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Jade K. Matthews, Diane L. Fraser and Peter J. de Lange

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Contact:
epress@unitec.ac.nz
www.unitec.ac.nz/epress/
Unitec | Te Pūkenga
Private Bag 92025
Victoria Street West, Auckland 1010
Aotearoa / New Zealand

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Biological control of weeds in Aotearoa / New Zealand: History, science and achievements to date

Jade K. Matthews[1], Diane L. Fraser[1], Peter J. de Lange[1]

Affiliations:
1. **School of Environmental & Animal Sciences, Unitec | Te Pūkenga, Private Bag 92025, Victoria Street West, Auckland 1142, New Zealand.**
* **Corresponding author: jkmatt333@gmail.com**

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Abstract

Aotearoa / New Zealand is the leading country globally in the use of biological control agents to combat introduced pest weed species. Here we review the history of biological control in Aotearoa / New Zealand, compile a list of current, self-introduced and accidentally introduced biocontrol agents, and list the agents currently under consideration for introduction to Aotearoa / New Zealand (accurate to 2021). We discuss the science and procedures in place for the safe introduction of a new biocontrol agent and discuss the public's perception of biological control within Aotearoa / New Zealand.

Since the 1920s there have been 79 control agents released; 68 of those species were deliberate introductions, eight self-introductions and three accidental introductions. Additionally, there have been eight reported occurrences of non-target-species attack by biological control agents in Aotearoa / New Zealand, all of which cause minor damage to their unintended hosts. Prior to their introduction to Aotearoa / New Zealand, potential biological control agents are required to undergo rigorous research and host-specificity testing to ensure that the agent does not pose a risk to indigenous taxa through non-target attack.

This research is essential, as it ensures a precautionary approach is taken prior to introductions, which, in turn, provides the wider public with confidence in the validity of biocontrol agents as a means to manage weed species in Aotearoa / New Zealand.

Keywords

Biocontrol agents, weed control, invasive plant species

Introduction

Aotearoa / New Zealand is considered one of the world's most weedy places, with invasive plants posing a threat to more than half of this nation's critically endangered ecosystems (Howell 2008; Hulme 2020). Aotearoa / New Zealand has numerous species of exotic weeds, many of which have established outside of cultivation with most originating as garden escapes (Hulme 2020). Pest weeds have historically been introduced into new enviroments either accidentally or deliberately. Accidental introductions can occur through contaminated agricultural products, ship ballast water, or other means, while deliberate introductions include cases where plants were intentionally brought in for agriculture, horticulture, forestry, or ornamental purposes. In the context of Aotearoa / New Zealand, a significant number of pest species were introduced by early Polynesian and European settlers, often alongside crop species (Howell 2008; Hulme 2020). Today, approximately half of all vascular plants found in Aotearoa / New Zealand plant communities are non-indigenous (Hulme 2020). For example, Schoenberger et al. (2021) note that 57% of the seed plants of Aotearoa / New Zealand are exotic taxa compared with an indigenous seed flora of 43%.

There is a range of weed control methods available, including manual removal, chemical herbicides and the introduction of biological control. The use of knapsack spraying and manual removal are two methods commonly used in accessible areas and, due to their targeted nature, have a low risk of by-kill. In wetland communities or inaccessible areas, methods such as aerial spraying using helicopters or drones are now commonly employed (Davenhill 2021). Due to society's increasing concern about the use of chemicals and the environmental effects of herbicides, the use of biological control agents is now seen as an alternative and more acceptable option (Julien et al. 2007; Thomas & Willis 1998). This is due to its reduced environmental impact, reduced non-target impacts, long-term cost effectiveness and its ability to access difficult terrain (Ferguson et al. 2007). For example, the control of ragwort without the intervention of biocontrol in the 1980s would have cost dairy farmers approximately $64 million in labour and chemical intervention, in comparison to the $468,000 put towards the introduction of the flea beetle *Longitarsus jacobaeae* Waterhouse, 1858 (Fowler et al. 2016).

Biological control or biocontrol (hereafter biocontrol) is the control of a pest species by the introduction of its natural enemy or predator (Blossey et al. 2018; Kenis et al. 2017). There are two types of biocontrol: classical and inundative. Classical biocontrol is the more frequently used type where an agent, usually an insect or fungus, is introduced, using multiple release events, to enable the establishment of a self-sustaining populations (Hayes 2010). Inundative biocontrol is the use of pathogens to create artificial disease epidemics (Hayes 2010). Unlike classical biocontrol, inundative biocontrol, also referred to as the bioherbicide method, requires the continuous reapplication of the agent as it usually does not persist in the environment for long periods.

Research Objectives

1. Review the history and overview of weed biocontrol agents in Aotearoa / New Zealand.
2. Discuss procedures in place for biocontrol agents (e.g., weed selection, agent selection, host testing, etc.).
3. Form a list of weed biocontrol agents.
4. Discuss public perception.
5. Future perspectives.

Methodology

Review of the national history of biological control

Investigation into biocontrol literature, relevant websites, internet web searches and correspondence with biocontrol experts in Manaaki Whenua / Landcare Research and Auckland Council.

The focus of this review included:

- Keywords: weed biocontrol, host-range, specificity, non-target impacts, biocontrol agents, Aotearoa / New Zealand
- The benefits and risks of biological control
- Predicting non-target effects
- Host-specificity testing
- Biological control in Aotearoa / New Zealand

Compilation of an up-to-date record of agents

This consisted of literature and historical accounts of biocontrol as well as the use of relevant websites such as Manaaki Whenua / Landcare Research and

Environmental Protection Authority. Additionally, there was correspondence with biocontrol experts at Manaaki Whenua / Landcare Research.

Discussion of the science and procedures in place to safely introduce a new biocontrol agent

This included the evaluation of papers on the procedures of host-specificity testing and the aspects to consider when selecting a new biocontrol agent. The EPA approvement process was also evaluated using information available on their website and correspondence with experts in host-range testing.

