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The benefits and potential of pre-emptive weed biological control: Three case studies in Queensland, Australia

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HIGHLIGHTS

- Pre-emptive biological control has been used successfully for arthropod pests.
- Benefits of pre-emptive biological control can be significant in terms of funds and time saved.
- *Chromolaena odorata* in Australia is an example of a weed targeted for pre-emptive biological control.
- Other priority weeds could be targeted for pre-emptive biological control, using effective agents utilized elsewhere.

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ABSTRACT

Invasive weed species can have significant impacts on agriculture, biodiversity and livelihoods. The cost and feasibility of managing these species using conventional means can be prohibitive depending on the size of the infestations or the habitats in which they invade. Under these conditions, biological control is seen as a viable, sustainable means to manage many weeds. However, biological control can take many years and at considerable cost to achieve the desired level of control, due to the numerous steps that are involved, including native range surveys and host-specificity testing of potential agents. Pre-emptive biological control targeting particularly high-risk species prior to their arrival in a country or emerging weeds can be cost-effective, especially if the respective biological control agents have been utilized in other countries. While pre-emptive biological control of arthropods has been investigated previously, there are few examples of pre-emptive biological control of weed species. The invasive weed species, *Chromolaena odorata*, *Mikania micrantha* and *Coccinia grandis* have all been or are currently targets of pre-emptive biological control in Australia. Research on the gall fly *Cecidochares connexa* was initiated prior to its host, *C. odorata* being detected in Australia. *Cecidochares connexa* was eventually released in Australia to control *C. odorata*, after initial research on the agent found it to be suitably host specific and effective against the target weed. *Cecidochares connexa* has also been released in numerous other countries in Africa, Asia and the Pacific, where it is providing very good control. Australia funded research on the rust *Puccinia spegazzinii* as part of a project involving Fiji and Papua New Guinea while the target weed, *M. micrantha* was a target for eradication in Queensland. The rust was later approved for release in Australia to control *M. micrantha* following additional host-specificity testing. However, research funded by Australia overseas suggests that the rust may not be able to suppress *M. micrantha* populations below current levels. Consequently, while *P. spegazzinii* has been released in numerous countries now, it has not yet been field released in Australia. Biological control research in Australia on *C. grandis* is relatively new as the weed is relatively minor and not yet declared a target for biological control. Consequently, no biological control agents have yet been released in the country. Pre-emptive biological control of *C. odorata* and *M. micrantha* has been particularly cost-effective, not just for Australia, but subsequently for numerous other countries where these weeds were well-established and problematic and the respective biological control agents were later released.

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1. Introduction

Biological control of invasive alien species is usually considered (and implemented) when the target pest has become widespread (Avila et al., 2023), is causing severe economic, social, agricultural or environmental impacts, and/or has become too difficult or costly to control using conventional control methods (Olckers, 2004). Weed biological control involves sourcing potential natural enemies from the native range of the target weed, confirming their host-specificity and releasing them in the introduced range with the aim of reducing target weed populations to a level below which they are causing economic or environmental harm (Julien and White, 1997).

Biological control research on exotic weeds is often conducted by one of five countries namely Australia, Canada, New Zealand, South Africa and the USA, with CABI also conducting research through several of its research centres scattered around the globe (Day et al., 2020). Many countries have benefitted from the initial research, with over 90 countries having now deliberately introduced at least one weed biological control agent (Winston et al., 2021). However, the time from initiating a biological control project to releasing a biological control agent can be several years, during which time, weed populations could continue to increase with concurrent increases in their impacts on agriculture and/or the environment (Avila et al., 2023).

With the increase in the global movement of people and goods, the risk of new incursions also increases, and there is belief that for some pests, it is not a matter of if these pests will establish in a particular country but when (Levine and D'Antonio, 2003; Westphal et al., 2008; Paini et al., 2016; Hulme, 2021). For this reason, there is a growing view that pre-emptive biological control should be investigated for particular organisms that are high-risk for a country. Typically, pre-emptive biological control involves conducting research on potential natural enemies of a pest prior to the pest arriving in a country. The rationale of considering pre-emptive biological control and investigating biological control options early is that much time is saved due to the protracted time it takes to find suitable host specific and effective biological control agents and provide sufficient evidence to gain approvals from national regulators for its release, by which time pest populations could increase (Avila et al., 2023). Consequently, biological control agents, may be approved for release in a country, prior to the pest arriving and establishing.

Pre-emptive biological control has been explored by Australia, New Zealand, Canada, the United Kingdom and the USA on a range of high-risk arthropod pest species. These species have been targeted because they are polyphagous, have high reproductive rates, few natural enemies in the particular country, are known to cause severe economic losses to agriculture or affect native species, and/or have been intercepted at borders previously (Avila et al., 2023).

