RESEARCH IMPACT EVALUATION

Biological control of invasive plants

October 2017

CSIRO

Contents

1   Executive Summary

The challenge

The impacts of invasive alien plants ("weeds") are widely acknowledged as causing the highest direct production losses to Australia agricultural production; and are a top three threat to Australian biodiversity and ecosystem services[12]. In Australia, and internationally, weeds cause very significant economic damage on agriculture, as well as extensive environmental and social impacts by degrading natural landscapes, waterways, and coastal areas[3].

The response

Since the 1930s, CSIRO's research, through classical weed biological control (in some instances with partners, and in most instances with direct engagement of landholders), has led to the introduction of 126 different agent species for biological control of 34 weeds in Australia. Internationally, CSIRO has also been involved in the successful management of several weeds in the US that are of Australian origin (e.g. broad-leaved paperbark tree in the Florida Everglades), using biocontrol agents from Australia with no non-target impacts. More recently, CSIRO has led the development and application of risk assessment and sector-specific frameworks to prioritise weeds as targets for biological control, thereby guiding investment by a range of stakeholders. CSIRO has demonstrated that carefully selected and risk assessed biocontrol agents can reduce weed populations with no adverse effects on native wildlife and plants, livestock and crops, or human health.

The impacts

CSIRO's contribution to classical weed biological control has been a great Australian success story. CSIRO remains the global research leader of risk analysis based classical biological control for weeds and pests; and is the only nationally focused agency in Australia providing biological control research for weeds of national significance. Successful biological control programs provide sustained weed control benefits; and enhance capability through scientific experience, improved knowledge, and infrastructure. Historically, CSIRO weed biological control research has developed protocols and approaches for the native range selection, risk assessment, and release implementation of biocontrol agents that have set the standard and influenced weed biological control implementation regulations and policy both nationally (including Biological Control specific legislation) and internationally. Therefore, conducting further research for effective future weed management research and implementation is expected to provide continued economic and non-economic benefits.

Economic data published in a report commissioned in 2006 by the former Cooperative Research Centre for Australian Weed Management[4] based on many historic benefit-cost analyses pioneered by CSIRO was refreshed to calculate the quantitative benefits of just eight of the CSIRO-led weed

biological control programs[i] . These programs comprise a mix of target weeds that affect waterbodies, agriculture, and the broader environment across different regions of Australia.

The present value of benefits across the eight biological control programs selected is approximately $3.7 billion in 2016/17 dollars under a 7 per cent discount rate. Attribution to CSIRO's involvement in the eight programs is significant. These programs have (conservatively) delivered an average annual value in excess of $50.9 million, which is well in excess of CSIRO's annual operating expenditure in weed biological control of approximately $6 million (2016/17 figure).

Clearly, this estimate of economic benefit would be substantially larger had research impact evaluation investments been made to evaluate and quantify the benefits across all CSIRO-led weed biological control programs up to the present day. The sensitivity analysis suggests that the CSIRO weed biological control program expenditure of $6 million per year (in real, present value terms) will continue to lead to average annual benefits (measured as savings in control costs and agricultural production, in real present value terms) between $20.5 million and $75.5 million per year. These estimations are largely based on improvements in agricultural production and rely on the assumptions made ("CSIRO in context"). The amount could be potentially doubled if data was available around health (e.g. allergies and landholder psychological health), social (e.g. land values and cultural services), and environmental (e.g. regulating and habitat supporting services) benefits that could also be quantified monetarily (e.g. via an ecosystem services-based approach[5]).

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[i] There is limited up-to-date quantitative data on the effectiveness of introduced biocontrol agents in the field to substantiate a comprehensive impact analysis.

INPUTS → ACTIVITIES → OUTPUTS → OUTCOMES → IMPACT

INPUTS

- CSIRO investment (FTE, in-kind contributions, equipment and facilities)
- Investment from collaborators
- Cost of adaptive development and extension

ACTIVITIES

34 weed biocontrol programs in Australia since 1930 – 13 of which are discussed in more detail as a representative sample related to outputs and outcomes for this case study; 4 of the 13 are discussed as examples illustrating stakeholder involvement:

- Paterson's curse
- Mimosa biocontrol in Arnhem Land: increasing indigenous awareness and engagement in weed biocontrol
- Bridal creeper biocontrol: non-specialist community rearing and release of two agents
- Parkinsonia biocontrol: stakeholder involvement in release and field evaluation of two agents

Biocontrol of weeds of Australian origin in the USA; one key example discussed

- Broad-leaved paperbark tree biocontrol in Florida with several agents

Framework development to prioritise biocontrol targets for weeds relevant to different customers

- Meat and Livestock Australia
- NSW Environmental Trust
- USDA

OUTPUTS

13 representative weed biocontrol programs

- Of the 73 different agents (including biotypes) released, 50 are established (68%) and are recorded at varying levels of scale and abundance (Appendix 1)
- Paterson's curse
- Mimosa biocontrol in Arnhem Land: Delivered information to establish biocontrol program through collaborative networks, working closely with traditional owners and ranger groups to assist landscape scale control of mimosa
- Bridal creeper biocontrol: By 2006, the two agents had been released at more than 2550 sites across Australia in partnership with the community
- Parkinsonia biocontrol: Involved 60+ different landholders and NRM groups to facilitate landscape scale dissemination of biocontrol agents

Broad-leaved paperbark tree biocontrol in the USA

- Three of the four biocontrol agents released successfully established and spread

Weed biocontrol target prioritisation
13 and 17 weeds, which are relevant to the livestock industry and NSW natural ecosystems, respectively, shortlisted as priority taxa for biocontrol investment. Prioritisation for the USDA is ongoing

Publications 1990-2017
356 publication; 11498 citations

OUTCOMES

13 representative weed biocontrol programs
Of the 37 established agents that have already generated measurable weed control outcomes, 9 (24%) achieved slight control, 12 (32%) variable; 7 (19%) medium and 9 (24%) significant control (Appendix 2).

- Paterson's curse
- Mimosa biocontrol in Arnhem Land: Increased biocontrol literacy of indigenous Australians
- Bridal creeper biocontrol: Two of the agents released have contributed to reduce the control cost of Murray Valley citrus industry and significantly suppress weed populations in coastal areas across Australia
- Parkinsonia biocontrol: Increased biocontrol literacy of 60+ landholders and groups in northern Australia

Broad-leaved paperbark tree: The weed has been physically removed from most public lands and biocontrol has limited its ability to regenerate and reinvade. Contributing to conservation and restoration efforts of the Florida Everglades

Weed biocontrol target prioritisation: The approach developed would be readily applicable to analogous decision-making challenges in other sectors and countries

IMPACT

Economic impact
- Increased agricultural production
- Reduced control costs

Environmental impact
- Improved biodiversity
- Improved soil quality
- Improved water quality

Social impact
- Improved incomes and employment in agriculture-dependent, rural communities

Figure 1: Impact Pathway for CSIRO's weed biocontrol program

2 Purpose and audience

This case study has been undertaken to assess the beneficial impacts arising from CSIRO's involvement in classical biological control of exotic/undesirable invasive alien plants (hereafter referred to as "weeds") in Australia and overseas. Classical biological control programs have had varying levels of success in managing target weeds. A representative sample of programs, which have been conducted since the 1930s, are presented in this case study, along with an explanation of the standard activities that are involved in such programs.

The case study has been prepared as a standalone report, which can be aggregated with other case studies to substantiate the impact and value of CSIRO's activities. The aim of this case study is address research evaluation and accountability, reporting, communication, and continual improvement of CSIRO weed biological control investments. This report is prepared for the Business Unit Review Panel, Members of Parliament, Commonwealth Departments, Industry and Environmental peak bodies, CSIRO, and the general public.

