CENTRE FOR
INVASIVE SPECIES SOLUTIONS

THE STATUS OF BIOLOGICAL CONTROL RESEARCH FOR 27 WEEDS OF NATIONAL SIGNIFICANCE

A SUMMARY OF PAST AND CURRENT BIOLOGICAL CONTROL RESEARCH, AND DIRECTIONS FOR FUTURE WORK

WILD MATTERS PTY LTD

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Prepared by:
Kerinne Harvey, Environmental Consultant
Royce Holtkamp, Horizon Ecological Consulting
Shauna Potter, Director, Wild Matters Pty Ltd

Valuable support, comments, information and review provided by:

Nigel Ainsworth, Agriculture Victoria, Department of Jobs, Precincts and Regions

Kay Bailey, Department of Primary Industries and Regional Development, Western Australia

Jason Callander, Queensland Department of Agriculture and Fisheries

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Ben Gooden, CSIRO

John Ireson, University of Tasmania; Tasmanian Institute of Agriculture

Raelene Kwong, Agriculture Victoria, Department of Jobs, Precincts and Regions

Greg Lefoe, Agriculture Victoria, Department of Jobs, Precincts and Regions

Patricia Lu-Irving, New South Wales Royal Botanic Gardens and Domain

Andrew McConnachie, New South Wales Department of Primary Industries

Kumaran Nagalingam, CSIRO

Michelle Rafter, CSIRO

Jackie Steele, Agriculture Victoria, Department of Jobs, Precincts and Regions

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INTRODUCTION

For over a century, Australia has successfully implemented the applied discipline of weed biological control (biocontrol) as an approach to alleviate issues caused by invasive high-risk weeds. The benefits of this approach lie not only in the efficacy of controlling the weed targets, but also in the environmentally friendly and self-sustaining attributes of many programs, with these benefits very often translating into a natural, successive process of ecological restoration. Proven to be an effective approach to weed management in Australia, close to 40% of programs have been considered successful—with an overall benefit-cost ratio of 23:1 (Page and Lacey 2006; Palmer et al. 2010). As a result, biocontrol often forms a vital component of integrated weed management strategies.

Despite some outstanding successes, these programs do require significant and consistent long-term financial investment and expertise to match the timescales of the issues. Inconsistent and sporadic cycles of resources is a common limiting factor that can influence the success of biocontrol programs. Such boom-bust funding cycles are neither sustainable nor efficient, and there is a high risk that research capacity can be lowered or lost. When lost, this capability is extremely difficult to regain (McConnachie et al. 2015; Harvey and Brown 2018; Allan 2019). Indeed, Australia has experienced major declines in capability for weed biocontrol research, extension and on-ground management over the past 15 years. For example, at the peak of biocontrol research in the 1980s to early 1990s, it is estimated that 33 full-time equivalent (FTE) scientists were working on Australian biocontrol programs, both within Australia and overseas. This number reduced to around 7.5 FTEs by 2014, and jeopardised Australia's reputation as being at the forefront of biocontrol (Palmer et al. 2014). Reduced capacity also hinders Australia's ability to facilitate an efficient and time-effective discovery-to-delivery research pipeline, recognised as key to enabling future impact at scale (Allan 2019).

Recognising the decline in weed biocontrol research capability and capacity at a state/territory and federal level, several funding commitments leveraging co-investment from state governments, research and development corporations, and trusts were implemented from 2014. Examples include the Rural Research and Development for Profit program, Agricultural Competitiveness White Paper, Established Pest Animals and Weeds Management Pipeline and the NSW Environmental Trust.

With many of these commitments concluding in 2023, there is a need to establish a process or framework to garner a broader funding base to maintain the core level of investment in biocontrol. National cost-sharing models implemented by the National Biocontrol Collective of New Zealand, and state-based funding models in Queensland (levy-based) and New South Wales (e.g. NSW Weed Biocontrol Taskforce), are investment model examples that aim to alleviate shortfalls in funding to maintain a continuum of programs (Harvey and Brown 2018; Allan 2019). Such models aim to provide a coordinated and sustained effort over time – critical for biological control science where it can take decades for research to result in on-ground management application. Greater efforts, however, are still required for establishing a national research, development and engagement alliance (CISS 2022).

The draft 20-year National Weed Biocontrol Pipeline Strategy developed by the Centre for Invasive Species Solutions in partnership with state and territory representatives is aiming to guide future weed biocontrol investment to meet Australia's agreed weed management priorities (CISS 2022). Part of this process includes the establishment of a national weed biocontrol alliance to strategically prioritise long-term investment. For programs to be strategically prioritised for investment, an understanding of historical and current biocontrol programs is required. As such, this report, commissioned by the national Weeds Working Group, a subgroup of the national Environment and Invasives Committee (EIC), provides a stocktake of past and current classical weed biocontrol programs for 27 Australian Weeds of National Significance (WoNS). Five WoNS (African boxthorn, cat's claw creeper, fireweed, gamba grass and Madeira vine) were excluded from this project. The information garnered from this report provides updated information for current best practice management in weed biocontrol for WoNS, while the stocktake identifies future research opportunities to assist with prioritisation and investment.

ABOUT THIS REPORT

Information for this report was compiled by literature review of unpublished and published material, and input from key scientists experienced in researching, developing and applying weed biocontrol methods (see Acknowledgements). Outcomes for this WoNS biocontrol stocktake include:

- an update on the biocontrol research status for each species
- a summary of [biocontrol] agent-release information per species and impact
- an update on active biocontrol research including information on the research provider/s, program support, expected outcomes, barriers, opportunities and progress towards delivery
- an update of biocontrol opportunities for non-active programs
- a summary table (Appendix 1), detailing historic and active biocontrol research, barriers and opportunities for development.

Programs where biocontrol options appear to have been exhausted are identified within this report, and may or may not conclude that no further investment is required at this time. However, it is important to note that biocontrol research is a dynamic field and continues to demonstrate significant advances in theory and practice (Palmer et al. 2010). This dynamic nature has and can lead biocontrol practitioners to revisit and improve upon existing programs. Thus, the currency of information within this report may change as future practice is informed by advances in technology, change associated with risk-assessment procedures, and importantly through the long-term evaluation of programs.

STATUS OF BIOCONTROL RESEARCH ON SELECTED WONS SPECIES

ALLIGATOR WEED (*ALTERNANTHERA PHILOXEROIDES*)

In warm temperate regions of Australia, alligator weed (*Alternanthera philoxeroides* (Mart.) Griseb.; Amaranthaceae) in its aquatic form is substantially controlled by the leaf-feeding beetle (*Agasicles hygrophila* Selman & Vogt). Imported from Argentina and released in the 1970s, this agent is now widely established. Additionally, the stem-boring moth (*Macrorrhinia endonephele* (Hampson): syn. *Arcola malloi* (Pastrana)), released in the 1970s, provides some level of control (Julien et al. 2012).

Current agents, however, are largely ineffective against the semi-aquatic and terrestrial form of alligator weed. The solid stems of alligator weed, found only in the terrestrial form, inhibit the main controlling agent's (flea beetle) ability to pupate. Thus, the flea beetle cannot complete its life cycle to effectively build up a population for control of alligator weed (Julien et al. 2012).

There are several native *Alternanthera* species in Australia, which has led to prospective biocontrol agents being rejected over time. Several other prospective candidates have been identified which still require testing, particularly for their ability to control the terrestrial forms of alligator weed, and for alligator weed growing in the cooler climates of Australia (Morin et al. 2016). A hiatus on export permits in the native range of alligator weed had prevented progress on these agents. Recent changes in export permissions, associated with a decrease in the Argentinian government's aversion to risk, are changing the current status quo. Moreover, excellent collaborative links with Fundación para el Estudio de Especies Invasivas (FuEDEI) in Buenos Aires, Argentina, may assist to facilitate research and the future import of biocontrol agents (A. McConnachie personal communication 2022).

ASPARAGUS WEEDS (*ASPARAGUS* SPP.)

Only bridal creeper (*Asparagus asparagoides* (L.) Druce) has current biocontrol agents available in Australia. Other asparagus WoNS, including *Asparagus aethiopicus* L., *Asparagus africanus* Lam., *Asparagus plumosus* Baker, *Asparagus scandens* Thunb. and *Asparagus declinatus* L. (Office of Environment and Heritage 2013) have no biocontrol agents available in Australia.

No submission has been made to the EIC to endorse these species as candidates for biocontrol research. As these weeds become increasingly widespread or impactful, due consideration may be required for their potential nomination for and investment in biocontrol research. Given that only one native *Asparagus* species is present in Australia (*Asparagus racemosus* Willd.), the likelihood of finding host-specific agents is promising, but consideration is required for cultivated asparagus (*Asparagus officinalis* L.).

ATHEL PINE (*TAMARIX APHYLLA*)

No biocontrol agents have been released on athel pine (*Tamarix aphylla* (L.) H.Karst.) in Australia, and athel pine has not been endorsed as a candidate species for biocontrol research by the EIC. In North America, where athel pine is also becoming invasive, several species of defoliating beetles (*Diorhabda* spp.) have been found to be effective against various species of *Tamarix* (Winston et al. 2022). Some releases have occurred and work is ongoing, with agents selected based on their ability to not compromise the value of athel pine as a desert shade tree in Mexico (Gaffke et al. 2022).

With a relatively restricted distribution in river systems of central southern Australia, prioritised investment for biocontrol of athel pine has not occurred (Morin et al. 2013). An assessment of athel pines' current distribution – and the potential for expansion and impact – warrants further investigation for determining future investment. Extensive dieback of athel pine observed in the Finke River (central Australia) in 2007 led to initial testing and trials for the development of a bioherbicide. No significant results were observed and the trials were abandoned (K. Bailey personal communication 2022). Despite this, reinvigoration of a bioherbicide program against athel pine is under way (Kay Baily personal communication) due to recent technological advancements that have led to the development and Australian Pesticides and Veterinary Medicines Associations (APVMA) approval of the first Australian registered woody-weed bioherbicide Di-Bak Parkinsonia™. Developed by BioHerbicides Australia and The University of Queensland, this bioherbicide uses Di-Bak Injecta 400® ADAMA capsule technology to inject three endemic endophytic fungi for inducing dieback in Parkinsonia (Galea 2021). The Northern Territory Weed Management Branch is currently investigating whether a bioherbicide utilising this technology can be developed to be effective against athel pine.

BELLYACHE BUSH (*JATROPHA GOSSYPIIFOLIA*)

Research for biocontrol of bellyache bush (*Jatropha gossypiifolia* L.; Euphorbiaceae) in Australia has occurred since the 1990s, and there is comprehensive knowledge of natural enemies across its native range of tropical America. One agent, the jewel bug (*Agonosoma trilineatum* (Fabricius)), was first released in 2003 in the Northern Territory but did not establish. This is possibly due to low genetic integrity from one importation, and a range of other biological or environmental factors inhibiting its establishment (Heard et al. 2012). Consideration may be required to re-release the jewel bug with a broader genetic basis from the native range (Morin et al. 2013).

Current research is ongoing and three additional agents have been prioritised. One of these, a leaf-mining moth (*Stomphastis thraustica* (Meyrick)), has recently been approved for release; a rust pathogen (*Phakopsora jatrophicola* Cumm.) is nearing the release submission stage (December 2022); and a newly described gall midge (*Prodiplosis hirsute* (authority unknown)) from Paraguay is awaiting import for testing in Brisbane (October/November 2022). Future investment requires consideration to progress these agents on-ground (K. Dhileepan personal communication 2022).

BITOU BUSH (*CHRYSANTHEMOIDES MONILIFERA* SUBSP. *ROTUNDATA*) AND BONESEED (*CHRYSANTHEMOIDES MONILIFERA* SUBSP. *MONILIFERA*)

Research for biocontrol of bitou bush (*Chrysanthemoides monilifera* (L.) Norl. subsp. *rotundata* (DC.) Norl.) and boneseed (*Chrysanthemoides monilifera* (L.) Norl. subsp. *monilifera*; Asteraceae) in Australia has occurred since the 1980s, and there is comprehensive knowledge of its natural enemies across the native range of South Africa. For example, surveys have identified 113 arthropods and four pathogenic fungi attacking *C. monilifera* in its native range. Of these, 42 arthropods and the four pathogens were identified as potential biocontrol agents warranting further investigation. Twelve agents have now been fully or partially evaluated, and nine subsequently approved for release (Adair et al. 2012).

