Review

Biological control of vines: A review of past efforts, evaluation, and future directions

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HIGHLIGHTS

• Invasive vines are frequently targeted for biological control efforts worldwide.
• The growth habit of vines presents unique challenges in ecological studies.
• 31 vine species representing 20 plant families have been targeted.
• Impacts of established agents are rarely assessed adequately.
• We provide recommendations for improving success of vine biological control.

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ABSTRACT

Vines are among the most damaging groups of invasive plants worldwide, and, as such, have been targets of numerous biological control efforts. In this article, we review these efforts, agent establishment, and impacts, and provide recommendations for future efforts. Researchers have targeted 31 species of vines representing 20 plant families for biological control in some capacity, the majority of which have occurred in the mainland USA. Of the targeted vine species, 17 have at least one established biological control agent, and 34 agents of vine species are considered established worldwide. The impacts of the established agents have been assessed experimentally in the field using either chemical exclusion or agent addition approaches in only 49% of cases. While studies often measured impact via various plant responses (e.g., percent cover) or demographic vital rates (e.g., seed production, germination), we did not find any published studies documenting population decline (e.g., numbers of individuals) of an invasive vine due to biological control that met our criteria, and few studies focused on the recovery of the native plant community. Based on our literature review, we recommend that researchers working on biological control of vines: (1) determine suitable impact metrics based on the vine species’ impact, (2) assess agent impact using chemical-exclusion studies, (3) scale up impact studies to vine populations, (4) evaluate the recovery of native plant communities and ecosystems, and (5) investigate how other control methods can be integrated with biological control of vines. We hope that incorporating our recommendations into research will ultimately improve the development, evaluation, and implementation of biological control of vines.

1. Introduction

Vines are among the most damaging groups of invasive plants worldwide. In the USA, there are 141 invasive vine species representing 8.9% of the country’s invasive plant species (Swearington and Bargeron, 2016). In Australia, 179 vine species are considered invasive (Harris et al., 2007), and in Queensland alone, 12.5% of the worst invasive species are vines (Batianoff and Butler Don, 2002). Vine species such as kudzu, field bindweed, and cats claw creeper harm native plant communities, ecosystem function, and agricultural production in their introduced ranges (e.g., Forsyth and Innis, 2004, Jurado-Expósito et al., 2005), and many non-native species of vines may pose a high risk of becoming invasive in the future (Gordon et al., 2017). As such, it is no surprise that vines have been targeted for numerous biological control efforts (e.g., King et al., 2021).

As a group, vines are generally defined by their climbing habit (Paul...
and Yavitt, 2011). Most species are considered either herbaceous or woody (lianas), and typically climb using a mechanism such as twining, tendril climbing, scrambling (i.e., hook climbing), or adventitious root climbing. Vines can achieve fast growth rates and high reproductive success, in part, because they invest relatively little in structural support, allowing them to quickly smother native vegetation and/or climb into tree canopies (Paul and Yavitt, 2011, Asner and Martin, 2012). Their growth habit presents numerous challenges to their control. First, because vines often intertwine with other vegetation, it can be challenging to apply conventional tactics such as mechanical removal, herbicide application, or fire without inadvertently harming non-target plants (e.g., Pemberton and Ferriter, 1998, Hutchinson & Langeland, 2008, Forseth and Innis, 2004, King et al., 2021, Collings et al., 2023).

Second, vines may grow into tree canopies, making them difficult and expensive to access and remove (Perez-Salicrup et al., 2001). Vine biological control agents can avoid both of these issues due to their mobility and host-specificity.

Furthermore, a vine’s growth habit can present unique challenges for ecological studies as well, particularly for assessment of biological control impact. Generally speaking, such ecological studies attempt to quantify how a management tactic, including biological control, might reduce the negative impact of the vine, yet several factors can impede such assessments. Both horizontal and vertical growth can be difficult to quantify, and in some cases, may present challenges in quantifying their effects on the underlying vegetation. Vertical growth may be difficult to measure in the field as it is highly dependent on the underlying vegetation structure; horizontal growth can be measured using commonly used metrics such as percent cover, but such metrics can be misleading due to overlapping stems. For many invasive vine species, the presence of dozens or even hundreds of stems growing in varying vertical and/or horizontal directions can introduce difficulties in distinguishing individuals from one another.