3 Background

Weeds have significant economic, environmental, and social impacts in Australia and internationally, damaging natural landscapes, ecosystems, agricultural lands, waterways, and coastal areas[6]. Weeds also affect domestic and international market access for Australian agricultural commodities. Sinden et al[7]. estimated that the cost of weeds to Australian agriculture (crops, livestock, and horticulture) is in excess of $5 billion per year. This study also estimated the annual costs of control as $20 million in natural environments, $81 million on public land, and $3 million on indigenous land. However, these estimates did not include any losses from environmental degradation, social impacts, or cultural value effects. A more recent analysis estimated the cost of weeds in Australian cropping systems alone at $3.3 billion annually, which represents an average of $146/ha in control activities expenditure and yield losses[8]. When combining and converting the costs of weeds in both reviews to 2016 dollars (using Consumer Price Index inflation calculator of x1.3), an overall current conservative estimate of the annual costs of weeds to Australian agriculture is between $5.970 billion and $7.260 billion per annum. Weeds are widely acknowledged as among the top three threats to natural resources and biodiversity of Australia[3]. The Australian Government estimates that the total cost of weed management on environmental assets is similar, if not greater, than estimates for agricultural industries.[9]

Populations of native plant species are under suppression from specialist natural enemies, such as arthropods and pathogens that attack the seeds, leaves, stems and/or roots of the plant. In the absence of such natural enemies, exotic plants can become invasive in their country of introduction posing significant economic, environmental, and social impacts. Classical biological control is a core component of Australia's response to the management of established invasive

weeds. This involves the deliberate introduction of specialist, host-specific natural enemies ("biocontrol agents") of the target weed from its native range into the region where it has become a problem. This is a sustainable and relatively cost-effective method of managing many of Australia's most problematic weeds with long-term effects which has been used for more than a century[10]. Biological control programs do not cease upon release and establishment of an agent. They require adequate evaluation and monitoring years into the future to document the realisation of benefits, which can be challenging and requires ongoing biological control capability.

CSIRO has been developing biological control solutions for weeds since the 1930s. The research was greatly facilitated with the establishment of overseas research laboratories in France, South America, and South Africa to investigate potential biocontrol agents for weeds of Mediterranean, South and Central American, and African origin. Of these, only the French laboratory, established in 1966, remains; and research in other regions is conducted in collaboration with local experts and institutions. Classical biological control is a demonstrably sustainable and cost-effective method of managing many of Australia's most impactful agricultural and environmental weeds in the long-term. Since 1930, CSIRO research has contributed to the introduction of 126 different agent species for biological control of 34 weeds in Australia either alone or in partnership with various stakeholders. CSIRO has worked for almost 90 years as one of the few agencies capable of providing biological control research and management support for several weeds of national significance. As a national agency it is capable of working across state jurisdictional boundaries.

Thirteen programs are included in this case study to demonstrate a representative range of CSIRO's involvement over time. More details regarding stakeholder involvement is provided for four weeds: Paterson's cure (Echium plantagineum), Bridal creeper (Asparagus asparagoides), Parkinsonia (Parkinsonia aculeata) and Mimosa (Mimosa pigra). CSIRO has also been involved in several weed biological control programs overseas, especially in the US. The example provided in this case study is the biological control of the Australian broad-leaved paperbark tree (Melaleuca quinquenervia) in the Florida Everglades. This program, developed in 1987, has successfully controlled broad-leaved paperbark tree populations without damage to non-target species. More recently, CSIRO research has led the development and implementation of frameworks to prioritise biological control targets for weeds relevant to different stakeholders in collaboration with leading experts in the field.

4 Impact Pathway

Project Inputs

For the period between 1999/2000 and 2017/18, CSIRO's weed biological control research has been the recipient of external investment to a value in excess of $46.55 million received from organisations such as the Australian Department of Agriculture and Water Resources, Department of Environment and Energy, state and territory government departments, and Rural Research and Development Corporations (Table 4.1).

Table 4.1: External cash and in-kind support to CSIRO classical weed biological control research ($ nominal)

Financial Year (FY)	External earnings ($)
1999/00	$2,125,171
2000/01	$2,512,704
2001/02	$6,987,321
2002/03	$3,246,207
2003/04	$2,157,354
2004/05	$2,260,643
2005/06	$3,227,847
2006/07	$3,733,105
2007/08	$2,775,813
2008/09	$1,182,998
2009/10	$1,220,420
2010/11	$2,206,325
2011/12	$1,625,830
2012/13	$1,155,583
2013/14	$1,408,593
2014/15	$1,638,039
2015/16	$3,195,181
2016/17	$2,251,548
2017/18	$1,635,978
Total	**$46,546,660**

Source: CSIRO

There are multiple secured funding contracts in the pipeline for 2018/19 and beyond. As of July 2017 these amounted to $4.85 million (Table 4.2).

Table 4.2: Contracts approved for external funding ($ nominal)

Financial Year (FY)	External earnings ($)
2018/19	$1,709,989
2019/20	$1,004,667
2020/21	$627,763
2021/22	$485,314
2022/23	$428,709
2023/24	$398,138
2024/25	$190,740
Total	**$4,845,319**

Source: CSIRO

Approach to a weed biological control program

The practice of managing an exotic weed by introducing its biocontrol agents from its native range involves a series of steps (Fig. 4.1), and is part of a broader management approach in which biological control is integrated with other forms of control (e.g. herbicides, mechanical control). Each biological control program will differ slightly depending on the target weed.
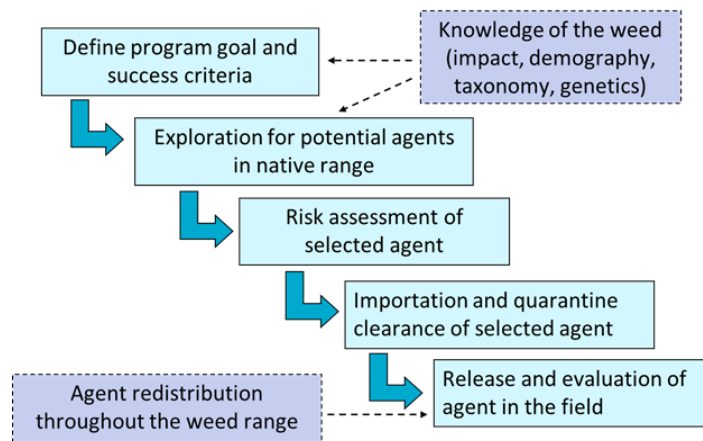
Figure 4.1: Typical steps followed in a weed biological control program

Activities first involve gathering relevant knowledge about the target weed, defining what can be realistically expected in terms of its eradication, and setting goals for the biological control program. This process is then followed by surveys and research in the native range to identify candidate agents that will be host-specific and effective at suppressing the target weed. Testing the specificity of the candidate agents, performed both prior to introduction in the native range and in a quarantine facility in Australia, is the key component of the risk analysis that is undertaken to determine if the agents pose direct threats to related non-target plant species. Once the agents are approved by the relevant authorities for introduction to Australia, they are cleared from quarantine and released in the field. In some instances, an active release and redistribution program is required throughout the distribution of the weed. Monitoring of the establishment and impact of the agents on the weed populations is important but often difficult to secure funding for; and can occur over small or large time and geographic scales depending on available resources.

Activities

CSIRO activities for weed biological control will be presented as four focus areas in this case study.

- Overview of weed biological control in Australia within defined periods;
- Stakeholder engagement in weed biological control
- Biocontrol of broad-leaved paperbark tree[11] in Florida, USA; and
- Development of frameworks for prioritising weed biological control targets.

CSIRO weed biological control programs in Australia

CSIRO's research has contributed to introduction of biocontrol agents for 34 different weeds in Australia since the 1930s, and extensive research on new weed targets is ongoing (Table 4.3). Discussing outputs and subsequent outcomes of such activities, 13 target weeds have been selected as a representative sample of CSIRO biological control programs (Appendices 1, 2).

Table 4.3: weeds targeted by biological control programs that involved CSIRO across three time periods: 1930-1989; 1990-2006; 2007-2017[2]. For the period 2007-2017, a biocontrol agent has so far been released only for Crofton weed and research is currently underway for the other targets.

