–505

Eilenberg J, Hajek A, Lomer C (2001) Suggestions for unifying the terminology in biological control. Biocontrol 46:387–400

El-Sayed AM, Suckling DM, Byers JA, Jang EB, Wearing CH (2009) Potential of lure and kill in long-term pest management and eradication of invasive species. J Econ Entomol 102(3):815–835

EPA (1997) PRN 97–3: Guidelines for Expedited Review of Conventional Pesticides under the Reduced-Risk Initiative and for Biological Pesticides. United States Environmental Protection Agency. Accessed 11/24/2025 via https://www.epa.gov/pesticide-registration/prn-97-3-guidelines-expedited-review-conventional-pesticides-under-reduced

EPA (2025a) Types of Pesticide Ingredients. United States Environmental Protection Agency. Accessed 11/24/2025 via https://www.epa.gov/ingredients-used-pesticide-products/types-pesticide-ingredients

EPA (2025b) Biopesticides. United States Environmental Protection Agency. Accessed 11/24/2025 via https://www.epa.gov/pesticides/biopesticides

EPA (2026) Federal Certification Standards for Pesticide Applicators. Accessed 3/9/2026 via https://www.epa.gov/pesticide-worker-safety/federal-certification-standards-pesticide-applicators

Ervin GN, Wetzel RG (2000) Allelochemical autotoxicity in the emergent wetland macrophyte *Juncus effusus* (Juncaceae). Am J Bot 87(6):853–860

Favaretto A, Scheffer-Basso SM, Perez NB (2017) Autotoxicity in tough lovegrass (*Eragrostis plana*). Planta Daninha 35:e017164046

Fusar Poli E, Campos JM, Martinez Ferrer MT, Rahmouni R, Rouis S, Yurtkuran Z, Fontefrancesco MF (2025) The difficult decision of using biopesticides: a comparative case-study analysis concerning the adoption of biopesticides in the Mediterranean Region. Agriculture 15(6):640

Georghiou GP (1972) The evolution of resistance to pesticides. Annu Rev Ecol Syst 3:133–168

Glare T, Caradus J, Gelernter W, Jackson T, Keyhani N, Köhl J, Marrone P, Morin L, Stewart A (2012) Have biopesticides come of age? Trends Biotechnol 30(5):250–258

Glen AS, Atkinson R, Campbell KJ, Hagen E, Holmes ND, Keitt BS, Parkes JP, Saunders A, Sawyer J, Torres H (2013) Eradicating multiple invasive species on inhabited islands: the next big step in island restoration? Biol Invasions 15(12):2589–2603

Gog L, Berenbaum MR, DeLucia EH, Zangerl AR (2005) Autotoxic effects of essential oils on photosynthesis in parsley, parsnip, and rough lemon. Chemoecology 15(2):115–119

Goh HH, Khairudin K, Sukiran NA, Normah MN, Baharum SN (2016) Metabolite profiling reveals temperature effects on the VOC s and flavonoids of different plant populations. Plant Biol 18:130–139

Gong JT, Li TP, Wang MK, Hong XY (2023) *Wolbachia*-based strategies for control of agricultural pests. Current Opinion in Insect Science 57:101039

Gould F, Schliekelman P (2004) Population genetics of autocidal control and strain replacement. Annu Rev Entomol 49(1):193–217

Graham S, Metcalf AL, Gill N, Niemiec R, Moreno C, Bach T, Ikutegbe V, Hallstrom L, Ma Z, Lubeck A (2019) Opportunities for better use of collective action theory in research and governance for invasive species management. Conserv Biol 33(2):275–287

Gurr GM, Barlow ND, Memmott J, Wratten SD, Greathead DJ (2000a) A history of methodological, theoretical and empirical approaches to biological control. In: Gurr G, Wratten S (eds) Biological Control: Measures of Success. Springer, Dordrecht, pp 3–37