In this article, we review previous efforts to develop, establish, and evaluate biological control agents of invasive vines, with a particular emphasis on assessing impact. Based on our review, we develop recommendations for researchers of biological control of vines to incorporate into their research in the hopes of improving the success of these efforts.

2. Literature review of vine biological control efforts

We assembled a dataset of all known target vine species and agents tested and/or released using the published literature. We did so based on The Biological Control of Weeds Catalogue (Winston et al., 2017), country-specific searches (e.g., Technical Advisory Group for Biological Control Agents of Weeds in the USA), as well as searches on Google Scholar. We recorded the country where the weed was targeted, the establishment status of the agents, and the plant tissue the agent attacked. Next, we investigated how agent impact has been quantified in the field by recording the provenance (native or introduced range), method (observational or experimental), and, in the case of experimental approaches, the experimental method (agent addition or chemical exclusion). We defined ‘agent addition’ as the intentional release of agents at select sites, and ‘chemical exclusion’ as the use of a chemical (e.g., pesticide) to exclude the agent from select sites or plants. We defined ‘a case’ as a field evaluation of an agent on a specific weed. This definition allowed for multiple cases per published article, as some articles evaluated more than one agent on a target weed and others evaluated more than one target weed for an agent. For the studies with field experiments (both native and invasive provenances), we recorded the response variables measured and categorized each response variable as one of the following: cover, reproduction (included flowering, fruit and seed production, and seedling recruitment), aboveground biomass, stems (including stem production and stem length), and belowground biomass.

2.1. Biological control efforts

In total, we found that researchers have targeted 31 species of vines representing 20 plant families for biological control, with 29 vine species having at least one permitted agent (Table S1). These efforts have been primarily directed towards vines invading the United States mainland (17 targeted vine species), Australia (4), Canada (4), and South Africa (4) (Fig. 1A). Nearly all of these vines are herbaceous and twining, with a few notable exemptions. Three of the vines were woody lianas – cats claw creeper (Dolichandra unguis-cati (L.) G. Lohmann), which uses tendrils and adventitious roots, banana poka (Passiflora mollissima L.H. Bailey), which uses tendrils, and the twining Pereskia aculeata Mill. – and two were herbaceous scramblers – mile-a-minute weed (Persicaria perfoliata (L.) H. Gross) and stickywilly (Galium aparine L.), which rely on hooks or thorns to climb. There have also been efforts to use biological control on parasitic plants in the Cuscutaceae family (love vines and dodders). While most target vines and their agents are limited to a single country, one notable exception is Mikania micrantha, a native of the neotropics that has been targeted in many countries in Asia and the South Pacific using the rust fungus Puccinia spegazzinii (reviewed in Barton, 2012).

Of the targeted vine species, 17 have at least one established biological control agent, and 34 agents of vine species are considered established worldwide. Some of these agents are known to target more than one weed species. These include defoliators, seed feeders, gallers, and pathogens. The vast majority of permitted agents feed on the leaves, and relatively few feed on the stems, reproductive tissues, or roots (Fig. 1B). Most permitted and established agents are members of Coleoptera and Lepidoptera (Fig. 1C).

For a number of notable vine species, researchers have thus far been unsuccessful at finding suitable candidates for biological control. For example, kudzu in the eastern USA (Pueraria montana var. lobata (Willd.) Maesen) has been a difficult weed for which to find agents with sufficient host specificity, a task complicated by the Fabaceae being a large family with several agronomically important crops (Frye and Hough-Goldstein, 2013). However, it is worth noting that the kudzu bug (Megacopta cribraria (F.)) is considered an invasive insect to the USA that utilizes not only kudzu, but also acts as a pest of soybean (Eger et al., 2010).

Researchers have similarly had difficulties in finding suitable agents for skunk vine (Paederia foetida L.) (Pemberton et al., 2005).