Perspectives on biocontrol

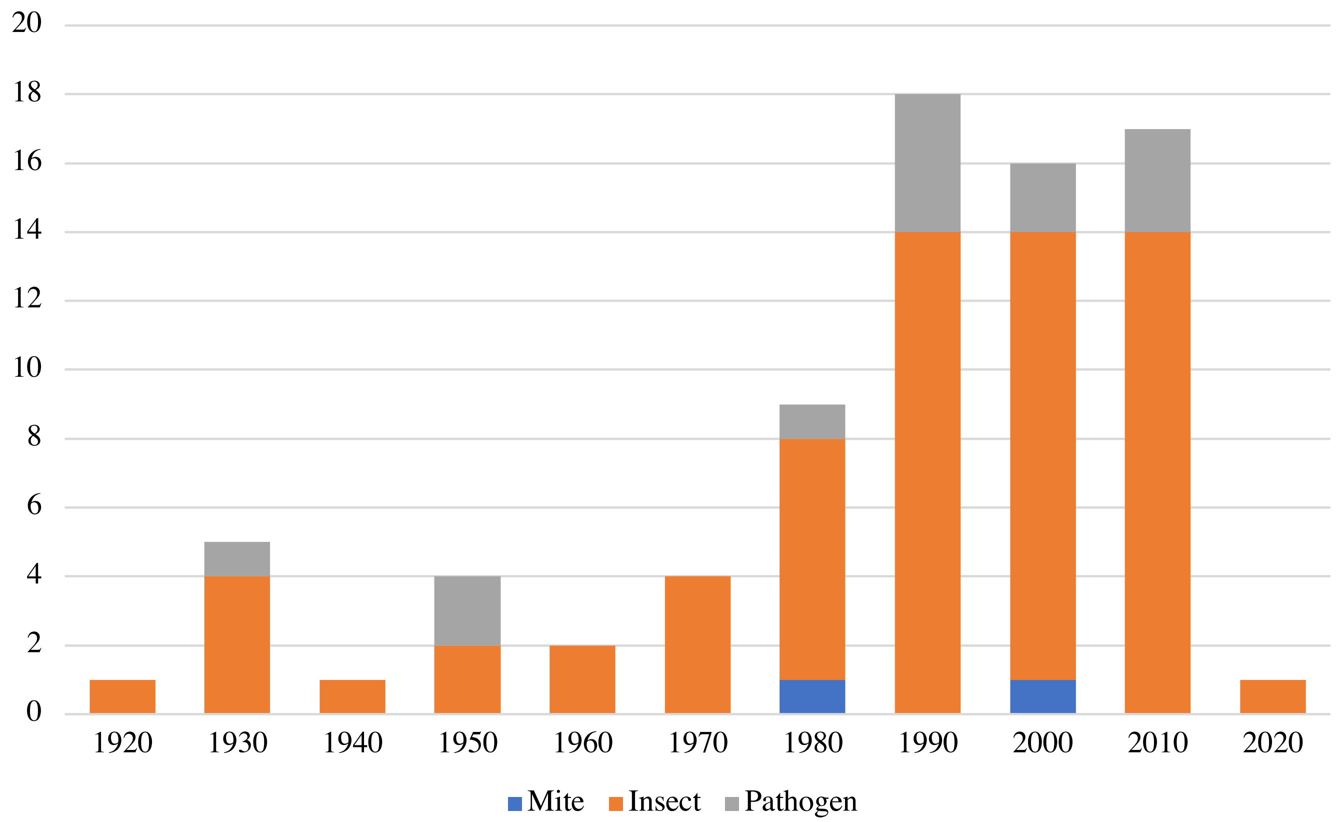
Through an evaluation of available papers, presentations and correspondence with biocontrol professionals and Māori representatives in the field, a review of public perceptions was evaluated and included where most appropriate.

History of Biocontrol in Aotearoa / New Zealand

The eleven-spotted ladybird (*Coccinella undecimpunctata* (Linnaeus, 1758)) (Figure 1) introduced in 1874 was the first biocontrol agent deliberately introduced into Aotearoa / New Zealand to target aphids (Cameron et al. 1993; Ferguson et al. 2009). The research of biocontrol of weeds began in 1925 at the Cawthron Institute, Nelson (Hayes et al. 2013). Between 1931 and 1965 there were only nine control agents released, of which two did not establish (*Antholcus varinervis* (Spin.) and *Botanophila seneciella* (Meade. 1892)) (Hayes et al. 2013).

During this time, the focus on using biocontrol agents decreased due to the development of new herbicides, which became popular due to their effectiveness (Fowler et al. 2010; Hayes et al. 2013). By the early 1970s, there was a resurgence in the use of biocontrol agents due to the disillusionment with the use of herbicides, which has increased to date (Cameron et al. 1993). According to Cameron et al. (1993), 221 species of agents had been deliberately released in Aotearoa / New Zealand before

Figure 1. Eleven-spotted ladybird (*Coccinella undecimpunctata* (Linnaeus, 1758)). Photo: J. Sullivan, 2016



Note. This is a combination of deliberate, accidental, and self-introduced agents.

Figure 2. Type of control agent per decade.

1993, primarily to control agricultural pests in vegetable or fruit crops, as well as pastureland pests such as Scotch broom (*Cytisus scoparius* (L.) Link), nodding thistle (*Carduus nutans* L.) and ragwort (*Jacobaea vulgaris* Gaertn). Since then, there has been an increase in control agents being imported to control pest weeds (Cameron et al. 1993) (Figure 2).

In the early days of biocontrol, natural insect predators were the primary agent introduced to combat invasive weeds; today they comprise 86% of biocontrol agents trialled in Aotearoa / New Zealand. In the last 30 years there has been an increase in pathogens used as biocontrol agents.

Process of Introduction of Biocontrol

Target weed selection

Aotearoa / New Zealand has numerous weeds with the potential for biocontrol, and limited resources, so the selection of target species is done using a prioritisation list (Hayes et al. 2013). This list is based on an assessment framework that helps identify the most appropriate target weed for biocontrol (Hayes et al. 2013). Hayes et al. (2013: 382) state, “this ranking system incorporates measures of the weed’s impact (importance), the likelihood of successful biocontrol (feasibility), and the likely effort (cost).” Determining the value for feasibility and cost of biocontrol is identified by compiling a dataset from worldwide biocontrol programmes and invasive weed knowledge. It is important to find the right balance between targeting the most important weeds and targeting the best biocontrol targets, as emphasised by Hayes et al. (2013).

Agent selection

When selecting a biocontrol agent, a local survey of Aotearoa / New Zealand species is conducted to determine whether any taxa already present cause significant damage to the selected target weeds; or, alternatively, whether any species currently present are likely to interfere with proposed biocontrol agents (Hayes 2010). While this survey is undertaken, research is done on the target weeds' indigenous range and natural enemies, from which a list of possible candidates is created. It is important to positively identify these species and review life-history traits to determine their suitability. Host-range testing is also conducted to determine if whether a biocontrol candidate might cause damage to species other than the target weed. If the candidate could cause damage, it is rejected. All agents must be put into a containment facility where they can be securely kept, positively identified and checked to ensure they do not carry any parasites, diseases or other unwanted contaminants (Hayes 2010).

Climate matching / seasonal phenology

Climate matching is important, as it reduces the chance of an agent failing to establish (Cameron et al. 1993). To increase success of establishment for an agent, climate matching is conducted to determine the suitability of an agent to the Aotearoa / New Zealand climate. Close climate matching with the native range of the agent has been difficult, due to the diverse climate range of Aotearoa / New Zealand (Cameron et al. 1993). Despite this, the biocontrol agents selected as possible candidates are usually sourced from areas of the pest's native range, which normally have a broadly similar climate to Aotearoa / New Zealand; factors such as rainfall, humidity, and temperature are elements to take into consideration when selecting an agent. For example, the ragwort flea beetle (*Longitarsus jacobaeae* Waterhouse, 1858) has been recorded as performing poorly in regions of higher rainfall, where the ragwort plume moth (*Platyptilia isodactylus* (Zeller, 1852)) was introduced in 2005 to control damper areas (Fowler et al. 2016., Hayes et al. 2013).

Host-specificity testing

Host-specificity testing is a method used to discard any candidate agents for biocontrol that might damage and attack indigenous or valued plant taxa (Fowler et al. 2012). Any biocontrol agent being introduced into Aotearoa / New Zealand must undergo various host-range testing to ensure that no non-target effects occur when it is introduced into the ecosystem (Paynter et al. 2008). If candidate agents could damage any other valued plants then they are immediately rejected (Paynter 2008). For example, a promising agent for controlling Scotch broom (*Cytisus scoparius* (L.) Link), which is a significant weed in Te Waipounamu / the South Island of Aotearoa / New Zealand, was rejected after tests showed that it could potentially damage the native kōwhai (*Sophora microphylla* Aiton) (Paynter 2008).