Gurr GM, Wratten SD, Barbosa P (2000b) Success in conservation biological control of arthropods. In: Gurr G, Wratten S (eds) Biological Control: Measures of Success. Springer, Dordrecht, pp 105–132

Hallett SG (2005) Where are the bioherbicides? Weed Sci 53(3):404–415

Handford CE, Elliott CT, Campbell K (2015) A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. Integr Environ Assess Manag 11(4):525–536

Hawkins NJ, Bass C, Dixon A, Neve P (2019) The evolutionary origins of pesticide resistance. Biol Rev 94(1):135–155

Hegazy AK, Mansour KS, Abdel-Hady NF (1990) Allelopathic and autotoxic effects of *Anastatica hierochuntica* L. J Chem Ecol 16:2183–2193

Heimpel GE, Mills N (2017) Biological Control: Ecology and Applications. Cambridge University Press
Helgason BL, Walley FL, Germida JJ (2009) Fungal and bacterial abundance in long-term no-till and intensive-till soils of the Northern Great Plains. Soil Sci Soc Am J 73(1):120–127
Hickman DT, Rasmussen A, Ritz K, Birkett MA, Neve P (2021) Review: Allelochemicals as multi-kingdom plant defence compounds: towards an integrated approach. Pest Manag Sci 77:1121–1131. https://doi.org/10.1002/ps.6076
Hierro JL, Callaway RM (2003) Allelopathy and exotic plant invasion. Plant Soil 256:29–39. https://doi.org/10.1023/A:1026208327014
Hierro JL, Callaway RM (2021) The Ecological Importance of Allelopathy. Annu Rev Ecol Evol Syst 52:25–45. https://doi.org/10.1146/annurev-ecolsys-051120-030619
Hoddle MS, Lake EC, Minteer CR, Daane KM (2021) Importation biological control. In: Mason PG (ed) Biological control: global impacts, challenges and future directions of pest management. CSIRO Publishing, Clayton South, pp 67–89
Hokkanen H, Pimentel D (1984) New approach for selecting biological control agents. Can Entomol 116:1109–1121
Huang X, Chen J, Liu J, Li J, Wu M, Tong B (2019) Autotoxicity hinders the natural regeneration of *Cinnamomum migao* H.W. Li in southwest China. Forests 10(10):919
Hu G, Zhang ZH (2013) Aqueous tissue extracts of *Conyza canadensis* inhibit the germination and shoot growth of three native herbs with no autotoxic effects. Planta Daninha 31:805–811
Inderjit, Duke SO (2003) Ecophysiological aspects of allelopathy. Planta 217(4):529–539
IPBES (2023) Summary for policymakers of the thematic assessment report on invasive alien species and their control of the intergovernmental science-policy platform on biodiversity and ecosystem services. Roy HE, Pauchard A, Stoett P, Renard Truong T, Bacher S, Galil BS, Hulme PE, Ikeda T, Sankaran KV, McGeoch MA, Meyerson LA, Nuñez MA, Ordonez A, Rahlao SJ, Schwindt E, Seebens H, Sheppard AW, Vandvik V (eds). IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.7430692
Isensee AR (2024) Bioaccumulation and food chain accumulation. Environmental Chemistry of Herbicides. CRC, pp 187–197
Islam AM, Karim SMR, Kheya SA, Yeasmin S (2024) Unlocking the potential of bioherbicides for sustainable and environment friendly weed management. Heliyon 10(16):e36088
Jabran K, Mahajan G, Sardana V, Chauhan BS (2015) Allelopathy for weed control in agricultural systems. Crop Prot 72:57–65
Jahantab E, Yazdanshenas H, Taheri N, Wang Y, Zhao QH (2021) Autotoxicity of *Amygdalus scoparia* Spach and *Atriplex canescens* (Pursh.) Nutt. on soil seed bank in Iranian arid lands. Allelopathy J 54(2):183–198
Jardine SL, Sanchirico JN (2018) Estimating the cost of invasive species control. J Environ Econ Manag 87:242–257
Karpavičienė B, Danilovienė J, Vykertaitė R (2019) Congeneric comparison of allelopathic and autotoxic effects of four *Solidago* species. Bot Serbica 43(2):175–186
Kato-Noguchi H, Nakamura K, Ohno O, Suenaga K, Okuda N (2017) Asparagus decline: autotoxicity and autotoxic compounds in asparagus rhizomes. J Plant Physiol 213:23–29
Kesic R, Elliott JE, Fremlin KM, Gauthier L, Drouillard KG, Bishop CA (2021) Continuing persistence and biomagnification of DDT and metabolites in northern temperate fruit orchard avian food chains. Environ Toxicol Chem 40(12):3379–3391
