Prospects for Biological Control of African Club Moss (*Selaginella kraussiana*: Selaginellaceae)

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Summary

Project and Client

The feasibility of biological control of *Selaginella kraussiana* (African club moss) in New Zealand was investigated for the Auckland Regional Council.

Objectives

- Record the distribution and weed status of *S. kraussiana* in New Zealand and worldwide.
- Determine whether there are any native, or commercially valued, plants in New Zealand that are closely related to *S. kraussiana*, so any potential conflicts of interest regarding biological control of the weed can be identified.
- Summarise information available on invertebrates and pathogens associated with *S. kraussiana*, and its closest relatives, in New Zealand and worldwide.
- Assess the likelihood of success of a biological control programme for *S. kraussiana* in New Zealand, and outline the steps and costs associated with such a programme.

Main Findings

- *Selaginella kraussiana* is native to Africa and several island groups near Africa, and this is where initial surveys for potential agents should be conducted.
- The plant has naturalised in Australia, Europe, and northern, central and southern America, as well as in New Zealand.
- It has become common on damp forest floors and stream banks in lowland sites in the North Island, in scattered localities in the South Island and in the Chatham Islands.
- The weed is quite shade tolerant and forms thick carpets that inhibit a range of native forest floor plants. It may also have detrimental effects on endangered native snails.
- It spreads easily via spores and regrowth from stem fragments.
- It is difficult to control because it readily reinvades areas cleared by chemical and/or mechanical methods.
- A mycoherbicide is unlikely to be useful against *S. kraussiana*, but it would be a good target for classical biological control.
- *Selaginella kraussiana* belongs to a primitive group of plants known as fern allies (class Lycopsida).
- There are no plants native to New Zealand that are closely related to *S. kraussiana*. A small number of *Selaginella* species may be grown here as ornamental plants, but given their potential as invasive weeds, this is unlikely to lead to significant conflicts of interest.
- No insects or pathogens have been reported from *S. kraussiana* worldwide.
- Four fungi and 17 insects have been reported associated with other *Selaginella* species. Some of these belong to groups that tend to be highly host specific (e.g. rust and smut fungi) and therefore may have potential as biocontrol agents.
- Only three pathogens and one insect have been described from relatives of *S. kraussiana* (fern allies) in New Zealand, and none of these have potential as biocontrol agents.
- There have been no biological control projects elsewhere in the world against *S. kraussiana*, or any other fern ally, and none are planned in the immediate future. There is therefore no body of research on the weed for biological control experts in New Zealand to build on at this time, and no financial assistance could be expected from other

countries where the weed has naturalised but is of little concern. However, classical biological control agents have been released against four species of true ferns overseas and at least two of these (both weevils) have proved extremely successful.

- It is possible, although by no means certain, that *S. kraussiana* could support fewer invertebrates with potential as biocontrol agents than would a flowering plant. This could prolong the time needed to survey for potential agents but would not necessarily reduce the chances of success; overseas studies have shown that a small number of biocontrol agents can be highly effective against true ferns.

Conclusions

- Given how little is known about the insects and pathogens associated with *S. kraussiana*, prospects for its biological control could be much better assessed after an initial survey in its home range in Africa. Chances are reasonably good that such a survey would reveal one or more organisms sufficiently host specific to have potential as a biocontrol agent for New Zealand.

Recommendations

- Survey populations of *S. kraussiana* and other *Selaginella* species in Africa with the goal of identifying potential biocontrol agents ($50,000–$100,000 over 2 years).
- On completion of an initial survey in Africa, review the prospects for successful biological control of *S. kraussiana*. If appropriate, prepare a costed programme for consideration by the ARC and/or other interested organisations.
- If a programme is to proceed, survey populations of *S. kraussiana, S. martensii* and *S. moellendorfii* throughout the species' known ranges in New Zealand to determine which invertebrates and pathogens are currently associated with them here. The purpose of this survey would be to eliminate organisms that have already established in New Zealand from consideration as classical biological control agents. The survey should not include looking for a pathogen with potential for development as a mycoherbicide ($50,000–$80,000 over 1 year).
- If an initial survey in Africa did not yield enough agents with good potential for biological control, consider searching for specific organisms that have been found associated with *Selaginella* species elsewhere (e.g. the two smut species known from India/Zimbabwe and Java) ($100,000–$200,000 over 2 years).

