Manaaki Whenua
Landcare Research

Feasibility of biocontrol for purple loosestrife (*Lythrum salicaria*)

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Feasibility of biocontrol for purple loosestrife (*Lythrum salicaria*)

Contract Report: LC5031

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Contents

Summary

Project and client

- The prospects of developing a biocontrol programme for purple loosestrife (*Lythrum salicaria*) in New Zealand were assessed by Manaaki Whenua – Landcare Research for Horizons Regional Council.

Objectives

- To review the literature to identify potential biocontrol agents for *L. salicaria* and assess their feasibility for release in New Zealand.
- To assess the prospects of achieving successful biocontrol of *L. salicaria.*
- To estimate and outline the cost of implementing a biocontrol programme for *L. salicaria* in New Zealand.

Methods

- We performed a literature survey using online resources, databases and internet searches, and we consulted with experts on the biological control of *L. salicaria* in North America.

Results

- *L. salicaria* is a noxious weed in North America and Canada, and is naturalised in New Zealand, South Africa, Chile and Argentina.
- In New Zealand, scattered and isolated populations of *L. salicaria* have been recorded in Auckland, Taranaki, Bay of Plenty, the Wellington region, the West Coast and Marlborough, and the weed is currently targeted for eradication in these regions. Fully naturalised populations of *L. salicaria* occur in Canterbury, and in Horowhenua in the Manawatū–Whanganui region. Eradication of these populations is no longer a feasible option.
- *L. salicaria* invades wetlands, lakesides, riparian zones, roadside ditches and pastures. Once established, populations expand rapidly to form dense, monospecific stands typically displacing all other wetland or riparian flora. Conventional control methods for managing *L. salicaria* are unsuccessful in the long term, and options are limited due to the sensitivity of the habitats where control interventions are required, such as wetlands.
- New Zealand has no native plant species in the loosestrife family, Lythraceae, and the closest native species are phylogenetically distant. In New Zealand there are three other species in *Lythrum*, in addition to *L. salicaria,* recorded as fully naturalised, and another species, *L. virgatum*, is present in cultivation as an ornamental with two cultivars, 'Dropmore Purple' and 'Rose Queen'.
- There is unlikely to be significant opposition to biocontrol of *L. salicaria.*
- A successful weed biocontrol programme for *L. salicaria* has been implemented in North America and Canada. Four insect biocontrol agents (two leaf beetles and two weevils) in different feeding guilds have been introduced, with varying levels of

success across the regions where *L. salicaria* is pervasive. Local eradication has been achieved in some areas, and in other areas populations have been dramatically reduced.

- All four agents are proposed for obtaining release permission from the Environmental Protection Authority (EPA), but only three (*Galerucella calmariensis*, *Galerucella pusilla* and *Hylobius transversovittatus*) are recommended for initial release.

Conclusions

- Biocontrol of *L. salicaria* using agents already released in North America is a highly viable option for managing this weed in New Zealand. Chemical and manual control methods will not provide long-term, sustainable control and are not suitable for heavily infested regions. These methods can also be damaging to the vulnerable ecosystems, such as wetlands, where they need to be applied.
- Four insect biocontrol agents, *Galerucella calmariensis*, *Galerucella pusilla*, *Hylobius transversovittatus* and *Nanophyes marmoratus*, have been released against *L. salicaria* in North America and Canada with a high degree of success. One of the most reliable predictors of a weed biocontrol agent's potential efficacy is its impact on the same target weed in a weed biocontrol programme elsewhere in the world. On this basis, the likelihood of achieving an acceptable level of control of *L. salicaria* in New Zealand, using the same biocontrol agents, is high.
- All four agents are sufficiently host specific for release in New Zealand since there are no native close relatives of *L. salicaria.* Some minor non-target feeding damage to the exotic ornamental crepe myrtle (*Lagerstroemia indica*) is likely, and minor damage to cultivars of the exotic ornamental *L. virgatum* and other naturalised *Lythrum* spp. is possible. Climate and predation and parasitism are unlikely to be significant factors that could limit populations of the biocontrol agents, further suggesting that biocontrol is a feasible option.
- All four agents should be considered for release, however it is recommended that *G. calmariensis*, *G. pusilla* and *H. transversovittatus* are prioritised if a programme is implemented until the impacts of the leaf beetles (*G. calmariensis* and *G. pusilla*) on populations of *L. salicaria* in New Zealand can be assessed.

Recommendations

- Complete the New Zealand surveys to look for any potential biocontrol agents, or any other organisms associated with *L. salicaria* (such as predators) that might interfere with the candidate biocontrol agents. This baseline information is essential for any weed biocontrol programme (Appendix 3) and with the continuation of current work, will be complete by June 2022. **Estimated cost:** $20,000 (already covered by Horizons Regional Council).
- Prepare and submit an EPA application to gain approval to release the two leaf beetles (*Galerucella calmariensis* and *G. pusilla*), the loosestrife root weevil (*Hylobius transversovittatus*), and the loosestrife seed weevil (*Nanophyes marmoratus*). The application will present host specificity and post-release data from North America as evidence that all four agents are sufficiently host specific for release in New Zealand.

Estimated cost: $55,000–$75,000 (one application will cover all four candidate agents).

- Import starter cultures of *G. calmariensis*, *G. pusilla* and *H. transversovittatus* once EPA approval is granted; apply for MPI approval to remove the agents from containment. **Estimated cost:** $20,000–$60,000.
- Mass rear and release the agents concurrently in Horowhenua in Manawatū–Whanganui. **Estimated cost:** $100,000–$250,000 per agent (the leaf beetles will be reared together).
- Assess whether the seed weevil *Nanophyes marmoratus* is also needed to achieve acceptable levels of control of *L. salicaria* in New Zealand. **Estimated cost:** $20,000 - $100,000.

Note: estimated costs are exclusive of GST and are based on 2021/22 figures. New estimates will need to be provided if work is to be undertaken well beyond those dates, and/or if complicating factors arise (e.g. disease infecting imported agents, ongoing disruption due to Covid-19).

1 Introduction

The feasibility of developing a biocontrol programme targeting purple loosestrife, *Lythrum salicaria* L. (Lythraceae) in New Zealand was assessed by Manaaki Whenua – Landcare Research for Horizons Regional Council.

2 Background

2.1 Biology and ecology of *Lythrum salicaria*

L. salicaria is an erect, herbaceous, perennial herb with shoots 20–300 cm long and a persistent woody rootstock. It typically grows in wetlands, along streams and rivers, and along the edges of lakes. Clonal colonies are formed with numerous (up to 30) shoots. Dead shoots persist through winter, sometimes decaying over several years, and new shoots are produced each spring from buds on the rootstock.

Figure 1. *Lythrum salicaria* in flower growing along a lake. (Credit: Trevor James)

L. salicaria shoots are woody, angular, with five or six sides and can either be smooth or covered with hair. The shoots have smaller, slender branches with evenly spaced nodes. Leaves are stalkless, 3–10 cm long, lanceolate to ovate, and arise from each node in opposite or alternate pairs or whorls of three (usually the lower leaves). The large, spiked inflorescences have numerous, showy, purple flowers in clusters. Flowers have five to seven sepals with a small yellow centre and are 15–20 cm in size. Seed capsules are rounded, 4–6 mm long, and open when mature to release >100 light brown seeds the size of poppy seeds. Seeds are thin-walled, with two cotyledons and no endosperm (Thompson et al 1987; Wilson et al. 2004).

Figure 2. *Lythrum salicaria* shoots tips and leaves. (Credit: Trevor James)

Figure 3. *Lythrum salicaria* spiked inflorescence. (Credit: Trevor James)

L. salicaria seeds germinate when soil temperatures reach 20ºC. Seedlings root in moist soil and can reach up to 1 m tall, with an extensive underground rootstock in their first season of growth. When *L. salicaria* plants are established they can tolerate a wide range of growing conditions such as permanent flooding, high and low water nutrient conditions, and low pH. Plants can grow in gravel and rock crevices, and in sandy, clay and organic soils. *L. salicaria* is highly tolerant of the varying physical and chemical conditions, typical of disturbed habitats: it tolerates nitrogen and phosphorus deficiencies through increasing root:shoot ratios; it responds to increasing water levels by growth of submerged stems; and it adapts to decreases in light levels with changes in leaf morphology (Blossey 2002; Thompson et al. 1987; Wilson et al. 2004).

2.2 Global distribution of *Lythrum salicaria*

Lythrum salicaria is native to the Old World, with distribution centres in Europe and Asia (CABI 2021). Its European distribution extends from Great Britain throughout Europe, with the exception of high, mountainous regions and the most northerly latitudes, such as the Faroe Islands, Iceland, and the northern-most regions of Scotland, Scandinavia and Russia. *L. salicaria* is common in southern and central Europe and the coastal fringes of the Mediterranean Basin, with the exception of Crete and the Balearic Islands (CABI 2021; Blossey 2002). The centre of its native distribution in Asia is the main islands of Japan, with outlying populations in parts of China, South-east Asia and India (Hulten & Fries 1986). In Australia *L. salicaria* is predominantly found in the south-eastern states and Tasmania.

L. salicaria was accidentally introduced to the east coast of North America in the early 1800s, most likely via ship ballast, contaminated sheep wool and/or live sheep. It was later intentionally introduced as a valued medicinal herb by European immigrants (CABI 2021; Malecki et al. 1993; Stuckey 1980). *L. salicaria* now occurs in all North American states with the exception of Florida and Alaska, and is a declared noxious weed in at least 23 of these states (Wilson et al. 2004). Its abundance varies throughout this range, with some populations still expanding, with the exception of the first regions infested in the eastern United States. A substantial proportion of all potentially available habitat has already been invaded in the Northeast and Midwest (Blossey 2002; Blossey, Skinner et al. 2001). *L. salicaria* is also invasive in nine southern states in Canada, and is introduced in South Africa, Chile, Argentina and New Zealand (CABI 2021).

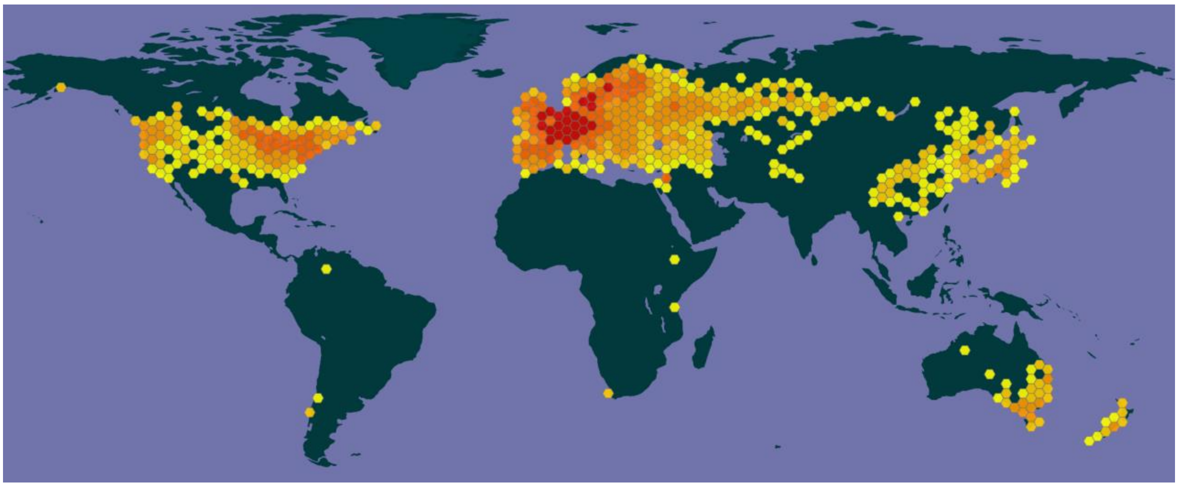

Figure 4. Global distribution of *Lythrum salicaria.*
(Source: https://www.gbif.org/species/3188736)

2.3 Pest status and distribution of *Lythrum salicaria* in New Zealand

Introduced to New Zealand as an ornamental garden plant, *L. salicaria* was first recorded in 1958 (Webb et al. 1988). As a wetland plant it was particularly popular for planting alongside residential ponds and streams, but it now invades wetland habitats, riparian and lakeside margins, roadside ditches, and even farmland, invading pastures and waterways and clogging drains.[1] *L. salicaria* is declared an unwanted organism by the Biosecurity Act 1993 and is a National Pest Plant Accord species. It is thus banned from sale, propagation and distribution.