Khamare Y, Chen J, Marble SC (2022) Allelopathy and its application as a weed management tool: a review. Front Plant Sci 13:1034649
Klassen W (2005) Area-wide integrated pest management and the sterile insect technique. In: Dyck VA, Hendrichs J, Robinson AS (eds) Sterile Insect Technique. Principles and Practice in Area-Wide Integrated Pest Management. Springer, Dordrecht, The Netherlands, pp 39–68
Kumari JA, Prasad PR (2018) Assessing the allelopathy and autotoxicity effects of *Parthenium hysterophorus* L., *Senna uniflora* (Mill.) H.S. Irwin and Barneby and *Hyptis suaveolens* (L.) Poit. Russ J Biol Invasions 9:290–298
Kyle GP, Beard KH, Kulmatiski A (2007) Reduced soil compaction enhances establishment of non-native plant species. Plant Ecol 193(2):223–232
Labarrere B, Prinzing A, Dorey T, Chesneau E, Hennion F (2019) Variations of secondary metabolites among natural populations of sub-Antarctic ranunculus species suggest functional redundancy and versatility. Plants 8(7):234
Labelle ER, Hansson L, Högbom L, Jourgholami M, Laschi A (2022) Strategies to mitigate the effects of soil physical disturbances caused by forest machinery: a comprehensive review. Curr Forestry Rep 8(1):20–37
Lankau RA (2011) Resistance and recovery of soil microbial communities in the face of *Alliaria petiolata* invasions. New Phytol 189(2):536–548
Leahy J, Mendelsohn M, Kough J, Jones R, Berckes N (2014) Biopesticide oversight and registration at the US Environmental Protection Agency. state of the art and future opportunities, Biopesticides, pp 3–18
Lee BM, Bearth A, Tighe RM, Kim M, Tan S, Kwon S (2024) Biocidal products: opportunities in risk assessment, management, and communication. Risk Anal 44(2):493–507
Liang X, Lin Y, Song Y, Wang R, Zeng R, Chen D (2018) Autotoxicity of *Celosia argentea* and its allelopathic effects on other plants. Journal of South China Agricultural University 39(5):32–38
Li J, Halitschke R, Li D, Paetz C, Su H, Heiling S, Xu S, Baldwin IT (2021) Controlled hydroxylations of diterpenoids allow for plant chemical defense without autotoxicity. Science 371(6526):255–260
Li S, Wang P, Su Z, Lozano E, LaMaster O, Grogan JB, Weng Y, Decker T, Findeisen J, McGarrity M (2018) Endocide-induced abnormal growth forms of invasive Giant Salvinia (*Salvinia molesta*). Sci Rep 8(1):8006
Li S, Wang P, Yuan W (2010) Induced endogenous autotoxicity in *Camptotheca*. Front Biosci 2:1196–1210
Li S, Wang P, Yuan W, Su Z, Bullard SH (2016) Endocidal regulation of secondary metabolites in the producing organisms. Sci Rep 6(1):1–17. https://doi.org/10.1038/srep29315
Liu HC, Song SW, Chen RY, Sun GW (2013) Study on Autotoxicity of Aqueous Extracts from Different Parts of Flowering Chinese Cabbage. Adv Mater Res 641–642:962–966
Li Z, Jennings A (2017) Worldwide regulations of standard values of pesticides for human health risk control: a review. Int J Environ Res Public Health 14(7):826
MacDonald GE (2004) Cogongrass (*Imperata cylindrica*)—biology, ecology, and management Critical Reviews in Plant Sciences, 23(5), 367–380
Mack RN, Lonsdale WM (2002) Eradicating invasive plants: hard-won lessons for islands. Turning the tide: The Eradication of Invasive Species - Proceedings of the International Conference on Eradication of Island Invasives (Veitch, C.R. and Clout, M.N. eds.), The IUCN Species Survival Commission 27. 164–172
Manning S, Miller J (2011) Manual, mechanical, and cultural control methods and tools. In: Leslie AR, Westbrooks RG (eds) Invasive Plant Management Issues and Challenges in the United States: 2011 Overview. American Chemical Society, pp 231–244
Marec F, Vreysen MJ (2019) Advances and challenges of using the sterile insect technique for the management of pest Lepidoptera. Insects 10(11):371
Mason PG, Flanders RG, Arrendondo-Bernal HA (2005) How can legislation facilitate the use of biological control of arthropods in North America? In Second International Symposium on