1. Introduction

African club moss (*Selaginella kraussiana*) is an invasive weed of damp forest floors in New Zealand. It has slender, wiry stems that root at the nodes, and it grows as a creeping, branched, fern-like ground cover (ARC 2002). The feasibility of using biological control against this weed was investigated by Jane Barton, on behalf of Landcare Research, for the Auckland Regional Council.

2. Objectives

- Record the distribution and weed status of *S. kraussiana* in New Zealand and worldwide.
- Determine whether there are any native, or commercially valued, plants in New Zealand that are closely related to *S. kraussiana*, so any potential conflicts of interest regarding biological control of the weed can be identified.
- Summarise information available on invertebrates and pathogens associated with *S. kraussiana*, and its closest relatives, in New Zealand and worldwide.
- Assess the likelihood of success of a biological control programme for *S. kraussiana* in New Zealand, and outline the steps and costs associated with such a programme.

3. Sources of Information

Information for this report was obtained by searching computer databases and Internet sites for information on *S. kraussiana*; by cross-referencing known publications; and through enquiries to:

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Paula Wilkie, Landcare Research, New Zealand

4. Main Findings

4.1 Distribution and weed status of *S. kraussiana* in New Zealand and worldwide

Global distribution

The native range of *Selaginella kraussiana* includes Africa and several island groups off the north-west coast of Africa. Specifically, it is native to: Angola, the Azores, Bioko Island (= Fernando Póo), Burundi, Cameroon, Canary Islands (Hierro, Teneriffa, Gran Canaria), Congo, Equatorial Guinea, Ethiopia, Kenya, Madeira, Malawi, Mozambique, Sierra Leone, South Africa (Transvaal, Oranje Free State, Natal, Cape Province), Rwanda, Sudan, Swaziland, Tanzania, Uganda, Zaire and Zimbabwe (Hassler & Swale 2002). Available literature did not reveal which of these areas might be the 'Centre of Origin' of the species.

In addition, *S. kraussiana* occurs in, but is not native to: **Australia:** New South Wales, Norfolk Island, South Australia, and Victoria; **Europe:** Belgium, Corsica, England, France, Germany, Ireland, Portugal, Scotland, Spain, Italy (including Sicily), and former Yugoslavia; **New Zealand:** Chatham Island, North Island and South Island; **USA:** Alabama, Georgia, Hawai'i (Oahu, Maui, Hawai'i Island) and Virginia; **Central America:** Panama and Jamaica; and **South America:** Brazil (Bignall 1980; Hassler & Swale 2002).

***Selaginella kraussiana* in New Zealand**

In New Zealand, *S. kraussiana* forms extensive dense carpets, especially in damp, shaded sites (Roy et al. 2004). It is most commonly found in or on damp forest floors, stream banks, gardens, nurseries, shade houses and ferneries (Roy et al. 2004). The weed was first recorded in the wild in New Zealand in 1919 (Webb et al. 1988). It is now common in lowland sites in the North Island and is also found in scattered localities in Nelson, Westland, Canterbury and Otago in the South Island (Roy et al. 2004), and in the Chatham Islands (Webb et al. 1988). One small infestation was found on Kapiti Island (Anon. 2003), but presumably this was removed.

The species is problematic because it grows rapidly (Ward & Henzell 2002), individual plants have limitless spread (Anon. 2004d), and it can form a thick carpet that chokes out native forest floor plants such as orchids, mosses and ferns (Ward & Henzell 2002; Anon. 2003). *Selaginella kraussiana* is quite shade tolerant (Reidy et al. 2002) and is particularly invasive in high rainfall areas (Newfield 2003). There is some concern that it may have a detrimental impact on endangered native snails (e.g. *Powelliphanta gilliesi* subsp. *kahurangica*), which live on the forest floor. These snails are quite large and would probably find it difficult to move through dense, stringy mats of *S. kraussiana* (M. Newfield, DOC, pers. comm.). In preliminary searches of areas where the snails are known to occur, they have not been found on forest floor covered by *S. kraussiana* (Newfield 2003).