1930-1989	1990-2006	2007-2017
Mistflower *(Ageratine riparia)*; ragwort *(Jacobaea vulgaris)*; St Johns' Wort *(Hypercium perforatum)*; Lantana *(Lantana camara)*; Creeping lantana *(Lantana montevidensis)*; Noogoora burr *(Xanthium strumarium)*		
Alligator weed *(Alternanthera philoxeroides)*; Bridal creeper *(Asparagus asparagoides)*; Nodding thistle *(Carduus nutans)*; Slender thistles *(Carduus spp. – C. pycnocephalus & C. tenuiflorus)*; Skeleton weed *(Chondrilla juncea)*; Paterson's curse *(Echium plantagineum)*; Common heliotrope *(Heliotropium europaeum)*; Scotch, Stemless & Illyrian thistles *(Onopordum spp.)*; Docks *(Rumex spp.)*; Salvinia *(Salvinia molesta)*; Water hyacinth *(Eichornia crassipes)*; Water lettuce *(Pistia stratiotes)*; Common wireweed *(Sida acuta)*; Arrowleaf sida *(Sida rhombifolia)*; Double gee, spiney emex *(Emex Australis)*; Devil's thorn *(Emex spinosa)*		
	Scotch broom *(Cytisus scoparius)*; Mesquite *(Prosopis spp.)*; Bellyache bush *(Jatropa gossypiifolia)*	
	Boneseed *(Chrysanthemoides monilifera subsp. monilifera)*; bitou bush *(Chrysanthemoides monilifera subsp. rotundata)*; Parkinsonia *(Parkinsonia aculeata)*; Montpellier broom, French broom, Cape broom *(Genista monspessulana)*; cabomba *(Cabomba caroliniana)*; Blue heliotrope *(Heliotropium amplexicaule)*; Fireweed *(Senecio madagascariensis)*	
		Crofton weed *(Ageratina adenophoro)*; African boxthorn *(Lycium ferocissimum)*; Flaxleaf fleabane *(Conzya bonariensis)*; sowthistle *(Sonchus oleraceus)*; Tropical soda apple *(Solanum viarum)*; Brazilian pepper tree *(Schinus terebinthifolius)*; Cape ivy *(Delairea odorata)*; Angled onion *(Allium triquetrum)*; Stinking passionflower *(Passiflora foetida)*; Sea spurge *(Euphorbia paralias)*; Wandering trad *(Tradescantia fluminensis)*; Balloonvine *(Cardiospermum grandiflorum)*
Blackberry *(Rubus fructisosus agg)*; Mimosa *(Mimosa pigra)*		

SOURCE: CSIRO

Enhancing CSIRO biological control programs with stakeholder involvement in Australia: Examples

Biological control of Paterson's curse across Southern Australia

In the 1970's, Paterson's curse was the most widespread, costly, and toxic broadleaved agricultural weed in Australia, covering more than 10 million hectares, and costing nearly $40 million a year in lost production. CSIRO initiated a biological control program for Paterson's curse in France in the 1970's[12]. Early releases led to a high court challenge by graziers and bee keepers from South Australia, showing assessment and management of conflicts of interest in biological control programs needed better policy instruments. This issue was ultimately resolved through an independent government inquiry (including the first comprehensive cost-benefit analysis of a classical biological control program globally) and the development and enactment of the Biological Control Act (1986).

Distribution and evaluation of agent impacts through an MLA funded CSIRO-led consortium involving all the southern States ended in 2006, although state-based redistribution of agents continued for several years after this time, as did observations of the impacts of the agents. Since CSIRO funded activities ended, the spread of agents has been a farmer led activity, some through

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[2] Biocontrol programs for each weed are specific to dates and years within each period, and are not consistently indicative of work carried out across entire periods.

small enterprise. The ownership of the program and its benefits passed to the farming community and Landcare groups.

Mimosa biological control in Arnhem Land

Since the 1990s, CSIRO has worked closely with traditional owners and indigenous land management agencies toward the biological control of Mimosa. The last agents were released in 2007. Work since that time has involved redistributing agents in partnership with the Northern Territory Government. In 2016, Alligator Energy (AE) commissioned CSIRO to provide inputs on the management of invasive weeds on its tenements in Arnhem Land, Northern Territory. CSIRO used their historic work on Mimosa biological control as an awareness raising and educational activity to engage with traditional owners and indigenous ranger groups and involved them in field collection, rearing, and dissemination of the biocontrol agent/s to facilitate landscape scale control of the weed. Activities involving awareness raising and education of stakeholder groups included: carrying out a survey of AE's tenements for the presence of Mimosa biocontrol agents; assessing the need for introduction/redistribution of biocontrol agents in relation to existing weed management practices as on-site integrated weed management approach; developing protocols for the rearing of the biocontrol agent/s in close proximity to the tenements and their dissemination; and assisting AE to work with traditional owners and their land management agencies in the field collection, rearing, and dissemination of the biocontrol agent/s.

Bridal creeper biological control[13]: non-specialist community rearing and release of two agents

The two main biocontrol agents for bridal creeper, an undescribed leafhopper (Tribe Erythroneurini) and a rust fungus (*Puccinia myrsiphylli*) were released in 1999 and 2000, respectively. Populations of the leafhopper can increase rapidly, with the insect having multiple generations per year. This meant that rearing by non-specialists was possible following the initial release. CSIRO activities have included training primary schools and community groups to rear leafhoppers in Western Australia and South Australia. Mass-culturing of the rust fungus was performed by CSIRO in Canberra, with materials supplied to participants in the large-scale release program. Participants were requested to report at the end of the bridal creeper growing season whether the agents had established and, if so, how far they had spread.

Parkinsonia biological control: release and field evaluation of two new agents

Two new agents for Parkinsonia, the closely related leaf-feeding moths *Eueupithecia cisplatensis* and *Eueupithecia vollonides* (UU1 and UU2, respectively), were released in 2012 and 2014. CSIRO devised an optimal release strategy to ensure widespread establishment of the moths across infested rangelands of northern Australia. The strategy involved collaboration with numerous stakeholders, who helped release the mass-reared agents, and documented their establishment and initial impacts (Figure 4.2). CSIRO undertook a preliminary cost-benefit analysis of the biological control program and identified the role that the biocontrol agents can play within an integrated management approach for Parkinsonia.
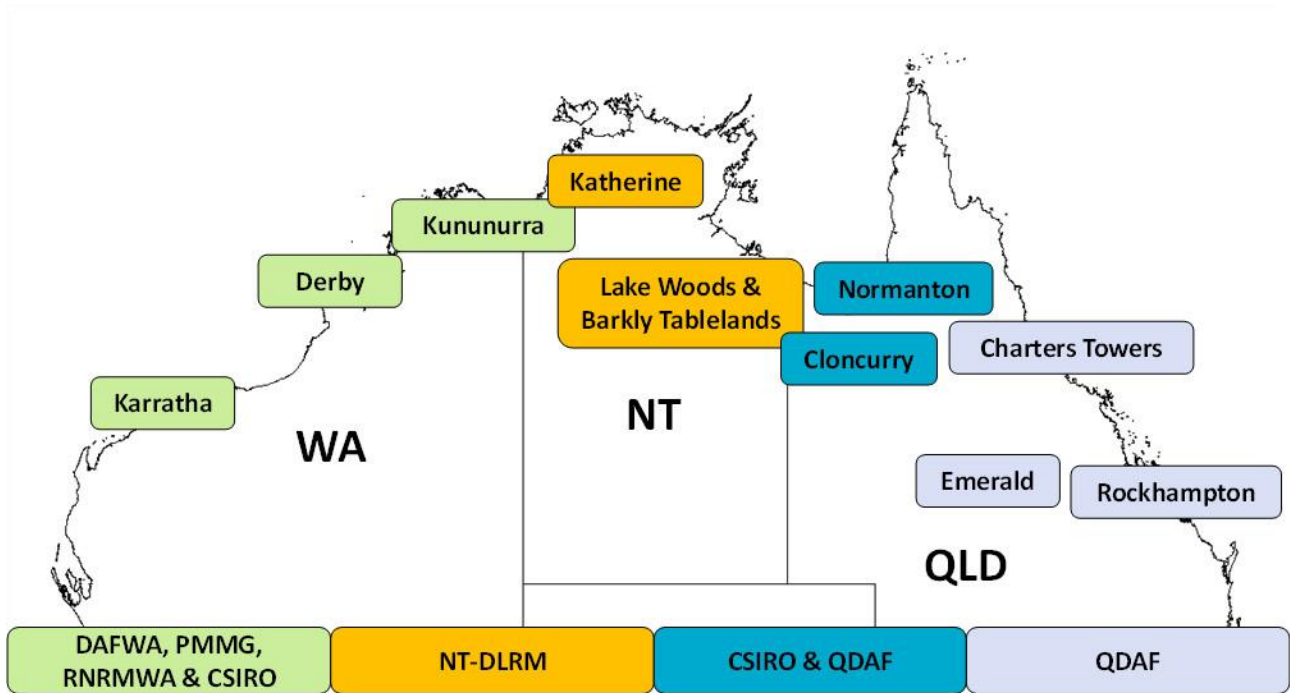
Figure 4.2: Coordinated release of E. cisplatensis and E. vollonoides across Parkinsonia infestations in Northern Australia was enabled by key collaborations in QLD (Department of Agriculture and Fisheries (QDAF)), WA (Department Of Agriculture and Food WA (DAFWA); Pilbara Mesquite Management Group (PMMG); Rangelands NRM WA (RNRMWA)) and NT (NT Department of Land Resources Management (NT-DLRM)).