Non-target species of concern are usually congeneric, i.e., taxa that are genetically similar to or of the same genus or taxonomic family as the target species (Manaaki Whenua / Landcare Research n.d.). The likely candidate to be a test plant in host-specificity testing as an alternative host plant is a congeneric species of the target weed (Sutton et al. 2017). This has now become a standard practice for the selection of test plants for host-specificity testing, in which they are selected by phylogenetic distance from the target weed (Sutton et al. 2017). Host-range testing can result in obtaining false (positive or negative) results. False positives occur when a test shows that the plant species can be fed or oviposited on by the test agent in containment, but these results will not occur in the field (Browne et al. 2000). False negatives occur when the test shows the selected test species is outside the host range of the agents, but the test plant would be attacked in the field (Browne et al. 2000). Host-range testing is determined by three tests: (1) no-choice, (2) choice and (3) multichoice (open-field) trials. However, there is an alternate form of testing: sequential no-choice testing, which, according to Sutton et al. (2017), can be more accurate than the standard testing methods of no-choice and choice testing.

The no-choice method tests one biocontrol agent against one test-plant species. Sutton et al. (2017) suggest that no-choice tests overestimate the results of host specificity because over time it increases the acceptance by the agent of selected test plants as host out of starvation. Choice tests involve the agent being exposed to two or more test species, including the target weed, which results in determining the agent's host-species preferences (Sutton et al. 2017). Multichoice testing in open-field conditions is a more reliable form of testing, as it determines the realised host range of the biocontrol agent. Unfortunately, due to agents being kept in quarantine, this choice of testing is not always possible (Sutton et al. 2017).

Sequential no-choice testing may reduce the probability of the results being false (positive or negative) compared to the standard testing methods of no-choice and choice testing (Sutton et al. 2017). This method involves the selected agent being offered a series of test plants that is alternated between the test species and the target weed (Sutton et al. 2017).

Environmental Protection Authority (EPA) approval

There are two types of applications for the introduction of a new organism under the EPA:

1. Application to hold the new organism in an approved containment facility (such as laboratories, glasshouses, zoos or field-test sites).
2. Application to release the new organism into the environment.

Approval from the EPA for the introduction of agents into, and removal from, containment is required under the Hazardous Substance and New Organism Act 1996 (HSNO Act), as outlined above, for the introduction of a potential biocontrol agent into Aotearoa / New Zealand (Suckling & Sforza 2014). Current research facilities for Manaaki Whenua / Landcare Research are located all across Aotearoa / New Zealand: their main office is located in Rīkona / Lincoln, and other locations include Tāmaki Makaurau / Auckland, Kirikiriroa / Hamilton, Papaioea / Palmerston North, Tūranganui-a-Kiwa / Gisborne, Te Whanganui-a-Tara / Wellington, Whakatū / Nelson, Ōtepoti / Dunedin and Manuherikia / Alexandra (Manaaki Whenua / Landcare Research 2021b).

To release the agent into the Aotearoa / New Zealand environment, permission must be granted by EPA. It is the responsibility of the EPA to ensure that there is sufficient information on the agent, that adequate robust research has been conducted, that these findings have been communicated to interested parties in Aotearoa / New Zealand, and a risk assessment and cost–benefit analysis have been completed before approving the release. As per the HSNO Act, the EPA is required to reject any application for a new organism if the agent would have significant impacts on ecosystems or native species. Therefore, the applicant must supply information on the level of risk of the agent. This process also ensures the assessment of possible impacts on Aotearoa / New Zealand's economic, societal, human health and cultural values before approving the new agent, including iwi consultations to take into account Māori perspectives (Environmental Protection Authority 2021; Ministry for the Environment 2013).

If conditions to import or release have been met for a new biocontrol agent, the approval will be granted, after which a further approval must be applied for, or an extension of the existing approval (Environmental Protection Authority 2021).

Agent distribution

Once approval has been granted, large numbers of the agents are then reared to be first released in target areas before being distributed widely across the nation. The breeding to upscale agent population is the responsibility of Manaaki Whenua / Landcare Research.

Timing of release

The successful establishment of the agent is contingent on releasing it at an appropriate time in the target weed's life cycle (BIREA 2007). For example, a study on the ragwort seed fly shows that releasing the adult outside the suitable period led to issues with establishment (Hayes 2007b). Timing is crucial, as biocontrol agents often need to be released within a narrow window when the target weed is conducive for their development (BIREA 2007). Introducing multiple agents for target weeds, at multiple life stages, can lead to competition, emphasising the need for careful consideration (BIREA 2007).

Release strategies

To enhance the likelihood of a suitable site match for agent establishment, its crucial to release agents at multiple sites, given variation in vegetation and microclimate at each location (BIREA 2007). The most straightforward approach to agent release is to release as many agents as possible at a site during the appropriate time of year. Alternatively, smaller releases can be made at regular intervals (BIREA 2007).

Establishing cost-effective new populations involves collecting agents from existing sites and introducing them to new locations (BIREA 2007). However, achieving a successful population through this method may require a longer timeframe.

Records of releases and measures of success

Manaaki Whenua / Landcare Research maintains a database of all biocontrol agents which have been released in Aotearoa / New Zealand since 1929. An abbreviated list of introduced species is accessible on the EPA and Manaaki Whenua / Landcare Research websites; in particular, covering intentional introduced or pending-release biocontrol agents. Monitoring of the control agents is continuously done until the agent has fully established or it has been considered to have failed (Hayes 2007b). Seven control agents listed in Table 1 were released more than ten years ago, but have not been recorded as established, suggesting resourcing may need to be allocated to further monitoring.

Table 1. List of deliberate introductions of weed biocontrol agents in order of year introduced.

	Taxonomic	Target weed	Year of first release	Established
1	Cinnabar moth *Tyria jacobaeae* (Linnaeus, 1758)	*Jacobaea vulgaris* Gaertn.	1929	Yes
2	Gorse seed weevil *Exapion ulicis* (Forster, 1771)	*Ulex europaeus* L.	1931	Yes
3	Sawfly *Antholcus varinervis* (Spin.)	*Acaena agnipila* Gand.	1936	No
4	Ragwort seedlfy *Botanophila jacobaeae* (Meade, 1892)	*Jacobaea vulgaris* Gaertn.	1936	Yes
5	Ragwort seed fly *Botanophila seneciella* (Meade, 1892)	*Jacobaea vulgaris* Gaertn.	1936	No
6	Lesser St John's beetle *Chrysolina hyperici* (Forster, 1771)	*Hypericum perforatum* L.	1943	Yes
7	Crofton weed gall fly *Procecidochares utilis* Stone, 1947	*Jacobaea vulgaris* Gaertn.	1958	Yes
8	St John's wart midge *Zeuxidiplosis giardia* (Kieffer)	*Hypericum perforatum* L.	1961	Yes
9	Greater St John's wort beetle *Chrysolina quadrigemina* (Suffrian, 1851)	*Hypericum perforatum* L.	1963	Yes
10	Nodding thistle receptacle weevil *Rhinocyllus conicus* (Frölich, 1792)	*Carduus nutans* L.	1972	Yes
11	Canada thistle stem mining weevil *Ceutorhynchus litura* (Fabricius, 1775)	*Cirsium arvense* (L.) Scop.	1976	Yes
12	Californian thistle gall fly *Urophora cardui* (Linnaeus, 1758)	*Cirsium arvense* (L.) Scop.	1976	Yes
13	Californian thistle flea beetle *Altica carduorum* (Guérin-Méneville, 1858)	*Cirsium arvense* (L.) Scop.	1979	No
14	Alligator weed beetle *Agasicles hygrophila* Selman & Vogt, 1971	*Alternanthera philoxeroides* (Mart.) Griseb.	1981	Yes
15	Alligator weed beetle *Disonycha argentinensis* Jacoby, 1901	*Alternanthera philoxeroides* (Mart.) Griseb.	1982	No
16	Californian thistle leaf beetle *Lema cyanella* (Linnaeus, 1758)	*Cirsium arvense* (L.) Scop.	1983	Yes
17	Ragwort flea beetle *Longitarsus jacobaeae* (Waterhouse, 1858)	*Jacobaea vulgaris* Gaertn.	1983	Yes
18	Alligator weed moth *Arcola malloi* (Pastrana, 1961)	*Alternanthera philoxeroides* (Mart.) Griseb.	1984	Yes
19	Nodding thistle crown weevil *Trichosirocalus horridus* (Panzer, 1801)	*Carduus nutans* L.	1984	Yes
20	Broom seed beetle *Bruchidius villosus* (Fabricius, 1792)	*Cytisus scoparius* (L.) Link.	1987	Yes