Since 1989, nine agents have been released in Australia against *C. monilifera*. Of these, four have established on bitou: the bitou tip moth (*Comostolopsis germana* Prout), bitou seed-fly (*Mesoclanis polana* Munro), leaf-roller moth (*Tortrix* sp.) and bitou tortoise beetle (*Cassida* sp. 3). Combined, agents are contributing to significant levels of control (French et al. 2019). Only one agent, the boneseed leaf buckle mite (*Aceria* sp.), has established on boneseed, albeit at a limited number of sites (Adair et al. 2012). There is anecdotal evidence of the establishment of *Tortrix* sp. on boneseed, but this is still to be confirmed.

No funding has been prioritised for future investment against bitou or boneseed. While other agents have been identified, their host ranges are either unknown or several provide considerable life cycle challenges that may impede culturing (Morin et al. 2016). If these challenges can be overcome, future investment may be warranted. The University of Wollongong, however, has conducted long-term, post-release monitoring and impact evaluation of agents released against bitou bush. This publication may provide considerable information for guiding and/or justifying future investment involving release programs and/or integrated management options (French et al. 2019). For example, in this study, the team found that the bitou tip moth and bitou seed-fly are distributed along the 870 km of eastern Australian coastline that represents the core area of bitou bush infestation. In combination, the moth and the fly were found to reduce the reproductive output of bitou bush (measured as decreased seed output) by between 50% and 70%. Impact also varied depending upon the habitat type (foredune or hind dune) and latitude (French et al. 2019).

Results of this work demonstrate the long-term effectiveness of agents released, which aids demonstration of the value of the program and justification of investment. Moreover, it allows a window into understanding where impacts are more pronounced and why. The critical information learned can then be used to model spread and impact to inform future investment in release programs and in integrated management options.

BLACKBERRY (*RUBUS FRUTICOSUS* AGGREGATE)

In Australia, blackberry is composed of a collective of at least 16 closely related species, subspecies, varieties and hybrids belonging to the *Rubus fruticosus* L. aggregate. Finding an agent that is host-specific is particularly challenging because several native and commercially grown blackberries are closely related to invasive blackberry (Morin 2018).

Surveys in Europe in the 1970s identified the rust fungus (*Phragmidium violaceum (Schultz, G.Winter))* as a potential biocontrol agent, but in 1984, while additional studies on isolates of the rust fungi were being conducted in Europe, the rust was discovered to be present in Australia following an unauthorised introduction. European studies resulted in the subsequent release of the official isolate F15 into Australia in the early 1990s. Unfortunately, different species, subspecies, varieties and hybrids belonging to the aggregate react differently to the rust fungus. Consequently, where infestations are made up of mixed species, a species that has been biologically controlled can be replaced by a species with a higher tolerance to the rust (Morin and Evans 2012). Eight additional isolates of the rust fungus have since been released into Australia to counter this problem and have had variable levels of impact (Morin et al. 2006b). The rust has had the greatest impact in areas of moderate temperatures (> 20 °C), with high rainfall and/or high humidity. More generally, successful biocontrol of blackberry is dependent on matching virulent rust strains to susceptible blackberry entities, and research continues.

A collaborative project between Agriculture Victoria and CSIRO in France, funded by Meat and Livestock Australia, is currently conducting a preliminary risk assessment of the cane-boring sawfly (*Phylloecus faunus* (Newman, 1838)). Delays in rearing a starter colony in France has delayed its importation to Australian quarantine for host-specificity testing. Testing was expected to commence by December 2022. Further funding is required to benefit both the introduction and host-specificity testing phases of this project (R. Kwong personal communication 2022).

Additional natural-enemy surveys on *Rubus anglocandicans* A.Newton (one of the most widespread species within the *R. fruticosus* aggregate) were conducted in June 2022 in the United Kingdom through a collaborative project between Agriculture Victoria and the Centre for Agriculture and Bioscience International (CABI), funded by the Forest Pest Management Research Consortium. With an aim to prioritise additional biocontrol candidates, a total of 56 invertebrate and three pathogen species were collected from 22 sites around central England where *R. anglocandicans* is widely distributed. Of these, the rust fungus (*Phragmidium violaceum*, with potential for new strains), a gall wasp (*Lasioptera rubi* Meig.), the bramble-feeding moth (*Thyatira batis* L.) and an unidentified eriophyid leaf buckle mite were considered as host-specific but require further investigation (R. Kwong personal communication 2022).

Conducted in parallel to natural-enemy survey research, a genetic comparison of *R. anglocandicans* populations between Australia and the United Kingdom indicated some population-level genetic differences between countries. This information is integral to understanding the invasive population's origin and will assist to better locate sufficiently effective host-specific agents, particularly for supporting the acquisition of more efficient strains of the rust fungus (R. Kwong personal communication 2022).

BRIDAL CREEPER (*ASPARAGUS ASPARAGOIDES*)

There is no active biocontrol research being conducted in Australia on bridal creeper (*Asparagus asparagoides* (L.) Druce). Surveys in southern Africa, the native range of bridal creeper, revealed several possible biocontrol candidates. Of these, three have been released in Australia: an undescribed Erythroneurini leafhopper, a rust fungus (*Puccinia myrsiphylli* (Thüm.) G.Winter), and a leaf beetle (*Crioceris* sp.) (Morin and Scott 2012). Now widely released and redistributed across southern Australia, the rust fungus and leafhopper are having an effective impact and bridal creeper is in decline (Morin et al. 2022). No funding has been prioritised for future investment.

An additional form of bridal creeper called the Western Cape bridal creeper is suspected to be a different species but grows alongside the common form. It has the potential to spread into and re-infest areas where the common form has been controlled, because it is resistant to the rust fungus (Office of Environment and Heritage 2013). It has not been prioritised as a target for biocontrol research and is under eradication or containment in some regions. The taxonomic status is unresolved (Office of Environment and Heritage 2013; Harvey et al. 2021).

BROOMS (*CYTISUS SCOPARIUS*, *GENISTA LINIFOLIA* AND *GENISTA MONSPESSULANA*)

Research for biocontrol of Scotch broom (*Cytisus scoparius* L. (Link); Fabaceae) and Cape broom (*Genista monspessulana* (L.) L.A.S.Johnson) has occurred since the 1990s in a collaborative program with CSIRO Australia, NSW and Victorian state governments, the International Institute of Biological Control (now CABI), and agencies within New Zealand and the United States of America (USA) (Hosking et al. 2012; Sheppard and Henry 2012). No agents have been tested for the biocontrol of flax-leaf broom (*Genista linifolia* L.), although this species was jointly approved with Cape broom in the late 1990s as targets for biocontrol research (Sheppard et al. 2006).

Surveys from the native range of Europe culminated in the testing and release of four agents against Scotch broom from 1993: the Scotch broom twig-mining moth (*Leucoptera spartifoliella* (Hübner)), Scotch broom psyllid (*Artainilla spartiophila* (Förster)), Scotch broom seed bruchid (*Bruchidius villosus* (Fabricius)), and Scotch broom gall mite (*Aceria genistae* Nalepa) (Hosking et al. 2012). No additional agents have been identified from the native range and are unlikely to be discovered as surveys were considered to be sufficiently thorough. However, in 2003 the broom rust (*Uromyces pisi-sativi* (Pers.) Liro) from France was discovered in Australia following an unauthorised introduction. Originally tested for its biocontrol potential in the late 1990s, it was rejected after tagasaste (tree lucerne, *Chamaecytisus palmensis* (Christ) F.A.Bisby & K.W.Nicholls), a fodder species used in Western Australia, was found to be susceptible to the rust (Morin et al. 2000). Now widespread throughout south-eastern Australia, research to determine presence and impact on all hosts was advised before making recommendations (Morin et al. 2006a). A long-term monitoring study of the broom rust is currently set up at Lake Dartmouth in north-east Victoria and has shown that the combined attack by the gall mite and rust fungus has had a measurable impact on plant health and mortality. Over the seven-year period, the mortality of broom plants within the experimental garden rose from an average of 10% to up to 65%, especially after 2016 when the galls reached peak levels of up to 2,000 galls per plant (R. Kwong personal communication 2022). Recommendations for further redistribution of this rust are not confirmed, but the rust appears to be capable of spreading by natural means.

The long-lived seed bank of Scotch broom and rapid recruitment following stand density reduction provides a considerable management challenge. Further, the Scotch broom gall mite, while widely distributed, may be climatically limited in cooler areas (Hosking et al. 2012). Its redistribution and potential integration with other control options warrants further investigation, with an aim to enhance efficacy of control (A. McConnachie personal communication 2022). Isolated establishment and a limited understanding of impact is known for the three other agents. However, a redistribution program for the seed-feeding bruchid at several Scotch broom sites is currently being monitored by Parks Victoria and Goulburn Murray Water. Further evaluation and investment are required (A. McConnachie personal communication 2022).

Surveys in 1999 of Cape broom's native range, from Turkey to Morocco to the northern Mediterranean region of Europe and north-western Spain and France, shortlisted only two biocontrol agents. These agents were the Cape broom psyllid (*Arytinnis hakani* Loginova) that attacks young shoots and an apionid weevil (*Lepidapion* nr. *argentatum* Gerstacker) that attacks seed pods. Culturing difficulties occurred with the weevil and the psyllid was found during testing to lay eggs and develop through to adults on some Lupinus species and as a result both agents were dismissed. However, in 2004, the presence of the Cape broom psyllid was found near Adelaide prior to its release (unauthorised introduction). After a risk assessment approved the redistribution of Cape broom biocontrol, it was widely redistributed from 2009 to 2014 throughout southern Australia. Now widely established, the Cape broom psyllid has recently been found to reach damaging population levels at sites in South Australia, Tasmania and parts of Victoria. Observations indicate that repeated defoliation may cause a decline in plant health (Sheppard and Henry 2012; Winston et al. 2022). Continued monitoring, evaluation and investment is required to determine the full extent of impact. Opportunities exist to further explore the potential of the seed weevil if culturing barriers can be overcome, and to locate additional host-specific agents from this species' native range. Funding is, however, required.

CABOMBA (*CABOMBA CAROLINIANA*)

An active biocontrol research program for cabomba (*Cabomba caroliniana* A.Gray) is currently led by CSIRO Australia and supported by the Rural Research and Development for Profit program in Australia. Surveys in the native range of South America from 2004 culminated in testing and approval in June 2021 for the release of a weevil (*Hydrotimetes natans* Kolbe). Two additional aquatic moths (*Paracles* sp. and *Paraponyx diminutalis* (Snellen)) were initially tested but rejected as not being host-specific (Schooler et al. 2012).

Trial releases have been made in south-eastern Queensland since March 2022 and a mass release and monitoring protocol is being developed for the weevil (K. Nagalingam personal communication 2022). Upon establishment and population growth, larvae of the cabomba weevil feed in the stems and are expected to cause the breakdown of plants and a reduction in biomass (Kumaran et al. 2020). Release and monitoring sites spanning a north–south bioclimatic gradient are set up to target integrated best-practice weed management against cabomba in collaboration with water asset managers and local stakeholders (AgriFutures Australia 2022).

Management of cabomba in water-supply dams is particularly challenging with conventional control options being unfeasible or expensive. For example, herbicides are largely restricted in use, particularly around water-supply dams, and mechanical removal of cabomba is expensive and has not proven viable in these situations. Thus, biocontrol may be the only existing control option for cabomba, particularly in water-supply dams (Kumaran et al. 2020).

Further research in north-eastern Argentina (part of a disjunct home range for cabomba) and other parts of South America is necessary to find other agents that may be viable for use in Australia. However, finding additional agents has been challenging for several biological reasons. For example, the climatic variation in the native range is narrow and cabomba grows predominately in oligotrophic conditions, whereas in Australia it occurs from tropical to colder climates and in both oligotrophic and eutrophic conditions (Schooler et al. 2012). Thus, context-specific integrated management options are being developed with water asset managers (Seqwater) as part of this biocontrol program (Kumaran et al. 2020). As funding ended in March 2023, future investment and collaboration with native-range collaborators will assist to progress culture maintenance, mass-rearing, release and evaluation of the cabomba weevil and to progress identification of additional agents (K. Nagalingam personal communication 2022).

CHILEAN NEEDLE-GRASS (*NASSELLA NEESIANA*)

Active biocontrol research for Chilean needle-grass (*Nasella neesiana* (Trin. & Rupr.) Barkworth; Poaceae) is ongoing, but progress has been on hold since 2012. Comprehensive surveys for natural enemies (particularly pathogens) were carried out in its native range of Argentina from 1994. From these, a rust fungus (*Uromyces pencanus* Arth. & Howl.) was prioritised for testing, and subsequently led to release application submissions for both Australia (2012) and New Zealand (2011) (McLaren et al. 2012).