Biological control of Australian broad-leaved paperbark tree[11] in Florida, USA

The cooperative CSIRO/USDA-ARS Australian Biological Control Laboratory has been involved in the broad-leaved paperbark tree project since its inception in 1987 through to 2017. CSIRO activities complemented a broader intention to restore the Florida Everglades by re-engineering hydrology to supply more water to the system at appropriate times of the year. Associated native plant communities were also identified as valuable for restoration of the Everglades. Weeds, in particular the Australian broad-leaved paperbark tree, are threatening the Florida Everglades by invading and transforming associated wetland habitat and plant communities. CSIRO became involved where traditional weed control measures (herbicide applications and mechanical harvesting) proved ineffective in controlling this invasive tree. It contributed to the development of a biological control program that would inhibit stand regeneration of the tree. Extensive consultation with relevant stakeholders informed achievable goals, particularly a reduction in the spread of this tree through targeting reproduction and regrowth. Progress was maintained through continued consultation with US stakeholders and their committed investment in the project, including an outreach program of tours and workshops with greater than 40 public agencies, private companies, and NGOs across 1.4 million acres.

The successful biological control program released agents that could prevent flowering or seed production, or increase mortality of seedlings and saplings. CSIRO performed extensive field surveys to find candidate biocontrol agents and testing to demonstrate their specificity. As a result four biocontrol agents were released in Florida: the weevil *Oxyops vitiosa*, the psyllid

Boreioglyaspis melaleucae, the gall-fly *Fergusonina turneri*, and the stem-galling midge *Lophodiplosis trifida*. CSIRO was involved in all stages of the project, including active participation in USDA-led workshops run in Florida related to this project.

Prioritisation of weed biological control targets through framework development[14]

Since 2015, CSIRO has developed and applied sector-specific frameworks to prioritise weed targets for biological control investments by a range of customers – Meat and Livestock Australia, the NSW Environmental Trust, and US Department of Agriculture (USDA). Built on CSIRO experiences prioritising weed species relevant to Australian livestock industries for biological control[15], the approach engages experts in prioritising weed lists relevant to a sector as targets for biological control based on their impacts or threats, and the likelihood and feasibility of biological control achieving desired management goals. Weeds were categorised within the frameworks using available evidence against agreed criteria for each category. These assessments drew on general ecological and biological control expertise, as well as knowledge of relevant biological control programs, to identify factors that may aid or prevent successful biological control, and to assess how easily any barriers could be to overcome. Written rationales for all categorisations, including identifying any areas of uncertainty, were captured.

Outputs

CSIRO Weed biological control programs in Australia

Since 1930, CSIRO's research has contributed to the introduction of 126 different agent species for biological control of 34 weeds in Australia. The number of different agent species introduced per weed, and the number established in the field, represent the applied outputs of these programs. Outputs from 13 biological control programs that targeted different weeds are included in this case study to provide a representative sample. For these 13 representative biological control programs, CSIRO was involved in the research that underpinned the introduction of 73 different agents. Of these, 50 agents are established in the field (68%) and are recorded at varying geographic scales and abundance (Appendix 1). How these established agents performed in the field and contributed to the management of the target weeds are discussed as part of the program's Outcomes.

Enhancing CSIRO biological control programs with stakeholder involvement in Australia: Examples

Biological control of Paterson's curse across Southern Australia

Over its 30 year life, the program developed into a national network across all southern states[12]. Seven biological control agents were selected, import risk assessed, and released into Australia of which six established and spread. Most of these agents were mass reared in most states and redistributed to contracted numbers of nursery sites in each of the affected areas, where impacts were monitored. Farmers were trained in biological control practices, and the Paterson's curse biocontrol agents in particular. These farmers obtained agents for their own properties/locations via field days leading to community led redistribution programs. The need for broader distribution

of agents also led a state-based federally funded national redistribution program (covering other weed biological control programs as well) from 2006-2009.

Mimosa biological control in Arnhem Land

Through engagement with the traditional owners and Alligator Energy, the value of CSIRO's historical Mimosa biological control program was expanded into Arnhem Land. This facilitated a rearing and release strategy for biocontrol agents of Mimosa in Arnhem Land and on AE's tenements. Foundational information to enable landscape-scale control of this weed was gathered as part of this work, and included:

- identifying locations of Mimosa presence in AE's tenements
- understanding need for introduction and redistribution of biocontrol agents related to existing on-site integrated weed management practices and approaches
- building capacity to work with traditional owners and land management agencies in rearing and dissemination of agents.

In addition to complementing AE's land management obligations, indigenous engagement enabled a productive three way exchange (traditional owners-industry-CSIRO) of insights and information about sustainable natural resource management in natural and post-mining landscapes. This engagement spanned six indigenous ranger groups in Arnhem Land under the broad umbrella of the Northern Land Council.

Bridal creeper biological control: non-specialist community rearing and release of two agents

Community groups and land managers across Australia embraced the biological control program of bridal creeper with enthusiasm and were actively involved in the large-scale release of the leafhopper and rust fungus. Primary schools and community groups were also involved in the rearing of the leafhopper in the early days of the release program – for example, by the end of 2000, up to 40 schools and groups in Western Australia and South Australia had participated in the rearing[16]. By 2006, the leafhopper and rust fungus had been released at more than 850 and 1700 sites across Australia, respectively, in partnership with the community[13]. The two agents readily established at release sites; but populations of the leafhopper greatly fluctuated over subsequent years.

Parkinsonia biological control: release and field evaluation of two new agents

Between 2014 and 2016, over 850 000 UU1 individuals were released at 112 sites across northern Australia (Queensland, Northern Territory, and Western Australia). Fourteen of these were nursery sites where higher numbers were released to enable rapid colonisation of agents. From 2015 to 2016, over 210 000 UU2 individuals were released at 19 sites across northern Australia. Nine of these were nursery sites. The coordinated release of UU1 and UU2 involved a network of collaborators in rearing and release activities, comprising 60 different landholders and NRM groups. Permanent populations of the two moths were established at more than 60 per cent of the release sites. In contrast, establishment success was greater than 75 per cent at nursery sites. Defoliation of the weed was evident in all sites where the agents established.

**Biological control of Australian broad-leaved paperbark tree in Florida, USA**

Of the four biocontrol agents released against broad-leaved paperbark tree in Florida, three successfully established and spread. The weevil established readily at dry and seasonally wet sites, but not in flooded sites. The psyllid established quickly and dispersed rapidly throughout the range of the weed in Florida. Mortality of coppicing stumps increased in conjunction with infestations of the weevil. The gall-fly failed to establish. The stem-galling midge was initially released at 24 sites distributed throughout southern Florida in stands of the weed of varying sizes and hydrology. Gall-midge dispersal has been occurring at a rate estimated to be 20 km per year since the release.

Prioritisation of weed biological control targets through framework development

The prioritisation framework developed from CSIRO's experiences prioritising the livestock industry shortlisted 13 weeds for consideration as biological control targets, based on the trade-off between potential impact and prospects for biological control[17]. Only two of the short-listed weeds are new targets for biological control, reflecting the maturity of the biological control discipline targeting weeds of the livestock industry in Australia. A similar prioritisation framework, specifically designed for the NSW Environmental Trust[18], short-listed 17 environmental weeds as priority targets for biological control. Recommendations from this prioritisation exercise were taken on board by the Trust, resulting in new investment for research on five of the short-listed weeds.