However, we believe that the concept of pre-emptive biological control can be expanded beyond just targeting species not yet in a country and can take the following forms depending on the organism and/or the country.

1. Biological control has never been initiated anywhere in the world for an organism that is high risk of entering a country, but not yet present. Consequently, all the usual steps of a typical biological control programme such as overseas exploration to find a potential biological control agent, host-specificity testing and obtaining approval to release, will need to be implemented (Julien and White, 1997).
2. A pest has been the target for biological control in one country and there is a high risk of it entering another country, possibly due to known incursion pathways. Here, the second country could undertake additional host-specificity testing and acquire approval to release the biological control agent as a safeguard, in case the pest enters the country and establishes (Avila et al., 2023). An example is research into the brown marmorated stink bug, *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) in New Zealand, using a promising parasitoid that is undergoing assessment in USA and Europe (Charles et al., 2019).
3. A variation of Point 2, is investigating the possibility of trying to control a pest in one country where it is having serious impacts on agriculture and/or the environment, with the added advantage of minimizing the risk of introduction or spread of the pest into neighbouring countries, where it has not been recorded. This is particularly relevant where there are known pathways due to trade or the movement of people or machinery, e.g. biological control of *Chromolaena odorata* (L.) R.M.King & H.Rob. (Asteraceae) in Indonesia, the Philippines and Papua New Guinea, all neighbouring countries to Australia (McFadyen, 1996; Orapa et al., 2002).
4. The established pest is a target for biological control in one country but is the target of an eradication programme in another country. Here, pre-emptive biological control could be investigated through gaining experience with the biological control agent during research conducted on behalf of the first country, in case the eradication programme is not successful, e.g. biological control of *Mikania micrantha* Kunth (Asteraceae) in Fiji and Papua New Guinea, while the weed is a target for eradication in Queensland, Australia(Day et al., 2013c, Day and Riding, 2018).
5. While not truly pre-emptive biological control in the strictest sense, a pest that is in the early stages of expansion or has a limited distribution in a country could be targeted for biological control to minimize spread and therefore limit impacts on agriculture and the environment (Olckers, 2004). Host specific and damaging biological control agents that have been utilized elsewhere, could be introduced before the pest populations become too widespread, damaging and costly to control, e.g., Solomon Islands and the Republic of the Marshall Islands, where there is a desire to reduce the spread of *C. odorata* to other islands. In addition, low priority or emerging weeds could be targeted simultaneously with higher priority, widely established weeds during exploratory surveys, as has been conducted by researchers in South Africa in an effort to be more pro-active and reduce costs of implementing biological control (Olckers, 2004).
6. A variation of Point 5 is where biological control of an established but localised weed or pest that is not necessarily a high priority for a country is implemented. However, there is the added benefit of a secondary pest being impacted upon either through reducing the risk of incursion or aiding its control indirectly, e.g. biological control of *Coccinia grandis* (L.) Voigt (Cucurbitaceae) in northern Australia may also lead to the reduced risk of the melon fly *Zeugodacus cucurbitae* (syn. *Bactrocera cucurbitae*) (Coquillett) (Diptera: Tephritidae) (Muniappan et al., 2009) spreading into Australia, as one of its hosts becomes less abundant.

Australia has previously explored the possibility of pre-emptive biological control on two insect pest species, the Russian wheat aphid, *Diuraphis noxia* Kurdjumov (Hemiptera: Aphididae) (Hughes et al., 1994) and *H. halys* (Caron et al., 2021). Biological control agents have not been released against either insect directly in Australia. However, the oligophagous parasitoid *Aphelinus varipes* (Foerster) (Hymenoptera: Aphelinidae) was collected from *D. noxia* in Ukraine in 1989–90 and introduced into Australia in an unsuccessful attempt to achieve establishment on another cereal aphid *Rhopalosiphum padi* (L.) (Hemiptera: Aphididae) in case *D. noxia* established in Australia (Hughes et al., 1994). This paper discusses three of the above situations where pre-emptive biological control has been used or is being considered in the management of invasive weeds in Queensland, Australia.

2. *Chromolaena odorata* (L.) R.M. King & H. Rob. (Asteraceae)

Chromolaena odorata is a woody plant native to tropical America. It has now invaded many countries in sub-Saharan Africa, Asia and the Pacific, including Australia. It is a major weed of grazing lands, but can also invade cropping lands, plantations and native forests, reducing productivity and biodiversity, and impacting on livelihoods (McWilliam, 2000; Orapa et al., 2002; Zachariades et al., 2009; Shackleton et al., 2017). *Chromolaena odorata* produces thousands of light-weight seeds that are mainly spread by wind, but the seeds can also be spread by machinery and animals, as well as on human possessions(McFadyen, 2003).