Selaginella kraussiana has two means of spread: dispersal of its spores, and regrowth from small fragments of stem that can sprout adventitious rootlets. Both spores and stem fragments are moved readily on tramping boots, livestock, machinery, contaminated soil and garden waste. The *S. kraussiana* plants on Kapiti Island were found beside a seat on a walking track and had probably been transferred there on someone's walking boots (Anon. 2003). Because the plant grows well in glasshouses and shade houses it often grows amongst other plants being sold in nurseries and garden centres (Anon. 2003). The weed is listed as an unwanted organism in the National Pest Plant Accord, which means it is illegal to sell, distribute or propagate it in New Zealand. One commercial grower who did nothing about the *S. kraussiana* that had escaped in his shade house (or his stock of another weed, *Acmena smithii* = monkey apple) was eventually faced with bulldozers and the destruction of $100,000 worth of his plants as a result (Anon. 2000).

Current control methods and potential advantages of biological control

Current control methods for *S. kraussiana* include hand weeding, raking up and removing all pieces of the weed, and foliar spraying with 1% Roundup + 0.02% Pulse (Ward & Henzell 2002). Trials involving treatment with herbicidal gels (e.g. 1% Roundup GII or 20% Greenscape) have achieved reasonable kill rates (c. 90% at 5 months) but such treatments resulted in 'moderate' impacts on non-target native species up to 0.5 m away (Ward & Henzell 2002). Other trials, which were completed recently by the New Zealand Department of Conservation (DOC), have suggested that Versatill (applied at 100 mL per 10 L, with 20 mL of penetrant and a dye) can give better results than other chemicals (glyphosate, metsulfuron and Grazon) in terms of knockdown and non-target damage (D. O'Halloran, DOC, pers. comm.).

Hand weeding of *S. kraussiana* must be rigorous and repeated regularly (Reidy et al. 2002). While treatment with herbicide causes *S. kraussiana* to die off, it reinvades treated sites very quickly (M. Newfield pers. comm.), so herbicide treatments must also be repeated to be effective (Reidy et al. 2002). For example, on Chatham Island, an area invaded by *S. kraussiana* was blanket sprayed with roundup five times in 2002, and three times in 2003, and yet the weed was still present in 2004 (C. Heginbotham, DOC, pers. comm.). Also, while herbicides can reduce the amount of *S. kraussiana* in an area, they fail to prevent it from spreading, especially once it has established beside a river, road or track (D. O'Halloran pers. comm.). Consequently, *S. kraussiana* is recognised within DOC as one of the more troublesome species to control (M. Newfield pers. comm.).

While a mycoherbicide could be developed that would be more specific to *S. kraussiana* than a chemical herbicide and therefore cause less non-target damage, the ability of the weed to quickly regrow suggests frequent applications would be necessary. This would almost certainly make a mycoherbicide a prohibitively expensive alternative, even without the years of research that would be required for its development. In some areas, the Bay of Islands for example, *S. kraussiana* is too widespread and rampant for chemical or manual control, or a mycoherbicide, to be viable options (D. O'Halloran pers. comm.).

Host-specific classical biological control agents could offer several advantages over current control methods: they should have less impact on non-target species than chemical herbicides; if an effective agent successfully establishes at a site it should be able to control existing infestations as well as regrowth and recruitment there; and the agents should be able to reach infestations that are inaccessible to land managers. Indeed, for inaccessible areas and places where non-target damage is unacceptable, classical biological control is the only viable method of tackling *S. kraussiana* (D. O'Halloran pers. comm.).