While the majority of agents are considered ‘classical biocontrol’ agents that have been imported from the native range, we note a few organisms are classified as bioherbicides that originated in the introduced range, and these agents were not included in our analyses. For example, the fungal pathogen Alternaria destruens E.G. Simmons (Dothideomycetes: Pleosporales) attacks at least two weedy species of dodder found in the USA (the invasive Cuscuta pentagona Engelm and the native weed Cuscuta americana L.) (Charudattan, 2005, Cook et al., 2009), and is commercially registered as Smolder (Sylvan Bioproducts, Inc.). Likewise, the pathogen Phytophthora palmivora E.J. Butler (Incertae sedis: Peronosporales) attacks milkweed vine (Morrenia odorata (Hook. & Arn.) Lindl) and is commercially available as DeVine (Charudattan, 1991).

2.2. Impact metrics on the target vine

Measuring impact of weed biological control agents has been a challenge for the field in general (Schaffner et al., 2020), and especially so for invasive vines (Table S2). The most commonly used metrics for evaluating impact on the target weed were percent cover and reproductive output (production of flowers, seeds, bulbil counts, bulbil biomass etc.), but many studies also considered some form of aboveground biomass. Less frequently, studies considered stem measurements or belowground biomass. The impacts of biological control on vertical growth and/or climbing in the field were only evaluated in two cases, both for agents of puncturevine (Tribulus terrestris L.) (Kirkland &
Some less frequently measured agent impacts, particularly those related to stem growth, could provide subtle means by which agents help control their target vine species. For instance, weevil damage to *P. perfoliata* reduced internode length and likely competitive ability (Hough-Goldstein and LaCoss, 2012). Similarly, a garden study of potted Old World climbing fern (*Lygodium microphyllum* (Cav.) R. Br.) in Florida, USA demonstrated the ability of the biological control agent *Floracarus perrepae* Knihinicki and Bocek (Acari: Eriophyidae) to reduce growth rates of rachises (i.e., individual stems) (David and Lake, 2020). Another consideration is the vine’s ability to compensate from natural enemy attack. For example, vines can compensate for herbivory by producing additional stems, or by continuing stem growth following loss of apical dominance (e.g., Hough-Goldstein and LaCoss, 2012), and invasive vines in particular may be more tolerant of herbivory than their native relatives (Ashton and Lerdau, 2008). The mite *F. perrepae* damages the growing rachis tips of *L. microphyllum*, but in some cases the rachises recover from this damage and continue growing (David and Lake, 2020). In another case, herbivory by *Hypena opulenta* Christoph (Lepidoptera: Erebidae) on swallowworts (*Vincetoxicum spp.*.) increased seed production under shaded field conditions (Livingstone et al., 2020). Further research is needed to assess how compensation may negate control efforts in such cases.

An emerging tool in the management of invasive species is aerial mapping, and this tool may be particularly useful for monitoring large infestations of vines and the effects of biological control agents on these infestations (de Sá et al., 2018; Dash et al., 2019). Such research may be accomplished through digital images taken from manned or unmanned aircraft. For example, *L. microphyllum* infestations are mapped via aerial imagery in south Florida (Rodgers et al., 2014) and *P. montana* var. *lobata* has been mapped using multispectral imaging in southeastern USA (Shen et al., 2021). Thus far, remote sensing methods have not been used to quantify impacts of biological control of vines, but future developments in imaging and data processing may allow such evaluations to be conducted.

### 2.3. Evaluating impact of biological control on the target vine

Of the 35 established agent × weed combinations, the impacts in the field of the introduced range have been assessed in some capacity in 53% of cases (Fig. 2A). Furthermore, we identified 17 cases of experimental field evaluations for a weed × agent combination, and, of these, 11 used a chemical exclusion approach only, three used an agent addition approach only, and three used both chemical exclusion and agent addition (Table S2). Fourteen cases took place in the introduced range compared to three in the native range.