Control can be difficult due to the size of many infestations. In many countries, slashing is the main form of control, which is laborious. In addition, plants can re-shoot from the stumps or stem fragments. In grazing lands, fire is often used but it does not necessarily kill the plants, as the below-ground portions of the plant are often not affected (Orapa et al., 2002; Day et al., 2016b). Fire is not ideal in some native areas or in plantations where particular species are desired and may be fire-sensitive. Herbicides can be used (Utulu, 1996; Vitelli et al., 2018) but they are mainly used by commercial enterprises (Goodall and Zacharias, 2002; Orapa et al., 2002).

Due to the difficulties in controlling *C. odorata* by conventional means, a biological control programme was initiated in West Africa in the 1960s, funded by the Nigerian Institute for Oil Palm Research (Cruttwell, 1974). Surveys were conducted in Trinidad by the Commonwealth Institute of Biological Control for potential biological control agents. *Apion brunneonigrum* Béguin-Billecocq (Coleoptera: Brentidae) was introduced into Malaysia and Nigeria in 1970, India in 1972, and Ghana and Sri Lanka in 1975 but did not establish in any country. *Pareuchaetes pseudoinsulata* Rego Barros (Lepidoptera: Erebidae) was introduced into Malaysia in 1970 and into Ghana, Nigeria, India and Sri Lanka in 1973, establishing in only Malaysia and Sri Lanka (Cock and Holloway, 1982; Winston et al., 2021). *Pareuchaetes pseudoinsulata* was re-introduced into Ghana in the 1990s where it established and subsequently spread to Nigeria and other countries in West Africa (Timbilla, 1996; Uyi, 2011; Winston et al., 2021).

Chromolaena odorata continued to spread throughout Southeast Asia and into the Pacific in particular, and biological control activities recommenced in the 1980s, involving the successful release of *P. pseudoinsulata* in India and several countries in the Pacific. Due to its importance and potential impacts on the Asia-Pacific region and the high risk of *C. odorata* spreading to Australia, where it had not yet been recorded (Cruttwell McFadyen, 1989), a new project funded by the Australian Centre for International Agricultural Research (ACIAR) and managed by the Queensland Government was initiated in 1993. The project involved the introduction of *P. pseudoinsulata* into Indonesia and the Philippines and the host-specificity testing of the gall fly *Cecidochares connexa* (Macquart) (Diptera: Tephritidae), which had been found in earlier native range surveys, with the aim of introducing and releasing this biological control agent as well (Cruttwell McFadyen, 1996).

The rationale for the project was that if *C. odorata* can be controlled in Southeast Asia, then there is less likelihood that the weed will spread into northern Australia, which is climatically suitable for the weed (Cruttwell McFadyen, 1989). There was also the added advantage of scientists in Australia gaining first-hand experience with *C. odorata*, as well as its biological control agents should the weed establish in the country.

Chromolaena odorata was first reported in Australia in 1994, in north Queensland (Waterhouse, 1994), having probably been introduced through imported pasture seed from Brazil in the 1960s. A national cost-share eradication programme commenced immediately upon detection (Waterhouse, 1998). During this time, the ACIAR-funded biological control programme continued, with both *P. pseudoinsulata* and *C. connexa* establishing in Indonesia and the Philippines. The project was expanded in 1998 to include Papua New Guinea (PNG), where *C. odorata* was becoming increasingly problematic and, being Australia's nearest neighbour, it posed the greatest threat of new incursions (Orapa et al., 2002). Both *P. pseudoinsulata* and *C. connexa* were successfully introduced into PNG in 1999 and 2001 respectively, with the gall fly providing very good control in all areas where it had established (Day et al., 2013a).

A review into the national cost-share eradication programme in 2008 suggested that based on the early results in PNG and elsewhere at the time, biological control should be investigated outside the eradication programme as a contingency should the eradication efforts not be successful (Wickes and Burley, 2008). Following a second review of the eradication programme in mid-2011 and based on its effectiveness overseas (Zachariades et al., 2009), *C. connexa* was imported into the quarantine facility at the Ecosciences Precinct, Brisbane for host-specificity testing in early 2012. As *C. connexa* had been tested against over 120 other plant species in numerous other countries, only 18 species, all in the Eupatorieae (the tribe to which *C. odorata* belongs), were tested. The gall fly developed on only *C. odorata* and to a much lesser extent, the exotic weed *Praxelis clematidea* (Griseb.) R.M.King & H.Rob. (Asteraceae) (Day et al., 2016b). Approval to field release in Australia was granted in 2018, with field releases commencing in 2019 (Pukallus et al., 2022).