Concerns raised during the risk assessment have delayed approvals for an Australian release. Additional testing on wheat cultivars and some Australian native *Stipa* species is required. New Zealand has fewer native stipoid grass species than Australia and received approval for release (McLaren et al. 2012). A hiatus on export permits over the years from the Argentinian government resulted in a 10-year delay to progress testing in Australia, and for New Zealand to receive a permit to import the agent. Recent changes in export permissions associated with a decrease in the Argentinian government's aversion to risk is changing the status quo. Manaaki Whenua – Landcare New Zealand has received permission to import the agent but is held up awaiting an additional import after the failure of the culture imported initially. As such, no releases have been made (Manaaki Whenua – Landcare Research 2021).

In Australia's case, excellent collaborative links with FuEDEI in Buenos Aires, Argentina, and Manaaki Whenua – Landcare New Zealand, may assist to facilitate research and the future import of biocontrol agents for testing (A. McConnachie personal communication 2022). Additionally, spores of the rust accession are stored overseas, which may prevent the need for additional field collections (Morin et al. 2016).

GORSE (*ULEX EUROPAEUS*)

Research for biocontrol agents against gorse (*Ulex europaeus* L.; Facaceae) in Australia has occurred since the 1920s, and there is comprehensive understanding of the natural enemies across its native range of Europe. Additional surveys were performed between 2005 and 2007, but no new agents were prioritised for research (Ireson and Davies 2012).

Since 1939, four agents have successfully been released and have established: the seed-feeding weevil (*Exapion ulicis* (Forster)), leaf-feeding thrips (*Sericothrips staphylinus* Haliday), soft shoot moth (*Agonopterix umbellana* Fabricius) and leaf-feeding spider mite (*Tetranychus lintearius* Dufour). The seed-feeding weevil (released 1939) and leaf-feeding spider mite (released 1998) are widespread and providing some impact, but damage levels are not high enough to reduce overall plant densities (Ireson and Davies 2012). Population densities of the leaf-feeding thrips (released 2001) have remained low and redistribution programs are encouraged. Similarly, redistribution programs for the gorse soft shoot moth (released 2007) are encouraged, with recent redistribution in 2016 and 2017 supported by the Rural Research and Development for Profit program (Allan 2019). Long-term impacts are unknown and post-release evaluation is ongoing, but funding has ceased.

Surveys in Europe have exhausted biocontrol options (Ireson and Davies 2012; Morin et al. 2016); however the gorse pod moth (*Cydia succedana* (Denis & Schiffermüller)) which has been released in New Zealand is still a possible candidate for introduction into Australia and requires further investigation (J. Ireson personal communication 2022). Endemic pathogens causing dieback have been observed in Tasmania (J. Ireson personal communication 2022) and could warrant further investigation for development into mycoherbicides. Considering current agents are slow in building populations and dispersing, their redistribution is encouraged (A. McConnachie personal communication 2022). Potential integration with other control options may also warrant investigation to improve impact efficacy.

HYMENACHNE (*HYMENACHNE AMPLEXICAULIS*)

No biocontrol agents have been released against hymenachne (*Hymenachne amplexicaulis* (Rudge) Nees) in Australia, and hymenachne has not been endorsed as a candidate species for biocontrol research by the EIC (Wearne et al. 2010). Surveys in the native range of South America (in the 2000s, focusing on pathogens) found no agents to demonstrate the level of host specify required for testing (Monteiro et al. 2003; Morin et al. 2016).

Hymenachne is closely related to native *Hymenachne* species, and its range partially overlaps with a native wetland indicator species *Hymenachne acutigluma* (Steud.) Gilliland (Bell et al. 2011; DAF 2020). As such, finding an agent that is host-specific may be particularly challenging. A persistent seed bank may also pose a challenge. For example, a seedbank longevity trial (from 1999 to 2007) demonstrated seed viability of up to 24% after eight years (Wearne et al. 2010). It was originally introduced as fodder for cattle in ponded pastures and value still may be placed on this species in parts of the grazing industry. Thus, due consideration is required to resolve any conflict over their potential nomination and investment in biocontrol research (Wearne et al. 2010). Despite challenges, biocontrol is a particularly attractive management option. Infestations are extensive and conventional controls have proven difficult, with highly resilient plants being able to rapidly reinfest following herbicide treatment (Monteiro et al. 2003). Further, excellent collaborative links with the Departamento de Fitopatologia, Universidade Federal de Viçosa, Brazil, may assist to facilitate research. No funding has been prioritised for future biocontrol research investment.

LANTANA (*LANTANA CAMARA*)

An active biocontrol research program for lantana (*Lantana camera* L.; Verbenaceae) is currently led and supported by Queensland Department of Agriculture and Fisheries (QDAF). Research for biocontrol agents for lantana has occurred since the early 1900s. Since 1914, 35 biocontrol agents have been released against lantana in Australia, of which 18 have established. Four of these are widely distributed and can cause good seasonal damage in some areas: the sap-sucking lace bug (*Teleonemia scrupulosa* Stål), leaf-mining beetles (*Octotoma scabripennis* Guérin-Méneville; *Uroplata girardi* Pic), and a stem-sucking bug (*Aconophora compressa* Walker) (Day 2012).

Comprehensive surveys across the tropical native range of lantana were originally undertaken from the southern parts of the USA to Argentina. This was originally regarded as the nominal native range of lantana. However, genetic studies have since shown that lantana is a large and highly variable group due to its long history of cultivation, hybridisation and invasiveness. In Australia, 29 different forms or taxa have naturalised. Unravelling differences through physical appearance alone is impossible, but genetic research is assisting to determine whether clear affinities between species exist or whether weedy forms of lantana in Australia result from one highly variable swarm. In the case of a hybrid form, weedy lantana thus possesses no native range so tracing its ancestry assists to narrow down countries and species for natural enemy surveys. As such, no one species in tropical America corresponds exactly to lantana as it is known in Australia.

For biocontrol to work, pinpointing the native range of invasive lantana is imperative for facilitating the exploration for the best-adapted and most effective natural enemies (Day 2012; Lu-Irving et al. 2022). Researchers did not have the advantage of the genetic research we have available today, so it is not surprising that many agents released in the past did not establish effectively. Characterising population-level genetic variation of lantana to identify source regions of its invasive forms is an active area of research currently supported by the QDAF (J. Callander and P. Lu-Irving personal communication 2022). It has been proposed that Australian lantana is more closely related to lantana in Venezuela and the Caribbean, but consensus is yet to be reached. More recent collections concentrated on the Caribbean region and as a result more success has been achieved with agent and plant matching, but patterns of agent establishment are not fully consistent with Australian lantana originating in the Caribbean. At least two established agents were sourced from Brazil, one relatively recently, in 2001. Further, some established agents prefer certain host types over others. This suggests that genetic variation within invasive lantana plays a pivotal role in biocontrol success and needs to be more fully understood. Research is ongoing (J. Callander, M. Day and P. Lu-Irving personal communication 2022).

A release application to be submitted by QDAF is currently in preparation for a rust fungus (*Puccinia lantanae* Farl.). Additionally, the lantana gall fly (*Eutreta xanthochaeta* Aldrich) from Hawaii has been reimported and host-specificity tests have commenced (M. Day personal communication 2022). Originally approved for release in the 1970s, few releases were made due to difficulties in mass rearing the agent (Day

2012). Advances in technology are assisting this re-release.

Apart from its complicated taxonomy, other compounding factors make prioritising biocontrol agents difficult for lantana. It has a vast geographical and climatic range. Lantana is highly drought tolerant, a prolific producer of seed, and can tolerate wide variations in temperature, rainfall and soil type (Day 2012). Additional investment will support the ongoing prioritisation of biocontrol agents.

MESQUITE (*PROSOPIS* SPP.)

Research for the biocontrol of mesquite (also called algaroba) (*Prosopis* L. spp.; Fabaceae) in Australia commenced in early 1990s, beginning with testing of two seed-feeding bruchids from a biocontrol program initiated in South Africa. Since then, four species of insects have been released in Australia: the two seed-feeding bruchids (*Algarobius bottimeri* Kingsolver, *Algarobius prosopis* (Le Conte)) from North America, and a leaf-feeding psyllid (*Prosopidopsylla flava* Burckhardt) and leaf-tying moth (*Evippe* sp.) from Argentina. Of these, only the seed-feeding bruchid (*A. prosopis*) and the leaf-tying moth have established. The leaf-tying moth is highly effective in supressing the seed production and growth rate of mesquite, particularly in the Pilbara region of Western Australia. Its presence in NSW, however, is rare and its impact is somewhat limited in the Northern Territory and Queensland. The seed-feeding bruchid (*A. prosopis*), while widely established, exerts only limited population-level regulation (van Klinken 2012; Winston et al. 2022).

There is no active biocontrol research being conducted in Australia against mesquite although promising agents do exist. For example, the weevil *Coelocephalapion gandolfoi* (Kissinger) has been identified as a potential candidate from an existing biocontrol program against mesquite in South Africa (van Klinken 2012; van Klinken 2014). Additional candidates could further be sourced from known or new natural-enemy surveys in the Americas (Morin et al. 2013; Morin et al. 2016). Biocontrol prospects are further enhanced because most natural enemies do not discriminate greatly between *Prosopis* species within the section *Algarobia* (referred to as mesquite). This means that potential agents could be sourced from any of the *Algarobia* species that exhibit similar impacts against taxa in Australia, including hybrids (van Klinken 2012). A hiatus on export permits in Argentina has prevented progress and further prioritisation of mesquite biocontrol (Morin et al. 2016). Recent changes in export permissions, associated with a decrease in the Argentinian government's aversion to risk, is changing the status quo. Moreover, excellent collaborative links with FuEDEI in Buenos Aires may assist to facilitate research and the future import of biocontrol agents. No funding has been prioritised for future investment.

MIMOSA (*MIMOSA PIGRA*)

Research for the biocontrol of mimosa (*Mimosa pigra* L.; Fabaceae) has occurred in Australia since 1979 and comprehensive knowledge of the natural enemies across its native range of tropical America is known (Heard 2012; Morin et al. 2013). A total of 13 insects and two fungi have been released on mimosa in Australia since the 1980s. Of these, 10 insects and one fungus are known to have established (Heard 2012; Welgama et al. 2022).

Mimosa is considered a challenging biocontrol target: natural enemies must be adapted to mimosa-invaded habitat that is inundated for up to several months a year (Morin et al. 2013). Despite this, the combined effect of biocontrol agents is demonstrating to be an effective long-term control strategy for mimosa (Welgama et al. 2022). Of established agents, two stem-mining moths (*Carmenta mimosa* Eichlin & Passoa, *Neurostrota gunniella* (Busck) (released 1989, and widely redistributed) are demonstrated to inflict severe damage on mimosa, leading to defoliation and a reduction in seed productivity, seed banks and stand regeneration (Paynter

2005, 2006; Heard 2012). Overall, seedbanks have fallen below 10% of the pre-biological-control levels, helping to reduce the rate of spread (Heard 2012). The root and leaf-feeding flea beetle (*Nesaecrepida infuscata* (Schaeffer) (released 2007) has also been effective, and can be abundant, but its impact is localised. Redistribution from release sites is likely needed to assist its spread (Winston et al. 2022). The seed-feeding weevil, (*Chalcodermus serripes* Fåhraeus), released in 1996, can cause heavy damage to flowers and seeds. It has been observed in several river systems and its numbers are still slowly increasing. It is anticipated that this insect will be become effective as its population increases (Heard 2012).

Many additional agents were prioritised from natural enemy surveys in the native range (across seven countries) up until 2009 but were tested and rejected for a variety of reasons (see Heard 2012). Although some areas remain unexplored, additional agents are unlikely to be discovered as surveys were sufficiently thorough in targeting the host range across North and South America (Heard 2012). While there is no active classical biocontrol research currently being conducted, opportunities exist to determine whether impacts of existing agents could be enhanced through redistribution and/or integrated management practice by assessing the large amounts of unpublished semi-analysed post-release data. Additionally, there is the potential to further explore whether there is any value in reintroducing agents that failed to establish or thrive (Morin et al. 2013).