4.2 Taxonomic status of *S. kraussiana* and its relatives in New Zealand

Taxonomy and description

Selaginella kraussiana (Kunze) A. Braun belongs to a group (class) commonly called ‘fern allies’ (Lycopsida). There are three families in the Lycopsida: the Isoetaceae (quillworts), the Lycopodiaceae (club mosses) and the Selaginellaceae (spike mosses). *Selaginella* is the only genus in the family Selaginellaceae. It is a very ancient genus, with a fossil record going back to the Carboniferous period (144–65 million years before present) (Allan Herbarium 2000). There are over 700 *Selaginella* species and they are found worldwide, especially in warm temperate to tropical regions (Webb et al. 1988). They are characterised by dichotomously branching stems covered in leaves of two distinct sizes. They reproduce via spores, which are also of two different sizes.

Relatives of *S. kraussiana* in New Zealand

New Zealand does not have any native species in the family Selaginellaceae (Anon. 2004d). However, two *Selaginella* species, in addition to *S. kraussiana*, have naturalised here: *S. martensii* Spring and *S. moellendorfii* Hieron (Allan Herbarium 2000). *Selaginella martensii* is native to Central America (Nicaragua, Costa Rica, Mexico, Guatemala and Panama) (Hassler & Swale 2002). The species has only been collected a few times in the wild in New Zealand: at Whangarei Falls, North Auckland; on Waiheke Island; and in Hamilton City (P. Heenan, Landcare Research, Lincoln, pers. comm.). It probably escaped from cultivation (Webb et al. 1988). *Selaginella moellendorfii* is native to South East Asia (including Cambodia, China, the Philippines, Taiwan and Vietnam) (Hassler & Swale 2002). In New Zealand it has been reported from damp, shaded sites around Auckland City and Rangitoto Island. According to Webb et al. (1988) ‘The sp. is cultivated in warmer parts of NZ and occasionally escapes’.

The two other families in the class Lycopsida contain a small number of species that are native to New Zealand. The family Isoetaceae contains two species that are not only native, but also endemic, to New Zealand (i.e. they only occur here). These are: *Isoetes alpinus* and *I. kirkii* (Allan Herbarium 2000). The family Lycopodiaceae contains four genera and 11 species that are native to New Zealand: *Huperzia australiana*, *H. varia*, *Lycopodiella cernua*, *L. diffusa*, *L. lateralis*, *L. serpentina*, *Lycopodium deuterodensum*, *Ly. fastigiatum*, *Ly. scariosum*, *Ly. volubile*, and *Phylloglossum drummondii* (Allan Herbarium 2000).

The class Lycopsida is in the division Pteridophyta (ferns). There are three other classes in this division with representatives in New Zealand: Equisetopsida (horsetails), Filicopsida (true ferns) and Psilotopsida (whisk ferns). *Equisetum* is the only genus in class Equisetopsida. There are three *Equisetum* species that occur wild in New Zealand, and they are all exotics that have naturalised here. There are 22 families and many genera of true ferns (Filicopsida) in New Zealand (Allan Herbarium 2000). Most are native, but there are also some naturalised species. There are two genera in the Psilotopsida that occur in New Zealand: *Psilotum* and *Tmesipteris*. There is one native *Psilotum* species, and there are four native *Tmesipteris* species, one of which, *T. tannensis*, is also endemic (Allan Herbarium 2000).

Several species in the Lycopsida are sold in New Zealand as ornamental plants. For example, *Selaginella uncinata* and *Huperzia phlegmarioides* (listed as *Lycopodium phlegmarioides*) are both recommended for growing in hanging baskets in a popular gardening book (Bryant 1995). Alarmingly, the text about *S. uncinata* says 'Once any of the species [of *Selaginella*] is established in a greenhouse (which they need in frosty climates) it will self-sow all over the place, coming up under pots and under the staging. Unless it is strangling other plants, leave it – it will help keep the air buoyant.' (Bryant 1995). *Selaginella uncinata*, known as 'Blue' or 'Peacock' spike moss, is a popular ornamental plant overseas and has naturalised in the USA and Japan. It is listed in the *Global Compendium of Weeds* (available at http://www.hear.org/).