Once established, *L. salicaria* populations expand rapidly to form dense, monospecific stands. *L. salicaria* has the potential to displace all other wetland flora, which drastically alters native wetland ecosystems. Wetland and marginal ecosystems transformed by *L. salicaria* infestations reduce food sources for many fish and bird species. The recreational and aesthetic value of lakes, streams, rivers and wetlands are reduced by dense infestations of *L. salicaria.* The tall plants block a view of the water and reduce native biodiversity, and access to water for recreational activities is made difficult.

In New Zealand *L. salicaria* flowers from December to February, with fruiting bodies maturing in autumn (May). Plants are not self-fertile, so seeds are only formed when more than one plant genotype is present. Seeds are mainly dispersed by water, but also by birds, livestock, contaminated machinery and hay. Sharing of garden cuttings may still contribute to its spread.[2]

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[1] www.nzpcn.org.nz/flora/species/lythrum-salicaria/; www.weedbusters.org.nz/what-are-weeds/weed-list/purpleloosestrife/

[2] www.nzpcn.org.nz/flora/species/lythrum-salicaria/

Scattered and isolated populations of *L. salicaria* have been recorded in Auckland, Taranaki, Bay of Plenty, the Wellington region, the West Coast and Marlborough. Fully naturalised populations of *L. salicaria* occur in Canterbury and in Horowhenua in the Manawatū–Whanganui region on the west coast of the North Island.[3] In Marlborough *L. salicaria* plants have been found in urban gardens and along the margins of Gibson's Creek in Renwick. This species is a surveillance pest plant in the Marlborough region, with Marlborough District Council monitoring any changes in its distribution to assess its future invasion status.[4]

In 2012 the Department of Conservation (DOC), in a combined effort with Christchurch City Council and Environment Canterbury, requested landowners in the region to report sightings of *L. salicaria* as a result of its escalating threat to pasture and waterways.[5] With the development of a new Regional Pest Management Plan for Canterbury, the goal of *L. salicaria* management has changed from eradication to sustained control.[6]

In most regions of New Zealand where *L. salicaria* is present, populations are actively managed or are targeted for eradication by district and regional councils. Eradication of *L. salicaria* in Manawatū–Whanganui (Lakes Horowhenua and Papaitonga, Hokio Stream and Lake Virginia[7]) was initially deemed feasible by Horizons Regional Council (HRC). At the time the infestations were estimated to cover 30 ha. However, in 2020 HRC reported that this objective was unlikely to be met around Lake Horowhenua. The main issues are safe access to sites around the lake and other land holdings, and limited herbicide tools available for use in wetlands. This has prevented management of the largest population of *L. salicaria* in New Zealand, with the expanding populations putting pressure on nearby lakes. New sites are being discovered, and previously well-managed infestations are at increased risk of reinvasion from *L. salicaria*.[8]

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[3] www.inaturalist.nz/taxa/61321-Lythrum-salicaria

[4] https://www.marlborough.govt.nz/repository/libraries/id:1w1mps0ir17q9sgxanf9/hierarchy/Documents/Environment/Biosecurity/Purple_Loosetrife.pdf

[5] https://doc.govt.nz/news/media-releases/2012/purple-loosestrife-a-garden-escapee-on-the-run/

[6] http://www.ecan.govt.nz/your-region/your-environment/our-natural-environment/pest-management/plant-pests/

[7] http://horizons.govt.nz/HRD/media/Media/One%20Documents//Operative-rppms-September-2007.pdf

[8] http://www.horizons.govt.nz/HRC/media/Media/Agenda-Reports/Strategy-and-Policy-Committee-2020-13-10/20142%20Pest%20Plan%20Updated.pdf

Figure 5. Distribution of *Lythrum salicaria* in New Zealand. (Source: https://inaturalist.nz/observations?nelat=68.13885164925574&nelng=180&place_id=any&subview=map&swlat=-69.90011762668539&swlng=-180&taxon_id=61321)

In 2021 a lake restoration project was initiated, with funding from the Government and HRC, in a bid to restore the water quality and native biodiversity of Lake Horowhenua, one of New Zealand’s most polluted lake systems. Weed management is essential to enhancing the lake’s social, cultural, environmental and economic values. Biocontrol of *L. salicaria* has been identified as a potentially viable control option to successfully suppress *L. salicaria* populations around the lake and to reduce spread.

2.4 Detrimental impacts of *Lythrum salicaria*

2.4.1 Environmental and ecological impacts

High seed production, a vigorous and persistent root system, and rapid growth rates contribute to the competitive dominance and rapid spread of *L. salicaria* in invaded ecosystems (CABI 2021). *L. salicaria* is a prolific seed producer, with seeds easily spread by water and wind, in footwear, and by waterfowl and other wildlife. Long-lived, mature plants in North America can produce more than 2.5 million seeds annually, which remain viable in the soil/sediment for many years. When *L. salicaria* densities are high, billions of seeds are produced per hectare. In North America, rootstocks of mature plants can weigh up to 1 kg or more, producing up to 30 annual shoots c. 350 cm in height (CABI 2021; Blossey 2002).

Research on *L. salicaria* invasions in North America has demonstrated the serious negative impacts of infestations on the structure, function and productivity of wetlands (Gabor et al. 1996; Emery & Perry 1996; Grout et al. 1997). *L. salicaria* is a competitively dominant species, typically excluding all native wetland species to form dense, monospecific stands (Weiher et al. 1996). It dominates the seed bank in areas with well-established *L. salicaria* populations (Welling & Becker 1990, 1993), and seeds germinate more rapidly and at higher rates than in most native wetland species (Shipley & Parent 1991).

These factors, together with high relative growth rates of seedlings (Shipley & Parent 1991), aid the rapid recovery of populations after management interventions. Gabor et al. (1996) showed that native plant communities previously outcompeted by *L. salicaria* recovered when populations were suppressed with the use of herbicides. However, without continued applications, *L. salicaria* re-invaded quickly, re-establishing dominance within a few years. A native and rare *Lythrum* species, winged loosestrife (*L. alatum*), is severely threatened by *L. salicaria* where their distributions overlap in North America. The presence of the taller, more conspicuous of the two species, *L. salicaria* reduces pollinator visitation to *L. alatum*, significantly reducing seed set for this species (Brown 1999).

The extensive and rapid invasion of *L. salicaria* in North American wetlands has negatively affected populations of specialised marsh and wetland bird species as well as mammals. Breeding populations of black terns, initially common at Montezuma National Wildlife Refuge, became locally extinct, coinciding with a population explosion of *L. salicaria.* The avoidance of *L. salicaria* for foraging and nesting by specialist marsh birds such as the Virginia rail, sora, least bittern, American bittern and pied-billed grebe (*Podilymbus podiceps*) was documented by Lor (2000). The long-billed marsh wren, a wetland specialist, was recorded as completely absent from *L. salicaria*-dominated wetlands, but was foraging and nesting in adjacent cattail marshes (Rawinski & Malecki 1984).

L. salicaria can alter hydrological and biochemical processes in wetlands and other water bodies where it invades. Its leaves decompose quickly when stems die back in autumn, resulting in a nutrient flush that differs from the phenology of native sedges, which drop their leaves in spring and decay slowly, supplying detritus throughout winter (Emery & Perry 1996; Grout et al. 1997). Grout et al. (1997) suggest this change in timing of nutrient release and suppression of native sedges important in detritus-based food webs could jeopardise detritivore communities. The nutrient flush could also accelerate eutrophication (Emery & Perry 1996).

2.4.2 Socio-economic impacts

One of the primary economic impacts of *L. salicaria* is the disruption of ecosystem services and products. In North America, dense stands of *L. salicaria* decrease the recreational value and use of wetlands for hunting, fishing and bird watching (Blossey 2002). Direct economic impacts occur when infestations clog drainage ditches and canals on farms, or degrade and/or destroy forage in low-lying pastures, reducing livestock stocking rates.[9]

There are significant economic impacts associated with control measures. Pimental et al. (2005) reported annual control costs of *L. salicaria* in North America to be US$45 million. In New Zealand, $40,000–$50,000 is spent annually by HRC on control measures for *L. salicaria.* This excludes unknown expenses to control the weed in areas managed by DOC. The control measures pose a risk to these habitats, which jeopardises the council's social licence to operate, with public concern over non-target impacts of the current control methods available. Also, these control methods do not mitigate the threat of *L. salicaria* to dunes, wetlands and streams in the region (C. Davey, HRC, pers. comm.).

2.5 Beneficial uses of *Lythrum salicaria*

In North America in the 1940s, *L. salicaria* was seen as valuable bee forage plant by beekeepers, which contributed to its spread. Seeds were intentionally spread along rivers and streams to increase the number and density of flowering *L. salicaria* plants (Thompson et al. 1987).

L. salicaria is reported to be a medicinal and a food plant. It is an astringent herb, mainly used for diarrhoea and dysentery. Externally, *L. salicaria* is used for cleansing and healing wounds, sores, impetigo, haemorrhoids, eczema, and varicose veins (Chevallier 1996; Bencsik et al. 2011). The stems are used to strengthen weak or bleeding gums (Chiej 1984). Modern research has shown that the whole plant is antibiotic and is particularly effective against the bacterium that causes typhus (Chevallier 1996).

L. salicaria leaves contain high levels of tannins, which help to preserve wood and other natural fibres. For example, a decoction of *L. salicaria* is impregnated into wood and rope to prevent rotting in water (Komarov 1968). A red hair dye has been made from the flowers (Roia 1996), and the dye has been used as a food colouring. The flowers and stems are used as food.[10]

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[9] http://issg.org/database/species/impact_info.asp?si=93&fr=1&sts=&lang=EN

[10] www.eatweeds.co.uk/purple-loosestrife-lythrum-salicaria

2.6 Phylogeny and taxonomy

The Lythraceae is a family of about 32 genera and 600 species in the order Myrtales (Heywood et al. 2007). *Lythrum* L., with about 36 species, has a native range extending across Eurasia, Australia and the Americas (Graham 2007). There are no New Zealand native representatives in the Lythraceae, and the closest native species are phylogenetically distant in the willowherb family (Onagraceae): three species of *Fuchsia* and 38 species of *Epilobium* (Schönberger et al. 2021). The sister relationship of Lythraceae and Onagraceae is based on morphological, anatomical and embryological evidence (Johnson & Briggs 1984; Graham 2007) and is confirmed by molecular analyses (Sytsma et al. 2004; Graham et al. 2005; Maurin et al. 2021). Other families in the Myrtales are more distantly related, including the Myrtaceae (Sytsma et al. 2004; Maurin et al. 2021), which is the only other family in the Myrtales with native species (Figure 6).