Publications/ Citation

The science output and profile of CSIRO's weed biological control research have been significant, as evident from the results of a search of the Web of Knowledge database (Figure 4.3). The total publications and citations between 1990 and 2017 are 356 and 11,498 respectively.
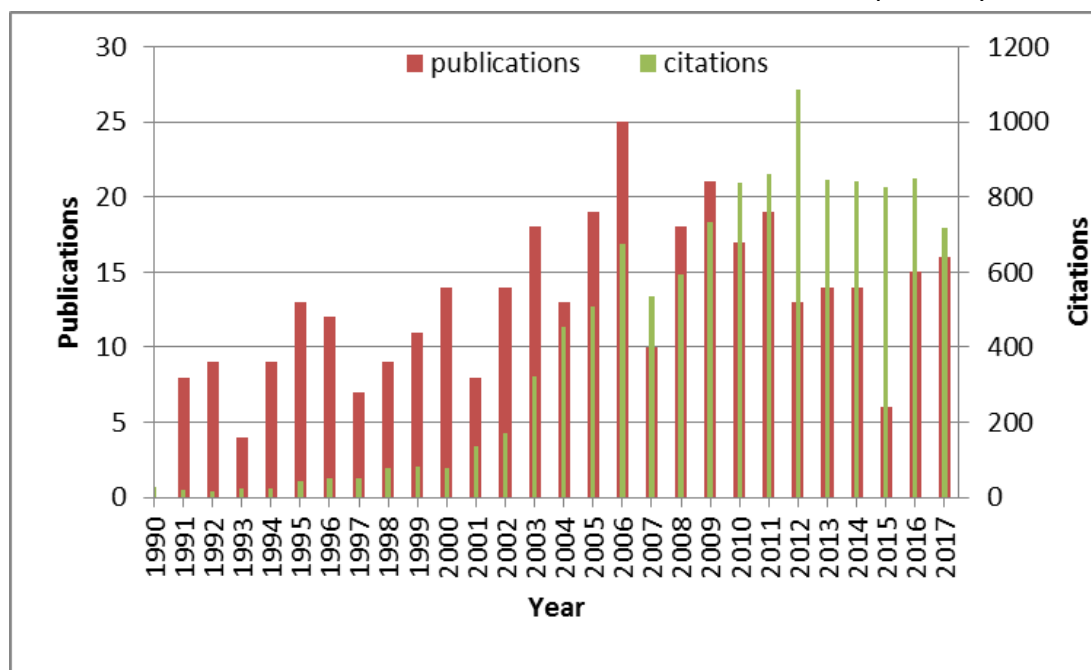
Source: CSIRO

Figure 4.3: Publications and citations of CSIRO'S research related to weed biological control

Outcomes

Beneficiaries of CSIRO research in weed biological control

The potential users of the research outputs include three main stakeholder groups (Table 4.4):

- Commonwealth and State environment protection agencies and regulators
- agricultural industries
- the broader community.

Table 4.4: Beneficiaries of CSIRO research in weed biological control, with selected examples of the benefits.

Stakeholder	Selected examples
	Biological Control Act (1986): CSIRO Paterson's curse biological control program's issues around conflicts of interest in the 1980's led to the enactment of new legislation – The Biological Control Act (1986) and new associated regulatory processes. CSIRO research has also continually contributed to regulatory processes applied for the selection of biological control targets and the import risk assessment for approval of importation and release permitting of potential biocontrol agents.
Government	**Australian Weeds Strategy**: CSIRO weed biological control research is directly relevant to Priorities 2.4 and 3.2 of the Australian Weeds Strategy.
	Target weed prioritisation frameworks: Accessing the in-depth functional understanding of experts resulted in explicit characterisation of the barriers to successful biological control and if/how they might be overcome, improved characterisation of uncertainty, and provided directed guidance for investment.
	Alligator weed agent: *Agascicles hygrophila* Successful control of floating mats in NSW within 2 years of release. Provided control in QLD within 10 months of redistribution. No effect in terrestrial habitat. It replaced Liverpool City Council's chemical control program costing approximately $26,000 per annum. *Arcola malloi*, a leaf-feeding moth, was first released in 1977, and established to attack alligator weed in warm temperate water but not on land. Associated benefits: improved water flows; greater light penetration; improved drainage; increased oxygen levels; reduced water loss through evapotranspiration; reduced sedimentation; reduced flooding; and the reduction in the number of disease vectors through the removal of alligator weed, which harbours these disease vectors.
Industry	**Skeleton weed agent:** *Puccinia chondrillina* This agent is the key contributor to this program considered one of the most successful biological control programs of a weed of broad acre crops. By 2000, annual savings to farmers amounted to $290 million. By 2005, skeleton weed was no longer considered a serious weed for cropping areas of southeast Australia.
	Paterson's curse biological control: The success of this program over the last ten years has brought widespread (national) multi-million dollar benefits to the livestock/grazing industries through improved animal health, increased productivity, and reduced control costs from Tasmania to Western Australia. The scale of the benefits puts this program second only to the successful prickly pear biological control program of the 1930's.
	Bridal creeper biological control:

	Biological control is a less intensive approach to manage bridal creeper compared to mechanical control and/or herbicide application. The two key agents released have reduced control cost of bridal creeper to Murray Valley citrus industry by approximately $10.7 million.
Public	**Parkinsonia biological control:** A network of biological control-literate collaborators comprising 60 different landholders and NRM groups.
	Bridal creeper biological control: The involvement of schools and community groups in the rearing and/or release of agents increased awareness among stakeholders of weed biological control and natural resource management in general. The two key agents released as part of the biological control program have resulted in a significant suppression of bridal creeper populations in natural ecosystems in coastal areas across Australia.
	Broad-leaved paper tree biological control in Florida: Original infestations of the weed, which occupied over 200,000 ha, have been reduced to about 110,000 ha, most of which are on private land.

CSIRO Weed biological control programs in Australia

Of the 50 established agents in the 13 representative weed biological control programs included in this case study, 37 have generated measurable weed control outcomes. Outcomes are measured on a control efficacy scale ranging from none, slight, variable, or medium, to significant. For 6 of the 50 established agents, it is too early post release to detect measurable weed control outcomes. Of the 37 established agents generating measurable control outcomes, 9 (24%) achieved slight control, 12 (32%) variable; 7 (19%) medium, and 9 (24%) significant control (see Appendix 2).

Enhancing CSIRO biological control programs with stakeholder involvement in Australia: Examples

Biological control of Paterson's curse across Southern Australia

This CSIRO-state program consortium led to the completely successful biological control program for this target across all states and territories, from three highly effective biocontrol agents for *Echium plantagineum*: the crown weevil *Mogulones larvatus*; the root weevil *Mogulones geographicus*; and the flea beetle *Longitarsus echii*[12]. The root feeding flea beetle was the most effective agent in drier areas including, Western Australia; while the weevils were more effective in higher rainfall areas, including Tasmania. While no funding has been available to formally evaluate the effectiveness of this program, the historic "blue hills", or even fields, of Paterson's curse in spring have progressively disappeared over the last 10 years. All collaborating farmers have confirmed that their horses and livestock are no longer dying from consumption of the weed; and that they no longer need to spray their properties for the weed. Surveys in northern Victoria suggest that weed densities and biomass have dropped between 80 and 90 per cent, with similar results being observed in South Australia and Western Australia. An economic assessment for this

control program has shown that for a research and development investment of $23.1 million, the net present value benefits are on target to be $1.2 billion by 2050[1].

Mimosa biological control in Arnhem Land
Mimosa biological control has successfully expanded into Arnhem Land through engagement with six indigenous ranger groups under the broad umbrella of the Northern Land Council. This represents increased awareness of biological control to facilitate weed management on land under native title. Stakeholder involvement is expected to provide a foundation for development and/or deployment of other biological control programs and integrated weed management approaches on indigenous lands.

Bridal creeper biological control: non-specialist community rearing and release of two agents
The involvement of schools and community groups in the rearing and/or release of agents increased awareness among stakeholders of weed biological control and natural resource management in general. The two key agents released as part of the biological control program have resulted in a significant suppression of bridal creeper populations in natural ecosystems in coastal areas across Australia. The rust fungus has been particularly effective. Repeated, severe infection of bridal creeper has provided substantial reduction of below-ground biomass and shoot production – effects that have increased over sequential years and in combination with the leafhopper. This biological control program has been so successful that there has been no need for redistribution of the biocontrol agents for many years.

Parkinsonia biological control: release and field evaluation of two new agents
Work toward integrated management of Parkinsonia involved a collaborative approach, which resulted in a network of biological control-literate collaborators comprising 60 different landholders and NRM groups. Among the permanent agent populations established at the release and nursery sites, defoliation of the weed was evident. Beyond this it is too soon to measure outcomes of the two released agents.