Endemic pathogens causing dieback have been observed in the Northern Territory and could warrant further investigation for development into mycoherbicides. Preliminary pathogenicity trials in 2015 conducted by the University of Queensland revealed the potential for fungal species from Botryosphaeriaceae to kill and cause lesion development in juvenile and adult plants, but a single causal agent was not identified (Sacdalan 2015). Active research towards progressing bioherbicide development for mimosa was not determined within this report.

OPUNTIOID CACTI (*AUSTROCYLINDROPUNTIA, CYLINDROPUNTIA* AND *OPUNTIA* SPECIES)

An active biocontrol research program for species of opuntioid cacti (representing the subfamily of Opuntioideae within Cactaceae family) is currently led by QDAF and the NSW Department of Primary Industries (NSW DPI). Biological control of opuntioid cacti dates to the early 1900s in Australia, with management efforts focused on species of *Opuntia* Mill. (famous prickly pears) and several species of *Cylindropuntia* (Engelm.) F.M.Knuth (Holtkamp 2012; Hosking 2012). From 1911 to 1939 over 20 species of biocontrol agents were released against prickly pears, with 14 establishing. Control of prickly pears was ultimately achieved with the *Cactoblastis* moth (*Cactoblastis cactorum* (Berg.)) and cochineal insects (*Dactylopius* spp. Costa) (see Hosking 2012; Harvey et al. 2021 for species details). Coexisting well in the field, damage by both agents is complementary (Hosking 2012). Biocontrol of prickly pears is heralded as the 'blue-ribbon example' of successful biocontrol in Australia. This program demonstrated a benefit–cost ratio of 312:1, equating to productivity gains of more than $3.1 billion (net present value) following biocontrol (Page and Lacey 2006).

While some information on the natural enemies associated with species of Austrocylindropuntia Backeb. is known (Moran and Zimmermann 1991), no biocontrol research on Austrocylindropuntia has been attempted (Pasiecznik 2019a, 2019b) and no submission has been made to the EIC endorsing species of Austrocylindropuntia as candidates for biocontrol research in Australia.

Biocontrol of *Cylindropuntia* species also dates to the 1900s with rope pear (*Cylindropuntia imbricata* (Haw.) F.M.Knuth) being the first *Cylindropuntia* species targeted for biocontrol. Resulting in the release of *Dactylopius tomentosus* (Lamark) in 1925, the agent is still effective today (Holtkamp 2012). However, a new 'cylindropuntia' lineage has also been released to complement and improve current biocontrol of rope pear (Harvey et al. 2021). The various lineages of *Dactylopius tomentosus* are additionally effective against other *Cylindropuntia* and *Opuntia* species. Each lineage (population of the same insect species) can vary in its impact, thus using the correct virulent lineage for each targeted species is imperative (Harvey et al. 2021). Much research today centres on adapting various lineages of *D. tomentosus* to other species *Cylindropuntia* and *Opuntia* species to optimise biocontrol outcomes (A. McConnachie and M. Day personal communication 2022).

Current research by QDAF and NSW DPI are adapting various lineages (six lineages currently observed) of *D. tomentosus* to rope pear, and the seven other *Cylindropuntia* species: Hudson pear, (*Cylindropuntia pallida* (Rose) F.M.Knuth (syn. *Cylindropuntia rosea*; white-spined Hudson pear) and *Cylindropuntia tunicate* (Lehm.) F.M.Kunth (brown-spined Hudson pear)), boxing glove cactus (*Cylindropuntia fulgida* var. *mamillata* (A.Schott ex Engelm.) Backeb.), jumping cholla (*Cylindropuntia prolifera* (Engelm.) F.M.Knuth), Klein's cholla (*Cylindropuntia kleiniae* (DC.) F.M.Knuth*),* pencil cactus (*Cylindropuntia leptocaulis* (DC.) F.M.Knuth), and snake cactus (*Cylindropuntia prolifera* (Engelm.) F.M.Knuth) (A. McConnachie and M. Day personal communication 2022). Supported by Rural Research and Development for Profit and partially supported by the Enhancing National Pest Animal and Weed Management – Federation Funding Agreement, this program aims to establish all six lineages of *D. tomentosus* in numerous *Cylindropuntia* species infestations across Australia, especially in outlying populations to limit further spread. Mass cochineal-rearing facilities have been established to expedite releases. A large-scale monitoring program is set up for monitoring biocontrol outcomes for boxing glove cactus and Hudson pear. Additional funding is required (after Rural Research and Development for Profit funding ended in March 2023) to further assist impact evaluation across *Cylindropuntia* species (A. McConnachie personal communication 2022).

The *Opuntia* component of current research led by QDAF focuses on identifying which, if any, of the released and established cochineal biocontrol agents can be used effectively against new emerging cacti threats from previously untested *Opuntia* species (e.g *Opuntia microdasys* (Lehm.) Pfeiff; *Opuntia englemannii* Salm-Dyck ex Engelm.), and to identify whether the impact of biocontrol can be optimised through minimal effort on farms with integrated weed management (J. Callander and M. Day personal communication 2022). This project is funded by the Advancing Pest Animals and Weeds Control Solutions Competitive Grant Program until June 2023.

PARKINSONIA (*PARKINSONIA ACULEATA*)

Active classical and non-classical biocontrol research for parkinsonia (*Parkinsonia aculeata* L.) is ongoing and has occurred in Australia since the 1980s. Extensive surveys in North America culminated in the release of two biocontrol agents in the 1990s: a seed-feeding bruchid (*Mimosetes ulkei* (Horn)) (first released in 1993) and a leaf-feeding mirid (*Rhinacloa callicrates* Herring) (first released in 1989). Further surveys in Argentina and Chile resulted in the release of another seed-feeding bruchid (*Penthobruchus germaini* (Pic)) (first released in 1995). Only *P. germaini* became widely established but is not causing population-level impacts on parkinsonia (van Klinken and Heard 2012).

Natural enemy surveys of parkinsonia in previously unexplored and underexplored parts of its native range across Central and South America were recommenced by CSIRO Australia from 1999 (van Klinken and Heard 2012). This work resulted in the release of two closely related leaf-feeding moths, *Eueupithecia cisplatensis* Prout and *Eueupithecia vollonoides* Hausmann (nicknamed 'UU1' and 'UU2'), that have undergone a mass-rearing and release program since 2013. This program is led by CSIRO and QDAF and supported by the Rural Research and Development for Profit program. Finding effective biocontrol agents across parkinsonia's wide range of environmental and land-management systems in Australia is challenging. As such, this program used an advanced understanding of the agent's physiology in relation to variations in temperature to identify optimal locations for release for establishing populations across northern Australia (Allan 2019). Since the commencement of mass rearing in 2013, releases of UU1 and UU2 totalling over 900,000 individuals at 162 sites and 220,000 individuals at 34 sites, have been made. The coverage of these releases has been extensive, and populations of these two species are being detected at more than 60% of release sites at least one year after their initial release. Evaluation is ongoing and the full impacts may take up to a decade to become apparent (Raghu et al. 2017).

Later surveys have prioritised additional agents for parkinsonia. For example, the stem-galling fly from Argentina (*Neolasioptera aculeatae* Gagné) and the stem-boring moth from Mexico (*Ofatulena luminosa* (Heinrich)) are predicted to have the capacity to reduce the growth and reproduction of parkinsonia. Culturing issues have limited their progress (Heard and van Klinken 2014). However, host-specificity testing led by CSIRO for the stem-galling fly was expected to begin again in late 2022, with a testing completion date in 2024.

Naturally occurring fungal pathogens have been identified as causing dieback within many infestations of parkinsonia across northern Australia. A detailed examination of the dieback resulted in the identification of 41 fungal species from 13 families (Diplock 2015). This research has led to initial testing, trials and registration of the first APVMA approved Australian registered woody weed bioherbicide Di-Bak Parkinsonia®, developed by BioHerbicides Australia and the University of Queensland (registered 2018 for widespread application in Australia). This bioherbicide uses Di-Bak Injecta 400® ADAMA capsule technology to inject three endemic endophytic fungi for inducing dieback in parkinsonia (Galea 2021). Treatment of parkinsonia with stem-implanted bioherbicide capsules results in successful infection, colonisation and movement of dieback through a population. Infection leads to deterioration of tree health, often leading to mortality (Galea 2021). Monitoring efficacy of the bioherbicide continues.

PARTHENIUM (*PARTHENIUM HYSTEROPHORUS*)

Research for the biocontrol of parthenium (*Parthenium hysterophorus* L.) in Australia has occurred since the late 1970s and comprehensive knowledge of the natural enemies across is native range of tropical America is known (Dhileepan and McFadyen 2012). Eleven agents, including nine insect species and two fungal pathogens, have been released in core parthenium-infested areas of central and northern Queensland, with all establishing. They are: a seed-feeding weevil (*Smicronyx lutulentus* Dietz), stem-boring weevil (*Listronotus setosipennis* Hustache), root-boring moth (*Carmenta* nr. *ithacae* Beutenmüller), leaf-feeding beetle (*Zygogramma bicolorata* Pallister), sap-feeding plant-hopper (*Stobaera concinna* (Stål)), leaf-mining moth (*Bucculatrix parthenica* Bradley), two stem-boring moths (*Epiblema strenuana* Walker and *Platphalonidia mystica* Razowski and Becker), stem-boring weevil (*Conotrachelus albocinereus* Fiedler) and two rust pathogens, the winter rust (*Puccinia abrupta* var. *partheniicola* (H.S.Jacks.) Parmelee)), and summer rust (*Puccinia xanthii* var. *parthenii-hysterophorae* Seier, Evans & Romero). Most of these agents are proving effective against parthenium in central Queensland (Dhileepan and McFadyen 2012). However, effectiveness varies seasonally and is strongly influenced by the amount and timing of summer rainfall (Dhileepan and McFadyen 2012). As such, the distribution of parthenium is still expanding into southern Queensland and northern NSW where many of the agents have not yet established (Callander and Dhileepan 2016).

To hasten the natural spread of agents into new locations, QDAF, supported by the Rural Research and Development for Profit program, embarked on a redistribution program from 2015 for five of the widespread released and agents that were identified as suitable for redistribution into southern Queensland: the seed-feeding weevil, stem-boring weevil and root-boring moth, and the two rusts (Callander and Dhileepan 2016; Allan 2019). Additional funding is required to optimise biocontrol outcomes for this redistribution program (K. Dhileepan personal communication 2022).

No funding has been prioritised for future investment. However, as biocontrol efforts have primarily focused on grazing areas in Australia, additional agents may be required to improve control over a wider range of habitats and seasons as the weed spreads (Dhileepan et al. 2018). No further agents from the native range have been identified but there is potential for future introductions, as not all potential agents have been fully investigated (Dhileepan and McFadyen 2012).

The redistribution program continues to monitor establishment and spread of agents. However, as agent efficacy is strongly influenced by a range of abiotic factors, with the major barrier being the timing of summer rainfall and total rainfall, potential integration with other control options may also warrant investigation to improve efficacy.

POND APPLE (*ANNONA GLABRA*)

No biocontrol agents have been released on pond apple (*Annona glabra* L.; Annonaceae) in Australia and pond apple has not been endorsed as a candidate species for biocontrol research by the EIC.

Introduced to Australia as grafting stock for commercially grown custard apple, pond apple is now present across approximately 2,000 ha of northern Queensland's Wet Tropics Bioregion with the potential to spread throughout coastal areas of tropical and subtropical Australia. Pond apple impacts a wide range of habitats as it grows in fresh, brackish and saltwater environments, particularly mangrove communities, pandanus and melaleuca wetlands, but also in rainforest areas, riparian areas, creeks, riverbanks, floodplains, sedge lands, agricultural drainage systems, beaches, coastal dunes and islands (Doak 2006; DEEDI 2011).

Conventional control options for pond apple have proven to be particularly difficult due to isolated and inaccessible sites, often in crocodile-infested habitats (Doak 2006). This makes biological control a particularly attractive management option. However, pond apple is a challenging biocontrol target. It is closely related to species of commercially grown *Annona* species such as custard apple (*Annona chermola* Mill.), bullock's heart (*Annona reticulata* L.) and sweet apple (*Annona squamosa* L.), and there are native representatives within Annonaceae with an overlapping range to pond apple (CRC for Australian Weed Management 2003; Pasiencznik 2008). The native range of pond apple is broad, and includes tropical wetlands in North, Central and South America and coastal West Africa (Pasiecznik 2008). Therefore, the invasive origin of pond apple is not confirmed sufficiently to progress biocontrol research.