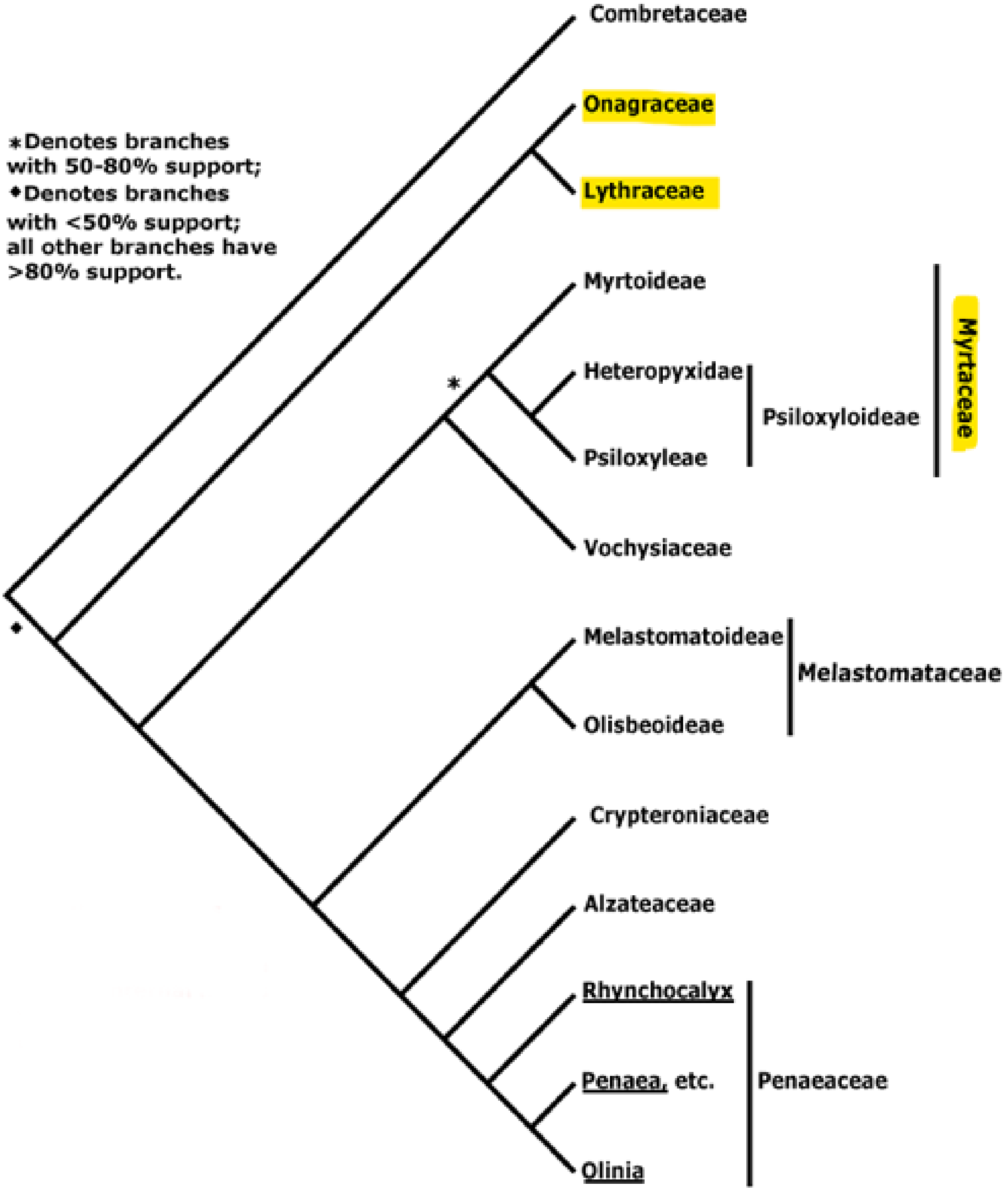

Figure 6. Relationships between the Lythraceae, Onagraceae and Myrtaceae. (Reproduced from APGII, Stevens 2017 onwards)

In New Zealand there are three other species in *Lythrum* (in addition to *L. salicaria*) recorded as fully naturalised, and another species, *L. virgatum*, is present in cultivation as an ornamental and is recorded with two cultivars, 'Dropmore Purple' and 'Rose Queen' (Table 1).

There are eight exotic, cultivated or naturalised, non-congeneric species belonging to the Lythraceae also present in New Zealand. These species occur in five different genera (Figure 7). Of these genera, *Heimia, Lagerstroemia* and *Rotala* are the most closely related to *Lythrum* in clade 4b (Figure 7), while *Cuphea* and *Punica* (represented in New Zealand by *P. granatum* L., pomegranate) are more phylogenetically distant in clade 4a.

Table 1. Species in the Lythraceae other than *Lythrum salicaria* recorded in New Zealand. (Source: Schönberger et al. 2021)

Other Lythraceae in New Zealand	Common name	Biostatus
Lythrum hyssopifolia L.	hyssop loosestrife	fully naturalised
L. junceum Banks & Sol. (known as L. f	rose loosestrife	fully naturalised
L. portula (L.) D.A.Webb (= *Peplis portula* L.)	water purslane	fully naturalised
L. virgatum L.	garden loosestrife	cultivated
'Dropmore Purple'		cultivated
'Rose Queen'		cultivated
Cuphea hyssopifolia Kunth	elfin herb	fully naturalised
C. ignea A.DC.	cigar flower	casual naturalised
C. lanceolata W.T.Aiton		casual naturalised
Heimia salicifolia Link	sun opener	casual naturalised
Lagerstroemia indica L.	crêpe myrtle	cultivated
L. limii Merr.	Chinese crêpe myrtle	cultivated
Punica granatum L.	pomegranate	cultivated (uncertain casual naturalised, possibly a relic)
Rotala rotundifolia (Buch.-Ham. ex Roxb.) Koehne	rotala	casual naturalised

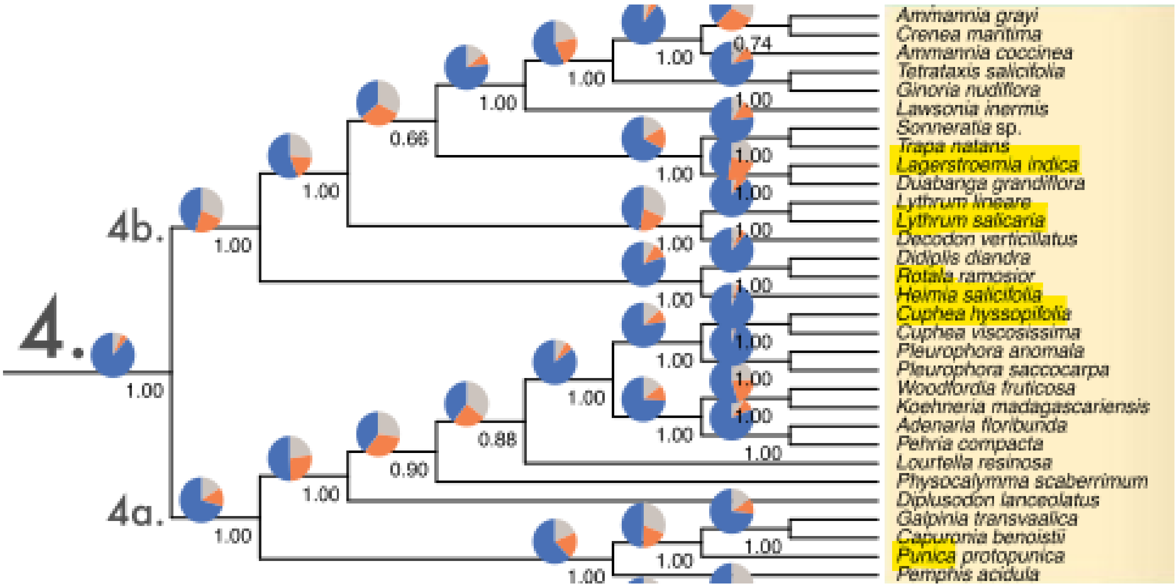

Figure 7. Phylogenetic relationships of the Lythraceae showing two main clades, 4a and 4b. Pie charts above branches display quartet score (QS) values for each node (blue = species tree topology QS; orange = first alternative topology QS; grey = second alternative topology QS). Values next to branches are bootstrap support percentages. (Source: Maurin et al. 2021)

2.7 Control options

Once established, *L. salicaria* infestations are very difficult to eradicate, requiring years of persistent, follow-up control measures. Physical control measures include grubbing or digging out plants, but this is only feasible for very small populations or isolated stems, and should preferably be applied before the plants set seed. The use of weed matting, which has to be left in place for at least 3–4 months, can kill whole patches of *L. salicaria*. Mowing, cutting and burning have been used with some success in North America, but they are costly, time-consuming and may have severe negative impacts for wetland ecosystems.

Where possible, water levels can be lowered so that mature plants can be mechanically removed. Water levels can also be raised for 2–3 weeks to drown infestations of the weed.[11]

Chemical control of *L. salicaria* is effective in the short term but is costly for large infestations due to the need for repeat applications until the infestation is completely eradicated. Cut-stump with chemical treatment of the stems or foliar sprays with systemic herbicides such as glyphosate are recommended. Glyphosate at 50–100 ml/10 L water can be applied around waterways (with a suitable adjuvant). Grazon at 30 ml per 10 L of water is also recommended.[12] Triclopyr 600 EC (30 ml/10 L) or triclopyr 120 g/L is recommended for terrestrial sites only.

In Minnesota, in North America, herbicides were applied to an average of 150–160 *L. salicaria* sites per year, from 1990 for a period of almost 10 years. Although these populations were temporarily suppressed, eradication was not achieved at some of the sites and the herbicide applications also suppressed desirable plant species (Skinner et al. 1994). Wetlands with extensive *L. salicaria* seedbanks occasionally ended up with worse infestations following herbicide applications due to the rapid recruitment of seedlings and simultaneous loss of native species (Skinner et al. 1994). Eventually the lack of control success and concerns over the potential harmful effects of herbicide over-exposure of workers resulted in reductions of the state-wide spraying programme (Blossey, Skinner et al. 2001).

A biological control programme was initiated in North America in 1986 as a result of the consistent failure of conventional methods to provide economically and ecologically sound and effective control of the weed. The release of biocontrol agents was expected to reduce the need for the use of herbicides in sensitive wetland habitats, and to facilitate the recovery of native biodiversity (Blossey, Skinner et al. 2001).

Although conventional control measures can eliminate small and young infestations of *L. salicaria*, they are all costly, require consistent, long-term application, and in the case of

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[11] https://weedbusters.org.nz/what-are-weeds/weed-list/purple-loosestrife/

[12] https://www.marlborough.govt.nz/repository/libraries/id:1w1mps0ir17q9sgxanf9/hierarchy/Documents/Environment/Biosecurity/Purple_Loosetrife.pdf

herbicides are non-selective and potentially harmful to the ecosystems where they are applied (Malecki et al. 1993). Due to the aquatic nature of *L. salicaria,* control with chemicals is often not possible or is inadvisable.

2.8 Potential advantages and disadvantages of biocontrol

Biocontrol of *L. salicaria* is a highly desirable management method for this weed due to its aquatic nature, which precludes the use of many herbicides. The application of conventional control methods in the sensitive ecosystems (such as wetlands) that *L. salicaria* invades is also not advisable. Physical and chemical control methods only provide a short-term solution, particularly for a weed with high seed outputs and competitive seedlings, which facilitate rapid reinvasion after areas are cleared. There is also a growing public disapproval of the use of chemicals to control weeds, particularly in waterways. Although chemical control can provide immediate, widespread reductions in infestations, the large-scale, rapid die-back of plants creates a disturbed habitat in which invasive weeds thrive.

Although much research goes into predicting the efficacy of candidate biocontrol agents, particularly in modern-day programmes, complete success where biocontrol is so effective that no other management interventions are required has only been achieved for approximately one-quarter of the programmes worldwide (Schwarzländer et al. 2018). When complete control is not achieved, in many cases substantial or partial control of the target weed is achieved, which dramatically reduces the demand for other control methods. Complete failure of weed biocontrol programmes is rare, and is often the result of a lack of funding to complete a programme to the point where all options have been exhausted (Paynter & Flannagan 2004).

If successful, classical biocontrol is more cost effective than other control methods because it is self-sustaining, acting in perpetuity, and the economic benefits can be substantial. In New Zealand it is estimated that net benefits of $11 million to $217 million annually are gained from weed biocontrol (Suckling 2013). A study by Fowler (2012) showed that the Net Present Value for biocontrol of St John's wort (*Hypericum perforatum*) is between $140 million and $1,490 million over 70 years, with benefit-to-cost ratios of 10:1 and 100:1. For ragwort (*Jacobaea vulgaris*), a major pasture weed, biocontrol with the ragwort flea beetle (*Longitarsus jacobaeae*) is estimated to have saved the dairy industry $40 million annually in herbicide costs alone, with a benefit-to-cost ratio of 14:1 (Fowler et al. 2016). Elsewhere in the world, the benefit-to-cost ratios of biocontrol to ecosystem services ranged from 50:1 for sub-tropical shrubs in South Africa, to 3,726:1 for weedy Australian acacias (de Lange & van Wilgen 2010). In Australia an economic analysis by Page and Lacey (2006) indicated a strong positive return on investment from weed biocontrol programmes, with a benefit of AU$23.10 for every dollar invested in weed biocontrol.