The network of biological control-literate collaborators will assist in monitoring agent performance, once already released UU1 and UU2 populations reach sufficient density. Once sufficient density is reached, evaluation and characterisation of impacts of the agents, including strengthening the inferred link between defoliation and demographic consequences for Parkinsonia, will assist to more robustly test the assumptions and projections of the cost-benefit analysis[19]. In addition this network of collaborators can be accessed to manage other similarly widespread weeds across Northern Australia.

Biological control of Australian broad-leaved paperbark tree in Florida, USA
Biological control of broad-leaved paperbark tree in the Florida Everglades has significantly contributed to conservation and restoration efforts of the Everglades National Park. This project provides a clear example of the contribution that CSIRO biological control expertise can play in conservation and restoration of highly human modified natural ecosystems. Broad-leaved

paperbark tree has been removed from most public lands; and biological control has limited its ability to invade further into the National Park and regenerate in invaded areas. No non-target damage has occurred. The reduction in use of other control measures required to arrest the invasiveness of this tree, as well as the restoration of native plants in previously invaded ecosystems, is testament to the success of the project. Original infestations, which occupied over 200,000 ha, have been reduced to about 110,000 ha most of which are on private lands. The processes following the successful implementation of a biological control program serve as a model for contemporary and future biological control projects.

Prioritisation of weed biological control targets through framework development
Accessing the in-depth functional understanding of experts resulted in the explicit characterisation of the barriers to successful biological control and if/how they might be overcome; improved characterisation of uncertainty; and provided directed guidance for investment. Such an approach would be readily applicable to analogous decision-making challenges in other sectors and countries. The prioritisation framework should be directly applicable to prioritising weed biological control investment in and across other sectors of agriculture and the environment, as evident with CSIRO's ongoing work with the US Department of Agriculture in prioritising weeds of the western US for biological control. This expanded role of experts should be applicable more broadly to similar decision-making challenges facing natural resource management[17].

Effective use of the prioritisation framework for target weeds is dependent on experts' functional understanding of the system, beyond elicitation of facts and judgements. As such, potential for increased critique of the resulting prioritisation will remain where identifying and addressing potential pitfalls in using experts is not addressed[17].

Evaluation of agent performance against target weeds
Post hoc evaluation of weed biological control programs is difficult to resource when (a) beneficial impacts increase over multi-year (often decadal) timeframes; and (b) there are many other potential target weeds that require funded biological control programs. Without funded monitoring and evaluation programs, it is very hard to rigorously analyse the beneficial impacts of such programs, which influences how outcomes are measured and evaluated, and undermines the understanding of the true benefits of the investments into weed biological control. Evaluation of agent performance at reducing the ecological, social, and economic impacts of weeds is also not without its challenges. Relying on baseline data and performance targets against which an agent performance can be measured over time is required to better evaluate outcomes. As with all environmental and social impact evaluation of applied research, reliable mechanisms for benefit quantification are still elusive; although the ecosystems services approach that emerged out the Millennium Ecosystem Assessment[20] is a way forward and is applicable to the evaluation of other biological control programs[21]. Investment in such research could remove a barrier to accurate measurement of outcomes[22].

Impacts

The impact or success of biological control can affect a range of stakeholders, from individual landholders through improved productivity or a decrease in control costs, to the community through social issues such as health impacts and amenity values, and the environment through reductions in threats to native ecosystems and biodiversity. Using CSIRO's triple bottom line impact classification approach, Table 4.5 summarises the nature of the existing and potential impacts.

Table 4.5: Summary of project impacts

TYPE	CATEGORY	INDICATOR	DESCRIPTION
Economic	Productivity and efficiency	Yield & production	Weeds compete with cultivated and forage plants for soil nutrients. Weeds may also host pathogens, be of low palatability, or encourage the growth of animal pests. By controlling weed populations, agricultural producers can avoid crop losses, increase yield or livestock stocking rates, and increase production.
Economic	Productivity and efficiency	Control costs	Traditional weed management programs are both time consuming and costly. The use of biocontrol agents to manage weed populations can reduce the need for farms to use herbicides, thus reducing operating costs.
Economic	Animal health	Improved animal condition and reduced mortality	Many pasture weeds are toxic to livestock and horses resulting in poor animal health and deaths. Effective control of such weeds leads to improvements in animal health.
Environmental	Ecosystem health and integrity	Biota health	Introduced plants can out-compete native flora. Biocontrol agents for weeds that have minimal adverse impacts on non-target species can improve ecosystem health and integrity.
Environmental	Land quality	Soil quality	Chemical leaching can contaminate soils. The use of biocontrol agents to control weed populations can reduce the need for farms to use herbicides, thus improving soil quality.
Environmental	Aquatic environments	Water quality	Chemical runoff and leaching can contaminate rivers, streams, and groundwater. The use of biocontrol agents to control weed populations can reduce the need for farms to use pesticides, thus improving water quality.
Social	Resilience	Income, employment	Improvements in agricultural output resulting from improvements in weed control increase the viability of many agriculture-dependent communities – especially those with fewer alternative employment opportunities.

Social	Health	Psychological wellbeing	Improvements to land values from intractable weeds and in animal health from toxic weeds produce significant psychological health improvements for land managers and farmers.
Social	Health	Allergies	Suppression of weeds with highly allergic properties to which they are exposed can lead to better direct outcomes for human health.
Social	Cultural	Aesthetic health	Suppression of monocultures of invasive plants leads to restoration of habitats, ecosystems and landscapes which improve the cultural and spiritual benefits from "country" including for traditional owners.

5   Clarifying the Impacts

Counterfactual

Numerous weed control methods exist and are used by land managers. Since the dependence on chemical control options from the 1950's, of particular concern for agricultural producers has been the reduction in the effectiveness of traditional chemical weed control methods as weeds develop resistance to herbicide treatment[23]. Also, increasing numbers of agrochemicals are being deregistered because of environmental concerns. Although chemical control methods will continue to be researched by some companies in both Australia and globally, the increasing costs of developing and approving new chemical actives is pushing the agrochemical sector into exploring biologicals. This situation, combined with changing community expectations regarding herbicides, means it is highly likely that the benefits of biological control evaluated in this report will compounded by the declining generic effectiveness of herbicide applications.
Biocontrol agents of weeds, once established, are mostly self-sustaining and do not have to be reapplied. Biological control is a demonstrably environmentally benign and relative cost-effective method of managing many of Australia's most pressing agricultural and environmental weeds in the long-term. The initial costs of biological control programs are generally high. This is because suitable candidate agents have to be found overseas, tested for safety in quarantine, and made to comply with regulations around release. However, once biocontrol agents are released, and affect the weeds across its invaded range, costs become negligible as follow up control costs are greatly reduced.

Extensive research on weeds in general in Australia in addition to CSIRO is performed by universities, industry, and state and federal government agencies. However, only three other agencies (QDAF, VicDEDJTR, and NSWDPI) are actively involved in the development and implementation of weed biological control solutions. As part of the cross jurisdictional regulatory processes, all exotic biocontrol agents undergo mandatory host-specificity testing to understand direct non-target risks to non-target species. The infrastructure needs and costs involved in

selecting low risk and effective biocontrol agents are substantial. As a national agency, CSIRO is the only agency capable of working across state jurisdictional boundaries; boundaries that are artificial in a weed management context.

The counterfactual scenario describes what happens if CSIRO's biological control technology is no longer supported and not implemented, and the status quo or extension of current trends prevails. The counterfactual scenario includes the following two broad key elements:

- Limited adoption of classical biological control as a benign and relatively cost-effective method of managing many of Australia's most pressing agricultural and environmental weeds. Current trend of significant economic, environmental, and social impacts of weeds on natural landscapes, agricultural land and waterways prevail.
- There remains high ongoing costs and environmental impacts of weed management using other methods of control such as herbicide applications.

6   Evaluating the Impacts

Modelling approach

This section examines the impacts that classical weed biological control programs have generated (economic, social, and environmental). This analysis explores two types of impacts: economic and non-economic. Economic impacts are considered to have a definitive dollar value, such as an increase in yield; an increase in productivity; or a reduction in costs expended to manage the target species. Non-economic impacts are those that are qualitative, such as decreased toxicity to the environment; preservation of native biodiversity and ecosystem services; preserved cultural values and scenic amenity; and decreased stress to farmers or facilities.