With advances in technology today, there is potentially an opportunity to progress initial native-range surveys based on a strong genetic understanding of the invasive origin of the species to locate sufficiently effective and host-specific agents. No funding is prioritised for biocontrol investment on pond apple and consideration of any possible conflicts of interest may be required prior to potential nomination and investment in biocontrol research.

PRICKLY ACACIA (*VACHELLIA NILOTICA* SUBSP. *INDICA*)

An active classical biocontrol research program for prickly acacia (*Vachellia nilotica* subsp. *indica* (Benth.) Kyal. & Boatwr.; syn. *Acacia nilotica* subsp. *indica* (Benth.) Kyal. & Boatwr.) is currently led by QDAF and supported by the Rural Research and Development for Profit program (K. Dhileepan personal communication 2022).

Comprehensive surveys for natural enemies (particularly pathogens) were carried out in the native range including Pakistan, Kenya, India and South Africa from the 1980s, culminating in the testing and release of six biocontrol agents in Australia (Palmer et al. 2012). Of these, two have established and include the seed-feeding beetle (*Bruchidius sahlbergi* Schilsky) from Pakistan (first released 1982) and the leaf-feeding moth (*Chiasmia assimilis* (Warren)) from Kenya and South Africa (first released 1999). Neither agent has had a significant impact on prickly acacia and they have failed to reach high densities across the climatic range of prickly acacia in Australia (Dhileepan et al. 2014).

Prickly acacia is considered to be a challenging biocontrol target because there are many native acacias, including eight species in the genus *Vachellia.* Thus, finding a suitably specific agent is difficult. In contrast to this problem, some agents undergoing prioritisation have been identified to be too specific and are effective on only other subspecies (Morin et al. 2013). Despite these challenges, surveys led by QDAF and supported by the Rural Research and Development for Profit program were redirected to parts of the unexplored native range, including Ethiopia and Senegal, based on herbarium records, plant genotype and bioclimatic modelling (Dhileepan et al. 2019; Shi and Dhileepan 2021). These surveys resulted in the prioritisation, testing and recent approval for release (June 2022) of one of the prioritised agents, the gall-inducing thrips (*Acaciothrips ebneri* (Karny)) from Ethiopia (K. Dhileepan personal communication 2022).

Bioclimatic modelling predicts that the inland region of northern Australia where prickly acacia is a serious problem is well suited for the gall thrips (Shi and Dhileepan 2021). While this research has been supported by the Rural Research and Development for Profit program, the program ended in March 2023 and additional funding is required to progress studies on *A. ebneri* and its delivery past the initial release phase (K. Dhileepan personal communication 2022).

Two additional agents prioritised from these surveys are undergoing host-specificity testing. These include a stem-inducing gall fly (*Notomma mutilum* (Bezzi)) from Senegal and an eriophyid gall mite (*Aceria* sp. type-3) from Ethiopia. The stem-inducing gall fly is undergoing testing in quarantine in Brisbane. Preliminary host-specificity testing has not yielded positive results, but testing continues. The gall mite will undergo host-specificity testing in South Africa on behalf of Australia, but work has been delayed due to civil unrest in Ethiopia. Work was to recommence when it was anticipated that it would be safe to conduct field visits in Ethiopia in late 2022 (K. Dhileepan personal communication 2022).

While the native range of prickly acacia has been comprehensively surveyed and may not yield additional agents, naturally occurring fungal pathogens have been identified as causing dieback of prickly acacia in north-western Queensland. Specifically, a Botryosphaeriaceae fungus (*Cophinforma* sp.) was isolated from stems tissues, but preliminary investigation showed no potential for mycoherbicide development (Haque et al. 2019). With the aim of developing a registered bioherbicide, work led by the University of Queensland and BioHerbicides Australia is persisting in researching fungal isolates that may induce dieback in Australia (BioHerbicides Australia 2022).

RUBBER VINE (*CRYPTOSTEGIA GRANDIFLORA*)

Research for the biocontrol of rubber vine (*Cryptostegia grandiflora* (Roxb.) R.Br.) in Australia has occurred since the 1980s and comprehensive knowledge of the natural enemies across is native range of Madagascar is known (Palmer and Vogler 2012). Two agents have been released in Australia, the leaf-feeding moth (*Euclasta whalleyi*) Popescu-Gorj & Constantinescu (first released 1988) and the rubber vine rust (*Maravalia cryptostegiae* (Vestergr.) Y.Ono) (first ascensions released in 1993, with additional strains released in 1995). Both have established widely (Winston et al. 2022).

The overlapping range of rubber vine with closely related native species including *Gymnanthera oblonga* (Burm.f.) P.S.Green has posed a challenge in identifying suitably specific biocontrol agents. Despite this, the leaf-feeding moth was released on the premise that rubber vine posed a far greater risk to the extinction of closely related species occupying similar habitats than any damage that the insect may inflict on closely related native species (Palmer and Vogler 2012). Taking several years to be detected post-release, the leaf-feeding moth on occasion can be abundant, causing significant damage to rubber vine. Some impact to native species has occurred when growing close to rubber vine; however, damage is considered minimal (Palmer and Vogler 2012; Winston et al. 2022). In contrast, the rubber vine rust established rapidly, and can cause significant damage in both wet and dry areas. Rust activity is highest in wet regions, with significant levels of control being achieved, as observed through reductions in the soil seedbank and seedling recruitment (Pollard and Thomas 2015; Winston et al. 2022). In contrast, rust activity is often reduced over the dry season. As such, rubber vine continues to spread, particularly westward into drier sites and suboptimal conditions for the rust (Winston et al. 2022). Current research driven by the CABI is looking for different isolates better suited to varying environmental conditions (K. Dhileepan personal communication 2022).

Apart from CABI searching for additional isolates of the rust, there is no active biocontrol research being conducted in Australia against rubber vine. Biocontrol programs for rubber vine are practical, due to the size and remoteness of infestations, which make mechanical and chemical control difficult. However, agents must be able to survive during the dry season and during drought years. More research is required to better understand the impacts of agents released (particularly in central and northern Queensland), to determine whether impacts can be increased through redistribution and or whether there is a need to identify new biocontrol agents from the native range (Morin et al. 2013). Despite this, the program has been highly successfully and has demonstrated a benefit-to-cost ratio of 108:1, equating to productivity gains following biocontrol of more than $232.5 million at net present value (Page and Lacey 2006).

SAGITTARIA (*SAGITTARIA PLATYPHYLLA* AND *SAGITTARIA CALYCINA*)

There is an active biocontrol research program for sagittaria (*Sagittaria platyphylla* (Engelm.) J.G.Sm.) and the closely related arrowhead (*Sagittaria calycina* Engelm.; Alismataceae) in Australia. This is currently led by Agriculture Victoria and partially supported by the NSW Government, NSW Environmental Trust, Murrumbidgee Irrigation, and Enhancing National Pest Animal and Weed Management – Federation Funding Agreement, with prior support from the Rural Research and Development for Profit program. After an in-depth biogeographical study on the genetic, demographic and rates of herbivory between populations in the native range of the USA and Australia, both sagittaria species were declared as targets for biocontrol research in 2015 by the EIC (Kwong 2020).

Surveys in the native range from 2010 to 2012 confirmed 19 insect species to be associated with sagittaria. While fungal pathogens were also identified, with leaf-spot symptoms present at 53% of study sites, none of the isolates were prioritised further as most were either generalist pathogens or secondary invaders. Four of the insects (all weevils) that attack various parts of the plants were prioritised for host-specificity testing: the fruit-feeding weevil (*Listronotus appendiculatus* LeConte), crown-boring weevil (*Listronotus sordidus* (Gyllenhal)), tuber-feeding weevil (*Listronotus frontalis* LeConte) and the foliar-feeder (adult) and petiole-miner (larva) (*Listronotus lutulentus* (Boheman)) (Kwong 2020). Three of these weevil species have undergone host-specificity testing within the AgriBio quarantine facility in Melbourne, and the crown-boring weevil and tuber-feeding weevil were recently rejected as not being host-specific, despite native-range studies indicating they had a narrow host range (R. Kwong personal communication 2022).

The fruit-feeding weevil was approved for release in Australia in December 2020. Since late 2021 there has been a collaborative mass-rearing and redistribution program for south-eastern Australia between Agriculture Victoria and NSW Department of Primary Industries, with mass-rearing facilities based at Tatura (Victoria) and the Grafton Primary Industries Institute (NSW). Suggested to be a strong biocontrol agent, the fruit-feeding weevil occurs across various climatic regions in its native range and can obtain high densities that will assist in limiting the spread of sagittaria by reducing the seedbank to mitigate future re-establishment (Kwong et al. 2018). However, on its own, the fruit-feeding weevil is unlikely to provide population-level impacts. Releases of the fruit-feeding weevil were planned for autumn 2023.

Further research is required to investigate additional agents, including fungal pathogens, that attack other life stages of sagittaria (Kwong et al. 2018). As the program is partially funded, future investment and collaboration with native-range collaborators will assist to progress culture maintenance, mass rearing, release and evaluation of the fruit-feeding weevil, and to progress investigation and testing of additional agents (R. Kwong personal communication 2022). Opportunities also exist to investigate how biocontrol can be integrated with other control techniques (e.g. herbicides) to better enable effective sagittaria management (Clements et al. 2018).

SALVINIA (*SALVINIA MOLESTA*)

In tropical, subtropical and warmer temperate regions of Australia, salvinia (*Salvinia molesta* D.S.Mitch; Salviniaceae) is substantially controlled by the salvinia weevil (*Cyrtobagous salviniae* Calder & Sands), with control being achieved faster in warmer climates. Imported from Brazil and released in 1980, this agent is now widely established. An additional agent, a moth (*Samea multiplicalis* (Guenée)), also from Brazil, was released in 1981. While the moth established and spread rapidly, its impact on salvinia is minimal as salvinia quickly outgrows leaf damage caused by the larvae (Julien 2012a; Winston et al. 2022).

Site-specific characteristics including temperature, shade, nutrient concentration, and waterbody size and type influence the level of weevil establishment and control. For example, the agent is less effective following flooding events (Julien 2012a; Winston et al. 2022). To overcome site-specific barriers, active release and redistribution programs are ongoing (Winston et al. 2022). The most recent release of weevils was in spring 2022.

Current work aims to identify whether the impact of biocontrol on salvinia can be optimised. This work is led by NSW DPI in partnership with the University of Wollongong and supported by the Enhancing National Pest Animal and Weed Management – Federation Funding Agreement and NSW Government. Through refining mass-rearing and release techniques, and through long-term post-release monitoring and impact evaluation, research aims to better understand where impacts are more pronounced and why. Results from this work can then be used to better model spread and impact, for informing future investment (A. McConnachie personal communication 2022).

SERRATED TUSSOCK (*NASSELLA TRICHOTOMA*)

An active classical and non-classical biocontrol research program for serrated tussock (*Nassella trichotoma* (Nees) Hack. ex Arechav) is currently led by Manaaki Whenua – Landcare Research New Zealand and Agriculture Victoria and partially supported by the Victorian Government. Comprehensive surveys for natural enemies, particularly pathogens, were carried out in the native range between 1994 and 2009 concurrent with the Chilean needle-grass biocontrol program (McLaren et al. 2012). Three potential candidates were identified: the rust fungus (*Puccinia nassellae* Arth. & Holw.), the smut fungi (*Tranzscheliella* spp.) and an unidentified fungus in the Basidimycota. The pathogens were either not sufficiently pathogenic to Australian accessions of the weed, or their biology and life cycle could not be fully determined, precluding further work (McLaren et al. 2012; Morin et al. 2016).

As serrated tussock is closely related to native stipoid grasses (*Austrostipa* spp.), the prospects of finding additional candidate pathogen agents that are host-specific are limited (Morin et al. 2013). However, endemic pathogens that cause serrated tussock dieback have been observed in Australia and in New Zealand, where serrated tussock is also invasive. This has recently led to an international effort to reinvigorate a biocontrol program against serrated tussock with collaborators from Australia, New Zealand (Manaaki Whenua – Landcare Research and Lincoln University) and Argentina.

Current research led by Landcare Research New Zealand and Agriculture Victoria aims to survey for potential endemic plant pathogens that could be developed into mycoherbicides from these initial observations. Over 65 fungal isolates have been in Australia to date. If suitable isolates are identified, research will progress towards developing seedling bioassays that will assist in determining the pathogenicity of the fungi for progressing mycoherbicide developments. Funding for this work concluded in October 2022, and additional funding is required to progress the research if suitable isolates are discovered (R. Kwong personal communication 2022). Additionally, Manaaki Whenua – Landcare Research is revisiting promising agents as part of a classical biocontrol program (Manaaki Whenua – Landcare Research 2020), that could show promise for Australia.