Non-target impacts such as 'spillover effects' (non-target attack on related plant species growing in the vicinity of the target weed) can be a consequence of weed biocontrol programmes (Paynter et al. 2020). However, rigorous assessments of candidate biocontrol agents prior to their release, designed according to international best practice, reliably predict the risk of non-target attack (Suckling & Sforza 2014; Paynter et al. 2020). Non-target plant species at risk of attack are generally closely related to the target weed (Taylor et al. 2007), and damage is usually localised and not of any consequence to populations of the non-target plants. Of the 512 insect biocontrol agents released against weeds in 75 countries prior to 2014, 7.6% had minor non-target impacts and only 0.8% (a total of four agents) had moderate to major adverse effects. For this very small proportion of agents that were intentionally released and had serious non-target effects, the non-target attack was predictable and those weed biocontrol agents would not be released today (Paynter et al. 2020).

2.9 Potential for opposition to biocontrol

We do not expect there to be serious opposition to biocontrol of *L. salicaria*. Gardening enthusiasts may have concerns over non-target feeding damage to cultivars of *L. virgatum* ('Dropmore Purple' and 'Rose Queen') and crepe myrtle (*Lagerstroemia indica*) cultivated as ornamentals. *Lythrum virgatum* was not tested in host range tests in North America, but their results suggest that some feeding damage to these cultivars is possible since the leaf beetles fed (nibbling slight to moderate) on other *Lythraceae* spp. in their tests (Blossey et al. 1994a). An online search suggests that *L. virgatum* cultivars are not very popular and are not widely available in New Zealand. Feeding damage to *L. indica* is likely, since the beetles are known to cause minor damage to this plant in the field in North America, but this is transient and the beetles don't reproduce on this non-target plant (Piper et al., 2004; B Blossey, Cornell University, pers. comm.; FS Grevstad, Oregon State University, pers. comm.).

2.10 Predicting establishment of biocontrol agents

Successfully predicting the likelihood of the establishment and potential efficacy of classical weed biocontrol agents is an important goal for programmes. Factors such as climate compatibility (Julien et al. 1995); predation, parasitism and disease (Paynter et al. 2010, 2018); the number and size of agent releases (Paynter et al. 2016); and the timing of releases (Day et al. 2004) can be crucial in the establishment success of agents in their new environments.

The best current predictor of establishment success of new weed biocontrol agents is the number and size of releases (Paynter et al. 2016). High rates of agent establishment in New Zealand (approximately 70%, Schwarzländer et al. 2018) is largely facilitated by the Technology Transfer Programme operated by Manaaki Whenua – Landcare Research in collaboration with regional councils, community and farmer groups, the Department of Conservation, forestry companies, and iwi groups (Hayes 2000). This system of national networks facilitates high numbers of releases throughout the distribution range of the weed. Releases of new agents generally take place in quick succession, annually, over several years.

Although invasive plants and their co-evolved natural enemies used as biocontrol agents should have similar climatic requirements, climate incompatibility has been an issue when candidate agents have been collected from a restricted part of a weed's native distribution that covers a range of environmental and climatic conditions (Julien et al. 1995). Exotic weeds may establish in novel ecosystems that do not occur in the native range, and adaption of the biocontrol agents to the new ecosystems may be poor, or they may only be effective in certain regions of the introduced range that are climatically similar to their origin. Increases or decreases in the number of annual generations can occur in response to differences in day length, which can influence agent establishment, especially when they are already climatically sensitive (Grevstad & Coop 2015).

Species distribution modelling and climate matching techniques can help identify and locate suitable biocontrol agents that are likely to be well adapted to the climates in the invaded range. For example, biocontrol agents sought from a specific region within the native distribution could be beneficial when control is only needed in a subset of the weed's fundamental niche. Further, modelling techniques are increasingly being used to make predictions of successful agent establishment, taking into consideration climate change impacts (Olfert et al. 2016).

2.11 Predicting impacts of biocontrol agents

Predicting the impacts of weed biocontrol agents in their introduced range is inherently difficult, and will be influenced by a multitude of factors such as climate compatibility, predation, parasitism, competition and host plant compatibility (for highly specialised insects and pathogens). All these factors can affect their ability to persist and thrive and reach the population densities required to suppress populations of their host plant.

Although some weed biocontrol programmes worldwide have been highly successful with the use of one agent, generally the release of multiple agents against a weed brings about effective control However, the 'lottery model' (which likens success to odds in a lottery, whereby multiple agents are released to increase the likelihood of releasing the most effective one) has been criticised as a result of the environmental risk associated with each agent that is introduced (Denoth et al. 2002). Best practice now determines that the smallest number of agents possible should be released to bring about effective control of the target weed, and so critical factors that will influence an agent's efficacy should be well understood before an agent is released.

Certain groups of insects and pathogens used for weed biocontrol are associated with higher success rates. A global analysis revealed that beetles (Coleoptera), bugs (Hemiptera) and fungal pathogens have the highest proportions of taxa with heavy impacts on the target weeds (or a combination of medium, variable, or heavy impact) (Schwarzländer et al. 2018). Beetles in the families Curculionidae (weevils) and Chrysomelidae (leaf beetles) have been identified as the most effective taxa at reducing host plant abundance (Crawley 1989; Clewley et al. 2012). So far only 6.4% of the total number of weed biocontrol agents released are made up by fungal pathogens (Schwarzländer et al. 2018), with no serious unpredicted impacts (Barton 2012). The most widely used pathogens for classical weed biocontrol are rust fungi, which can complete their life cycle on one host (i.e. they're 100% host specific), are highly virulent, and can disperse over long distances (Barton 2012).

For some weed biocontrol programmes it has been essential to match host plant biotypes between the native and introduced ranges. Some pathogen and arthropod natural enemies used in weed biocontrol programmes are highly specialised and can only feed, develop and/or thrive on certain varieties, subspecies or genotypes of the target weed. For example, a phytophagous mite, *Floracarus perrepae*, originating from the same geographical location as the invasive haplotype of their host plant, *Lygodium microphyllum*, was more effective for biocontrol than *F. perrepae* mites originating from more distant locations (Goolsby et al. 2005).

Parasitism, predation and interspecific competition can have substantial effects on the success of weed biocontrol agents. A study by Paynter et al. (2010) showed that parasitism rates of between 41 and 100% significantly reduced the impacts of five weed biocontrol agents in New Zealand. Further research in this area indicates that using agents that do not have any native analogues (i.e. closely related native species that share the same niche on the target weed) in the natural fauna in the introduced range can greatly reduce the probability that they will accumulate parasitoids that can reduce their efficacy (Paynter et al. 2018). Limiting predation risks is more difficult because predators tend to be generalists. However, investigating food webs and trophic structures of the weed and candidate biocontrol agents in their native range can provide insights into how predation impacts can be minimised or avoided in the area of introduction (Paynter et al. 2018).

Interspecific competition or competitive displacement, especially from other weed biocontrol agents, can reduce the effectiveness of weed biocontrol programmes. For example, interference competition between two biocontrol agents released against spotted knapweed (*Centaurea stobe* L. ssp. *micranthos*) reduced the overall seed destruction of knapweed relative to seed destruction by the weevil alone (Crowe & Bouchier 2006). Hence, when considering the release of multiple agents against a target weed, selecting agents from different feeding guilds can reduce the potential for interspecific competition, or competitive displacement of one agent that may be more effective at reducing growth and productivity of the weed.

Defining the aims and determining an acceptable level of control at the outset of a programme can be crucial. These objectives should be known to all stakeholders involved so that success or failure can be accurately and objectively assessed. Unidentified differences between stakeholders in what constitutes a successful biocontrol programme can impede progress towards achieving the goals of the programme. For example, some stakeholders may have unrealistic expectations, anticipating that biocontrol impacts will occur faster than is reasonably possible, which can negatively affect impressions of the programme’s success.

Finally, the most reliable predictor of the efficacy of biocontrol agents is their successful use elsewhere in the world. Repeat programmes or transfer projects using biocontrol agents already successfully released on the same target weed in other countries have a good track record of success.

2.12 The biocontrol programme for *Lythrum salicaria* in North America

Field surveys for potential biocontrol agents for the management of *L. salicaria* in North America began in Europe in 1986. By 1992 surveys for natural enemies of *L. salicaria* in its native range had been conducted in Finland, Norway, Denmark, Sweden, Germany, Austria, Switzerland and France, building on the initial observations of Batra et al. (1986). The surveys covered 140 sites, including the northern-most distribution to the Mediterranean Basin, thus including a range of habitat types and climates (Blossey 2002). In order to cover the invaded range, surveys were also conducted in North America, from Maryland to Nebraska (Hight 1990). The initial surveys in North America yielded no native or accidentally introduced herbivores that had potential as biocontrol agents for *L. salicaria.* Some native pathogens were later identified and evaluated as potential biocontrol agents (Nyvall 1995; Nyvall & Hu 1997).

The native range surveys conducted in Europe identified more than 100 insect species that were commonly associated with *L. salicaria* (Batra et al. 1986), but only nine of these were selected for further evaluation (Blossey 1995a). Six of these nine insect natural enemies underwent host range testing to assess their suitability for release. They were selected for further study based on published literature on their host specificity, their availability and distribution in the native range, and observations of their impact on the growth and vigour of *L. salicaria*. They are the root-mining weevil, *Hylobius transversovittatus* Goeze (Coleoptera: Curculionidae); two leaf beetles, *Galerucella calmariensis* L. and *Galerucella pusilla* Duftschmidt (Coleoptera: Chrysomelidae); a flower-feeding weevil, *Nanopyhes marmoratus* Goeze (Coleoptera: Curculionidae); a seed-feeding weevil, *Nanophyes brevis* Boheman (Coleoptera: Curculionidae); and a gall midge, *Bayeriola salicariae* Gagné (Diptera: Cecidomyiidae) (Blossey 2002; Malecki et al. 1993).

All six of the candidate biocontrol agents were assessed against 48 test plants in 32 genera. Five of them, *H. transversovittatus*, *G. calmariensis, G. pusilla*, *N. marmoratus* and *N. brevis*, were approved for release in North America. The gall midge, *B. salicariae*, was able to complete development on three other *Lythrum* species that were tested: *L. alatum*, *L. californicum* Torr & Gray, and *L. hyssopifolia* L. (Blossey & Schroeder 1995a. Although they were inferior hosts in comparison to *L. salicaria*, the gall midge was not proposed for release (Blossey 2002; Malecki et al. 1993).

The flower- and seed-feeding weevils, *N. marmoratus* and *N. brevis*, were shown to be monophagous, entirely restricted to their host plant, *L. salicaria* (Blossey & Schroeder, 1995a). *Nanophyes marmoratus* was first released in New York State and Minnesota in 1994, and in New Jersey in 1996. Although *N. brevis* was approved for introduction into North America, it was never released due to a nematode infection and the potential for non-target effects.

For the leaf beetles, *G. calmariensis* and *G. pusilla*, the host range tests indicated that two native North American plant species, *Decodon verticillatus* (L.) Ell. and *L. alatum*, were susceptible and potential hosts for the beetles (Blossey et al. 1994a). Both species are in the loosestrife family, Lythraceae. However, the Technical Advisory Group (TAG) in North America reviewed the results and determined that *D. verticillatus* and *L. alatum* were at greater risk from further invasion by *L. salicaria* than they were from the beetles. Both of these test plants were also shown to be susceptible to the root-feeding weevil *H. transversovittatus* but to a lesser degree than the leaf beetles. The TAG approved its release on the same basis: that *L. salicaria* invasions pose a greater threat to populations of *D. verticllatus* and *L. alatus* than the weevil.

The first releases of the leaf beetles and the weevil took place in 1992 (Hight et al. 1995) in Virginia, Maryland, Pennsylvania, New York, Minnesota and southern Ontario. Predictions of spill-over feeding by the beetles on other species at high population densities (Blossey et al. 1994a; Blossey & Schroeder 1995) were confirmed by Corrigan et al. (1998) and Blossey, Casagrande et al. (2001), but this attack was transient and was only recorded in newly eclosed (emerged) beetles.

The weed biocontrol programme for *L. salicaria* in North America has been one of the most widely implemented programmes there. As a result, infestations of the weed were reduced by up to 90% in several states in the first 10 years (Piper et al. 2004). Successful biological control has reportedly reduced the demand for herbicide use, as indicated by reduction of herbicide purchases (Blossey 2002). Local eradication has been achieved at some sites, and dramatic declines, measured as a reduction in stem density (up to 85%), in *L. salicaria* abundance have been achieved at others (Endriss et al. unpubl.).