21	Gorse spider mite *Tetranuchus lintearius* Dufour, 1832	*Ulex europaeus* L.	1989	Yes
22	Gorse soft shoot moth *Agonopterix umbellana* (Fabricius, 1794)	*Ulex europaeus* L.	1990	Yes
23	Gorse thrips *Sericothrips staphylinus* Haliday, 1836	*Ulex europaeus* L.	1990	Yes
24	Nodding thistle gall fly *Urophora solstitialis* (Linnaeus, 1758)	*Carduus nutans* L.	1990	Yes
25	Gorse pod moth *Cydia succedana* (Denis & Schiffermüller, 1775)	*Ulex europaeus* L.	1992	Yes
26	Broom psyllid *Arytainilla spartiophila* (Foerster, 1848)	*Cytisus scoparius* (L.) Link.	1993	Yes
27	Gorse colonial hard shoot moth *Scythris grandipennis* (Haworth, 1828)	*Ulex europaeus* L.	1993	No
28	Heather beetle *Lochmaea suturalis* (Thomson, 1866)	*Calluna vulgaris* (L.) Hull.	1996	Yes
29	Old man's beard leaf fungus *Phoma clematidina* (Thüm.) Boerema (1978)	*Clematis vitalba* L.	1996	Yes
30	Old man's beard leaf miner *Phytomyza vitalbae* Kaltenbach, 1872	*Clematis vitalba* L.	1996	Yes
31	Mist flower fungus *Entyloma ageratinae* R.W.Barreto & H.C.Evans (1988)	*Ageratina riparia* (Regel) R.M.King & H.Rob.	1998	Yes
32	Old man's beard sawfly *Monophadnus spinolae* Klug, 1816	*Clematis vitalba* L.	1998	No
33	Gorse colonial hard shoot moth *Pempelia genistellla*	*Ulex europaeus* L.	1998	Yes
34	Hieracium gall wasp *Aulacidea subterminalis* Niblett, 1946	*Pilosella* spp.	1999	Yes
35	Hieracium plume moth *Oxyptilus pilosellae* (Zeller, 1841)	*Pilosella* spp.	1999	No
36	Scotch thistle gall fly *Urophora stylata* (Fabricius, 1775)	*Cirsium vulgare* (Savi) Ten.	1999	Yes
37	Mist flower gall fly *Procecidochares alani* Steyskal, 1974	*Ageratina riparia* (Regel) R.M.King & H.Rob.	2000	Yes
38	Hieracium root-feeding hoverfly *Cheilosia urbana* (Meigen, 1822)	*Pilosella* spp.	2002	Too early
39	Hieracium gall midge *Macrolabis pilosellae* (Binnie, 1877)	*Pilosella* spp.	2002	Yes
40	Ragwort crown-boring moth *Cochylichroa atricapitana* (Stephens, 1852)	*Jacobaea vulgaris* Gaertn.	2005	Too early
41	Ragwort plume moth *Platyptilia isodactylus* (Zeller, 1852)	*Jacobaea vulgaris* Gaertn.	2005	Yes
42	Hieracium crown hoverfly *Cheilosia psilophthalma* (Becker, 1894)	*Pilosella* spp.	2006	Too early

43	Buddleia leaf weevil *Cleopus japonicus*	*Buddleja davidii* Franch.	2006	Yes
44	Green thistle beetle *Cassida rubiginosa* Müller, 1776	*Cirsium arvense* (L.) Scop.	2007	Yes
45	Broom leaf beetle *Gonioctena olovacea* (Forster, 1771)	*Cytisus scoparius* (L.) Link.	2007	Yes
46	Boneseed leafroller *Tortrix* s.l. sp. "chrysanthemoides"	*Osteospermum moniliferum* L. subsp. *moniliferum*	2007	Yes
47	Broom gall mite *Aceria genistae* (Nalepa, 1891)	*Cytisus scoparius* (L.) Link.	2008	Yes
48	Broom shoot moth *Agonopterix assimilella* (Treitschke, 1832)	*Cytisus scoparius* (L.) Link.	2008	Yes
49	Californian thistle stem miner *Ceratapion onopordi* (W. Kirby, 1808)	*Cytisus* spp., *Carduus* spp.	2009	Too early
50	Woolly nightshade lace bug *Gargaphis decoris* Drake, 1931	*Solanum mauritianum* Scop.	2010	Yes
51	Tradescantia tip beetle *Neolema abbreviata*	*Tradescantia fluminensis* Vell.	2013	Too early
52	Tradescantia leaf beetle *Neolema ogloblini* (Monrós)	*Tradescantia fluminensis* Vell.	2011	Yes
53	Tradescantia tip beetle *Neolema abbreviate* (Lacordaire, 1845)	*Tradescantia fluminensis* Vell.	2013	Too early
53	Tradescantia stem beetle *Lema basicostata* Monrós, 1947	*Tradescantia fluminensis* Vell.	2012	Too early
54	Honshu white admiral *Limenitis glorifica* Fruhstorfer, 1909	*Lonicera japonica* Thunb.	2014	Yes
55	Darwin's barberry seed weevil *Berberidicola exaratus* (Blanchard, 1851)	*Berberis darwinii* Hook.	2015	Yes
56	Chinese privet lace bug *Leptoypha hospita* Drake & Poor, 1937	*Ligustrum sinense* Lour.	2015	Yes
57	Lantana leaf rust *Prospodium tuberculatum* (Spegazzini) Arthur	*Lantana camara* L.	2015	Yes
58	Lantana blister rust *Puccinia lantanae* Farl.	*Lantana camara* L.	2015	Too early
59	Honeysuckle long-horn beetle *Oberea shirahatai* Ohbayashi, 1956	*Lonicera japonica* Thunb.	2016	Too early
60	Tutsan beetle *Chrysolina abchasica* (Weise, 1892)	*Hypercium androsaemum* L.	2017	Too early
61	Field horsetail weevil *Grypus equiseti* (Fabricius, 1775)	*Equisetum arvense* L.	2017	Too early
62	Tutsan moth *Lathronympha strigana* (Fabricius, 1775)	*Hypercium androsaemum* L.	2017	Too early
63	Giant reed gall wasp *Tetramesa romana* (Walker, 1873)	*Arundo donax* L.	2017	Yes

64	Clearwing moth *Chamaesphecia mysinoformis* Boisduval, 1840	*Marrubium vulgare* L.	2018	Too early
65	Horehound plume moth *Wheeleria spilodactylus* Curtis, 1827	*Marrubium vulgare* L.	2018	Too early
66	Tradescantia yellow leaf spot fungus *Kordyana brasiliensis* D.M.Macedo, O.L.Pereira & R.W.Barreto	*Tradescantia fluminensis* Vell.	2018	Yes
67	Moth plant beetle *Freudeita* cf *cupripennis* Bechyné, 1950	*Araujia hortorum* Brot.	2019	Too early
68	Rhizome-stem feeding scale *Rhizaspidiotus donacis* (Leonardi, 1920)	*Arundo donax* L.	2021	Too early

The collective data in the table above was sourced from Hayes et al. 2013; Manaaki Whenua / Landcare Research 2020; 2021a; Paynter et al. 2018.