Biological Control of Arthropods (Hoddle, M.S. ed.), USDA Forest Service Publication FHTET-2005-08. 701–714
Mazzoleni S, Bonanomi G, Incerti G, Chiusano ML, Termolino P, Mingo A, Senatore M, Giannino F, Cartenì F, Rietkerk M, Lanzotti V (2015) Inhibitory and toxic effects of extracellular self-DNA in litter: a mechanism for negative plant–soil feedbacks? New Phytol 205(3):1195–1210
Meurisse N, Marcot BG, Woodberry O, Barratt BI, Todd JH (2022) Risk analysis frameworks used in biological control and introduction of a novel Bayesian network tool. Risk Anal 42(6):1255–1276
Möhler H, Diekötter T, Herrmann JD, Donath TW (2018) Allelopathic vs. autotoxic potential of a grassland weed—evidence from a seed germination experiment. Plant Ecol Divers 11(4):539–549. https://doi.org/10.1080/17550874.2018.1541487
Möhring N, Ba MN, Braga ARC, Gaba S, Gagic V, Kudsk P, Larsen A, Mesnage R, Niggli U, Qaim M, Schreinemachers P, Stamm C, de Vries W, Finger R (2025) Expected effects of a global transformation of agricultural pest management. Nat Commun 16:10901. https://doi.org/10.1038/s41467-025-66982-4
Miller DA (1996) Allelopathy in forage crop systems. Agron J 88(6):854–859
Moon K, Blackman DA, Brewer TD (2015) Understanding and integrating knowledge to improve invasive species management. Biol Invasions 17(9):2675–2689
Moore BD, Andrew RL, Külheim C, Foley WJ (2014) Explaining intraspecific diversity in plant secondary metabolites in an ecological context. New Phytol 201(3):733–750
Muller CH (1966) The Role of Chemical Inhibition (Allelopathy) in Vegetational Composition. Bull Torrey Bot Club 93(5):332–351. https://doi.org/10.2307/2483447
Muller CH (1969) Allelopathy as a Factor. Ecol Process Vegetation 18(1/6):348–357. http://www.jstor.org/stable/20035472
Munther WE, Fairbrothers DE (1980) Allelopathy and autotoxicity in three eastern North American ferns. Am Fern J 70(4):124–135
Newman EI (1978) In: Harborne JB (ed) Allelopathy: adaptation or accident? Biochemical aspects in plant and animal coevolution. Academic, London, pp 327–342
Nicola L, Vrhovsek U, Soini E, Insam H, Pertot I (2016) Phlorizin released by apple root debris is related to apple replant disease. Phytopathologia Mediterranea, 432–437
Nuñez MA, Kuebbing S, Dimarco RD, Simberloff D (2012) Invasive species: to eat or not to eat, that is the question. Conserv Lett 5(5):334–341
Okada S, Kato-Noguchi H (2021) Involvement of kiwifruit root autotoxicity in its replant problem. Plant Root. https://doi.org/10.3117/plantroot.15.79
Paramanik RC, Chikkaswamy BK, Roy DG, Achinto Paramanik AP, Kumar V, V.K (2008) Effects of biochemicals of *Artemisia annua* in plants. J Phytological Res 21(1):11–18
Parkes JP, Panetta FD (2009) Eradication of invasive species: progress and emerging issues in the 21st century. In: Clout MN, Williams PA (eds) Invasive species management. A handbook of principles and techniques. Oxford University Press, pp 47–60
Pellerin BA, Hernes PJ, Saraceno J, Spencer RG, Bergamaschi BA (2010) Microbial degradation of plant leachate alters lignin phenols and trihalomethane precursors. J Environ Qual 39(3):946–954