3 Objectives

- To review the literature to identify potential biocontrol agents for *L. salicaria* and assess their feasibility for release in New Zealand.
- To assess the prospects of achieving successful biocontrol of *L. salicaria.*
- To estimate and outline the costs of implementing a biocontrol programme for *L. salicaria* in New Zealand.

4 Methods

4.1 Identifying arthropod biocontrol agents for *Lythrum salicaria*

A list of the biocontrol agents released in North America is presented in Appendix 1. Scientists in North America who have extensively studied the biocontrol agents in both pre- and post-release evaluations were consulted (Dr Bernd Blossey, Cornell University; Dr Stacey Endriss, Cornell University; Dr Fritzi Grevstad, Oregon State University). Other information was acquired through searching online databases and internet sites such as Google, Googlescholar, CAB abstracts and the ‘Purple Loosestrife Bibliography’: http://www.purpleloosestrife.org/research/plbbiblio.html.

4.2 Identifying fungal pathogens of *Lythrum salicaria*

A table was compiled of the fungi that have been reported as being associated with *L. salicaria*. The information was obtained by searching online databases and Internet sites. Online databases searched included:

- USDA Fungus-host database (FDSM) (Farr & Rossman 2021): http://nt.ars-grin.gov/fungaldatabases/fungushost/FungusHost.cfm

- Kew Royal Botanic Garden Fungi species browser (previously IMI fungal herbarium): http://www.herbimi.info/herbimi/searchassorg.htm
- New Zealand fungi and bacteria database (NZFUNGI): http://nzfungi2.landcareresearch.co.nz/

In addition, CAB abstracts, Current Contents, PubMed, Ingenta, Web of Science, Agricola, Science Direct, and Google were searched, using the terms '*L. salicaria* or Purple loosestrife or Spiked loosestrife' and sub-searched using the terms 'pathogen* or fungi*'. Once a list had been created, further information about each fungus was sought in the published literature as well as in the following online databases:

- Index Fungorum: http://www.indexfungorum.org/Names/Names.asp
- Global Biodiversity Information Facility (Global Biodiversity Information Facility 2017): http://data.gbif.org/species/
- MycoBank: http://www.mycobank.org/quicksearch.aspx

5 Results

5.1 Arthropods attacking *Lythrum salicaria*

The most promising candidates for biocontrol of *L. salicaria* in New Zealand are the four beetles (two leaf beetles and two weevils) that were intentionally released in North America and Canada in their classical biocontrol programmes for this weed. However, only three of these could be prioritised at the outset if a programme against *L. salicaria* is implemented.

5.1.1 The black-margined loosestrife beetle, *Galerucella calmariensis*, and the golden loosestrife beetle, *Galerucella pusilla*

Two leaf-feeding beetles, *Galerucella calmariensis* and *G. pusilla*, should be prioritised as the first two agents for possible release in New Zealand for biocontrol of *L. salicaria. G. calmariensis* and *G. pusilla* are nearly identical beetles in both morphology and life history. Both beetle species are light brown, and the only feature separating them morphologically is a black triangle or black line on the thorax of *G. calmariensis*, whereas this line is very thin or nearly absent in *G. pusilla* (these characteristics are only visible in overwintered adults).

The adult beetles are small (4–6 mm in length) and live for 8–10 weeks. Females lay up to 400 eggs during their lifetime. The newly hatched larvae transfer to leaf buds to start feeding. Older, larger larvae feed openly on stems and leaves. Mature larvae pupate in the leaf litter beneath *L. salicaria* unless the plants are submerged, in which case pupation takes place in the spongy, aerenchyma tissue that develops on the submerged sections of the stems (Blossey 2002; Wilson et al. 2004; Piper et al. 2004). Complete development from egg to adult takes 30–40 days. The number of generations per year is dependent on the critical photoperiod, which varies geographically, and which is the cue for the beetles to stop reproducing and enter diapause (suspended development) (Grevstad & Coop 2015; FS Grevstad, pers. comm.).

Figure 8. The black-margined loosestrife beetle, *Galerucella calmariensis* (left), and the golden loosestrife beetle, *G. pusilla* (right).

G. calmariensis and *G. pusilla* have been effective biocontrol agents for *L. salicaria* in North America. At high population densities (two to three larvae per centimetre of shoot length) the beetles completely defoliate whole infestations of *L. salicaria* (Blossey 1995a; Landis et al. 2003; B Blossey, pers. comm.; FS Grevstad, pers. comm.), leading to population declines and subsequent recovery of native vegetation (Albright et al. 2004; Landis et al. 2003; Endriss et al. unpubl.). Both the adults and larvae feed on the buds of *L. salicaria*, causing stunted growth and reduced seed output by significantly reducing flowering. Heavily defoliated plants die or have suppressed shoot production the following season.

G. calmariensis has established well at most sites where it was released and has reduced *L. salicaria* biomass by 90% in several US states. Under favourable conditions, heavily defoliated *L. salicaria* plants recover and even flower the following season, but the beetle populations usually build up again and quickly suppress the resurging plant populations. After several seasons of intensive attack by *G. calmariensis*, plant size is significantly reduced and plant mortality increases (Piper et al. 2004).

G. pusilla also causes heavy defoliation of *L. salicaria* stands. Heavily defoliated and skeletonised plants turn brown, with reduced shoot production and high mortality rates. Although *G. calmariensis* and *G. pusilla* co-exist with apparently limited interspecific competitive interactions (Blossey 1995b), at some locations in North America one of the two species eventually dominated after several years. The reasons for this are not known (Piper et al. 2004).

Release size and human-aided dispersal may be important factors to speed up the beetles' impacts and achieve population-level declines of *L. salicaria* (Grevstad 2006), although they have been recorded to spread up to 10 km from original release sites (Landis et al. 2003). One study indicated that releases of 500 individuals increases the probability of establishment (Grevstad 1999). *G. calmariensis* is reportedly a better disperser than *G. pusilla* (Grevstad 1998; Dech & Nosko 2002), easily finding new host populations (Piper et al. 2004). In some cases only one of the two beetle species has established at release sites, or one is more abundant (Grevstad 2006), and therefore more damaging than the other.

Some adult and larval feeding damage on two native (*Decodon verticillatus* and *Lythrum alatum*) and two exotic (*L. hyssopifolia* and *Lagerstroemia indica*) plant species has been recorded in the field in North America (Blossey, Cassagrande et al. 2001; Schooler et al. 2003; Piper et al. 2004). Non-target attack outside the Lythraceae family (e.g. on wild roses) has also been documented (Albright et al. 2004; Blossey, Skinner et al. 2001; FS Grevstad, pers. comm.). However, the beetle larvae cannot complete development on any non-targets, and damage is highly localised and transient and of minor consequence to these species. This non-target damage is caused by newly emerged adult beetles colonising other species from local *L. salicaria* stands (Schooler et al. 2003), and 'spill over' feeding when population densities are high (FS Grevstad, pers. comm.).

The leaf beetles are widely distributed in North America, suggesting they are tolerant of variable climatic conditions. The phenology and voltinism of the beetles in new areas are predictable, based on the critical photoperiod, which varies geographically (Grevstad & Coop 2015; Wepprich & Grevstad 2020). With these predictions it may be possible to select beetle populations that will have two generations per year rather than one (FS Grevstad, pers. comm.).

Galerucella calmariensis and *G. pusilla* adults and larvae are likely to be vulnerable to predation by generalist predators such as spiders and predatory beetles (e.g. ladybugs) and bugs. One study revealed significant effects of predation on population increases of *G. calmariensis*, but establishment and dispersal were still considered possible, even when populations were declining (Sebolt & Landis 2004). In North America, adult *G. calmariensis* and *G. pusilla* are parasitised by a nematode that feeds and develops inside them, eventually killing them. Five other beetle species in the genus *Galerucella* are native to North America, so it is not surprising that *G. calmariensis* and *G. pusilla* have accumulated their specialist parasite. We do not expect the leaf beetles to be attacked by specialist predators or parasitoids in New Zealand due to the absence of any native, closely related Chrysomelid beetles. The beetles are also attacked by specialist parasitoid wasps in their native range (Wilson et al. 2004), but are still damaging to their host plant, further suggesting their high impact potential in New Zealand. A field study on the impact of the leaf beetles on their host plant in the native range showed high plant mortality, reduced shoot growth, and reduced seed output to <1%. The compensatory ability of plants after attack by the beetles was also severely affected (Blossey 1995a).

Although the leaf beetles have had substantial impacts on *L. salicaria* at some sites and in some regions of North America, the root-feeding weevil, *Hylobius transversovittatus*, should also be considered for biocontrol of *L. salicaria* in New Zealand. The weevil's damage is complementary to the damage caused by the beetles. The larvae of *H. transversovittatus* feed on *L. salicaria* root masses, which remain after heavy defoliation by *G. calmariensis* and *G. pusilla* (Grevstad 2006; B Blossey, pers. comm.; FS Grevstad, pers. comm.).

5.1.2 The loosestrife root weevil, *Hylobius transversovittatus*

Hylobius transversovittatus is a large (10–14 mm), reddish-brown weevil that has one generation per year or one generation over 2 years. Adults feed on the leaves and stem tissue of *L. salicaria*, but this is of little consequence to the plant; it is the larvae, which attack the root system, that are the damaging life stage. Overwintered adults emerge in spring, soon after *L. salicaria* shoots start to sprout. The adults are predominantly nocturnal but can occasionally be seen early in the morning or evening, or on cool, overcast or rainy days (Wilson et al. 2004). On warmer, sunny days they hide in the leaf litter at the base of *L. salicaria* plants. The emerging, overwintered adults feed for approximately 2 weeks before mating and oviposition take place. Females lay eggs in the stems or in the soil close to the root crown of *L. salicaria* plants. Adults are long-lived (2–3 years) and females produce up to 100 eggs per year. Early instar larvae feed on the root cortex, and older larvae feed in the central part of the root system for 1 to 2 years. Larvae pupate in chambers in the upper part of the root.

Figure 9. The loosestrife root weevil, *Hylobius transversovittatus.*

The impact of *H. transversovittatus* on *L. salicaria* is dependent on root size, and the intensity and duration of attack. With increasing populations, larval feeding on roots reduces shoot growth, shoot and root biomass, and seed output, and can eventually lead to plant mortality (Blossey 2002). Small *L. salicaria* roots infested with several larvae can be completely destroyed within 2 years. Larger root systems are severely affected after several consecutive years of feeding damage by the weevil (Piper et al. 2004). This agent has been important in the success of the weed biocontrol programme for *L. salicaria* in North America (B Blossey, pers. comm.). Feeding on *L. salicaria* root storage reserves by the weevil severely inhibits the ability of plants to recover after heavy defoliation by the leaf beetles *G. calmariensis* and *G. pusilla.*

Hylobius transversovittatus is well established in several US states and has a wide environmental tolerance, with the exception that the larvae cannot tolerate prolonged flooding of sites (Blossey 2002; Piper et al. 2004). In host specificity testing in North America, *H. transversovittatus* was able to feed and develop on two other Lythraceae species, *L. alatum* and *Decodon verticillatus*, but non-target impacts have not been reported in the field (B Blossey, pers. comm.; FS Grevstad, pers. comm.).

The weevil can be successfully mass-reared on a semi-artificial diet, with up to several hundred weevils being produced weekly (Blossey et al. 2000). Once *H. transversovittatus* populations are well established in the field, adults can easily be collected at night for redistribution. Although this agent is slower to increase and disperse compared to the leaf beetles, the combined impact of the weevil and the leaf beetles is likely to lead to higher plant morality rates and increase the likelihood of success of a weed biocontrol programme for *L. salicaria.*

5.1.3 The loosestrife seed weevil, *Nanophyes marmoratus*

The loosestrife seed weevil, *Nanopyhes marmoratus*, is the last agent that could be considered for release against *L. salicaria* in New Zealand. *N. marmoratus* is a tiny weevil that attacks the flower buds, young leaves and leaf buds of *L. salicaria.* Overwintered adults emerge in spring and first feed on the young leaves and buds of *L. salicaria.* When the plants start to produce flowers, adults move to the upper parts of flower spikes for mating and oviposition. Eggs are laid singly in flower buds, and females produce 60 to 100 eggs during their lifetime. The larvae feed on the stamens, petals and ovaries of unopened *L. salicaria* flower buds, completely destroying the buds, which fail to develop to produce seeds. Larvae pupate in a chamber inside the damaged flower buds. Egg to adult development takes approximately 1 month and this weevil has one generation per year.