We calculated the biological control research outcome deployment and counterfactual scenarios to determine the value of the entire research program benefits (where quantification is possible). The counterfactual scenario represents the pathway where the research is not implemented and a 'status quo' or extension of current trends prevails. The benefits calculated in the analysis are the net benefits from the program – that is, the difference between the "with" and "without program" scenarios. The analysis is equivalent to carrying out separate analyses for the "with program" and "without program" scenarios and calculating the difference between them.

Many of the assumptions required to value the impacts for each biological control investment are uncertain due to data constraints. While reasonable and conservative assumptions have been made in the analyses, the results should be viewed with some caution. This valuation provides a ballpark estimate of the potential net benefits. There is, therefore, a need for a follow-up revision of the valuation once more accurate and timely data becomes available, particularly related to efficacy of control profiles across sites, and where relevant adoption and uptake for release of agents across more sites.

We believe that the best way to define the "with" and "without" scenarios is to adopt the approach employed by Page and Lacey (2006). The steps in quantifying the gains from the program are as follows:

Weed distribution
- Include data about densities of weed species by different zones such as high rainfall, wheat-sheep and pastoral zone.
- Scientific literature summarised in relation to distribution and potential for weed.

Agricultural production
- Include data about livestock numbers and areas cropped by ABARES region.
- Gross margin data summarised for different states and average derived for cattle, crop, and other industries.

Valuation of Impact
- Weed distributions are superimposed over values of agricultural production in each region.
- Estimates of reduced carrying capacities, yield losses and weed management costs.
- Aggregate weed-related costs are calculated.
- Health impacts valued where possible.
- Biodiversity impacts valued where possible.
- Total costs (control and losses).

Refresh of the Cost Benefit Analysis results from 2006

We have refreshed and updated an economic analysis undertaken in 2006[4] for a sample of eight weed biological control programs to bring the costs and benefits calculated up to date (Table 6.1). The 8 programs were selected as aligned with the representative 13 programs discussed above, comprising a mix of target weeds that affect waterbodies, agriculture, and the environment across different regions of Australia.

Costs and benefits have been recalculated in order for them to be expressed in a dollar value at a common point in time, namely in 2016-17 dollars, using the Consumer Price Index. Present value calculations of costs and benefits have also been harmonised so that they have a common base year (2016-17) across the programs. A real discount rate of 7 per cent has been assumed in these present value recalculations[3]. It is important to emphasise that we have not sought to review the assumptions underpinning the 2006 report.

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[3] One key metric of a cost-benefit analysis is the Present Value (PV) of costs and benefits. Net Present Value (NPV) is the difference between the present value of benefits and the present value of costs over the chosen analysis period (which varies between programs) under the chosen discount rate (in this case 7 per cent). The discount rate is applied to reflect the fact that the value of a dollar in the future is less than it is now.

The costs considered in the cost-benefit analyses include the costs incurred by CSIRO and its research partners to produce research outputs, such as staffing costs and in-kind contributions (including those relating to equipment/facilities and background intellectual property). Where data are available, usage and adoption costs borne by end-users (such as the cost of releasing agents in the field and monitoring their establishment and impact) are also included.

Benefits considered include increased economic activity in Australia generated by the implementation of the biological control programs, specifically savings in control costs and agricultural production, as well as the valuation of any environmental benefits that flow from the research undertaken by CSIRO and collaborators.

Table 6.1: Summary of the refreshed cost-benefit analysis results from eight selected weed biological control programs with CSIRO'S involvement, based on 2006 analysis[4]

Weed project	Period (CSIRO involvement)	PV benefits (2016/17 $m)	PV costs (2016/17 $m)	NPV (2016/17 $m)
Alligator weed (*Alternanthera philoxeroides*)	1976-2004	0.4	1.1	-0.7
Bridal creeper (*Asparagus asparagoides*)	1990-2004	11.1	5.4	5.7
Nodding thistle (*Carduus nutans*)	1986-2000	109.8	16.1	93.7
Skeleton weed (*Chondrilla juncea*) *	1960-2006	1924.4	17.1	1907.3
Paterson's curse/ salvation Jane (*Echium plantagineum*)*	1972-2006	1621.8	31.2	1590.6
Mimosa (*Mimosa pigra*)	1981-2004	8.2	10.3	-2.1
Scotch, stemless and Illyrian thistles (*Onopordum* spp.)*	1988 - 2006	27.1	2.8	24.3
Mesquite (*Prosopis* spp.)*	1992-2006	1.1	2.2	-1.1
Ragwort (*Jacobaea vulgaris*)	1977-2005	131.2	4.1	127.1
Total where benefits have been quantified		**3835.1**	**90.3**	**3744.8**

* It is unclear what the start and/or end date of the research period and estimates were made based on best available information.

For some programs, the expected annual environmental benefits are reported when full adoption of the research outcomes has been achieved (e.g. mesquite) [4]. These annual benefits were not included in Table 6.1 for reasons of consistency.

The present value of benefits across the 8 weed biological control programs selected, where benefits data was available, is approximately $3.8 billion in 2016/17 dollars under a 7 per cent discount rate. Also, benefits from effective biological control have continued to grow for some targets since 2006 (e.g. Paterson's curse), suggesting some updated values based on 2006 data may now be very conservative estimates of return on investment.

Estimated annualised benefits from CSIRO weed biological control research compared to operating expenditure

Classical biological control research can be viewed as a rolling and evolving investment. In the discussion below, we assume this portfolio has evolved to a point of being reasonably stable in its performance through time. Some biological control research approaches mature and are passed out to industry, government, and general public users. Some do not live up to expectations. New

opportunities emerge, or existing approaches under development begin to show greater promise and more resources are applied. Over time, we assume that outcome is a rolling investment strategy with a flow of benefits. There will be occasional major breakthroughs of very high value (i.e. highly impactful agents), but we assume that it is reasonable to proceed on the basis of CSIRO's biological control research having a portfolio that involves annual investments and a rate of benefit generation.

The same logic can be applied down to the level of individual weed biological control programs - and the eight programs considered in this economic impact evaluation. Each of these involve investment over a number of years – that can be translated to an average level of annual expenditure. Each program yields impacts with value – value that will typically accumulate over many years into the future, and that can be summarised in terms of a net present value.

Contribution of CSIRO

Outcomes from the eight weed biological control programs selected can, to a significant extent, be attributed to CSIRO. Commonwealth and State governments, as well as Rural Research and Development Corporations, provided important co-financing for these programs. Industries and natural resources managers have also played an important role by providing access to trial sites, without which some of the research could not have been undertaken. Since both CSIRO and collaborators were considered necessary to achieve the ultimate objective of the biological control programs, it was appropriate to attribute benefits among the programs on a cost-sharing basis.

We estimate that CSIRO accounted for approximately 50 per cent of the total research costs. Consequently, in this analysis, it is assumed that roughly 50 per cent of impacts arising from the biological control programs can be attributed to CSIRO. The other 50 per cent is attributed primarily to government and industry.

Quantitative results from the eight weed biological control programs[4] updated to 2016/2017 values are summarised (Table 6.2), based on a standard discount rate of 7%. This CSIRO weed biological control research portfolio infers, as a conservative estimate that the eight programs delivered an average annual value in excess of $50.9 million. This is well above CSIRO's annual operating expenditure in weed biological control of approximately $6 million (2016/2017 price), comprising $3 million in external earnings annually. This amount is expected to be significantly higher had health and environmental benefits data been available and considered. It is also important to note that, in addition to its financial investment, CSIRO provides a contributions to weed biological control projects beyond direct financial investments. These are the intangible contributions; background IP, knowhow, key staff capabilities, not taken into account in this analysis, but without which impacts leading to the same level of public benefit would not be realised.