To be considered a successful agent, a new biocontrol release can be categorised as either established or recovered. If the agent has only one generation per year (univoltine), it will be considered established if it has increased in numbers for two or more years after its release. It will be considered a recovered agent if it is found a year after release (Hayes 2007b). If the agent has more than one generation per year (multivoltine), it will be considered established if it has completed several generations, increased in number and has successfully survived a single winter (Hayes 2007b). It is noted that the reduction of weed density is not a reliable way to record the effectiveness of a control agent, as the weed decline can be due to other factors rather than just the agent (Hayes 2007b).

To be considered a success in controlling the target weed, the level of damage stage must be below the damage threshold (Greathead & Greathead, 1992). For example, Standish (2001) has established biomass thresholds for *Tradescantia fluminensis* Vell, where the threshold is based on regenerating native forest.

Biocontrol Agents

Current use of agents in Aotearoa / New Zealand

Since the introduction of biocontrol agents to combat pest weeds, which began in the 1920s, there have been a total of 79 taxon introductions into Aotearoa / New Zealand (Table 1). Overall, 86% of these agents were deliberately introduced, whereas 14% were accidental or self-introductions. Of this 14%, only three, all pathogens, are believed to have been accidental introductions. Additionally, there were eight self-introductions, five of which are pathogens and three of which are insect species (Table 2).

Deliberately introduced agents

Invertebrates were the most popular type of biocontrol agent at the beginning of pest-weed agent introduction. However, in recent years there has been an increase in pathogen biocontrol introductions (rusts and fungi) to combat pest weeds. For example, *Kordyana brasiliensis* D.M.Macedo, O.L. Pereira & R.W. Barreto is one of four agents introduced to combat *Tradescantia fluminensis* Vell. This agent was introduced to attack areas of Tradescantia where the three beetle biocontrol agents (*Neolema ogloblini* (Monrós), *Neolema abbreviate* (Lacordaire, 1845) and *Lema basicostata* Monrós, 1947) were not successful (i.e., in more shaded and wet areas). Overall, 90% of deliberate introductions are insects, 7% pathogens and 3% mites. Table 1 provides a list of deliberate introductions arranged by taxon, common name, target weed, the year that they were first introduced and whether the agent has become established.

Accidental introductions

Accidental introductions have not occurred since 1999; there are currently procedures in place that have helped to prevent accidental introductions through other biocontrol agents or anthropogenic means. Since the 1920s there have been three accidental biocontrol agents introduced, all of which are pathogens.

These include two agents to target *Cirsium arvense*

Table 2. List of self-introductions of biocontrol agents.

Agent	Target	Estimated date of introduction	Origin of introduction
Broom twig miner *Leucoptera spartofoleilla* (Hübner, 1813)	Wild broom *Cytisus scoparius* (L.) Link.	1950	Ornamental broom plants
Tutsan rust *Melampsora hypericorum* (DC.) Schröter	Tutsan *Hypercium androsaemum* L.	1952	Unknown
Blackberry rust *Phragmidium violaceum* (Schultz) G.Winter (1880)	Blackberry *Rubus laciniatus* Willd.	1984	Blown over from Australia
Hemlock moth *Agonopterix alstromeriana* (Clerck, 1759)	Hemlock *Conium maculatum* L.	1990	Unknown
Hieracium rust *Puccinia hieracii* var. *piloselloidarum* (Probst) Jørst	Hawkweeds *Pilosella* spp.	1995	Unknown
Bridal creeper rust *Puccinia myrsiphylli* G.Winter	Smilax *Asparagus asparagoides* (L.) Druce, 1914	2005	Wind dispersed – possibly from Australia
California thistle rust *Puccinia punctiformis* (F. Strauss) Röhl.	Californian thistle *Cirsium arvense* (L.) Scop.	2006	Unknown
Lantana plume moth *Lantanophaga pusillidactyla* (Walker, 1864)	Lantana *Lantana camara* L.	2019	Unknown

(L.) Scop. – white soft rot (*Sclerotinia sclerotiorum* (Lib.) de Bary (1884)) and Phoma leaf blight (*Phoma exigua* var. *exigua* Sacc., (1879)). It is not known how these agents were introduced into Aotearoa / New Zealand. Lastly, the Mexican devil weed leaf fungus (*Passalora ageratinae* Crous & A.R.Wood)t, first recognised in Aotearoa / New Zealand as *Cercospora eupatorii* Peck (Dingley 1965), was probably accidentally introduced via a deliberate introduction of a gall fly (*Procecidochares utilis* Stone, 1947) in 1958 to control Mexican devil weed (Manaaki Whenua / Landcare Research 2020).

Self-introductions

Self-introductions are continuously occurring globally, whereas Aotearoa / New Zealand only has a record of eight self-introductions from the 1950s to 2019. These are a combination of insects (37%) and rusts (63%), which have either blown over from neighbouring countries, e.g., Australia, have been introduced through ornamental and horticultural plant species, or the origin of introduction is unknown (Table 2).

Overview of Agents in Aotearoa / New Zealand

Over the past few decades, there has been a reported decrease in accidental introductions, which is probably due to improved biosecurity procedures that Aotearoa / New Zealand now has in place to prevent new incursions. However, there has been an increase in self-introduced agents, the most recent of which is *Lantanophaga pusillidactyla* (Walker, 1864), the lantana plume moth, as reported by Barton (2011). The pathway introduction of this species to Aotearoa / New Zealand is not verified; however, it has likely come from Australia, where it was previously introduced as a biological agent (Day & Neser 2000). Rusts are the most common self-introduced agent, but with changing environmental conditions there could be an increase of rust self-introductions, as demonstrated by Myrtle rust (*Austropuccinia psidii* (G.Winter) Beenken, 2017) (Ministry for Primary Industries 2023).