4.3 Potential agents for biological control of *S. kraussiana*

All of the pathogens and invertebrates that have been recorded associated with *Selaginella* species worldwide are listed in Appendix 1. *Selaginella kraussiana* is not amongst the hosts on this list, but may well be susceptible to attack from one or more of these organisms. Indeed, several of the organisms listed could potentially be very useful as biocontrol agents for *S. kraussiana*. The two smut fungi, *Melaniella oreophila* and *M. selaginellae,* are highly unusual in being amongst only five of the c. 1200 known species of smuts (class Ustilaginomycetes) that occur on hosts that are not flowering plants (Bauer et al. 1999). They are quite taxonomically isolated (a new family, Melaniellaceae, was erected to accommodate them (Bauer et al. 1999)) and are almost certainly specific to hosts in the genus *Selaginella*, or at least to the Lycopsida. While smut fungi seldom kill their host (the mist flower fungus, *Entyloma ageratinae*, is an exception to this rule) they can severely reduce the growth and reproduction of their hosts and therefore could make good biocontrol agents. If no *Melaniella* species were encountered during surveys for potential biocontrol agents in the native range of *S. kraussiana* (Africa) then it might be worth specifically targeting the localities where these two species were previously collected (Zimbabwe, India and Java) in an attempt to re-locate them (Appendix 1).

Rusts, like smuts, are almost always associated with flowering plants, so the discovery of *U. vetus* on a *Selaginella* species was noted to be 'of exceptional interest because *Selaginella* represents the most primitive group of vascular plants…on which a member of the Uredinales has ever been found' (Bauer et al. 1999). More than half of the pathogens that have been released as classical biological control agents against weeds have been rusts (Barton (née Fröhlich) 2004). They lend themselves to biological control because they tend to be highly host specific, they are often highly pathogenic, and they have wind-borne spores that are readily dispersed. Rust fungi have complicated life cycles involving up to five types of spores. Sometimes pustules containing one type of rust spore will be found in isolation, and it can be difficult, or even impossible, to determine which rust such pustules belong to. The species *Uredo vetus* is an example of this situation. This name, which may well prove temporary, refers to one spore stage (the only one found on *Selaginella*) of an otherwise unknown, or at least unrecognised, rust. The complex life cycles of rusts often involve more than one host. Since *Uredo vetus* only comprises part of a rust life cycle, further investigation into the biology of this organism would be necessary before it could be considered as a potential biocontrol agent. Unfortunately, the species is only known from two collections, one from China (no further details available) and one from an area of Hong Kong that is now covered by an international airport (Hennen 1997). Thus, it may not be possible to locate a living specimen of the fungus for further study.

Many of the insects listed in Appendix 1 may also have potential as biocontrol agents for *S. kraussiana*. *Acrophtalmia artemis* and *Ragadia luzonia* are butterflies whose larvae apparently feed on several *Selaginella* species (Mound et al. 1994). Both have been successfully hand-reared, which suggests they might be easy to work with in the laboratory/glasshouse. The thrips *Echinothrips selaginellae* has only been reported from one *Selaginella* species, and may not attack *S. kraussiana*. Two thrips have been released as classical biological control agents. Gorse thrips was released in Hawai'i in 1991, and was found to be very slow to spread and to cause little damage (Julien & Griffiths 1998). It was also released in New Zealand, in 1990, but its impact here has yet to be fully assessed. Alligator weed thrips, *Amynothrips andersoni*, was released in the USA in 1967 (Julien & Griffiths 1998). It was also slow to spread, and tends to cause only light, scattered damage. However, its introduction is considered successful because it is the only agent released in the USA that in places has a significant impact on the terrestrial form of alligator weed (Julien & Griffiths 1998). Thus, *Echinothrips selaginellae* is unlikely to be the best biocontrol candidate, but it should not be discounted entirely.