Perry LG, Thelen GC, Ridenour WM, Weir TL, Callaway RM, Paschke MW, Vivanco JM (2005) Dual Role for an Allelochemical: (±)-Catechin from Centaurea maculosa Root Exudates Regulates Conspecific Seedling Establishment. J Ecol 93(6):1126–1135. http://www.jstor.org/stable/3599662
Picman J, Picman AK (1984) Autotoxicity in *Parthenium hysterophorus* and its possible role in control of germination. Biochem Syst Ecol 12(3):287–292
Pimentel D (1963) Introducing parasites and predators to control native pests. Can Entomol 95:785–792
Pimentel D (2005) Environmental and economic costs of the application of pesticides primarily in the United States. Environ Dev Sustain 7:229–252
Pimentel D (2014) Pesticides applied for the control of invasive species in the United States. In: Abrol DP (ed) Integrated Pest Management. Academic, pp 111–123
Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52(3):273–288
Pérez DJ, Okada E, Menone ML, Costa JL (2017) Can an aquatic macrophyte bioaccumulate glyphosate? Development of a new method of glyphosate extraction in *Ludwigia peploides* and watershed scale validation. Chemosphere 185:975–982
Putnam AR (1985) Allelopathic research in agriculture: past highlights and potential. In: Thompson AC (ed) The Chemistry of allelopathy: Biochemical interactions among plants. American Chemical Society, Washington, D.C., pp 1–8
Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM (2020) Scientists' warning on invasive alien species. Biol Rev 95(6):1511–1534
Reardon RC, Dubois N, McLane W (1994) *Bacillus thuringiensis* for managing gypsy moth: a review. Radnor (PA): USDA Forest Service FHM-NC-01-94. 33
Reaser JK, Burgiel SW, Kirkey J, Brantley KA, Veatch SD, Burgos-Rodríguez J (2020) The early detection of and rapid response (EDRR) to invasive species: a conceptual framework and federal capacities assessment. Biol Invasions 22(1):1–19
Regnault-Roger C, Philogène BJ (2008) Past and current prospects for the use of botanicals and plant allelochemicals in integrated pest management. Pharm Biol 46(1–2):41–52
Renne IJ, Sinn BT, Shook GW, Sedlacko DM, Dull JR, Villarreal D, Hierro JL (2014) Eavesdropping in plants: delayed germination via biochemical recognition. J Ecol 102:86–94. https://doi.org/10.1111/1365-2745.12189
Robles C, Bonin G, Garzino S (1999) Potentialités autotoxiques et allélopathiques de *Cistus albidus* L. Comptes Rendus de l'Académie des Sciences-Series III-Sciences de la Vie 322(8):677–685
Robson AD (1989) Soil acidity and plant growth. Academic Press Inc
Ruan X, Li Z-H, Wang Q, Pan C-D, Jiang D-A, Wang GG (2011) Autotoxicity and allelopathy of 3,4-dihydroxyacetophenone isolated from *Picea schrenkiana* needles. Molecules 16(10):8874–8893. https://doi.org/10.3390/molecules16108874
Schulz AN, Lucardi RD, Marsico TD (2019) Successful invasions and failed biocontrol: the role of antagonistic species interactions. Bioscience 69(9):711–724
Schuster MJ, Wragg PD, Reich PB (2018) Using revegetation to suppress invasive plants in grasslands and forests. J Appl Ecol 55(5):2362–2373
Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nat Commun 8(1):14435
Simberloff D (2001) Managing established populations of introduced species. In: Claudi R, Hendrickson O, Ottens H (eds) Alien invasive species: A threat to Canadian biodiversity. Natural Resources Canada, Canadian Forest Service, Ottawa, pp 269–278