Cecidochares connexa was the only biological control agent considered for importation into Australia, as it was the most effective biological control agent of the two agents that had been utilized against *C. odorata* in Papua New Guinea and other Pacific island countries (Zachariades et al., 2009; Day et al., 2013b; Winston et al., 2021). The gall fly does not need large patches of *C. odorata* to become established and female flies can seek out individual *C. odorata* plants, on which mating and oviposition occur. It was thought that *C. connexa* could locate single plants that members of the eradication team may miss, particularly in dense vegetation. Conversely, *P. pseudoinsulata* was difficult to establish, required larger infestations of *C. odorata* and was only seasonally abundant and damaging (Day and Bofeng, 2007; Day et al., 2013b) and therefore, not really suited in areas where weed populations were patchy and small.

In late 2012, the eradication programme for *C. odorata* was terminated as it was thought that eradication of the weed was no longer feasible, due mainly to an inability to delimit the infestation (DAFF, 2013). Even though *C. connexa* was imported into quarantine prior to the eradication programme terminating, there was considerable time between when host-specificity testing was complete and approval to field release being granted. In fact, there was seven years between when the eradication programme finished and field releases of *C. connexa* commenced, by which time, *C. odorata* populations in north Queensland had expanded further.

The initial project on the biological control of *C. odorata* in Indonesia and the Philippines is a classic example of pre-emptive biological control to manage an invasive weed. The project started prior to *C. odorata* being reported in Australia, with the aim to control the weed in neighbouring countries, reduce the risk of *C. odorata* entering Australia and gain valuable information on prospective biological control agents, should the weed establish in Australia. By the time *C. odorata* had entered Australia and was deemed beyond eradication, there was substantial information on the host specificity and effectiveness of both biological control agents widely in use (Day et al., 2016b; Winston et al., 2021). In addition, due to the number of plant species tested elsewhere against *C. connexa*, the number of species that was required to be tested in Australia, was limited to those in the same tribe, Eupatorieae, as *C. odorata* (Day et al., 2016b). Therefore, the time, effort and funds spent testing *C. connexa* before seeking approval for its release was considerably reduced. The one downside was the release of *C. connexa* in Australia did not coincide with the cessation of the eradication programme.

3. *Mikania micrantha* Kunth (Asteraceae)

Mikania micrantha is a fast-growing vine native to tropical America. It has now invaded many countries in Asia and the Pacific region, including Australia. *Mikania micrantha* can produce vast quantities of light-weight seed that can be spread by wind, machinery, animals or on human possessions. It can also spread through broken stem fragments (Day et al., 2016a). *Mikania micrantha* has significant social (Day et al., 2012), agricultural (Shen et al., 2013) and environmental impacts (Murphy et al., 2013). Productivity can be reduced by as much as 70 % in some crops (Shen et al., 2013). Due to its fast growth (up to 8 cm/day) (Choudhury, 1972), *M. micrantha* can quickly become the dominant species by smothering crops and other vegetation, blocking light, and preventing growth, flowering and seeding of these species (Day et al., 2012, 2016a). *Mikania micrantha* can tolerate a wide range of environmental conditions (Zhang and Wen, 2009) and eco-climatic modelling suggests that it could potentially expand its range to many areas and countries where it is not currently recorded (Day et al., 2016a).

Control of *M. micrantha* in many countries in the Pacific and Asia, is mainly by hand-pulling or slashing plants (Clements et al., 2019). This method can be very time-consuming and laborious, and infestations can quickly re-establish if not all plants are removed or destroyed. Plants can regenerate from stem fragments left on the ground from slashing unless they are burnt or buried. Hand-pulling is only effective if infestations are small and confined and is not suited to large infestations, while slashing can also affect other vegetation (Clements et al., 2019).

There are numerous herbicides, e.g., 2,4-D, picloram or sulfometuron-methyl, which are effective against *M. micrantha* (Day et al., 2016a). However, many small block subsistence farmers cannot afford expensive chemicals or equipment and the appropriate personal protective clothing. Chemicals cannot generally be used where valued species are grown and can have severe impacts on human and environmental health. Herbicides are a particular concern to the highly sensitive coral atolls where fresh water is critical (Clements et al., 2019).

As a consequence, options for biological control were first investigated in the 1970s (Cock, 1982a). The thrips *Liothrips mikaniae* (Priesner) (Thysanoptera: Phlaeothripidae) was tested and deemed suitable for release in the Solomon Islands and Malaysia but failed to establish in either country. *Liothrips mikaniae* was also introduced into Papua New Guinea but it was never released (Cock, 1982b).