To complement this research, Agriculture Victoria is comparing the levels of genetic diversity between invasive Australian and New Zealand populations of serrated tussock to native populations from Argentina. This genetic component aims to assist in ensuring biocontrol agents are effective against different weed genotypes (R. Kwong personal communication 2022).

SILVERLEAF NIGHTSHADE (*SOLANUM ELAEAGNIFOLIUM*)

Active biocontrol research for silverleaf nightshade (*Solanum elaeagnifolium* Cav.; Solanaceae) is ongoing, with current research led by Agriculture Victoria. Early research from the 1970s identified several candidate biocontrol agents that led to releases in South Africa and the USA (Heap and Wu 2018; Winston et al. 2022). Evidence from South Africa indicated that successful control can be achieved with defoliating agents (Kwong 2006; Winston et al. 2022). No biocontrol agents, however, have been released in Australia.

Biocontrol of silverleaf nightshade in Australia is particularly challenging due to its close phylogenetic relationships with many native *Solanum* species, and with crop varieties, including potatoes and eggplants (Morin et al. 2016; Heap 2018). However, two agents were prioritised for testing from the successes achieved overseas. These are the leaf-galling nematode (*Ditylenchus phyllobius* (Thorne)) released in the late 1980s in the USA and the silver nightshade leaf beetle (*Leptinotarsa texana*) released in South Africa in 2016. Both agents failed host-specificity testing for their potential release in Australia (Kwong and Sagliocco 2012; Heap 2018).

Effective and host-specific biocontrol agents are still sought for Australian conditions. Renewed survey efforts in the native range of serrated tussock are being conducted. These surveys are based on recommendations made to better evaluate biocontrol prospects by understanding the genetic variation and origin of Australia populations, and to conduct research in more climates comparable to Australia's (Kwong 2006; AgriFutures Australia 2020).

Based on an international genetic study (Gopurenko et al. 2014; Heap 2018), current research led by Agriculture Victoria and supported by the Rural Research and Development for Profit program is focused on conducting natural-enemy surveys and host-specificity testing on the selection of new agents from Argentina and Texas (USA) (Heap 2018; Heap and Wu 2018). The two potential agents that have been identified are a leaf-feeding lace bug (*Gargaphia arizonica* Drake & Carvalho) and a mite (*Aceria* nov. sp.), with both undergoing host-range studies overseas.

As funding ended in March 2023, future investment and collaboration with native-range collaborators is required to continue surveys to investigate new agents, and to progress further research if preliminary testing proves suitable to progress these agents towards delivery (R. Kwong personal communication 2022).

WATER HYACINTH (*PONTEDERIA CRASSIPES*)

Research for the biocontrol of water hyacinth (*Pontederia crassipes* Mart.; Pontederiaceae; syn. *Eichhornia crassipes* (Mart.) Solms) has occurred since the 1970s. This research has culminated in the release of four biocontrol agents from tropical South America: two stem- and leaf-feeding weevils (*Neochetina eichhorniae* Warner, *Neochetina bruchi* Hustache) and two stem-boring moths (*Niphograpta albiguttalis* (Warren) and *Xubida infusella* (Walker)). The two weevils cause considerable damage to water hyacinth, and control can be achieved over a few years in tropical and subtropical regions. They are, however, less effective in more temperate areas of Australia. Both species of moth have a limited impact on water hyacinth when used in isolation, but one of these (*N. albiguttalis*) coexists well with the weevils and in combination with them can assist in the management of water hyacinth. The other moth (*X. infusella*) is only known to have established at one site (Julien 2012b; Harvey et al. 2021).

While successful control of water hyacinth has been achieved at many locations, site-specific characteristics including flooding events, temperature, shade, nutrient concentration, waterbody size and type influences the level of weevil establishment and control. To overcome site-specific barriers, active release and redistribution programs may be required (Harvey et al. 2021), but there is a need to develop integrated management strategies to improve efficacy, and to import additional agents (Julien 2012b).

Current work aims to identify whether the impact of biocontrol can be optimised and fast-tracked by increasing the number, coverage and impact of agents released. This work is led by NSW DPI in partnership with the University of Wollongong and supported by the Enhancing National Pest Animal and Weed Management – Federation Funding Agreement and NSW Government. Through refining mass-rearing and release techniques and through long-term, post-release monitoring and impact evaluation, research aims to better understand where impacts are more pronounced and why. Results from this work can then be used to better model spread and impact for informing future investment (A. McConnachie personal communication 2022).

There is still the need for additional agents in Australia, particularly agents more suited to more temperate environments. Several agents have been prioritised, with releases made in both the USA and South Africa. Specifically, a sap-sucking bug (*Megamelus scutellaris* Berg) demonstrates promise for cooler regions (Winston et al. 2022). First released in 2010 in Florida, USA, and soon after in Mississippi, Louisiana and California, the sap-sucking bug has established, dispersed from the release sites and survived cold winters. The full extent of the impact is still to be determined (Goode et al. 2021). In South Africa, the sap-sucking bug released in 2013 is already proving to be successful in cooler climates, with the capability of reaching higher densities than the other established agents (Miller 2019; Coetzee et al. 2022).

Following the success in the USA, CSIRO undertook host-specificity testing of the sap-sucking bug in Australia, but a related native aquatic plant, *Monochoria cyanea*, was found to be within the fundamental host range, and the program was terminated (Julien 2012c). The success of *M. scutellaris* now demonstrated in South Africa and new host-specificity-testing approaches are providing encouragement to revisit this program. Funding is required to progress testing of *M. scutellaris* and for the prioritisation of additional candidates from the native range (A. McConnachie personal communication 2022).

WILLOWS (*SALIX* SPP.)

There is no active biocontrol research being conducted in Australia on willows (*Salix* spp. 32 naturalised taxa including primary hybrids; WoNs exclusions: *Salix* × *babylonica* L., *Salix* × *calodendron* Wimm. and *Salix reichardtii* A.Kern) (ARMC 2001; Holland Clift and Davies 2007). No submission has been made to the EIC endorsing willows as candidates for biocontrol research in Australia either. However, in 2004 the willow sawfly (*Nematus oligospilus* Förster) was discovered in Canberra following an unauthorised introduction. By 2006, the sawfly was identified as being present throughout south-eastern Australia and south-western Western Australia (Caron et al. 2014). Repeated severe defoliation events can lead to tree deaths, but despite high population levels no tree deaths from the sawfly have been observed in Australia (Ede et al. 2011). Preliminary host-specificity testing of the sawfly against 35 native plants demonstrated a narrow host range, but further research is required to understand the agents in the field of the host ranges and to understand potential as a biocontrol agent (Caron et al. 2011).

There may be considerable potential for biocontrol to be used to manage willows. No members of the willow family (Salicaceae) are native to Australia (ARMC 2001) and comprehensive surveys in the native range have revealed potential candidates for biocontrol (Sagliocco and Bruzzese 2002; Adair et al. 2006). Further, a review evaluating the potential for biological control of six *Salix* taxa was commissioned by the Victorian Catchment Management Authority and carried out by the Keith Turnbull Research Institute in 2001. This report recommended that host-specificity surveys be undertaken in the native range and that several candidates be selected for further investigation, including those already recorded on willows in Australia (Harman 2004).

Pursuing biocontrol for species of *Salix* in general may present considerable management challenges. Several species are of economic or ornamental value and conflicts of interest could arise with planning their suppression (Adair et al. 2006). Site-specific issues for determining the appropriate level of control to reduce environmental impacts requires careful consideration, for example mitigating impacts for land managers in managing the consequences of tree death, and the loss of willow in situations where they provide shade and riverbank stability. Potential impacts on non-target willows also requires careful evaluation (ARMC 2001), which is further complicated by hybridsation within the group. For example, if an agent is effective against naturally occurring hybrids, then desirable hybrids involving *S*. × *calodendron* and *S.* × *reichardtii* may be at risk. A strong understanding of population-level genetic differences is required to progress sufficiently effective host-specific agents, particularly for invasive hybrids.

No funding is prioritised for biocontrol investment on willows, but due consideration may be required to unravel any conflict for their potential nomination and investment in biocontrol research.

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APPENDIX 1. SUMMARY OF PAST AND ACTIVE BIOCONTROL RESEARCH, BARRIERS AND OPPORTUNITIES FOR AUSTRALIAN WONS

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Alligator weed *Alternanthera philoxeroides* **Current biocontrol research activity:** No active biocontrol research						
3 agents released: Alligator weed flea beetle (*Agasicles hygrophila*) and stem-boring moth (*Macrorrhinia endonephele* syn. *Arcola malloi*) have established.	CSIRO Australia	Southern Australia; Argentina	The flea beetle is widely distributed. It provides effective control (context or situation dependent) of the aquatic form only, particularly in warm temperate environments.	Current agents provide limited to no control of semi-aquatic and terrestrial form or of aquatic alligator weed in cool climates.	Host-range testing of several candidates identified in native range (Argentina) for semi-aquatic and terrestrial forms, and for agents more suited to cooler climates (aquatic form)	No current support but excellent links with FuEDEI in Argentina
Asparagus weeds *Asparagus aethiopicus, A. africanus, A. plumosus, A. scandens, A. declinatus. For bridal creeper (A. asparagoides), see separate entry* **Current biocontrol research activity:** No active biocontrol research						
None	Not determined	Southern Africa (native range)	Determine feasibility for biocontrol research	No initial assessments that prioritise candidates Not currently endorsed by EIC for biocontrol research Prioritisation status for biocontrol research is undetermined Closely related to cultivated asparagus	Determine feasibility for biocontrol research using Australian native species *Asparagus racemosus*, which may increase the ability to find host-specific agents Potential to progress initial host-range surveys	No current support

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Athel pine *Tamarix aphylla* **Current biocontrol research activity:** Active classical and non-classical biocontrol research in USA and Australia						
Ongoing: several beetles in the genus *Diorhabda* are being tested against various *Tamarix* species (USA).	US Department of Agriculture	North America; northern Africa and Asia (native range)	Determine feasibility for classical biocontrol research (Australia)	Not currently endorsed by EIC for biocontrol research Species may be limited to dry areas of central southern Australia	Understanding of current Australian distribution and impact Determine feasibility or prioritisation of biocontrol research for progressing host-range surveys and/or testing of *Diorhabda* species	No current support
Ongoing: investigation in Australia of native pathogens suspected to cause dieback of populations in invaded range	University of Queensland; Northern Territory Government	Northern Territory	Identify fungal isolates that induce dieback Then develop a registered bioherbicide (utilising the Di-Bak Injecta technology originally developed for parkinsonia control)	No significant results from early trials	Potential to progress bioherbicide development using Di-Bak Injecta technology	University of Queensland BioHerbicides Australia Northern Territory Government
Bellyache bush *Jatropha gossypiifolia* **Current biocontrol research activity:** Active biocontrol research						
1 agent released, the jewel bug (*Agonsoma trilineatum*)	CSIRO Australia; Northern Territory and Queensland governments	Tropical America	Agent did not establish, potentially due to only 1 importation and-/or other biological and environment factors	Low genetic integrity from agent initially released	Targeted exploration in native range to re-import the jewel bug with a broader genetic basis	No current support

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
3 agents prioritised: a leaf-mining moth (*Stomphastis thraustica*), approved for release; a rust fungus (*Phakopsora jatrophicola*), pending submission for release approval (Dec. 2022); and a gall midge (*Prodiplosis hirsute*), awaiting import for testing (Oct/Nov 2022).	QDAF	Queensland; South America	Release and evaluation of the leaf-mining moth Submission and release approval for the rust fungus Host-specificity testing of gall midge	Not determined	N/A (research current)	Meat and Livestock Australia Future investment is required to progress delivery
Bitou bush *Chrysanthemoides monilifera* subsp. *rotundata* **Current biocontrol research activity:** No active biocontrol research except for post-release monitoring (University of Wollongong)						
9 agents released, with 4 establishing on bitou: bitou tip moth (*Comostolopsis germana*), bitou seed-fly (*Mesoclanis polana*), bitou leaf- roller moth (*Tortrix* sp.) and bitou tortoise beetle (*Cassida* sp. 3)	CSIRO Australia	Eastern Australia	Varying levels of impact observed on the growth parameters of bitou bush Some level of control best achieved with several complimentary agents in the field, combined with conventional control methods	Considerable investment has occurred and further investment not prioritised for bitou bush and boneseed Additional agents identified, but considerable life-cycle challenges a hurdle for undertaking host-specificity testing	Potential for host-specificity testing for identified candidates for biocontrol of bitou bush and boneseed if life-cycle challenges inhibiting culturing can be overcome	No current support