Simberloff D (2012) Risks of biological control for conservation purposes. Biocontrol 57:263–276
Simberloff D, Stiling P (1996) How risky is biological control? Ecology 77(7):1965–1974
Singh HP, Batish DR, Kohli RK (1999) Autotoxicity: concept, organisms, and ecological significance. CRC Crit Rev Plant Sci 18(6):757–772
Sirikantaramas S, Yamazaki M, Saito K (2008) Mechanisms of resistance to self-produced toxic secondary metabolites in plants. Phytochem Rev 7(3):467–477
Smith CJ, Perfetti TA (2020) A comparison of the persistence, toxicity, and exposure to high-volume natural plant-derived and synthetic pesticides. Toxicol Res Appl 4:2397847320940561
Smith RG, Maxwell BD, Menalled FD, Rew LJ (2006) Lessons from agriculture may improve the management of invasive plants in wildland systems. Front Ecol Environ 4(8):428–434
Stenberg JA, Sundh I, Becher PG, Björkman C, Dubey M, Egan PA, Friberg H, Gil JF, Jensen DF, Jonsson M, Karlsson M, Khalil S, Ninkovic V, Rehermann G, Vetukuri RR, Viketoft M (2021) When is it biological control? A framework of definitions, mechanisms, and classifications. J Pest Sci 94(3):665–676
Stern H (1906) The Autotoxicoses: Their Theory, Pathology, and Treatment. G.P. Engelhard and Company, Chicago, IL, p 222
Strugstad M, Despotovski S (2012) A summary of extraction, synthesis, properties, and potential uses of juglone: A literature review. J Ecosyst Manage, *13*(3)
Su P, Liu X, Wang R, Liu T, Zhao W, Sun M, Wang H, Liu Y, Wu Q (2022) Autotoxicity of *Ambrosia artemisiifolia* and *Ambrosia trifida* and its significance for the regulation of intraspecific populations density. Sci Rep 12:17424
Teem JL, Alphey L, Descamps S, Edgington MP, Edwards O, Gemmell N, Harvey-Samuel T, Melnick RL, Oh KP, Piaggio AJ, Saah JR (2020) Genetic biocontrol for invasive species. Front Bioeng Biotechnol 8:452
Thomas MB, Willis AJ (1998) Biocontrol—risky but necessary? Trends Ecol Evol 13(8):325–329
Umetsu N, Shirai Y (2020) Development of novel pesticides in the 21st century. J Pestic Sci 45(2):54–74. https://doi.org/10.1584/jpestics.D20-201
van den Bosch R, Messenger PS, Gutierrez AP (1982) The history and development of biological control. In: Gutierrez AP, Messenger PS, van den Bosch R (eds) An Introduction to Biological Control. Springer US, New York, NY, pp 21–36
van der Werf HMG (1996) Assessing the impact of pesticides on the environment. Agric Ecosyst Environ 60(2–3):81–96
van Driesche R, Hoddle MS (2017) Non-target effects of insect biocontrol agents and trends in host specificity since 1985. CABI Reviews 2016:1–66
Viator RP, Johnson RM, Grimm CC, Richard EP Jr. (2006) Allelopathic, autotoxic, and hormetic effects of postharvest sugarcane residue. Agron J 98:1526–1531
Walker KA, Ridley SM, Lewis T, Harwood JL (1988) Fluazifop, a grass-selective herbicide which inhibits acetyl-CoA carboxylase in sensitive plant species. Biochem J 254(1):307–310