Figure 10. Adult of the loosestrife seed weevil.

Although this agent should be listed as a potential candidate agent for release in New Zealand, it is of low to medium priority at the outset of a programme. *N. marmoratus* is only likely to be effective if the leaf beetles *G. calmariensis* and *G. pusilla* fail to establish or significantly reduce flowering of *L. salicaria* (as is typical at sites heavily infested with the leaf beetles). The seed weevil may become more important if the abundance of *L. salicaria* declines and the leaf beetles and *H. transversovittatus* become less effective. The weevil is an excellent disperser and can persist where *L. salicaria* plants are scattered and at low densities (Piper et al. 2004), thus limiting seed production and spread of remaining, low-level *L. salicaria* populations. The loosestrife seed weevil is well established in North America and is highly tolerant of a wide range of environmental conditions. Both adult and larval feeding cause flower abortion, significantly reducing seed output (up to 70%). This weevil is not suitable for sites with prolonged flooding and with high populations of the leaf beetles, which inhibit flowering.

5.2 Pathogens attacking *Lythrum salicaria*

Species from 65 fungal genera were isolated from *L. salicaria* (Appendix 2), predominantly causing damage to the leaves. Fifteen species were not identified to species level and therefore their impact on *L. salicaria* is unknown.

Fungi previously associated with *L. salicaria* included *Pilildium lythri* (*=Hainesia lythri*), *Septoria lythrina*, and *Zasmisium lythri* (*=Stenella lythri*) isolated from leaves; *Leptosphaeria lythri* isolated from stems*, Rhizoctonia solani* isolated from roots; and *Ophiobolus niesslii,* whose origin of isolation is unknown (Farr et al. 1989). In the Nyvall

(1995) study, *Pilidium lythri, S. lythrina* and *R. solani* were recorded from *L. salicaria* leaves only.

Interestingly, several *Fusarium* species were associated with *L. salicaria* (Nyvall 1995), including *Fusarium graminearum*, a known plant pathogen causing *Fusarium* head blight of wheat and barley (Leonard & Bushnell 2003). These were frequently associated with leaf spots at a site surrounded by corn fields. However, no pathogenicity of *F. graminearum* and the other species to *L. salicaria* was ever observed (Nyvall & Nu 1997). The authors postulated that the abundant *Fusarium* inoculum could have been produced on corn that saprophytically colonised lesions caused by other pathogens (Nyvall 1995).

Four Basidiomycota species are reported associated with *L. salicaria. Rhizoctonia solani* is predominantly a soil-borne pathogen causing a wide range of commercially significant plant diseases. *Aecidium pallidum and Puccinia lythri* are associated only with *L. salicaria*, while *P. minutissima* is a heteroecious rust fungus having two hosts and would not be sufficiently host specific.

A single Chytridiomycota species, *Synchytrium lythri* M.T.Cook, was reported as associated with *L. salicaria* (Nyvall 1995). However, the host species are *L. alatum* Pursh (winged loosestrife) and *L. alatum* var*. lanceolatum* (Elliott) Torr. & A.Gray ex Rothr. (Karling 1964).

Among the 65 fungal species isolated from L. salicaria, Erysiphe lythri, Pseudocercospora lythri, Septoria lythrina, and Zasmidium lythri are restricted to the Lythraceae family, while Phomopsis lirelliformis var. gredensis, Dwiroopa lythri (=Harknessia lythri), Naeviopsis simulans, Lachnum salicariae, Septoria brissaceana, Leptosphaeria salicaria, Aecidium pallidum, and Puccinia lythri were isolated from L. salicaria only. All remaining species have wide, cosmopolitan host ranges and are unlikely to be suitable for biocontrol.

Phomopsis lirelliformis (=*Phomopsis lirelliformis* var. *gredensis*) is a saprophytic species living on dead or dying plant material of *L. salicaria* in Europe (Nyvall 1995). However, other *Phomopsis* species are known plant pathogens, including *Phomopsis viticola*, which causes cane and leaf spot of grapes grown in most regions of Australia and is a prohibited disease in Western Australia.[13] This species is unlikely to be suitable for biocontrol.

Dwiroopa lythri (=*Harknessia lythri*) was identified as a potential biocontrol agent for *L. salicaria* (Nyvall 1995; Farr & Rossman 2001). There are presently only two other *Dwiroopa* species, which have only been found once each, namely *D. ramya* on branches of an unknown tree in India*, and D. punicae on pomegranate* (Subramanian & Muthumary 1986; Farr & Rossman 2001; Xavier et al. 2019). *Dwiroopa ramya* is considered a saprophyte and was isolated from dead twigs, while *D. punicae* is a pathogen of pomegranate.

Naeviopsis simulans was isolated from *L. salicaria* stems in Sweden. No further information regarding this species is available. There are 15 species within the genus *Naeviopsis*, most are regarded as plant pathogens, while a few are saprophytes.

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[13] https://www.agric.wa.gov.au/table-grapes/phomopsis-viticola-prohibited-disease

Lachnum salicariae was isolated from *L. salicaria* stems in Sweden. It is a saprophyte and lives on dead or dying plant material. No further information regarding this species is available. iNaturalist reports that the fungus was found on living roots of *L. salicaria* in Canada.[14] It is unlikely to be suitable for biocontrol.

Septoria brissaceana is associated with *L. salicaria* and *L. virgatum* L. (European wand loosestrife) in Europe. No further information regarding this species is available. However, *Septoria* species cause numerous leaf spot diseases on field crops and vegetables, including tomatoes, and are responsible for yield losses. *Septoria passiflorae* was used as a biocontrol agent to control the invasive *Passiflora mollissima* (banana poka) in Hawai'i (Trujillo et al. 2001).

Leptosphaeria salicaria is associated with *L. salicaria* only. No further information regarding this species is available. Another species, *Leptosphaeria maculans* (Sowerby) P.Karst. caused blackleg disease on Brassica crops, and stem canker of canola (Howlett et al. 2001).

Aecidium pallidum is a rust fungus associated with *L. salicaria* only. No further information regarding this species is available.

Puccinia lythri, a rust fungus, is associated with *L. salicaria* from a single reference in Poland (Majewski 1979). The species forms telia and uredinia only and is monoecious, completing its life cycle on *L. salicaria* only. Severity of damage to the *plant* is unknown, and no further information regarding this species is available.

6 Conclusions

Biocontrol of *L. salicaria* using agents already released in North America is a highly viable option for managing this weed in New Zealand. Chemical and manual control methods will not provide long-term, sustainable control of *L. salicaria* and are therefore not suitable for heavily infested regions of New Zealand. These methods can also be damaging to the vulnerable ecosystems, such as wetlands, where they need to be applied.

Four insect biocontrol agents, *G. calmariensis*, *G. pusilla*, *H. transversovittatus* and *N. marmoratus*, have been released against *L. salicaria* in North America and Canada, with a high degree of success. One of the most reliable predictors of a weed biocontrol agent’s potential efficacy is its impact on the same target weed in a weed biocontrol programme elsewhere in the world, so the likelihood of achieving some level of control using the same biocontrol agents is high. Climate, predation and parasitism and plant biotype mismatches are unlikely to significantly limit population increases in the biocontrol agents.

All four biocontrol agents are widely established in North America, which strongly suggests they will adapt well to the New Zealand climate, and the likelihood of their persistence here is high. Sites with the worst current infestations of *L. salicaria* are not permanently or even seasonally inundated and thus suit the habitat requirements of all

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[14] https://www.inaturalist.org/photos/84293546

four agents. The two leaf beetles, in particular, may be vulnerable to generalist predators, but they are unlikely to accumulate any specialist parasites or parasitoids that could severely limit their populations.

Although an EPA application is recommended for all four candidate agents, only three of them are proposed for immediate release, should approval be granted. The loosestrife seed weevil may be important further down the line for locating isolated infestations, and reducing seed production and spread from those sites.

A biocontrol programme for *L. salicaria* in New Zealand is likely to have a high cost-to-benefit ratio. Limited resources will be required to implement a programme given that extensive research has already been conducted on the agents in North America. Repeat programmes are cost-effective in comparison to novel weed biocontrol programmes, where significant resources are invested in preparatory work such as surveying the native range for promising natural enemies, and developing rearing and host specificity testing protocols to study them for possible release. In the case of *L. salicaria*, the agents are recommended for release without host specificity testing in New Zealand, since there are no native, closely related species in the Lythraceae. All four agents have a high degree of host specificity and have not had any significant non-target impacts since their release three decades ago in North America and Canada. There is thus sufficient evidence to pre-determine that the candidate agents are sufficiently host specific for release in New Zealand. The risk to any native plant species in New Zealand by the agents is negligible.

In conclusion, an EPA release application for the two leaf beetles, *G. calmariensis* and *G. pusilla*, the loosestrife root weevil, *H. transversovittatus*, and the loosestrife flower weevil is recommended under one new organism application to the EPA. The leaf *beetles, G. calmariensis* and *G. pusilla* and the loosestrife root weevil, *H. transversovittatus*, should be prioritised, mass-reared and released concurrently. This will not incur major additional costs, since effective mass-rearing protocols for the agents have already been developed, they can be released at the same sites, and their combined impact is likely to achieve the greatest levels of suppression of *L. salicaria* populations in Horowhenua. Both beetle species should be released, as it is not possible to predict which species will be effective for long-term control of *L. salicaria* in New Zealand.

Although *L. salicaria* is still targeted for eradication in many regions of the country where the weed has naturalised, it is highly possible that current efforts will be as unsuccessful as they were in Horowhenua. The demand for an effective control method for this weed may increase.

There is a paucity of promising classical fungal biocontrol agents associated with *L. salicaria.* Fifteen fungal species identified by Nyvall (1995) were tested for virulence and suitability as potential mycoherbicides against purple loosestrife in the United States (Nyvall & Nu 1997). Six of the 15 were found to be virulent, with *Septoria lythrina* the most virulent, followed by *Alternaria alternata, Botrytis cinerea, Colletotrichum truncatum, Epicoccum sorghinum* (=*Phoma sorghina*), and *Microsphaeropsis olivacea* (=*Coniothyrium olivaceum*). However, no follow-up studies were published subsequent to Nyvall & Nu 1997. The potential for biocontrol of *L. salicaria* using pathogens is therefore not a feasible option.

7 Recommendations

- Complete the New Zealand surveys to look for any potential biocontrol agents, or any other organisms associated with *L. salicaria* (such as predators) that might interfere with the candidate biocontrol agents. This baseline information is essential for any weed biocontrol programme (Appendix 3) and with the continuation of current work, will be complete by June 2022. **Estimated cost:** $20,000 (already covered by Horizons Regional Council).
- Prepare and submit an EPA application to gain approval to release the two leaf beetles (*Galerucella calmariensis* and *G. pusilla*), the loosestrife root weevil (*Hylobius transversovittatus*), and the loosestrife seed weevil (*Nanophyes marmoratus*). The application will present host specificity and post-release data from North America as evidence that all four agents are sufficiently host specific for release in New Zealand. **Estimated cost:** $55,000–$75,000 (one application will cover all four candidate agents).
- Import starter cultures of *G. calmariensis*, *G. pusilla* and *H. transversovittatus* once EPA approval is granted; apply for MPI approval to remove the agents from containment. **Estimated cost:** $20,000–$60,000.
- Mass rear and release the agents concurrently in Horowhenua in Manawatū–Whanganui. **Estimated cost:** $100,000–$250,000 per agent (the leaf beetles will be reared together).
- Assess whether the seed weevil *Nanophyes marmoratus* is also needed to achieve acceptable levels of control of *L. salicaria* in New Zealand. **Estimated cost:** $20,000 - $100,000.

Note: estimated costs are exclusive of GST and are based on 2021/22 figures. New estimates will need to be provided if work is to be undertaken well beyond those dates, and/or if complicating factors arise (e.g. disease infecting imported agents, ongoing disruption due to Covid-19).