![Fig. 1. Overview of biological control efforts against vines.](image)

![Fig. 2. Field impact studies for established biological control agents of invasive vines in their introduced ranges.](image)
Importantly, agents for only five target vine species have been evaluated with a chemical exclusion approach in the field in the introduced range (Table S2), with mixed findings of the level of agent impact. Two studies of a weevil on mile-a-minute weed (*Persicaria perfoliata*) showed strong agent effects on vine cover, particularly when combined with native plant seeding (Hough-Goldstein and LaCoss, 2012; Cutting and Hough-Goldstein, 2013). Similarly, two species of weevils have been effective at reducing puncturevine (*Trubalis terrestris*) in grazing lands (Kirkland and Goeden, 1978; Huffaker et al., 1983). In a recent, five-year chemical exclusion study of the beetle *Lilioceris cheni* on air potato (*Dioscorea bulbifera*), Rayamajhi et al. (2019) demonstrated reduced vine cover and reproductive output (biomass and counts of aboveground, vegetative bulbils). Yet despite these successes, evaluation of a leaf-mining fly and fungal pathogen on old man’s beard (*Clematis vitalba*) showed significant yet minor effects on vine performance (Paynter et al., 2006), while evaluation of a noctuid foliar feeder on hedge bindweed (*Calyxtena septum*) had no effect on the vine (Tipping and Campobasso, 1997).

2.4. Scaling up impact studies to vine populations

A goal of weed biological control is to reduce the weed population to manageable levels (e.g., Morin et al., 2009). Yet, in our literature review, we found no published study for any biological control agent contributing to the population decline (i.e., numbers of individuals) of an invasive vine. In some cases, population decline was inferred from changes in percent cover (e.g., Jurado-Expósito et al., 2005; Rayamajhi et al., 2019); however, due to the clonal nature of many vine species, percent cover, while a useful proxy, is not a true measure of population size. Given the challenges of conducting ecological studies with vines, it may be unfeasible to conduct a population level analysis for many species. Yet, population studies of vines can be conducted in some cases, and we highlight such methods here.

Detailed demographic, population studies of target weeds are rare in biological control systems (e.g., Davis et al., 2006; Blossey et al., 2018), but they are also rare for vines in general. The literature of native vines, particularly for lianas and rattans (Old World climbing palms) offers a few examples of such demographic studies (Escalante et al., 2004; Nabe-Nielsen, 2004; Siebert, 2004; Wong & Ticktin, 2015). Individuals of these vine species are often spaced far enough apart to distinguish genets, which can be treated as individuals. Researchers measure the diameter, height, and reproductive output of asexually-produced ramets of each genet, and can assign stage classes based on these measurements. Yearly transitions among stage classes are then combined into Leslie matrices and used to calculate population growth rates.

A similar approach to vine demography has been taken by researchers of pale (*Vincetoxicum rossicum*) (Kleopow) Barbarich) and black swallow-worts (*V. nigrum* (L.) Moench) invading eastern North America. To distinguish individuals, the authors focused on low density populations to quantify population vital rates (Milbrath et al., 2017). These demographic data were used to calculate population growth rates and simulate the effects of varying levels of biological control damage on the vine populations, and report that only very high levels of damage in some vine populations could lead to vine population decline (Milbrath et al., 2018). This demographic work may ultimately facilitate the evaluation of the population-level impacts of the recently released *H. opulenta* on swallow-worts.

In the absence of vine population estimates, data related to vine demographic vital rates are also useful towards understanding their population growth. For example, studies of invasive vines have reported germination success, survival, and reproductive output (Allred and Tingey, 1964; Grice, 1996; Vivian-Smith and Panetta, 2005; Hyatt & Araki, 2006; Rask & Andreasen, 2007). As with the previously mentioned demographic studies, a study of relatively isolated *L. microphyllum* plants was used to quantify individual plant survival following fire (David et al., 2020). However, we caution that in some circumstances the presence of isolated plants could be indicative of marginal quality habitat for the vine species, and caution should be taken when translating such results to high quality habitat where the vine species is abundant. Similar to the approach described earlier for native liana demography, Osunkoya et al., (2009) excavated whole individuals of the liana *D. unguis-cati* to measure belowground (tubers, rhizomes) and aboveground (ramets, stem diameter and length, leaves). Yet, with the exception of Osunkoya et al., (2009), none of these studies attempt to measure the vertical component or productivity of the vine in the field.

2.5. Impacts on ecological communities

A goal of invasive weed management is not only to reduce the weed population, but also to restore community and ecosystem function. Few studies in the vine biological control literature have investigated these higher level impacts. In one such study, Cutting and Hough-Goldstein (2013) demonstrated that introduced weevils led to decreased *P. perfoliata* abundance and higher establishment of native species introduced in a seed mix. Given the profound impact many invasive vines have on plant communities and ecosystem functioning, additional work is needed across weed systems to address the role of biological control agents in restoring these functions.