A new effort into the biological control of *M. micrantha* commenced in 1996. The pathogenic rust fungus *P. spegazzinii* was introduced into India after host-specificity testing by CABI in the United Kingdom and by researchers in India showed that the rust was specific to *M. micrantha* (Ellison et al., 2008; Kumar et al., 2016). Following host-specificity testing on additional plant species in China and Taiwan, *M. micrantha* was also introduced into these two countries in 2006 and 2008 respectively (Fu et al., 2006; S. S. Tzean *et al.* unpublished data). However, the rust established in only Taiwan (Ellison and Day, 2011).

Mikania micrantha was first reported on the Australian mainland in north Queensland in 1998, and was thought to have been brought in as a herbal medicine. Another infestation was discovered in 2001, thought to be introduced as a contaminant of imported palm seed (Waterhouse, 2003). In 2001, *M. micrantha* became the target of a national cost-share eradication programme (Waterhouse, 2003; Brooks et al., 2008). Due to the large infestations of *M. micrantha* in Fiji and Papua New Guinea, where it was causing significant impacts on agriculture and livelihoods, a biological control project funded by ACIAR and managed by the Queensland Government was initiated in 2006 (Pene et al., 2007).

There were two main aims of the project. The first was to import the rust *P. spegazzinii* into both Fiji and Papua New Guinea to help manage the weed and reduce its impacts (Pene et al., 2007). If populations of *M. micrantha* could be reduced in these countries, then the risk of further introductions into Australia while eradication was being attempted, would be lessened (Day and Panetta, 2010). The second aim was to provide researchers in Queensland with first-hand experience working with *P. spegazzinii* to be able to gauge its usefulness as a biological control agent for *M. micrantha* in Queensland if the eradication of *M. micrantha* was not successful. Following additional host-specificity testing of a few species relevant to the Pacific, the rust was released and established in both Fiji and PNG, with initial results showing it was having an impact on the weed in some locations (Ellison and Day, 2011; Day et al., 2013c).

In the 2013 review of the *M. micrantha* eradication programme in Queensland, it was suggested that biological control be investigated as an option to either assist with eradication efforts or be implemented if the programme could not eradicate the weed. Consequently, *P. spegazzinii* was imported into the quarantine facilities in Brisbane in 2015, where further host-specificity testing was conducted. An additional 19 species, mainly in the tribe Eupatorieae to which *M. micrantha* belongs, were tested. No other species were attacked in these trials (Day and Riding, 2018) and the rust was approved for release on the Australian mainland.

Field monitoring of *P. spegazzinii* and its impact on *M. micrantha* at several sites in PNG found the rust could reduce percent cover of *M. micrantha* from 100 % in some areas down to below 40 %, with a decrease in flowering and seed set (Day et al., 2013d). However, by the time the rust was approved for release in Australia, populations of *M. micrantha* in Queensland were already well below 40 % cover due to the eradication efforts and patches suitable for the release of the rust were limited. Consequently, *P. spegazzinii* has not been released in Queensland to date, despite approval to do so.

Research on the biological control of *M. micrantha* in Fiji, PNG and later Vanuatu, has resulted in significant reductions of weed populations in these countries (Winston et al., 2021). Thus, reducing the risk of further incursions of *M. micrantha* into Australia. In addition, the research project enabled researchers in Queensland to make objective assessments on the potential to utilize *P. spegazzinii* to control *M. micrantha* on the Australian mainland. While the rust has not yet been released in Queensland, the rust is being considered for use on Christmas Island, an Australian territory in the Indian Ocean, and where there are large infestations of *M. micrantha*. An application to release *P. spegazzinii* there was submitted, and the field release of the rust has subsequently been approved.

4. *Coccinia grandis* (L.) Voigt (Cucurbitaceae)

Coccinia grandis or ivy gourd is a fast-growing perennial vine, native to tropical north-eastern Africa, but it is also reported to occur naturally throughout the Indomalayan region (Singh, 1990; Chun, 2001). There are 25 species in the genus *Coccinia*, and with the exception of *C. grandis*, all are restricted to tropical Africa (Holstein, 2015). *Coccinia grandis* is now found in many countries in Asia, Oceania, the USA and the Caribbean, where it was introduced for its edible fruits, and medicinal properties derived from roots and leaves (Muniappan et al., 2009; CABI, 2022).

The species has since escaped cultivation in many areas and has become a commonly reported agricultural and environmental weed in southeast Asia and the Pacific region (Waterhouse, 1997; Chun, 2001; Muniappan et al., 2009). The seeds are dispersed by birds and animals eating the fruits, but the plant can also spread vegetatively through broken stems and roots. *Coccinia grandis* can smother trees, crops and understory vegetation, blocking sunlight and preventing growth. It can also grow on, and cause damage to infrastructure such as fences and utility lines in residential and agricultural areas (Chun, 2001; Muniappan et al., 2009). The fruits of *C. grandis* serve as an alternative host for several pest species, including the serious horticultural pest, melon fly, *Zeugodacus cucurbitae* (syn. *Bactrocera cucurbitae*) (Coquillett) (Diptera: Tephritidae) (Uchida et al., 1990; CABI, 2022).