Figure 3. Gorse pod moth (*Cydia succedana*). Photo: Ustatyansev, 2017

Non-target impacts

A global review of non-target impacts of weed biocontrol conducted in 2014 concludes that impacts on non-target species rarely occur, which indicates the host-range testing procedures are adequately assessing the risks of candidate agents (Suckling & Sforza 2014). However, Paynter et al. (2018) suggests that this result can still be argued against, as the number of detected cases is only a fraction of those that have occurred. Furthermore, Paytner et al. (2020) note that there is a lack of rigorous monitoring of non-target impacts recorded when monitoring biocontrol agents present in Aotearoa / New Zealand. These authors state that the extent of agents known to impact non-target species in Aotearoa / New Zealand (24%) is higher than the world average (13%). However, they go on to say that this could be due to more sampling efforts, though they acknowledge that minor non-target impacts remain a potential concern (Paynter et al. 2020). Phylogenetically similar species are the most at risk when it comes to non-target impact, yet there is little to no scientific literature showing the presence or absence of non-target damage in the field. For example, the gorse pod moth (*Cydia succedana* Denis & Schiffermuller, 1775) (Figure 3), introduced in 1992 as a control agent for gorse (*Ulex europaeus* L.) (Family: Fabaceae) has been recorded in Aotearoa / New Zealand to feed on several other species of Genisteae, such as *Cytisus scoparius* (L.) Link, *Genista monspessulana* (L.) L. Johnson., *Lupinus arboreus* Sims. and a species of lotus (*Lotus pedunculatus* Cav.) (Paynter et al. 2008). During the testing of the *U. europaeus* agent, which was conducted at Chobham Common and Yateley Common in the United Kingdom, it was determined that the gorse pod moth was highly host-specific. The event of a non-target attack of the gorse pod moth was therefore unexpected (Paynter et al. 2018). Paynter et al. (2018) further deduced that the presence of non-target attacks could be linked to the flowering of *U. europaeus*, with

Table 3. Non-target observations recorded in Aotearoa / New Zealand.

Agent	Year introduced	Target	Non-target
Cinnabar moth *Tyria jacobaeae* (Linnaeus, 1758)	1929	Ragwort *Jacobaea vulgaris* Gaertn	NZ indigenous *Senecio* species
St John's wort beetle *Chrysolina hypericin* Forster, 1771	1943	St. John's wort *Hypericum perforatum* L.	NZ natives of *Hypericum* species (*Hypericum pusillum* Choisy & *H. rubicundulum* Heenan)
Greater St John's wort beetle *Chrysolina quadrigemina* Suffrian, 1851	1963	St. John's wort *Hypericum perforatum* L.	NZ natives of *Hypericum* species (*Hypericum pusillum* & *H. rubicundulum*)
Alligator weed beetle *Agasicle hygrophia* Selma & Vogt, 1971	1981	Alligator weed *Alternanthera philoxeroides* (Mart.) Griseb.	*Alternanthera denticulata* R.Br *Alternanthera nahui* Heenan & de Lange
Broom seed beetle *Bruchidius villosus* (Fabricius, 1793)	1987	Wild Broom *Cytisus scoparius* (L.) Link	*Cytisus proliferus* L.f.
Leaf miner *Phytomyza vitalbae* Kaltenbach, 1872	1996	Old man's beard *Clematis vitalba* L.	*Clematis foetida* Raoul & *C. forsteri* J.F.Gmel.
Green thistle beetle *Cassida rubiginosa* Muller, 1776	2008	Thistle *Cirsium arvense* (L.) Scop.	*Cynara scolymus* L.

non-target attack noted when *U. europaeus* was not in bloom (Paynter et al. 2008).

The safety of classical biocontrol has been a matter of debate concerning the risks that it potentially poses through the introduction of exotic agents as enemies to non-target organisms (Schaffner 2001). The assessment of the integrity of host-range testing of biocontrol agents arose due to the recent findings of non-target effects caused by introduced agents (Schaffner 2001). However, the data collected from host-range testing of biocontrol candidates is relevant to assess the potential effects to non-target organisms (Schaffner 2001).

In addition to gorse pod moth, there has been evidence of seven other incidents of non-target biocontrol impacts observed in Aotearoa / New Zealand (Table 3). However, these have been assessed as minor and not unexpected (Fowler et al. 2010; Paynter 2008).

Perspectives of Biocontrol

The use of biocontrol as a pest-plant management tool is an approach that is still not widely known to the general population of Aotearoa / New Zealand. However, where it has been advocated there appears to be a general acceptance for its use as an alternative tool to chemical methods (Catton 2021). Those who are knowledgeable about biocontrol are generally those concerned about pest-weed management issues, groups that are interested in invertebrates (e.g., butterfly enthusiasts), professionals working in the field, or organisations that see biocontrol as a benefit to their business (Catton 2021).

However, perception of biocontrol can also vary between tribe, person or organisation. As T. Malcolm explains, "Maori forestry industries, for example, have supported biocontrol that protects their industry" (personal communication to J.K. Matthews, October 2021), whereas some Māori communities see *Tradescantia fluminensis* Vell. as useful habitat for indigenous geckos (Diplodactylidae). "Farmers are likely to be more accepting of biocontrol as they see tangible benefits to their own business" (H. Cox to J.K. Matthews, personal communication, November 2021). Landowners and community groups have shown some understanding of the general concept of biocontrol, though often negatively, e.g., the introduction of mustelids (Mustelidae) to target rabbits (*Oryctolagus cuniculus* (Linnaeus, 1758)), resulting in serious biodiversity losses.

Once the science and procedures are explained, the concept of biocontrol becomes more acceptable. However, there is still a level of uncertainty on the part of the public about biocontrol regardless of their knowledge base. Common concerns raised are the changing of hosts (i.e., non-target attack) by agents; unsuitability of the agents, with suggestions of another potential agent (often unsuitable); the agents aiding in the spread of the target weed; and concerns about the introduction of wasps as agents due to the already large threat of wasps in Aotearoa / New Zealand (Q. Paynter, personal communication to J.K. Matthews, October 2021). Overall a majority of people still associate biocontrol with the failures of mustelids or mammalian pests rather than the success with pest-weed biocontrol (Barratt et al. 2017).

Biocontrol Agents: Success Stories

Carduus nutans L. Nodding thistle

Nodding thistle is a serious invasive weed in Aotearoa / New Zealand due to its ability to infest pastureland throughout the country (Hayes 2007a). Nodding thistle was first discovered in Aotearoa / New Zealand during the 1950s, after which time it eventually became one of the most widespread weeds in the country (Hayes 2007a). Since then, five biocontrol agents have been introduced to control this weed: a receptacle weevil *Rhinosyllys conicus* (Frölich, 1792), introduced in 1972; the crown weevil, *Trichosirocalcus horridus* (Panzer, 1801), introduced in 1984; the gall fly, *Urophora solstitialis* (Linnaeus, 1758), introduced in 1990; and newly introduced agents the stem miner, *Certapion onopordi* (W. Kirby, 1808), released in 2009 and the green thistle beetle, *Cassida rubiginosa* Müller, 1776), released in 2008 (Hayes et al. 2013; Manaaki Whenua / Landcare Research 2007). Crown weevil was shown to be the most effective according to Hayes (2007a). Similar results are occurring in Australia, where receptacle weevil, gall fly and crown weevil are also being used; Australian researchers recorded that the crown weevil can reduce the number of thistle seeds produced by 67% (Hayes 2007a). Added together with the other two agents (the stem miner and the green thistle beetle), 67% raises to 80%. Additionally, the receptacle weevil reduced the density of nodding thistle by 95% in Canada and 80% to 99% in the USA (Hayes 2007a). Overall, the control of *C. nutans* is partial and is working well in some areas of Aotearoa / New Zealand (Hayes et al. 2013).