Table 6.2: Annualised benefits and cost 7% discount date

Weed project	Period (CSIRO involvement)	PV benefits (2016/17 $m) A	Contribution of CSIRO (%) B	CSIRO's PV benefits (2016/17 $m) C= A*B	R&D Time period (years) D	CSIRO's PV of benefits per year of R&D (D= A/C)
Alligator weed (*Alternanthera philoxeroides*)	1976-2004	0.4	50	0.2	12	0.0
Bridal creeper (*Asparagus asparagoides*)	1990-2004	11.1	50	5.6	15	0.4
Nodding thistle (*Carduus nutans*)	1986-2000	109.8	50	54.9	15	3.7
Skeleton weed (*Chondrilla juncea*)	1960-2006	1924.4	50	962.2	47	20.5
Paterson's curse/ salvation Jane (*Echium plantagineum*)	1972-2006	1621.8	50	810.9	35	23.2
Mimosa (*Mimosa pigra*)	1981-2004	8.2	50	4.1	24	0.2
Scotch, stemless and Illyrian thistles (*Onopordum* spp.)	1988 - 2006	27.1	50	13.6	18	0.8
Mesquite (*Prosopis* spp.)	1992-2006	1.1	50	0.6	14	0.0
Ragwort (*Jacobaea vulgaris*)	1977-2005	131.2	50	65.6	29	2.3
All projects where the available data enabled R&D costs and benefits to be annualised						**50.9**

7   Sensitivity analysis

Several weed biological control programs that CSIRO has led are Australian success stories. Analysis in this case study does, however, rely on data published in the Page and Lacey (2006) report[4] which is considered to influence the final results. In addition, the overall benefits of weed biological control programs significantly depend on eventual level of control achievement of social, economic, and environmental benefits[4].

Given these uncertainties, it is useful to look at results under different discount, adoption, and attribution rates. While the parameters used in the base-case scenario seemed reasonable in light of the current situation, it is important to test the robustness of our conclusions with variations in these assumptions. NPV calculations are particularly sensitive to changes in underlying parameters, so it is important to understand the results by perspective. Based on 40 simulations, we have therefore analysed variation in discount rate (1% to 10%) and the weed biological control program benefits (+/- 20% benefits) from the central cost benefit analysis (CBA). Results of this sensitivity analysis, provide that the PV benefits of the eight biological control programs is estimated between $20.5 million and $75.5 million per year.

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[4] There is a recognised limitation in readily available information about actual impacts on the target weed, other plant communities, pastures and ecosystems over time and various scales. Further explanation provided in section 8.

Table 7.1. Results of sensitivity analysis

Approach	Min (average low)	Mode (average weighting)	Mean (average mid-range)	Mean (average weighting)	Average high
Annual benefits ($m) 2016/17	20.5	44.6	36.7	39.5	75.5

8   Limitations and Future Directions

This evaluation used a mixed methodology to assess research impact of CSIRO's contribution to weed biological control programs. It combined quantitative and qualitative methods to illustrate the nature of economic, environmental, and social impacts. In cases where the impacts can be assessed in monetary terms, a CBA was used as a primary tool for evaluation. As a methodology for impact assessment, CBA relies on the use of assumptions and judgments made by the authors. This relates primarily to economic indicators for impact contribution, attribution, and the counterfactual.

For our analysis, we have relied on refreshed results from an existing study[4]; consultation with lead CSIRO researchers; and relevant literature. The distribution of biocontrol agents and actual effectiveness of the agent across the country were based on historic estimates only[4]. This is recognised as a limitation of our analysis. Given the scope and budget for this analysis, we acknowledge limitations in the evidence base of impacts. The refreshed results are therefore also subject to such limitations. However, it is important to emphasise that the Page and Lacey (2006) report is also based on a compilation of independent program based CBAs, and such CBA meta-analyses (albeit that this one is now a decade old) rarely exist for other applied research disciplines. It is also noted that benefits from the effective biological control have continued to grow for some targets since 2006 (e.g. Paterson's curse), suggesting some updated values are now very conservative estimates of return on investment.

These results were also subjected to sensitivity analysis and/or discretion as explicitly advised for the report. Social and environmental benefits are recognised through qualitative analysis and discussion, but are not quantified owing to a lack of reliable data and limitations by scope, time and budget for analysis. This data may be available in future years as ecosystem services approaches are increasingly adopted to quantify such benefits.

Impact analyses of outcomes are therefore associated with some uncertainty; and it is recognised that more data is required to substantiate analysis of effectiveness of biocontrol agents. A revisit to the analysis is therefore highly recommended when more up-to-date data become available. These limitations should be considered when interpreting the results presented in this case study.

9 References

1. Invasive Plants and Animals Committee. Australian Weeds Strategy 2017 to 2027. Canberra. Australian Government Department of Agriculture and Water Resources, 2016.

2. Biodiversity Assessment Working Group of the National Land and Water Resources Audit for the Australian Government. Threats to Australian biodiversity. Chapter 5 in: Assessment of Australia's Terrestrial Biodiversity. Canberra. Commonwealth of Australia, 2008.

3. Metcalfe D, Bui E. Regional and landscape-scale pressures: Invasive species. Land, 2016.

4. Page AR, Lacey KL. Economic Impact Assessment of Australian Weed Biological Control. CRC for Australian Weed Management, 2006. Technical Series No. 10, Glen Osmond, Australia.

5. Pejchar L, Mooney HA. Invasive species, ecosystem services and human well-being. Trends in Ecology & Evolution, 2009;24(9):497-504.

6. Biodiversity Assessment Working Group of the National Land and Water Resources Audit for the Australian Government, 2008.

7. Sinden J, Jones R, Hester S, Odom D, Kalisch C, James R, Cacho O. The economic impact of weed in Australia: report to the CRC for Australian Weed Management. CRC for Australian Weed Management Technical series 8, 2004.

8. Llewellyn R, Ronning D, Clarke M, Mayfield A, Walker S, Ouzman J. Impact of Weeds on Australian Grain Production – The cost of weeds to Australian grain growers and the adoption of weed management and tillage practices. Report for GRDC. CSIRO, Australia, 2016.

9. Weeds in Australia Database, Department of Environment and Energy. Impact of weeds.

10. Julien M, McFadyen R, Cullen J. Biological Control of Weeds in Australia, CSIRO Publishing

11. Center TD, Purcell MF, Pratt PD, Rayamajhi MB, Tipping PW, Wright SA, Dray Jr A. Biological control of *Melaleuca quinquenervia*: an Everglades invader. Biocontrol, 2012;57:151-165.

12. Sheppard A, Smyth M. *Echium plantagineum* L. – Paterson's curse. (Ed) Julien M, McFadyen R, Cullen R. In Biological control of weeds in Australia 1960 to 2010. 2012. pp. 211-227.

13. Morin L, Neave M, Batchelor KL, Reid A. Biological control: a promising tool for managing bridal creeper in Australia. Plant Protection Quarterly 2006;21:69-77.

14. Van Klinken R, Morin L, Sheppard A, Raghu S. Experts know more than just facts: eliciting functional understanding to help prioritise weed biological control targets. Biological invasions 2016;18:2853-2870.

15. Morin et al. Prioritisation of weed biocontrol targets for NSW. A Report for the NSW Environmental Trust, CSIRO, Canberra, 2016.

16. Morin L, Heard T, Scott J, Sheppard A, Dhileepan K, Osunkoya O, van Klinken R. Prioritisation of weed species relevant to Australian Livestock industries for biological control. Final Report. Meat & Livestock Australia Limited, 2013. ISBN: 978192504697.

17. Batchelor K, Woodburn TL. Community involvement in distributing the bridal creeper leafhopper *Zygina* sp., a biocontrol agent for bridal creeper; *Asparagus asparagoides*. In: Australian Weeds Conference

Papers and Proceedings (Eds.) Spafford JH, Dodd J, Moore JH.. Plant Protection Society of WA Inc. Perth. 2012:701-703.

18. Raghu S, White A, Fichera G. 2015. Parkinsonia biocontrol: release and field evaluation of two new agents. Meat & Livestock Australia Limited, 2015: p. 21.

19. Millennium Ecosystem Assessment. Ecosystem and Human Well-being: A Framework for Assessment. Island Press, 2005.

20. Fiedler AK, Landis DA, Wratten SD. Maximizing ecosystem services from conservation biological control: the role of habitat management. *Biological control*, 2008;45(2):254-271.

21. Morin L, Reid AM, Sims-Chilton NM., Buckley YM., Dhileepan K., Hastwell GT., Nordblom TL., Raghu S. Review of approaches to evaluate the effectiveness of weed biological control agents. Biological Control 2009;51:1-15.

22. Damalas CA, Eleftherohorinos IG. Pesticide exposure, safety issues, and risk assessment indicators. International Journal of Environmental Research and Public Health. 2011;8(5):1402-1419.

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As Australia's national science agency we've been pushing the edge of what's possible for over 85 years. Today we have more than 5,000 talented people working out of 50-plus centres in Australia and internationally. Our people work closely with industry and communities to leave a lasting legacy. Collectively, our innovation and excellence places us in the top ten applied research agencies in the world.

WE ASK, WE SEEK AND WE SOLVE