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Appendix 1 – Record of invertebrates approved for biocontrol of *Lythrum salicaria* in North America

Order and family	Species	Type of organism	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in New Zealand? Likely to be highly damaging?
COLEOPTERA					
Curculionidae	*Hylobius transversovittatus* Goeze	Root-feeding weevil	Europe (CABI 2020). Introduced in North America and Canada (Blossey 2002; Blossey & Schroeder 1995b; Hight et al. 1995)	Yes (Blossey et al. 1994b)	Not present in NZ. Yes, synergistic with the leaf beetles (Piper et al. 2004; Grevstad 2006; Wilson et al. 2004)
	Nanophyes marmoratus	Flower-feeding weevil	Europe (CABI 2020). Introduced in North America (and Canada) (Blossey 2002; Blossey & Schroeder 1995b; Hight et al. 1995)	Yes (Blossey & Schroeder 1995a)	Not present in NZ. Good disperser and significantly reduces seed production, but may not be needed if the leaf beetles inhibit flowering, and successfully locate new infestations of the weed. (Piper et al. 2004; Wilson et al. 2004)
Chrysomelidae	*Galerucella calmariensis*	Leaf beetle	Europe (Blossey 2002; Blossey & Schroeder 1995b; Hight et al. 1995)	Yes (Blossey et al. 1994a)	Not present in New Zealand. Yes, synergistic with the loosestrife root weevil (Piper et al. 2004; Grevstad 2006; Wilson et al. 2004)
	Galerucella pusilla	Leaf beetle	Europe. Introduced in North America and Canada (Blossey 2002; Blossey & Schroeder 1995b; Hight et al. 1995)	Yes (Blossey et al. 1994a)	Not present in New Zealand. Yes, synergistic with the loosestrife root weevil (Piper et al. 2004; Grevstad 2006; Wilson et al. 2004)

Appendix 2 – Records of plant pathogens associated with *Lythrum salicaria*

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
ASCOMYCOTA					
Amphisphaeriales					
Sporocadaceae	*Discosia aquatica* Fautrey	Saprophyte, plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Caused leaf spots on Japanese persimmon in NZ (Thangavel et al. 2013).	Present in NZ. Severity of damage unlikely to be high. Associated with leaf spot of *Diospyros kaki* in NZ in 2013 (Thangavel et al. 2013).
Chaetomellales					
Chaetomellaceae	*Pilidium lythri* (Desm.) Rossman (= *Pezizella oenotherae* (Cooke & Ellis) Sacc. = *Discohainesia oenotherae* (Cooke & Ellis) Nannf. = *Hainesia lythri* (Desm.) Höhn)	Plant pathogen, leaf spot	New York, France, Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Causes fruit rot, leaf spot, and anthracnose on a wide host range (Farr & Rossman 2021).	Present in NZ. Severity of damage unknown. Associated with damage to several *Eucalyptus* and other plant species in NZ. Its synonym, *Discohainesia oenotherae*, is listed as a regulated fungal species for *Fragaria* (Import Health Standard: Importation of Nursery Stock 155.02.06) [https://www.mpi.govt.nz/dmsdocument/1152/direct].
Chaetosphaeriales					
Chaetosphaeriaceae	*Catenularia* Grove	Saprophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021)	*Catenularia* is an uncommon fungus inhabiting mainly decaying bark, wood and bamboo culms of various hosts (Réblová et al. 2021).	Record of *Catenularia* species in NZ (Hughes 1965). Unlikely to be damaging as most species are saprophytic.
Diaporthales					

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[15] Synonyms (old, invalid names for a taxon) are only given here where that (old) name is the one reported in the literature.

Phylum/ order/ family	**Species**[15]	**Symptoms or lifestyle**	**Geographic range on *L. salicaria***	**Likely to be sufficiently host specific?**	**Present in NZ? Likely to be highly damaging?**
Diaporthaceae	*Phomopsis lirelliformis* (Sacc.) Bubák (= *Phomopsis lirelliformis* var. *gredensis*)	Saprophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Yes. *Phomopsis lirelliformis* var. *gredensis* is listed as only associated with purple loosestrife (Nyvall 1995; Farr & Rossman 2021).	Not present in NZ. Unlikely to be damaging as it is a saprophyte.
	Diaporthe Fuckel	Endophyte, minor plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. *Diaporthe* are minor plant pathogens on a wide host range of woody plants (Udayanga et al. 2014).	Present in NZ. Several *Diaporthe* species associated with many woody host plants in NZ. Damage unlikely to be high as considered a minor plant pathogen.
Dwiroopaceae	*Dwiroopa lythri* (D.F. Farr & Rossman) D.F. Farr & Rossman (=*Harknessia lythri* D.F. Farr & Rossman)	Plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Yes. Only associated with purple loosestrife (Farr & Rossman 2021).	Unknown in NZ. Severity of damage unknown. Considered as a potential biocontrol agent against *L. salicaria* (Farr & Rossman 2021)
Gnomoniaceae	*Diplodina* Westend	Leaf and gall fungus, endophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species.	*Diplodina* records in NZ on *Acer* spp. (twig dieback) and Rhododendron. Extent of damage unknown.
Schizoparmaceae	*Coniella fragariae* (Oudem.) B. Sutton	Plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. *Coniella fragaria* associated with *Fragaria* spp. (Rosaceae); reports from other hosts need confirmation (Alvarez et al. 2016).	Present in NZ. Found on cultivated strawberry or garden strawberry (*Fragaria* × *ananassa*) [Anonymous 2014]. The genus *Coniella* consists of pathogens associated with foliar, fruit, stem and root diseases in a wide range of hosts.
Glomerallales					
Glomerellaceae	*Colletotrichum* Grove	Anthracnose, saprophyte, endophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021).	Unknown species. Can have a wide host range (Cannon et al. 2012).	Causes anthracnose with necrotic lesions on leaves, stems, flowers and fruits, crown, stem rots, seedling blight. Also saprophytic or can be endophytic (Cannon et al. 2012).

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
Plectosphaerellaceae	*Verticillium* Nees	Soil-borne plant pathogen, saprophyte, causes *Verticillium* wilt	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. *Verticillium* spp. known to attack a large host range of more than 350 plant species (Pegg & Brady 2002; Barbara & Clewes 2003).	*Verticillium* wilt associated with a wide host range in NZ (Dingley 1969; Pennycook 1989; Gadgil 2005). Extent of damage unknown.
Helotiales					
Dermataceae	*Naeviopsis simulans* B. Hein	Plant pathogen	Sweden (Farr & Rossman 2021)	Yes. Only associated with *L. salicaria.*	Not present in NZ. Severity of damage unknown.
Erysiphysaceae	*Erysiphe lythri* L. Junell	Powdery mildew, plant pathogen	Denmark, Finland, France, Germany, Hungary, Italy, Montenegro, Norway, Poland, Romania, Russia, Sweden, Switzerland, United Kingdom, Soviet Union, Yugoslavia (Farr & Rossman 2021)	Yes. Only associated with *Lythrum* species (Farr & Rossman 2021).	Unknown in NZ. Severity of damage unknown. Many of the species in this genus are plant pathogens that cause powdery mildew.
	Erysiphe pisi var. *pisi* (= *Erysiphe communis* DC.)	Powdery mildew, plant pathogen	Denmark, Finland, France, Germany, Hungary, Italy, Japan, Norway, Poland, Romania, Sweden, Switzerland, Soviet Union (Farr & Rossman 2021)	No. Causes powdery mildew of various Fabaceae species.	Unknown in NZ. Severity of damage unknown. Many of the species in this genus are plant pathogens that cause powdery mildew.
	Blumeria Golovin ex Speer (= *Oidium* Link)	Powdery mildew	USSR (Farr & Rossman 2021)	Unknown species. Affects a wide range of host plants. Many species in this genus are plant pathogens.	Many host records of *Oidium* on a wide range of hosts in NZ and Pacific Island nations.

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
Helotiaceae	*Hymenoscyphus scutula* (Pers.) A.W. Phillips	Saprophyte	Germany (Farr & Rossman 2021)	No. This species is saprophytic and found on dead stems only.	Present in NZ. Severity of damage unlikely to be high as this species found on dead stems of *Aquilegia vulgaris* and *Melissa* in NZ.
Hyaloscyphaceae	*Lachnum salicariae* (Rehm) Raitv.	Saprophyte	Sweden, UK (Farr & Rossman 2021)	Yes. Only associated with dead roots and stems of *L. salicaria* (Farr & Rossman 2021).	Unknown from NZ. Severity of damage unlikely to be high as this species associated with decomposition and dead/dying plant material.
Pezizellaceae	*Calycina* Nees ex Gray	Saprophyte	Germany (Farr & Rossman 2021)	Yes. Species found on dead stems of *L. salicaria* (Lotz-Winter et al. 2011).	Species of this genus found in NZ. Associated with living and dead plant material of *Metrosideros excelsa, Nothofagus* spp., *Elaeocarpus dentatus and Celmisia sp.* [https://nzfungi2.landcareresearch.co.nz].
Sclerotiniaceae	*Botrytis cinerea* Pers.	Plant pathogen, leaf and fruit rot, grey mould	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan species (Kew 2021). Associated with over 200 plant species (Williamson et al. 2007).	Present in NZ. Extent of damage unknown. *Botrytis cinerea* is a pathogen on economically important crops such as strawberries and grapes (Donmez et al. 2011).
Hypocreales					
Nectriaceae	*Fusarium anthophilum* (A. Braun) Wollenw.	Soil-borne pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan group of fungi associated with a wide variety of plant species (Farr & Rossman 2021).	Present in NZ. Extent of damage unknown. Associated with several crops including rice, asparagus, and flower species such *as Narcissus, Vaccinium* and *Cymbidium* orchids in NZ [https://nzfungi2.landcareresearch.co.nz].

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
Nectriceae (cont.)	*Fusarium avenaceum* Raillo	Plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan group of fungi associated with a wide variety of plant species (Farr & Rossman 2021).	Present in NZ. Extent of damage unknown. Associated with maize, wheat, apples, peaches and many other crop and tree species (Gadgil 2005) [https://nzfungi2.landcareresearch.co.nz].
	Fusarium graminearum Schwabe	Plant pathogen of cereals	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Causes *Fusarium* head blight, a devastating disease on wheat and barley (Leonard & Bushnell 2003).	Present in NZ. Extent of damage unknown. Associated with several cereals and other important crop and grass species (Braithwaite et al. 1998).
	Fusarium incarnatum (Roberge ex Desm.) Sacc. (= *Fusarium semitectum* Berk. & Ravenel)	Plant pathogen of cereals	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan group of fungi associated with a wide variety of plant species (Farr & Rossman 2021).	Present in NZ. Extent of damage unknown. Associated several cereals, avocado (Hartill 1991) and other crops (Pennycook 1989). Recorded on crops in Fiji, Tonga, Vanuatu and Cook Island [https://nzfungi2.landcareresearch.co.nz].
	Fusarium oxysporum Schltdl.	Plant endophyte, soil saprophyte, plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan group of fungi associated with a wide variety of plant species (Farr & Rossman 2021).	Present in NZ. Extent of damage unknown. Although *F. oxysporum* are soil saprophytes and endophytic, species within the complex are pathogenic to plants, especially in agricultural settings (Kistler 2001).
	Fusarium sporotrichioides Sherb.	Leaf spot, grain blight	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Associated with a wide variety of plant species (Farr & Rossman 2021).	Present in NZ. Extent of damage unknown. Can cause blight in crops such as wheat.
	Fusarium tricinctum (Corda) Sacc.	Plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan group of fungi associated with a wide variety of plant species (Farr & Rossman 2021).	Present in NZ. Associated with several crop species such as wheat, apples, carrots and alfalfa in NZ [https://nzfungi2.landcareresearch.co.nz].