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Blackberry *Rubus fruticosus* aggregate **Current biocontrol research activity:** Active biocontrol research						
Various strains of the rust fungus (*Phragmidium violaceum)* have been released across Australia	CSIRO Australia; Agriculture Victoria	Southern Australia	The rust is highly efficient in spreading by natural means, but its impact can be highly variable and dependent on a conducive location	Several native and commercially grown blackberries are closely related to invasive blackberry	None identified	Not applicable
Preliminary risk assessment of feasibility of cane-boring sawfly (*Phyllocecus faunus*) as a biocontrol agent being conducted	CSIRO European Laboratory; Agriculture Victoria	France; Australia	Preliminary host-specificity testing occurred in France, Delay in rearing starter colony in France has delayed importation to Australia, but host-specificity testing has commenced in quarantine	Challenges associated with rearing a starter colony in France has delayed importation to Australian quarantine	N/A (research current)	Meat and Livestock Australia, but future investment is required to progress delivery
Natural enemy surveys in native range (United Kingdom) conducted in July 2021	CSIRO Australia; Agriculture Victoria; CABI United Kingdom	United Kingdom	A rust fungus (*Phragmidium violaceum*), galling wasp (*Lasioptera rubi*), bramble-feeding moth, (*Thyatira batis*) and an unidentified eriophyid leaf-buckle mite were prioritised for further biocontrol feasibility studies. A genetic comparison of *Rubus anglocandicans* populations between countries showed population-level differences. Genetic research aims to pinpoint the origin of invasion to better locate host-specific agents.	Some barriers in understanding the origin of the invasive species Genetic research supporting the acquisition of more efficient and host-specific agents	Further studies required to resolve genetic matching between Australia and UK populations of *R. anglocandicans*	Forrest Pest Management Research Consortium, but future investment is required to progress delivery

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Boneseed *Chrysanthemoides monilifera* subsp. *monilifera* **Current biocontrol research activity:** No active biocontrol research						
1agent, the leaf buckle mite (*Aceria* sp.), established on boneseed	CSIRO Australia; Agriculture Victoria	Eastern and southern Australia	Isolated establishment at a limited number of sites and impact largely unknown	See above for bitou bush	See above for bitou bush	No current support
Bridal creeper *Asparagus asparagoides* **Current biocontrol research activity:** No active biocontrol research						
3 biocontrol agents released: an undescribed Erythroneurini leafhopper, a rust fungus (*Puccinia myrsiphylli*), and a leaf beetle (*Crioceris* sp.)	CSIRO Australia	Southern Australia	Rust fungus and leafhopper widely released and redistributed across southern Australia, and effective, with bridal creeper in decline	Additional form, the Western Cape bridal creeper, suspected to be a different species. Grows alongside the common form. Has the potential to re-infest areas where the common form has been controlled. Western Cape bridal creeper is resistant to the rust fungus.	Determine taxonomy of the Western Cape form Determine whether this form should be prioritised as a target for biocontrol research (noting that this form is under eradication or containment in some parts)	No current support
Brooms Scotch broom (*Cytisus scoparius*), Cape broom (*Genista monspessulana*) and flax-leaf broom (*G. linifolia*) **Current biocontrol research activity:** No active biocontrol research except for redistribution programs						
4 biocontrol agents released against Scotch broom: Scotch broom twig-mining moth (*Leucoptera spartifoliella*), Scotch broom psyllid (*Artainilla spartiophila*), Scotch broom seed bruchid (*Bruchidius villosus*), and Scotch broom gall mite (*Aceria genistae*)	CSIRO Australia; NSW and Victorian governments	Southern Australia	Scotch broom gall mite is widely distributed, but redistribution encouraged as natural dispersal is slow. All other agents have had isolated establishment and/or impacts are unknown.	All suitable candidates have been explored for Scotch broom after comprehensive surveys across the native range. Additional agents prioritised for Scotch broom and Cape broom (e.g the broom rust and a seed weevil) have come up against barriers in culturing Scotch broom also identified as a high risk to tagasaste fodder crop in WA. Longevity of broom seed banks a substantial barrier	Integrate other weed-management options to reduce the long-lasting seed bank Further impact evaluation required to enhance current redistribution programs Identify additional agents for Cape broom.	No current support

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Following unauthorised introduction the broom rust (*Uromyces pisi-sativi*) is being monitored in north-east Victoria for its impact on tagasaste fodder crops			The broom rust is widespread in south-eastern Australia but recommendations for its redistribution are currently unknown.			
Cape broom psyllid (*Arytinnis hakani*) has been redistributed for Cape broom after unauthorised introduction. No agents have been tested for biocontrol of flax-leaf broom.			Cape broom psyllid widely redistributed and now widely established in southern Australia. Its impact is largely unknown and redistribution programs are encouraged.			
Cabomba *Cabomba caroliniana* **Current biocontrol research activity:** Active biocontrol research						
Ongoing: the cabomba weevil (*Hydrotimetes natans*) was approved for release in 2021. An effective release protocol is being developed. Program in release phase.	CSIRO Australia; FuEDEI	South-eastern Queensland	Implement release protocol for the best establishment of the cabomba weevil Sset up nursery trials and provide post-release evaluation of program Provide integrated weed management in collaboration with Seqwater	Narrow climatic variation in native range compared to invasive range in Australia In native range, cabomba occurs mostly in oligotrophic conditions, but in Australia occurs in oligotrophic and eutrophic conditions	Continue host-range surveys in north-eastern Argentina to prioritise additional candidates	Rural Research and Development for Profit ended March 2023 and future investment is required to progress host-range surveys (in native range) and prioritise additional candidates.

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Chilean needle-grass *Nassella neesiana* **Current biocontrol research activity:** Active biocontrol research on hold						
Ongoing: host testing of a rust fungus (*Uromyces pencanus*) from Argentina led to submission to release in 2012. Release approval is on hold pending further host-specificity testing. (Release of this rust has been approved in New Zealand, after a 10-year delay.)	Victorian Government; FuEDEI; Manaaki Whenua – Landcare Research New Zealand	Argentina; south-eastern Australia; New Zealand	To complete host-specificity testing to resolve assessors' concerns about closely related native stipoid grasses (*Austrostipa* spp.)	Recent changes in export permissions associated with a decrease in the Argentinian government's aversion to risk is changing the current status quo, but prior complications may still result in delays. Chilean needle-grass is closely related to native stipoid grasses (*Austrostipa* spp.) which creates a challenge for finding host-specific agents.	Complete host-specificity testing to address concerns raised by assessors. Spores of the rust accession are stored in an Argentinian laboratory for host-specificity testing, which may prevent need for field collections. New Zealand could assist with Australian program by testing native stipoid grasses.	No current support. Future investment is required to progress delivery. Strong collaborative ties with the University of Bahia Blanca, Argentina, FuEDEI and Manaaki Whenua – Landcare Research, New Zealand
Gorse *Ulex europaeus* **Current biocontrol research activity:** No active biocontrol research except for redistribution program						
4 agents released: the seed weevil (*Exapion ulicis*), thrips (*Sericothrips staphylinus*), the soft shoot moth (*Agonopterix umbellana*), and the spider mite (*Tetranychus lintearius*). Current redistribution programs to enhance impact	CSIRO Australia; Agriculture Victoria; Department of Primary Industries, Parks, Water and Environment Tasmania; Landcare New Zealand	Southern Australia	All released agents have established but damage levels are not high enough to reduce plant density.	All classical biocontrol options exhausted after comprehensive native-range surveys dating from the 1920s.	Further impact evaluation required to enhance redistribution programs Integrate other weed-management options to reduce plant density Progress biocontrol feasibility for gorse pod moth (*Cydia succedana*) Investigate native dieback observed in Tasmania to determine how this could enhance biocontrol	Rural Research and Development for Profit program (funding ceased). No current support. Future investment required.

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Hymenachne *Hymenachne amplexicaulis* **Current biocontrol research activity:** No active biocontrol research						
None, but some host-range surveys in native range conducted in 2000s No agents prioritised	Not determined	Central and South America	Determine feasibility for biocontrol research	Not currently endorsed by EIC for biocontrol research; endorsement may be challenged by parts of the grazing industry. Closely related to native *Hymenachne* spp., which creates a challenge for finding host-specific agents.	Host-range surveys in native range to determine feasibility for biocontrol research	No current support. Strong collaborative ties with the Departamento de Fitopatologia, Universidade Federal de Viçosa, Brazil.
Lantana *Lantana camara* **Current biocontrol research activity:** Active biocontrol research						
Ongoing: 35 biocontrol agents released with 18 establishing	CSIRO Australia; QDAF; Royal Botanic Garden Sydney	Eastern Australia; coastal parts of the Northern Territory and Western Australia	4 established agents, the sap-sucking lace bug (*Teleonemia scrupulosa*), leaf-mining beetles (*Octotoma scabripennis* and*Uroplata girardi*) and a stem-sucking bug (*Aconophora compressa*) can cause seasonal damage, depending on context or situation.	Taxonomy of invasive lantana is unclear due to a long history of cultivation, hybridisation and invasiveness. Tracing origins is essential to locate host-specific and effective agents.	N/A (research current)	QDAF (limited) Future investment required
Release application for the rust fungus (*Puccinia lantanae*) being prepared			Submission and approval of release application, development of release protocol Release and evaluation			
Reimportation of prior candidate, the lantana gall fly (*Eutreta xanthochaeta*), for host-specificity testing under way for re-release approval			Host-specificity testing and release approval			

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Genetic research to better understand invasive origins			Genetic understanding of invasive origins			
Mesquite (algaroba) *Prosopis* spp. **Current biocontrol research activity:** No active biocontrol research						
4 biocontrol agents released: the seed-feeding bruchids (*Algarobius bottimeri* and *Algarobius prosopis*), a leaf-feeding psyllid (*Prosopidopsylla flava*) and leaf-tying moth (*Evippe* sp.)	CSIRO Australia; Queensland government	North and South America	2 agents have established: the seed-feeding bruchid (*A. prosopis*) and leaf-tying moth Damage levels not high enough to reduce plant density Population-level impacts by leaf-tying moth, but impact restricted to Pilbara, Western Australia (Queensland and NSW negligible) Seed predation by bruchid is low and unlikely to cause population-level impacts.	No prioritised investment	Host-range testing of potential agents, including evaluation of South African work (especially on weevil *Coelocephalapion gandolfoi* from Argentina) Continued host-range surveys in native range to prioritise additional candidates that could be sourced across any of the mesquite species	No current support but excellent links with FuEDEI in Argentina.
Mimosa *Mimosa pigra* **Current biocontrol research activity:** No active biocontrol research						
13 biocontrol agents released, with 11 establishing		Northern Australia	The combined impacts of biocontrol agents providing good long-term control: 2 stem-mining moths (*Carmenta mimosa* and *Neurostrota gunniella*), the root and leaf-feeding flea beetle (*Nesaecrepida infuscata*) and a seed-feeding weevil (*Chalcodermus serripes*) anticipated to be effective once populations build.	All suitable candidates have been explored after comprehensive surveys across the native range Natural enemies must be adapted to habitat that is inundated for several months a year	Impact evaluation to enhance redistribution programs; re-introduce agents that have failed to establish or thrive Integrate other weed-management options Investigate native dieback to determine how biocontrol could be enhanced	No current support

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Opuntioid cacti *Austrocylindropuntia* **Current biocontrol research activity:** No active biocontrol research						
None	Not determined	Not determined	Determine feasibility for biocontrol research	Not currently endorsed by EIC for biocontrol research Prioritisation status for biocontrol is undetermined	Understanding of current Australian distribution and impact to determine feasibility for biocontrol research	No current support
Cylindropuntia **Current biocontrol research activity:** Active biocontrol research						
Ongoing: the cochineal insect *Dactylopius tomentosus* and its lineages have been released against 8 *Cylindropuntia* species. Ongoing work to optimise biocontrol solutions through better adapting cochineal lineages to *Cylindropuntia* species and expediating releases across greater infestations.	QDAF; NSW DPI	National, but focused on Brisbane, Queensland, and Orange and Lightning Ridge, NSW	To establish all 6 cochineal lineages of *D. tomentosus* across *Cylindropuntia* infestations, targeting outlying populations to limit spread Mass rearing of agents to expedite releases with focused post-release evaluation on boxing glove cactus and Hudson pear	Funding to extend monitoring across all *Cylindropuntia* species	Conduct long-term post-release evaluation across all 8 *Cylindropuntia* species	Rural Research and Development for Profit (funding ended March 2023) Enhancing National Pest Animal and Weed Management – Federation Funding Agreement (partially supported)