The deep, tuberous root system of *C. grandis* and its growth habit makes control of this weed very difficult. Foliar spray of herbicides is effective on the smaller plants (Motooka et al., 2003), but the waxy leaf surface impedes uptake. As *C. grandis* grows over other vegetation, there is also the risk of non-target damage to preferred species (Motooka et al., 2003; Muniappan et al., 2009). Larger plants require a cut-stump method to penetrate the tuber, and complete coverage of the foliage using a foliar herbicide. Follow up herbicidal application is also necessary as the plants can regrow from their deep roots, even after treatment.

Control by mechanical means can be temporarily effective. However, slashing or bulldozing may impact on native vegetation or other preferred species, and hand-pulling out the weed is labour-intensive (Muniappan et al., 2009; CABI, 2022). The plant's ability to regenerate from broken roots and stem fragments presents a serious challenge to mechanical control. In this respect, the difficulties of controlling *C. grandis* mirrors that of *M. micrantha* where plants need to be destroyed or buried after slashing to prevent re-growth (Day et al., 2016a).

Having spread rapidly throughout Hawai'i, following its introduction in 1968, *C. grandis* was legislated as a noxious weed. Consequently, the United States Department of Agriculture Division of Plant Industry initiated a biological control programme against this weed in the 1990s (Chun 2001). Native range surveys were conducted in Kenya and East Africa in 1992. Thirty insect species were reported to feed on *C. grandis*, of which three species were imported into the Hawai'i Department of Agriculture quarantine facility for comprehensive host-specificity testing (Muniappan et al., 2009).

A stem-boring moth, *Melittia oedipus* Oberthür (Lepidoptera: Sesiidae), and two leaf-mining weevils, *Acythopeus burkhartorum* O'Brien (Coleoptera: Curculionidae) and *A. cocciniae* O'Brien, were confirmed sufficiently host specific and approved for release in Hawai'i (Muniappan et al., 2009). Supplementary host-specificity testing was conducted prior to both weevils being approved for release and introduced into Guam and Saipan (Muniappan et al., 2009). *Melittia oedipus* and *A. cocciniae* established in all three regions and continue to contribute to the control of *C. grandis*. However, *A. burkhartorum* did not establish in Guam or anywhere else it was released (Reddy et al., 2013; Winston et al., 2021).

Apart from Guam, Saipan (Northern Marianas) and Hawai'i, *C. grandis* is reportedly present in other countries in the Pacific, namely Fiji, Federated States of Micronesia (Pohnpei), French Polynesia, Marshall Islands, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu (Day and Winston, 2016). However, its importance in each of these countries varies. The variety seen in Tonga may be a horticultural variety and less prone to spread. Nevertheless, it is a plant of some concern and introduction to other islands has been discouraged.

As part of the Restoring Island Resilience programme, funded by the New Zealand Ministry of Foreign Affairs and Trade and managed by Manaaki Whenua Landcare Research, a biological control programme against *C. grandis* was initiated in Samoa, as it was ranked one of the priority weeds for that country (L. Hayes, pers. comm. 2023). The Queensland Government was asked to undertake the research, given that *C. grandis* is also present in Australia.

In Australia, the origin of *C. grandis* is not clear. *Coccinia grandis* is considered native in the Northern Territory (FloraNT, 2013). However, this is not universally accepted, with some believing the species was introduced to this region by humans prior to European settlement of Australia, along Indonesian fishing routes (Waterhouse and Mitchell, 2012). In Arnhem Land, within the Northern Territory, *C. grandis* is considered an environmental weed (North East Arnhem Region Weeds Group, no date) and in north Queensland, *C. grandis* is considered naturalised and an invasive weed. In Western Australia, the species is a declared pest (Weeds Australia, 2021; ALA, 2024).

There are several sound reasons for undertaking research into the biological control of *C. grandis*, despite the weed not yet being declared as a restricted species in Queensland, or it being nominated nationally as a candidate for weed biological control. The first is that *C. grandis* is viewed as a weed in Queensland of potentially increasing importance and undertaking research into its control before the weed becomes too widespread is cost-effective (Olckers, 2004; Weeds Australia, 2021; ALA, 2024. Csurhes, QDAF, pers. comm., 2024). The second reason for undertaking the research is that *C. grandis* is an alternative host for *Z. cucurbitae*, which is reported to be present in neighbouring countries but not yet present in Australia. Therefore, controlling *C. grandis* should reduce the risk of *Z. cucurbitae* spreading and establishing in Queensland. The final reason for undertaking the research is that there is strong rationale for controlling weeds common to several countries as part of a regional weed management strategy. Many of the weeds present in the Pacific are found in some or just a few countries and controlling these weeds in countries where it is present, reduces the risk of spread to other countries (Day and Winston, 2016). This is similar to part of the justification for initiating the biological control programme against *C. odorata*.