Wang C, Liu Z, Wang Z, Pang W, Zhang L, Wen Z, Zhao Y, Sun J, Wang ZY, Yang C (2022) Effects of autotoxicity and allelopathy on seed germination and seedling growth in *Medicago truncatula*. Front Plant Sci 13:908426
Weeks JJ, Hettiarachchi GM, Santos E, Tatarko J (2021) Potential human inhalation exposure to soil contaminants in urban gardens on brownfields sites: a breath of fresh air? J Environ Qual 50(3):782–790
Weidenhamer JD, Hartnett DC, Romeo JT (1989) Density-dependent phytotoxicity: distinguishing resource competition and allelopathic interference in plants. J Appl Ecol 26(2):613–624
Weston LA (1996) Utilization of allelopathy for weed management in agroecosystems. Agron J 88(6):860–866
Wink M (1993) The Plant Vacuole: A Multifunctional Compartment. J Exp Bot 44:231–246. http://www.jstor.org/stable/23694159
Wu B, Long Q, Gao Y, Wang Z, Shao T, Liu Y, Li Y, Ding W (2015) Comprehensive characterization of a time-course transcriptional response induced by autotoxins in Panax ginseng using RNA-Seq. BMC Genomics 16(1):p1010
Xin A, Li X, Jin H, Yang X, Zhao R, Liu J, Qin B (2019) The accumulation of reactive oxygen species in root tips caused by autotoxic allelochemicals–A significant factor for replant problem of *Angelica sinensis* (Oliv.) Diels. Ind Crops Prod 138:111432
Xu Y, Wu YG, Chen Y, Zhang JF, Song XQ, Zhu GP, Hu XW (2015) Autotoxicity in *Pogostemon cablin* and their allelochemicals. Revista Brasileira de Farmacognosia 25(2):117–123
Yu JQ, Shou SY, Qian YR, Zhu ZJ, Hu WH (2000) Autotoxic potential of cucurbit crops. Plant Soil 223:149–153
Zhang B, Li X, Wang F, Li M, Zhang J, Gu L, Zhang L, Tu W, Zhang Z (2016) Assaying the potential autotoxins and microbial community associated with Rehmannia glutinosa replant problems based on its 'autotoxic circle'. Plant Soil 407(1):307–322
Zhang S, Jin Y, Zhu W, Tang J, Hu S, Zhou T, Chen X (2010) Baicalin Released from *Scutellaria baicalensis* Induces Autotoxicity and Promotes Soilborn Pathogens. J Chem Ecol 36:329–338
Zhang XH, Zhang EH, Lang DY (2011) Autotoxic compounds from rhizosphere soil of *Humulus lupulus* L. extracts: identification and biological activity. Agron J 103(3):695–701
Zhang Z, Zhang Z, Han X, Wu J, Zhang L, Wang J, Wang-Pruski G (2020) Specific response mechanism to autotoxicity in melon (*Cucumis melo* L.) root revealed by physiological analyses combined with transcriptome profiling. Ecotoxicol Environ Saf 200:110779
Zhong S, Guo C, Su L, Jiang H, Wang X, Shi L, Li X, Liao X, Xue J (2024) Physiological and transcriptomic analyses provide preliminary insights into the autotoxicity of *Lilium brownii*. Front Plant Sci 15:1330061. https://doi.org/10.3389/fpls.2024.1330061
Zuber SM, Villamil MB (2016) Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. Soil Biol Biochem 97:176–187