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
	Fusidium Link	Saprophyte, soil fungus	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. Saprophytic lifestyle.	Unknown in NZ. Several *Fusidium* species associated with woody host plants in NZ including *Metrosideros excelsa, Podocarpus hallii, Nothofagus* spp., and others (Cooper 2005; McKenzie et al. 2000).
Microascales					
Haplosphaeriaceae	*Culcitalna* Meyers & R.T. Moore	Marine fungus	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. *Culcitalna achraspora* is described as a lignicolous marine fungus (Johnson Jr. & Sparrow Jr 1961).	Unknown. Not enough information given.
Mycosphaerellales					
Mycosphaerellaceae	*Pseudocercospora lythri* H.D Shin & U. Braun	Leaf spot	Japan, South Korea (Farr & Rossman 2021)	Yes. Only associated with *Lythrum* species in Korea (Shin & Braun 2000) and Japan (Nakashima et al. 2011).	Not present in NZ. Severity of damage unknown. Not likely to be damaging as fungus causes leaf spots only.
	Septoria brissaceana Sacc. & Letell.	Plant pathogen	Bulgaria, Poland , Romania, Russia, Scotland (Farr & Rossman 2021)	Yes. Only associated with *L. salicaria* (Farr & Rossman 2021).	Not present in NZ. Severity of damage unknown. However, *Septoria* species cause leaf spot diseases on field crops, forage, and many vegetable crops (Kirk et al. 2008).
	Septoria lythrina Peck.	Leaf spot	Kansas, Minnesota, New York, Wisconsin (Nyvall 1995; Farr & Rossman 2021)	Yes. Only associated with leaf spots on *Lythrum* species (Farr & Rossman 2021).	Not present in NZ. Severity of damage unknown. Most likely damage would be limited.

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
	Zasmidium lythri (Westend.) U. Braun & H.D. Shin (= *Cercospora lythri* Westend.; = *Cercospora sanguinea* Fuckel; = *Stenella lythri* (Westend.) J.L. Mulder)	Leaf spot	Belgium, Spain, Germany, Bulgaria, England, Poland, Asia, Europe (Farr & Rossman 2021)	Yes. Only associated with leaf spots on *Lythrum* species (Farr & Rossman 2021)	Not present in NZ. Severity of damage unknown. Most likely damage would be minimal.
	Periconiella Sacc	Plant pathogen, superficial growth on plants	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. Plant pathogen with narrow host range or growing superficially on plants from many different host species.	Several *Periconiella* species recorded in NZ on a wide host range (McKenzie 1996; Gadgil 2005) [https://nzfungi2.landcareresearch.co.nz].
Myriangiales					
Elsinoaceae	*Sphaceloma* de Bary	Anthracnose, scab	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. Plant pathogen causing anthracnose and scab symptoms. Genus is widespread, estimated to contain 52 species (Kirk et al. 2008).	*Sphaceloma* species associated with a wide host range in NZ and Pacific Island nations (Pennycook 1989).
Pleosporales					
Didymellaceae	*Boeremia exigua* (Desm.) Aveskamp, Gruyter & Verkley var. *exigua* (= *Phoma exigua* Desm. var. *exigua* Brunaud)	Leaf spot; opportunistic plant pathogen	Poland, China, Czech Republic (Farr & Rossman 2021)	No. Associated with *Lycopersicon esculentum* (tomato), *Solanum tubersosum* (potato), *Agapanthus* and *Agrostis capillaris* in NZ [https://nzfungi2.landcareresearch.co.nz].	Present in NZ. Unlikely to be highly damaging as it's an opportunistic pathogen. May cause necrosis on leaves and stems, root and tuber rot, leaf and stem rot (Farr & Rossman 2021).
	Didymella glomerata (Corda) Qian Chen & L. Cai (= *Phoma glomerata* (Corda) Wollenw. & Hochapfel)	Plant pathogen; leaf blight	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Associated with brown leaf spot and stem cankers, leaf spot of apple and *Phoma* spot of wheat and found on harakeke in NZ (Johnston 1981).	Present in NZ. Severity of damage unlikely to be high.

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
Didymellaceae cont.	*Didymella macrostoma* (Mont.) Qian Chen & L. Cai (= *Phoma macrostoma* Mont.)	Weak wound pathogen, saprophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. A plurivorous species causing leaf spots of minor importance in *Eriobotrya japonica* (loquat) and spotting of apples (Dingley 1969). Associated with *Actinidia deliciosa*, *Eriobotrya japonica*, *Magnolia* spp., *Malus × domestica* (Gadgil 2005).	Present in NZ. Severity of damage unlikely to be high as this species is either saprophytic or a weak wound pathogen; more commonly found on woody plants (Johnston 1981).
	Epicoccum nigrum Link	Saprophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan saprophyte with worldwide distribution.	Present in NZ. Severity of damage unlikely to be highly damaging as this species is considered a saprophyte.
	Epicoccum sorghinum (Sacc.) Aveskamp, Gruyter & Verkley (= *Phoma sorghina* Sacc.)	Common, facultative plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Common plant pathogen with a wide host range.	Unknown in NZ. Recorded on sugarcane in the Cook Islands, Vanuatu, Federated states of Micronesia and the Solomon Islands [https://nzfungi2.landcareresearch.co.nz].
	Phoma Sacc.	Soil-borne pathogen, saprophyte, weak pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. Plant pathogen of cultivated plants or living saprophytically or weakly pathogenic on several hosts (Farr & Rossman 2021).	Unknown species. Severity of damage unknown. *Phoma* species associated with a multitude of host species in NZ and Pacific Island nations (Pennycook 1989).
Leptosphaeriaceae	*Leptosphaeria salicaria* Pass.	Plant pathogen	Denmark, Italy (Farr & Rossman 2021)	Yes. Only associated with *L. salicaria* (Farr & Rossman 2021).	Unknown species. Severity of damage unknown.
Lophiostomataceae	*Lophiostoma vagabundum* Sacc.	Saprophyte	Belgium, UK (Kew 2021)	No. Associated with leaf material of *Lythrum salicaria* (Kew 2021).	Not present in NZ. Damage unlikely to be high as species is saprophytic.
Microsphaeriopsidaceae	*Microsphaeropsis olivacea* (Bonord) Höhn. (= *Coniothyrium olivaceum* Bonord)	Saprophyte, plant pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Cosmopolitan species. Mostly saprophytic and found on branches and twigs. Pathogenic on *Alhagii maurorum* in Iran (Razaghi & Zafari 2016).	Present in NZ. Severity of damage unknown. Associated with blueberries, European plum, *Rhododendron*, karo, and Norfolk pine in NZ (Anonymous 2001, 2004, 2005).

Phylum/ order/ family	**Species**[15]	**Symptoms or lifestyle**	**Geographic range on *L. salicaria***	**Likely to be sufficiently host specific?**	**Present in NZ? Likely to be highly damaging?**
Phaeosphaeriaceae	*Ophiobolus niesslii* Baümler	Saprophyte	United States (Farr & Rossman 2021)	No. The genus *Ophiobolus* contains mostly saprophytic species on herbaceous plants (Phookamsak et al. 2017).	Not present in NZ. Severity of damage unknown but unlikely as the genus is mostly saprophytic.
Pleosporaceae	*Alternaria alternata* (Fr.) Keissl.	Leaf spot	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Opportunistic pathogen. Recorded causing leaf spot and other diseases on over 380 plant species https://en.wikipedia.org/wiki/Alternaria_alternata.	Present in NZ. Severity of damage unknown. Causes leaf spots, and fruit and root rots of over 380 plant species.
Pleosporaceae cont.	*Bipolaris sorokiniana* (Sacc.) Shoemaker	Seedling blight, leaf spotting (spot blotch), root rot and black point of mainly wheat and barley	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Wide host range primarily on the Poaceae (Farr & Rossman 2021).	Present in NZ. Severity of damage unknown.
	Curvularia Boedijn	Facultative pathogen, mould fungus	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. *Curvularia* species are facultatively pathogenic, which means they occasionally cause infection.	Unknown species. Severity of damage unknown. *Curvularia* species associated with several plant species in NZ and the Pacific Island nations [https://nzfungi2.landcareresearch.co.nz].
	Stemphylium Wallr.	Leaf spot	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. Plant pathogen and saprophyte lifestyle on wide host range.	Unknown species. Severity of damage unknown. *Stemphylium* species associated with a wide host range in NZ (Pennycook 1989; McKenzie et al. 2000).
Pezizales					

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
Pezizaceae	*Chromelosporiopsis carnea* (Schumach.) Hennebert	Saprophyte	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Live on other leaves, bark, mosses, and organic debris on soil, in forests (Hennebert 2020).	Present in NZ. Damage unlikely to be high as the species lives on *Typha* leaf litter, and on dead leaves of *Fagus sylvatica* and *Quercus pedunculata* (Hennebert 2020).
Rhytismatales					
Rhytismataceae	*Hypoderma commune* (Fr.) Duby (= *Leptothyrium vulgare* (Fr.) Sacc.)	Saprophyte	United Kingdom (Farr & Rossman 2021)	No. Lives on dead or dying plant material.	Unknown in NZ. Severity of damage unknown.
Saccharomycetales					
Dipodascaceae	*Geotrichum* Link	Opportunistic yeast fungus	Minnesota (Nyvall 1995; Farr & Rossman 2021)	Unknown species. Multiple species known.	Associated with papaya fruit in the Cook Islands and rotten potato and soft rot of squash in NZ [https://nzfungi2.landcareresearch.co.nz]
	Candida Berkhout	Yeast fungus	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. Many species of yeast live on trees, including other opportunistic pathogenic *Candid*a species (Bensasson et al. 2019).	Associated with *Kunzea ericoides* branches in NZ [https://nzfungi2.landcareresearch.co.nz]. Severity of damage unknown.
Incertae sedis					
Incertae sedis	*Coremiella cubispora* (Berk. & M.A. Curtis) M.B. Ellis	Saprophyte	UK (Kew 2021)	No. Associated with dead leaf material (Kew 2021).	One ICMP record in NZ on leaves of *Aechmea bromeliifolia* (bromeliad) [https://nzfungi2.landcareresearch.co.nz].
BASIDIOMYCOTA					
Cantharellales					

Phylum/ order/ family	Species[15]	Symptoms or lifestyle	Geographic range on *L. salicaria*	Likely to be sufficiently host specific?	Present in NZ? Likely to be highly damaging?
Ceratobasidiaceae	*Rhizoctonia solani* J.G. Kühn	Predominantly a soil-borne pathogen	Minnesota (Nyvall 1995; Farr & Rossman 2021)	No. A cosmopolitan soil-borne pathogens causing a wide range of commercially significant plant diseases	Present in NZ. Severity of damage unknown. However, the plant pathogen is associated with many plant species in NZ [https://nzfungi2.landcareresearch.co.nz].
Pucciniales					
Pucciniaceae	*Aecidium pallidum* Schneid.	Rust fungus	Belgium (Marchal & Verplancke 1926; Farr & Rossman 2021)	Yes. Only one record associated with *Lythrum salicaria* in Belgium (Marchal & Verplancke 1926).	Unknown from NZ. Severity of damage unknown.
	Puccinia lythri Syrgij	Rust fungus	Poland (Majewski 1979; Farr & Rossman 2021)	Yes. Only one record on *Lythrum salicaria* in Poland (Majewski 1979).	Not present in NZ. Severity of damage unknown.
	Puccinia minutissima Arthur	Rust fungus	Turkey (Farr & Rossman 2021)	No. A heteroecious rust fungus with an aecial host (*Decodon veticillatus*, swamp loosestrife) and a telial host (*Caryx* spp.) in the USA (Farr & Rossman 2021).	Not present in NZ. Severity of damage unknown.

Appendix 3 – Steps in a biocontrol project

A classical biocontrol programme typically works through the following steps. This is usually done in a sequential manner, but some activities may take place concurrently.

- Explore the feasibility of the project. If the project looks feasible, proceed.
- Survey the weed in places where biocontrol is desired. If any potential agents are found, explore ways to maximise them. If any likely impediments are found, look for ways to mitigate them.
- Undertake molecular studies of the weed to help narrow down the best place in the native range to find natural enemies.
- Unless natural enemies are already well known, survey the weed in its native range. Identify and study the life cycles of the natural enemies found.
- Determine the host range for potential agents. Abandon any species that do not appear to be safe or effective enough.
- Apply to authorities for permission to release the agents.
- If permission is granted, import, clear through containment, and develop rearing techniques for the new agents (if not already known).
- Mass-rear and release agents over several years.
- Harvest and redistribute agents.
- Evaluate the success of the project. Decide if further agents are needed.