2.6. Integrated weed management of vines

There are a few aspects of vines that make integrated management particularly unique for vines. Vines are often early colonizers following disturbances that can shape the successional trajectory of the recovering ecological community (Horvitz and Koop, 2001; Paul and Yavitt, 2011). Furthermore, depending on the management activity, the presence of other plants (dead or living) may be altered, and thus influence the climbing of the vine in the post-treatment landscape. For example, a vine species that shifts from vertical to horizontal growth following a fire that has destroyed the supporting trees may affect whether biological control agents are able to sufficiently colonize and impact the regrowth. Finally, as discussed earlier, the intertwined growth with other plants raises concerns about non-target impacts when applying herbicide or prescribed fire, and some of the canopy-growing vines may be inaccessible to managers.

Similar to the dearth of impact and population studies, research on integrated management of vines is lacking. Many invasive vine infestations are in degraded habitats that require immediate management, often in the form of herbicde application, but such management is best coordinated with biological control efforts as well as with native plantings (e.g. Cutting and Hough-Goldstein, 2013). In a recent review of integrated management of weeds with biological control, only one vine, *P. perfoliata*, has been studied in this context (Lake and Minteer, 2018), and only one of the studies included considered integration with herbicide (Lake et al., 2014). For example, additional research is needed on how agents respond to management techniques and the altered landscape. In some of our recent work, we have shown that biological control agents of *L. microphyllum* have quickly colonized regrowth of the plant following prescribed fire (David et al., 2020) and herbicide (David et al., 2021), suggesting the management strategies are compatible with biological control.

Furthermore, effective results from biological control may take years compared to the seemingly immediate benefits of herbicide treatment. In some cases, additional research on the perceived short-term benefits of herbicide treatments versus potential long-term benefits of biological control may be useful for effective management decisions (e.g., Larson et al., 2007; Peterson et al., 2020), but such work is lacking in vine systems. Moreover, in some cases integrated management could be less effective than biological control alone. Herbicide treatment of a smothering vine that intertwines with other plants carries a higher risk of accidental spraying of non-target species than non-vegetative functional
groups. A recent study demonstrated that management of the pale swallowwort (V. rossicum) using herbicide and manual removal treatments actually reduced native plant diversity compared to unmanaged plants (Collings et al., 2023); these results could suggest that the relatively less intrusive biological control might be better suited for controlling these vine species. More research is clearly needed to best utilize biological control of vines within an integrated weed management framework. The integration of biological control agents with other techniques could improve invasive vine suppression and the response of the native plant community.

3. Recommendations for future directions

Given the harm invasive vines continue to cause in natural and agricultural systems, it is imperative to develop suitable biological control agents for long-term, sustainable management. Our review of the literature illuminated several aspects of the research approaches taken in these systems that could be improved. To advance the field and ultimately better achieve management goals, we provide the following recommendations to researchers working on biological control of vines.

3.1. Determine suitable impact metrics

Vines vary widely in their growth form and climbing abilities, and researchers should ensure that their chosen response metric for field evaluation is ecologically relevant and indicative of a negative impact of the vine. Percent cover, the most common response metric measured in field experiments, is generally most suitable for horizontally spreading vines, although caution should be taken when quantifying multiple layers of horizontal growth. Reproductive-related measurements can also be critical metrics indicative of the population spread. For many vine species, the damage they cause is linked to their ability to climb into taller shrubs or tree canopies. Productivity, which is calculated as the biomass per unit of time (e.g., year), may be particularly informative for quantifying the extent of vertical impact, though may be challenging to measure in the field. Yet, biological control agents that can limit the vertical growth of vines, even if they have minimal effects on productivity, can be important for management. In these cases, a metric that specifically captures the vertical component of growth (e.g., stem length) may be most informative. In other cases, a measure of the ability to smother neighboring plants or physically damage the underlying vegetation may be most appropriate. The installation of trellises in the field or in gardens may be especially useful for capturing vertical growth of the vines. For example, we are using 3 m trellises in an ongoing integrated weed management study to better understand the combined effects of biological control and herbicide treatment on vertical growth of L. microphyllum (Fig. 3). We are using these trellises to both quantify the height of the vine’s rachises, and the productivity (plant tissue attached to the trellis that is harvested quarterly), two metrics that capture L. microphyllum’s impacts in the field.