Jacobaea vulgaris Gaertn. Ragwort

Ragwort is a pastureland weed that displaces pasture grasses and is toxic to livestock. To date, six biocontrol agents have been released to control it (Paynter et al. 2018): the cinnabar moth, *Tyris jacobaeae* (Linnaeus, 1758), released in 1929; two seed flies, *Botanophilia jacobaeae* (Hardy, 1872) and *B. seneciella* (Meade, 1892), both released in 1936; a flea beetle, Longitarsus jacobaeae (Waterhouse, 1858), released in 1983; a crown boring moth, *Cochylis aticapitana* (Stephens, 1852), released in 2005; and a plume moth, *Platyptilia isodactyla* (Zeller, 1852), also released in 2005 (Paynter et al. 2018). Of the six agents, the flea beetle has been the most successful, but the introduction of the crown boring moth and plume moth was intended to cover areas where conditions were not suitable for the beetle (Hayes 2007a). These agents have been so successful that no other control is needed in some areas of Aotearoa/ New Zealand (Hayes et al. 2013). Of the 16 trial sites for the flea beetle, 50% of sites had ragwort completely eliminated (Fowler et al. 2016).

Alternanthera philoxeriodes (Mart.) Griseb. Alligator weed

Alligator weed is a highly invasive aquatic weed that was first accidentally introduced into Aotearoa / New Zealand through ship ballast water in the 1880s (Waikato Regional Council 2015). It was first detected near Wairoa, Hawkes Bay, in 1906 and has now infested many bodies of water across Te Ika a Māui / the North Island of Aotearoa / New Zealand as far south as the Waikato (Hayes 2007a). Three agents have been released to control alligator weed: two beetles, *Agasicles hygrophila* Selman & Vogt (1971), released in 1981, and *Disonycha argentinensis* Jacoby, 1901, released in 1982, and a moth, *Arcola malloi* (Pastrana, 1961) (previously called *Vogtia malloi*), released in 1984, have been proven to be effective. Due to this success, applications for the import of other agents are being investigated (Hayes 2007a; Paynter et al. 2018). But, overall, the current agents are only partially controlling the weed in places where it grows in static water bodies (Hayes et al. 2013).

Cytisus scoparius (L.) Link.
Broom

Four control agents have been released to control broom: a seed beetle, *Bruchidius villosus* (Fabricius, 1792), released in 1987; a psyllid, *Arytainilla spartiophila* (Foerster, 1848), released in 1993; a shoot moth, *Agonopterix assimilella* (Treitschke, 1832), released in 2008; and a gall mite, *Aceria genistae* (Nalepa, 1891), also released in 2008 (Paynter et al. 2018). These agents have partially controlled the weed in some areas, though, overall, their impact is still lower than had been hoped for (Hayes et al. 2013).

Calluna vulgaris (L.) Hull
Heather

The heather beetle, *Lochmaea suturalis* (Thomson, 1866), released in 1996, is partially controlling *Calluna vulgaris* (L.) Hull. Notably, optimal control has been observed in areas where outbreaks of the heather beetle have been identified (Hayes et al. 2013; Paynter et al. 2018).

Ageratina adenophora (Spreng.) King & H.Rob.
Mexican devil weed

Crofton weed gall fly, *Procecidochares utilis* Stone, 1947, released in 1958, and the leaf fungus *Passalora ageratinae* Crous & A.R.Wood, discovered in Aotearoa / New Zealand following a field survey, are both biocontrol agents of Mexican devil weed, *Ageratina adenophora* (Spreng.) King & H.Rob. It is suspected that the leaf fungus was accidentally introduced with the gall fly in 1958 (Manaaki Whenua / Landcare Research 2020). *Ageratina adenophora* is now partially controlled and, while still common, is less of a threat now than it once was (Hayes et al. 2013).

Ageratina riparia (Regel) R.M.King & H.Rob
Mist flower

Mist flower, a smothering creeper in the native bush, has become a problem in Northern parts of Aotearoa / New Zealand. As such, two biocontrol agents were introduced: a fungus, *Entyloma ageratinae* R.W.Barreto & H.C.Evans (1988), released in 1998; and a gall fly, *Procecidochares Alani* Steyskal, 1974, released in 2000 (Paynter et al. 2018). These agents have since been shown to be successfully controlling mist flower from spreading further, as well as reducing the abundance of the weed within its known range (Hayes 2007a). Today, no other control agent is required to control mist flower (Hayes et al. 2013).

Hypericum perforatum L.
St John's wort

St John's wort was once one of Aotearoa / New Zealand's worst four weeds. It is a pastureland weed that displaced pasture and poisoned livestock (Hayes 2007a). Three control agents have been imported to control this weed: two beetles, St John's wort beetle (*Chrysolina hyperici* Forster, 1771), released in 1963, and the lesser St John's beetle (*C. quadrigemina* Suffrian, 1851), released in 1943; and a gall midge, *Zeuxidiplosis giardia*, released in 1961 (Hayes 2007a; Paynter et al. 2018). All three agents were successfully established and proved to be successful four years after introduction. The beetles managed to clear over 180 hectares of *Hypericum perforatum* in Marlborough (Hayes 2007a). Today, the three agents are successfully controlling the spread so that no other control is required (Hayes et al. 2013).

Future Prospects

Climate change

Climate change projected scenarios also known as representative concentration pathways (RCPs) were created to predict future climate outcomes (Ministry for the Environment 2018). The RCPs include four projections, but two project current conditions with the removal of some CO_2 from the atmosphere (RCP 2.6) and a pathway predicting the outcome with no change to the current increase of greenhouse gases (RCP 8.5) (Ministry for the Environment. 2018). As a result, there is a change of greenhouse gases in the atmosphere which will cause little change to the climatic conditions (RCP 2.6). However, with RCP 8.5 in the current trajectory of climatic conditions, there will be an exponential increase in the concentration of CO_2 in the atmosphere (Figure 4).

Climate change is expected to drastically alter biodiversity, cause changes in species ranges, phenology, genetic composition, ecosystem processes and species interactions (Hellmann et al. 2008). The invasive properties that make an invasive species

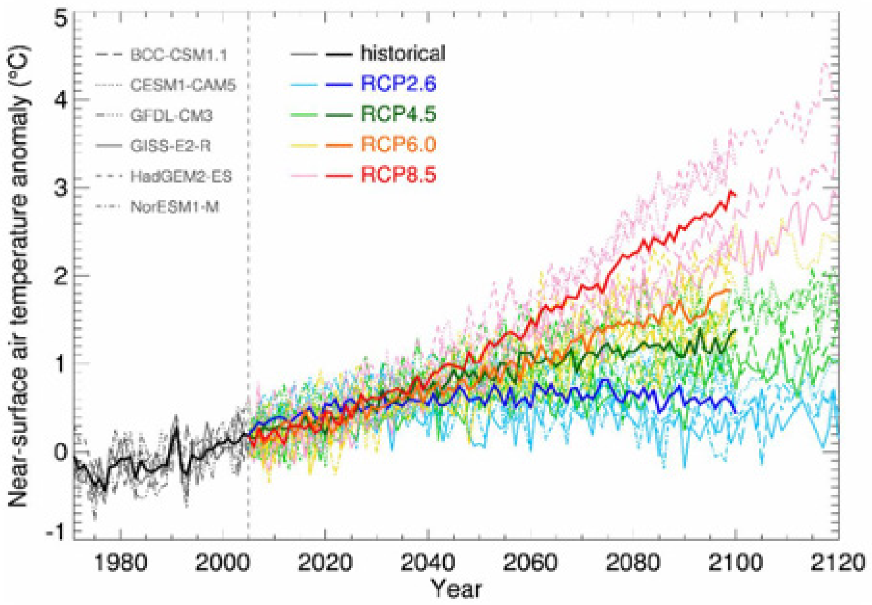


Figure 4. Climate projections for Aotearoa / New Zealand to the year 2120 from the 24 RCM simulations provided by NIWA (NIWA n.d.).

Table 4. Agents already approved by the EPA.