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Opuntia species **Current biocontrol research activity:** Active biocontrol research						
Ongoing: 20 species of biocontrol agents have been released against prickly pears. Ongoing work to identify which cochineal agents can be used against previously untested *Opuntia* species and how biocontrol can be optimised through integrated weed management.	QDAF	Queensland	Control of prickly pears has been achieved with the cactoblastis moth (*Cactoblastis cactorum*) and cochineal insects (*Dactylopius* spp. and lineages). To identify and target untested *Opuntia* spp. and optimise control using integrated weed management.	None observed	To expand program to expedite releases and conduct long-term post-release evaluation once cochineal species are identified and tested against the previously untested species	Advancing Pest Animals and Weeds Control Solutions (funding ends June 2023)
Parkinsonia *Parkinsonia aculeata* **Current biocontrol research activity:** Active biocontrol research (classical and non-classical)						
Ongoing: 5 biocontrol agents released: seed-feeding beetles *(Penthobruchus germaini* and *Mimosetes ulkei), a leaf bug (Rhinacloa callicrates) and leaf-feeding moths Eueupithecia cisplatensis, Eueupithecia vollonoides)*	CSIRO; University of Queensland; BioHerbicides Australia	Northern Australia	Agents released in 1990s largely ineffective The mass-rearing and redistribution program for the leaf-feeding moths is ongoing and requires further monitoring to understand impact.	Finding biocontrol agents effective throughout parkinsonia's distribution is challenging as it occurs across a wide range of environments and land-management systems	Impact evaluation required to enhance redistribution programs Integrate other weed-management options to reduce plant density Final native-range exploration that targets unexplored regions in Argentina, Colombia and Brazil	Rural Research and Development for Profit program Meat and Livestock Australia University of Queensland BioHerbicides Australia
Ongoing: research on existing prioritised candidates including the gall midge (Neolasioptera aculeate)			To complete host-specificity testing of the gall midge and progress the agent towards delivery if host-specific			

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Bioherbicide Di-Bak Parkinsonia® developed from naturally occurring pathogens (APVMA registered 2018)			To monitor implementation and efficacy of bioherbicide			
Parthenium *Parthenium hysterophorus* **Current biocontrol research activity:** No active biocontrol research except for redistribution program						
11 biocontrol agents released Agents identified as priority for redistribution: the seed-feeding weevil (*Smicronyx lutu-lentu*), the stem-boring weevil (*Listronotus setosipennis*), and the root-boring moth (*Carmenta* nr. *ithacae*), the winter rust (*Puccinia abrupta* var. *parteniicola*), and the summer rust (*Puccinia xanthii* var. *parthenii-hysterophorae*) Ongoing: monitoring of redistributed agents	QDAF	North and South America; Queensland and northern NSW	To enhance the spread and impact of current biocontrol agents into southern Queensland and northern NSW	Agents strongly influenced by climatic factors and impacts vary seasonally Parthenium still spreading south into a variety of habitats where agents are not established	Assess if impact can be further enhanced using integrated weed management Ongoing redistribution mass-rearing, release and evaluation of current agents	Rural Research and Development for Profit funding ended, no current support Funding required for further redistribution and evaluation
Pond apple *Annona glabra* **Current biocontrol research activity:** No active biocontrol research						
None	Not determined	Coastal west Africa, America (native range)	Determine feasibility for biocontrol research Understand origin of invasion	Not currently endorsed by EIC for biocontrol research Broad native range so invasive origin unclear Closely related to *Annona* species of commercial value	Genetic research to pinpoint the origin of invasions to locate host-specific agents Determine feasibility for biocontrol research Conduct initial host-range surveys	No current support

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Prickly acacia *Vachellia nilotica* subsp. *indica* **Current biocontrol research activity:** Active biocontrol research						
6 agents released with 2 establishing: the seed-feeding beetle (*Bruchidius sahlbergi*) and the leaf-feeding moth (*Chiasmia assimilis*)	QDAF	Ethiopia; Senegal; South Africa; Queensland, Australia	Agents currently released ineffective against prickly acacia	Many native acacias (including 8 *Vachellia* spp.) create a challenge for finding host-specific agents Civil unrest in Ethiopia has caused delays in conducting field surveys and in exporting agents to South Africa for host-specificity testing	Continued host-range surveys prioritise additional candidates Progress current testing towards delivery Progress bioherbicide development	Rural Research and Development for Profit Future support to progress prioritisation of additional candidates and delivery BioHerbicides Australia
Ongoing: the gall-inducing thrips (*Acaciothrips ebneri*) was approved for release in 2022.			Implement effective release protocol for establishment of thrips; set up nursery trials; provide postrelease evaluation of program.			
Ongoing: host-specificity testing on 2 additional agents, a stem-inducing gall fly (*Notomma mutilum*) and eriophyid gall mite (*Aceria* sp. type 3)			To complete host-specificity testing on additional agents			
Ongoing: investigation of native pathogens suspected to cause dieback of populations in invaded range (Australia)			To identify fungal isolates that induce dieback To develop registered bioherbicide			

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Rubber vine *Cryptostegia grandiflora* **Current biocontrol research activity:** No active biocontrol research						
2 agents released: the leaf-feeding moth (*Euclasta whalleyi*), and the rubber vine rust (*Maravalia cryptostegiae*) CABI looking for additional isolates of the rust more suited to various environmental conditions	QDAF	Queensland	The rust established rapidly in both wet and drier areas, but activity is highest in wet regions where it significantly reduces the seed bank Minor and isolated impact by the leaf-feeding moth	At drier sites (suboptimal for the rust), rubber vine continues to spread, particularly westward into drier environments Rubber vine closely related to the native *Gymanthera oblonga*, which grows in close association with rubber vine, thus providing a challenge to finding host-specific agents	Evaluate and/or quantify distribution and effectiveness of the 2 existing agents, to determine whether their impact can be increased through redistribution and/or if there is a need to identify new biocontrol agents	No current support
Sagittaria *Sagittaria platyphylla* and *Sagittaria calycina* **Current biocontrol research activity:** Active biocontrol research						
Ongoing: the fruit-feeding weevil (*Listronotus appendiculatus*) was approved for release in 2020 Program undergoing release phase	Agriculture Victoria; NSW DPI	Victoria and NSW	Implement effective mass-rearing and release protocol for best establishment Set up nursery trials Provide post-release evaluation of program	The fruit-feeding weevil alone is unlikely to provide population-level impacts, additional agents are required that attack various life-history stages of plant. Program is partially funded.	Evaluate effectiveness of the fruit-feeding weevil Provide integrated weed management in collaboration with affected stakeholders to improve efficacy Progress investigation and testing for additional agents	NSW Government NSW Environmental Trust Enhancing National Pest Animal and Weed Management – Federation Funding Agreement Only partially supported, with limited funding for delivery and evaluation

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Salvinia *Salvinia molesta* **Current biocontrol research activity:** No active biocontrol research (exception non-classical: mass-rearing and redistribution program)						
2 agents released: the salvinia weevil (*Cyrtobagous salviniae*) and moth (*Samea multiplicalis*) Ongoing mass rearing and repeated releases from mass-rearing facilities in Queensland and NSW Post-release monitoring by University of Wollongong	NSW DPI; University of Wollongong	NSW and Queensland	To fast-track and optimise the release of weed biocontrol agents through increasing the number, coverage and impact of agents released	Repeated redistribution and releases often required due to site-specific characteristics and poor dispersal Agents require re-releases after flood events as flooding flushes salvinia and agents out to sea	To optimise and improve release and impact efficacy through long-term post-release evaluation	NSW Weed Action Program Enhancing National Pest Animal and Weed Management – Federation Funding Agreement
Serrated tussock *Nassella trichotoma* **Current biocontrol research activity:** Active biocontrol research (classical and non-classical)						
Ongoing: investigation of native pathogens suspected to cause dieback and potential regulation of populations in invaded range (Australia and New Zealand) Ongoing: Search for biocontrol candidates in native range	Manaaki Whenua – Landcare Research New Zealand; Agriculture Victoria	Australia; New Zealand; Argentina	To survey for potential plant pathogens and identify suitably pathogenic isolates that could be developed into mycoherbicides To identify the levels of genetic diversity between Australia, New Zealand, and native range of Argentina for determining any implications for different weed genotypes on biocontrol program	Like Chilean needle-grass, serrated tussock is closely related to native stipoid grasses (*Austrostipa* spp.), which creates a challenge for finding host-specific agents	To progress towards developing seedling bioassays and mycoherbicide development if isolates are identified and suitably pathogenic To determine if genetic diversity has implications towards any biocontrol outcomes	Landcare Research New Zealand Agriculture Victoria (program funding ended October 2022)

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Silverleaf nightshade *Solanum elaeagnifolium* **Current biocontrol research activity:** Active biocontrol research						
Ongoing: no agents have been released in Australia and new agents are under investigation from native range 2 prioritised: the lace bug (*Gargaphia arizonica*) from Texas and a mite (*Aceria* nov. sp.) from Argentina	Agriculture Victoria	Australian; USA; Argentina	To identify and locate host-specific agents in climatically similar areas to Australia where genetic factors additionally maximise chances	Risk analysis is complex due to the large number of closely related native, ornamental and crop species occurring in Australia	To identify additional agents for testing and progress research on current priorities	Rural Research and Development for Profit program (program ended March 2023)
Water hyacinth *Pontederia crassipes* **Current biocontrol research activity:** No active biocontrol research (exception non- classical: mass-rearing and redistribution program)						
4 agents: leaf-feeding weevils (*Neochetina eichhorniae*, *Neochetina bruchi*) and 2 stem-boring moths (*Niphograpta albiguttalis* and *Xubida infusella*). Ongoing mass rearing and repeated releases of the 2 weevils and post-release monitoring by University of Wollongong	NSW DPI; University of Wollongong	NSW and Queensland; Argentina	The stem- and leaf-feeding weevils and 1 stem-boring moths are widely established, causing variable levels of damage predominately in subtropical and tropical environments. Current work aims to fast-track and optimise the release of the weevil biocontrol agents through increasing the number, coverage and impact of agents released.	Current biocontrol agents released are less effective in temperate environments of Australia Water hyacinth closely related to 4 native species of *Monochoria*, namely *M. australasica*, *M. cyanea*, *M. hastata* and *M. vaginalis,* which biogeographically overlap with water hyacinth.	To optimise and improve release and impact efficacy of existing agents through long-term post-release evaluation To revisit the program using a more temperate agent, the water hyacinth plant hopper (*Megamelus scutellaris*)	NSW Weed Action Program Enhancing National Pest Animal and Weed Management – Federation Funding Agreement No current support for testing of new agents

Research status	Research providers	Research locations (past, active and/or potential)	Program outcomes or expected outcomes	Barriers	Opportunities	Program support
Willows *Salix* spp. except *S. babylonica, S.* × *calodendron* and *S.* × *reichardtij* **Current biocontrol research activity:** No active biocontrol research						
No biocontrol research has occurred in Australia, but a review was commissioned to evaluate biocontrol potential for *Salix* species in 2001. The natural enemies in the native range are partially known. A sawfly is present following unauthorised introduction and is causing defoliation of trees in Australia, but its potential for biocontrol has not been determined. No are agents prioritised.	Not determined	Europe and North America (native range)	Determine feasibility for biocontrol research	Willows are not currently endorsed by EIC for biocontrol research Biocontrol may present considerable management challenges because of economic or ornamental value, and barriers associated with planning suppression.	Determine feasibility or prioritisation of biocontrol research for progressing host-range surveys and testing	No current support

Abbreviations: APVMA, Australian Pesticides and Veterinary Medicines Authority; *CABI, Centre for Agriculture and Bioscience International; EIC, Environment and Invasives Committee; FuEDEI, Fundación para el Estudio de Especies Invasivas; NSW DPI, NSW Department of Primary Industries; QDAF, Queensland Department of Agriculture and Fisheries*

CENTRE FOR INVASIVE SPECIES SOLUTIONS

Building 22, University of Canberra
University Drive South, BRUCE ACT 2617
T 02 6201 2887
E communications@invasives.com.au

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