For target weed projects in the early phases, it is helpful to first identify a response metric that addresses a negative impact of the vine (e.g., smothering of native vegetation), and develop candidate agents that address that metric. For example, if the goal is to prevent stem growth, resources could be directed towards developing stem borers, stem gallers, or other guilds that attack the stem. Furthermore, simulated herbivory experiments may be a useful test of whether a particular guild of agents can be effective biological control agents (Frye and Hough-Goldstein, 2013).

3.2. Assess agent impact using chemical-exclusion studies

While this point is not entirely unique to vines, we emphasize that such studies focusing on vines are poorly represented in the literature. Field studies that chemically exclude the agent in the introduced range are the best way for researchers to assess agent impact. Weed biological control as a field needs more chemical exclusion studies for evaluation, and studies using this technique with vines are particularly lacking. In some cases, conducting controlled, experimental herbicide applications on a vertically growing vine presents safety and logistical challenges to researchers that need to be carefully considered.

3.3. Scale up impact studies to vine populations:

The goal of biological control is to reduce weed populations and their ecological impacts so little or no management is needed, and, generally speaking, this goal cannot be accomplished until the weed population has declined. Monitoring vine populations presents numerous, unique challenges. At a minimum, tracking percent cover through time can provide some insights into population dynamics, but, as discussed above, cover is not always ecologically relevant. In some cases, reduction of climbing ability could be sufficient to meet management goals without a corresponding decline in population. Demographic studies that focus on low density populations can track individuals through time.

Fig. 3. Images of an ongoing integrated weed management study that uses trellises to quantify the vertical growth of Old World climbing fern (Lygodium microphyllum). Trellises are used to quantify height and productivity of the vine in response to biological control and herbicide treatments. Left image shows a 3 m trellis with substantial L. microphyllum growth in Martin County, FL, USA (Photo Credit: A.S. David). Right image shows four 5x5m plots (3 herbicide treated, 1 untreated in the upper left), each with two trellises within an infestation in Broward County, FL, USA (Photo credit: Jonathan Glueckert, Univ. of Florida).
Successful control of an invasive vine should be evaluated, at least in part, by the recovery of the invaded community, and an increased emphasis on the native plant community’s response to biological control efforts is needed. Specifically, research on whether the invasive vine is climbing, smothering, or otherwise reducing growth or reproduction of the native species should be required for evaluating agent impact. In instances where the vine creates a known alteration in an ecosystem process (e.g., fire behavior), researchers should evaluate whether the ecosystem process has been restored as a result of the biological control agent. Finally, the impact of biological control agents on the vine and, in particular, the native plant community may take decades to realize, and studies that take long-term approaches are needed for proper evaluation of the agent.

3.5. Investigate how other control methods can be integrated with biological control of vines.

Integrated weed management studies that combine biological control with other control factors (e.g., herbicide, fire, mechanical treatment) are lacking (Lake and Minteer, 2018) but are often needed to have the best chance of successful control for other plant groups. However, because of the entangled growth of the vine on the surrounding vegetation, an argument could be made that management is best left to biological control alone based on this tactic being less intrusive than others. Yet, we find that there is insufficient evidence to evaluate the use of integrated weed management of vines at present; we recommend that additional research focus on how other management tactics of vines can best be integrated with biological control.

4. Conclusions

Vines represent some of the most harmful invasive plant species worldwide, and the need for the development of effective biological control as a management tool for these species is critical. Yet, the impact of existing biological control agents on individual plants and, particularly at the population and community levels are generally poorly evaluated. Some of these deficiencies may be uniquely attributed to the difficulty in quantifying vine metrics, while others may be attributed to the general lack of experimental evaluation of agents in the field of biological control of weeds. We hope incorporating our recommendations into research will ultimately improve the development, evaluation, and implementation of biological control of vines.

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Aaron S. David: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. Ellen C. Lake: Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2023.105257.

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