Agent	Target	Approval for release	Reasons for delay of introduction
Moth plant beetle *Freudeita cupripennis* (Lefèvre, 1877)	Moth plant *Araujia hortorum* Brot.	2011	Collection of population in Argentina
Rust fungus *Uromyces pencanus* Arth. & Holw.	Chilean needle grass *Nassella neesiana* (Trin.et Rupr.) Barkworth	2011	Approvals of import needed
Darwin's barberry flower weevil *Anthonomus kuscheli* Clark 1989	Darwin's barberry *Berberris darwinii*	2012	Population needs to increase before release
Sawfly *Zaraea lewisii*	Japanese honeysuckle *Lonicera japonica* Thunb.	2012	Unknown
Moth plant rust *Puccinia araujiae* Lév.	Moth plant *Araujia hortorum* Brot.	2015	Unknown
Red piercer moth *Lathronympha strigana* (Fabricius, 1775)	Tutsan *Hypericum androsaemum* L.	2016	Unknown
Gall mite *Aceria vitalbae* (Canestrini, 1892)	Old man's beard *Clematis vitalba* L.	2018	As of November 2021, it has been imported into Aotearoa / New Zealand

successful will aid in the spread of invasive species as they allow open access to areas previously unsuitable for pest species due to the regions being too cold (Auckland Regional Council 2019).

However, it is important to note that the change in climate won't just influence the weeds; it will also impact the biocontrol agents introduced to manage them. Weeds may benefit from the increase in temperature due to the rise in humidity, making their environment more similar to their natural host range. However, the introduced agents, often insects, may be affected differently. Insects are less tolerant of temperature changes, which could potentially impact the population and effectiveness of these agents in combating the target weed.

Many invasive species have a range of climatic tolerances, large geographic ranges, can facilitate rapid range shifts, have low seed mass and fast seed maturity (Hellmann et al. 2008). The increase of severe weather (e.g., hurricanes and cyclones) can spread invasive species into new regions, and damage native ecosystems, making them more susceptible to invasion. Native species can also be affected by changing climate conditions and therefore be less able to compete against invasive species (Auckland Council 2019). This could potentially increase the number of sleeper weeds becoming a bigger problem in the future (Groves 1999). Sleeper weeds are those species that have not exponentially increased in their population in a specific region (Groves 1999). Therefore, the need for more tools in the battle against invasive weeds is increasingly important and, as such, the need to engage the public in the use of biocontrol agents as an alternative to chemical control also becomes more important.

New agents approved for release

The Environmental Protection Authority has granted approval for the release of a number of agents, some of which received approval two decades ago but remain unimplemented. As of now, the most recent introduction of a biocontrol agent is the gall mite (*Aceria vitalbae*) for old man's beard (*Clematis vitalba* L.) (Table 4).

Conclusion

This review brings together information on the history, records and science of biocontrol in Aotearoa / New Zealand, and discusses the public perception of these and their introduction in this country. Biocontrol aims to manage the abundance of pest species in the environment. Biocontrol primarily helps to reduce the reliance on alternate pest-control methods such as insecticides and herbicides. In this regard, biocontrol has reduced the competitiveness and reproductive capacity of target weeds, making them more manageable. In the 1970s pest weed management mostly involved herbicides, but by 2013 biocontrol agents had become a more commonly used and viable means of achieving the same management objectives. Research into biological control of pest weeds began in 1925 at the Cawthron Institute, Whakatū / Nelson. Since then, there has been an increase in control agents being imported to control pest weeds.

The process of introduction of new agents into Aotearoa / New Zealand is developed and managed by Manaaki Whenua / Landcare Research and the Environmental Protection Authority. To assit the process, Manaaki Whenua has created an assessment framework for the selection of target weeds (Hayes et al. 2013). Biocontrol agents selected as possible candidates are usually sourced from areas of the pest's native range (Hayes 2010). All potiential agents are tested for their impact on non-target species (host-specificity testing) and if impact is observed then the candidate is rejected (Paynter et al. 2020). Climate matching is conducted to determine the suitability of an agent to the Aotearoa / New Zealand climate, including factors such as rainfall, humidity and temperature (Cameron et al. 1993).

The process of agent introduction has been developed over time, and since the 1920s there have been 79 biocontrol agents introduced into Aotearoa / New Zealand. Of the 79 agents, 68 of those are deliberate introductions, eight self-introductions and three accidental introductions.

Invertebrates were the most popular biocontrol agent type at the beginning of pest-weed agent introduction. Aotearoa / New Zealand has a record of eight self-introductions ranging from the 1950s to 2019. These agents are a combination of insects (37%) and rusts (63%), which have either blown over from neighbouring countries, e.g., Australia, or have been introduced through ornamental and horticultural plant species. Additionally, there have been eight reported occurrences of non-target species attack by biocontrol agents in Aotearoa / New Zealand, all of which pose minor threat according to Manaaki Whenua / Landcare Research scientists (Quentin Paynter, pers. comm., July 2021).

Although the use of biocontrol as a pest-plant control tool is somewhat unknown by the wider population of Aotearoa / New Zealand, there appears to be a general acceptance of its use as an alternative to chemical use. As such, with the expected negative effects of climate change on biodiversity, species ranges, phenology, genetic composition, ecosystem processes and species interactions, the engagement of the public with the use of biocontrol agents as an alternative for chemical control methods becomes increasingly important.

This research is important, as it provides insight into various aspects of biocontrol that may be unknown to the wider public, and makes them accessible to a range of people involved in teaching, research and the profession of biocontrol of weed species in Aotearoa / New Zealand.

Author Contributions

Jade Matthews: Conceptualisation (equal); data curation (lead); investigation (lead); methodology (lead); validation (equal); visualisation (equal); writing – original draft (lead); writing – review and editing (equal).

Diane Fraser: Conceptualisation (equal); writing – review and editing (equal).

Peter de Lange: Conceptualisation (equal); validation (equal); visualisation (equal); writing – original draft (lead); writing – review and editing (equal).

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Authors

Jade K. Matthews is a graduate of the Bachelor of Applied Sciences degree at the School of Environmental Sciences, Unitec | Te Pūkenga. She currently works for Ecolab, where she is a pest service specialist. Jade is enrolled in the Master of Applied Science at the School of Environmental Sciences, Unitec | Te Pūkenga, and has interests in biosecurity, biocontrol and pest management. jkmatt333@gmail.com

Dr Diane L. Fraser is an Associate Professor in Biosecurity teaching at the School of Environmental and Animal Sciences, Unitec | Te Pūkenga. Having an undergraduate and postgraduate education in agricultural animal science and postgraduate education in biosecurity and conservation, Diane teaches into zoo husbandry and biosecurity within Aotearoa / New Zealand. Her research interests are varied; however, her main focus is invasion biology, particularly invasive avian species. Diane is a member of several environmental groups but is particularly involved with volunteer work on Tiritiri Matangi Island in the Hauraki Gulf. dfraser@unitec.ac.nz

Dr Peter J. de Lange is a Professor teaching at the School of Environmental and Animal Sciences, Unitec | Te Pūkenga. A biosystematist, Peter regularly publishes on plant taxonomy, conservation, threat listing and the flora of South Pacific and outlying Aotearoa / New Zealand islands. A recipient of the New Zealand Botanical Society Allan Mere Award (2006) and Loder Cup (2017), Peter is a Fellow of the Linnean Society and a lifetime member of the New Zealand Plant Conservation Network. pdelange@unitec.ac.nz

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