In this new project, the moth *M. oedipus* will be targeted first as it is the most damaging of the two biological control agents that have established (Winston et al., 2021). Host specificity of the moth will be confirmed against closely related plants found in Samoa and Australia but not previously tested in Hawai'i or Guam. Closely related plants found in neighbouring countries such as PNG, Solomon Islands and Vanuatu could also be tested as part of the regional programme. Testing additional plants at the same time is cost-effective even if the biological control agent is not released in these other countries in the short-term, as it saves re-importing the agent into a quarantine facility in the future, establishing a colony, maintaining plants, and conducting further host-specificity testing.

5. Discussion

In each of these three case studies involving Queensland, the weed species was already a target for biological control elsewhere and there were at least some host specific and effective biological control agents available. This made pre-emptive biological control particularly appealing and cost-effective, as biological control agents had already been found, tested and released elsewhere, compared with weed targets where biological control agents are not available, saving hundreds of thousands of dollars in exploration and testing (Julien et al., 2007). For *C. odorata*, the ACIAR-funded biological control project was proposed several years before the weed was recorded in Queensland (Waterhouse, 1994; Cruttwell McFadyen, 1996). There was already one biological control agent, the moth *P. pseudoinsulata* that had been released in numerous countries and was having some impact on the weed (Zachariades et al., 2009). However, the new ACIAR-funded project investigated the specificity and potential of a new biological control agent, namely the gall fly *C. connexa* in the hope of achieving greater control of *C. odorata* in these countries.

The ACIAR-funded biological control project for *M. micrantha* project, was similar to the *C. odorata* project in that both projects principally involved releasing biological control agents into Australia's neighbouring countries to control and minimize the impacts of highly invasive weeds there, and also reduce the risk of spread of the weeds into Australia (Cruttwell McFadyen, 1996). However, the *M. micrantha* project differed to the *C. odorata* project in two ways. First, *M. micrantha* was already present in Queensland and the target of a national cost-share eradication programme when the biological control project was proposed. Therefore, apart from releasing the pathogen into neighbouring countries to help control the weed, the research also determined whether the biological control agent could be used as part of the eradication programme or only to be utilized if the eradication programme was unsuccessful. The second difference was that there was only one biological control agent, *P. spegazzinii*, to be considered and this had been already tested and was being utilized elsewhere, albeit in only one country.

As a result of these two projects, both *C. odorata* and *M. micrantha* have been successfully controlled in Australia's neighbouring countries, reducing the impacts, and costs of managing these weeds, as well as increasing productivity for farmers in those countries (Day et al., 2013d, 2016a; A. Kawi, NAQIA, pers. comm. 2023). The gall fly was then tested, released and has established in numerous countries in Africa, Asia, and several other countries in the Pacific, where it is contributing to the control of *C. odorata* (Winston et al., 2021). Research into the biological control of *C. odorata* using the gall fly, *C. connexa* was particularly worthwhile for Australia. Based on extensive host-specificity testing by numerous countries since it was first released in Indonesia, and its success overseas (Day et al., 2013a, 2016b; Winston et al., 2021), the gall fly was prioritized and subsequently introduced into Queensland, with minimal additional testing, saving several years of research and thousands of dollars. *Cecidochares connexa* is now widely established and beginning to have some impact of populations of *C. odorata* in Queensland. The gall fly has also been introduced into the Northern Territory where there are isolated populations of *C. odorata* (Pukallus et al., 2022).

In addition to Fiji and PNG, *Puccinia spegazzinii*, was subsequently released into Vanuatu, through a project funded by the Australian Government and into the Cook Islands, funded by the New Zealand Government, and established in both countries. The rust was also introduced into Guam and Palau but failed to establish in either country (Winston et al., 2021). Post-release monitoring has shown that *P. spegazzinii* is having an impact on *M. micrantha* in all countries in which it has established (Winston et al., 2021). However, this level of control, while substantial in the context of the original infestations in those countries, was not sufficient for *P. spegazzinii* to be considered for release in Queensland where populations of *M. micrantha* are small and patchy due to the current eradication efforts. *Puccinia spegazzinii* can still be considered for release if the eradication programme is not successful. However, based on host-specificity testing and results overseas, *P. spegazzinii* has been recently approved for release on Christmas Island, an Australian territory in the Indian Ocean.

Investing in pre-emptive biological control projects, where the weed is not yet present or the target of eradication, has to be weighed against funding biological control projects against established weeds, which are already impacting on agriculture and/or the environment. However, in the case with both *C. odorata* and *M. micrantha*, ACIAR, who had already funded numerous successful weed biological control projects overseas (Lubulwa and McMeniman, 1998), as part of their aid programme, could see benefits in not only controlling the two weeds in Australia's neighbouring countries to reduce impacts and improve livelihoods, but also the potential benefits to Australia if the weeds became established in the country. There was the additional advantage that there were at least some effective biological control agents available and that the chance of successful control of the weeds was high.

With *C. connexa* now present and controlling *C. odorata* in Africa, Asia and the Pacific, and *P. spegazzinii* now reducing *M. micrantha* infestations in four countries in the Pacific, this more than justifies the initial investment by ACIAR and the Queensland Government to fund these projects. In comparison, in novel weed biological control projects, there is considerable investment in conducting native range surveys, looking for potential biological control agents, host-specificity testing and field release (Julien et al., 2007), sometimes with little impact on weed infestations (Winston et al., 2021).

The third project, investigating the biological control of *C. grandis* differed significantly from the *C. odorata* and *M. micrantha* projects. As part of the Restoring Island Resilience programme, funded by the New Zealand Ministry of Foreign Affairs and Trade and managed by Manaaki Whenua Landcare Research, the principal aim was to determine whether biological control agents that had been utilized in some parts of the Pacific could be utilized elsewhere in the Pacific, particularly in Samoa. The Queensland Government as a partner of other weed biological control projects managed by Manaaki Whenua Landcare Research, took on the project for two main reasons. First, *C. grandis* was already an established moderate weed along the coastal areas of Queensland and northern Australia, with a few small infestations in Western Australia (ALA, 2024). Therefore, investigating its control would be beneficial before weed populations spread significantly. Second, as observed in Guam, control of *C. grandis* provides the added benefit of reducing the possibility of establishment of the melon fly, *Z. cucurbitae* (Muniappan et al., 2009).

This project is similar to projects undertaken in South Africa, where surveys in the native range of some of South Africa's major weeds, also involved looking for potential natural enemies of some of their lower priority weeds (Olckers, 2004). Native range surveys can be quite costly and finding effective biological control agents can be difficult. So, it is logical to be able to target several weeds during the same survey, especially if the weeds are found in the same area. While *C. grandis* is not yet a major weed in Australia, and has not yet been nominated a candidate for weed biological control, being involved in a regional biological control programme, with external funding is cost-effective, and with little impact on other projects tackling higher priority weeds.

While weed biological control normally targets weeds that are widespread and causing significant impacts, several other countries have also reported targeting weeds that have limited distribution and impacts, to limit their spread. The Republic of the Marshall Islands, with funding from the New Zealand Government, facilitated by Manaaki Whenua Landcare Research and assistance from Australian researchers, have recently introduced *C. connexa* to control *C. odorata* on Bikini Island, the only island where the weed occurs in the country. The rationale behind the decision is that as more people visit and re-settle the island, the greater the risk of the weed spreading to other islands.

The Solomon Islands with funding from the Australian Government, have also taken steps to introducing the gall fly. Currently, *C. odorata* is found on only Malaita Island and so there are significant benefits in introducing *C. connexa* to try to control the weed and hopefully, reduce the risk of the weed spreading to other islands.

Pre-emptive biological control has been attempted in Australia on arthropod pests, without success. *Aphelinus varipes* was released into Australia in an unsuccessful attempt to establish the parasitoid on other cereal aphids as a pre-emptive measure in case the Russian wheat aphid becomes established (Hughes et al., 1994). However, pre-emptive biological control had not been tried before on invasive weeds. The research on *C. odorata* shows that pre-emptive measures can be useful to reduce the risk of weed species entering Australia or other countries. There are other high risk species, e.g. *Sesbania punicea* (Cav.) Benth. (Fabaceae) and *Myriophyllum spicatum* L. (Haloragaceae) that are declared as prohibited under Queensland legislation and not yet present in Australia. *Equisetum arvense* L. (Equisetaceae) is also declared as prohibited and high risk to Queensland (DAF, 2019) but a few populations exist in New South Wales and Victoria. Some of these species have host specific and damaging biological control agents that have been utilized elsewhere (Winston et al., 2021), offering other opportunities for pre-emptive biological control.

There are numerous other species which are currently the target for eradication in Queensland and pre-emptive biological control could be investigated (S. Csurhes, QDAF, pers. comm., 2024). The incentives or potential benefits of pre-emptive biological control become even greater if the weed species are present and causing high impacts on neighbouring countries, where biological control agents can also be released.

CRediT authorship contribution statement

M.D. Day: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **J.T. Callander:** Writing – review & editing, Writing – original draft, Visualization, Investigation.

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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