The butterfly genus *Euptychia* apparently includes many species that utilise *Selaginella* species as hosts. Only one member of the Nymphalidae family has been used for classical biological control of a weed to date: *Actinote anteas* Doubleday was released in Sumatra (Indonesia) in around 2000 (Zachariades 2000) and China in 2002 (Ye et al. 2004) to control *Chromolaena odorata*. It is not yet known if it has established.

An important point to note is that *Euptychia* species are not African and, therefore, will not have encountered *S. kraussiana* in nature. A relationship such as this where a potential biocontrol agent and its target weed have not evolved together is described as a 'new association'. There has been much debate in the literature with respect to the relative merits of 'old' versus 'new' associations for weed control (e.g. Evans & Ellison 2004). Since an association can only be 'new' if the target weed is not the usual host of the proposed agent, it precludes agents that are specific to a single host species. However, many insects are specific at the level of the host genus, and if a *Euptychia* species that was restricted to *Selaginella* species, and which could cause significant damage to *S. kraussiana*, could be found it would be an excellent 'new association' biocontrol candidate for New Zealand. While most classical biological control agents released to date have had 'old' associations with their target weeds, there have been some great successes with 'new' associates. The most relevant of these to this study is the spectacular success of the weevil *Strenopelmus rufinasus* against red water fern (*Azolla filiculoides*) (see section 4.4). While both the weevil and the fern occur on the American continent, their geographic ranges do not overlap and the usual host of the weevil is a different *Azolla* species (*A. caroliniana*) (McConnachie 1999). Perhaps because this association is 'new' the weevil is apparently capable of causing complete eradication of the target weed at some sites (i.e. local extinctions) (McConnachie et al. 2004). This is an unusual outcome for a biocontrol agent, as more usually some sort of equilibrium is reached whereby populations of the agent and the weed co-exist at a low level, and/or the two organisms go through regular 'boom and bust' cycles.

The unidentified cecidomyids and sawfly listed in Appendix 1 might have potential as biocontrol agents (insects from both groups have been released as biocontrol agents previously (Julien & Griffiths 1998)), but obviously they would require considerable further study. The other organisms listed in Appendix 1 are unlikely to be useful as biocontrol agents, either because they do not damage living plant tissues or because they have very broad host ranges.

There have not been any pathogens or insects recorded on *Selaginella* species in New Zealand, but three pathogens and one invertebrate have been found associated with other members of the class Lycopsida (see Appendix 2). These four organisms are saprobic (living on dead organic material and therefore unlikely to cause damage to living tissues) and/or have very broad host ranges. Therefore, these organisms do not have any potential as biocontrol agents for *S. kraussiana*.

4.4 Prospects for achieving successful biological control of *S. kraussiana* in New Zealand

Selaginella kraussiana has naturalised in many countries (see section 4.1), but it is only in New Zealand that the weed is being considered as a potential target for biological control. In Australia, Europe and the UK the plant is apparently uncommon and of little concern as a weed (C. Ellison, CABI, Ascot, UK, pers. comm.; J. Hosking, NSW Agriculture, Australia, pers. comm.). Likewise, the plant is not causing alarm in Southern, Central or Northern America, and biological control would be difficult there due to the presence of native *Selaginella* species (Hassler & Swale 2002; Anon. 2004b; M. Ielmini, USDA Forest Service, Washington, DC, USA, pers. comm.; L. Kok, Virginia Tech, Virginia, USA, pers. comm.).

No biocontrol agent has ever been released against a *Selaginella* species, or indeed, any member of the class Lycopsida (Julien & Griffiths 1998). The closest relatives of *S. kraussiana* that have been targeted by biological control are four species of true ferns (Filicopsida): red water fern (*Azolla filiculoides*); old world climbing fern (*Lygodium microphyllum*); bracken (*Pteridium aquilinum*); and salvinia (*Salvinia molesta*) (see Appendix 3). One of the agents released against salvinia (a weevil, *Cyrtobagous salviniae*) has achieved good control everywhere it has been released (Julien & Griffiths 1998; Goolsby et al. 2003). Also, as mentioned in section 4.3, another weevil (*Stenopelmus rufinus*) has proven itself extremely effective against red water fern in South Africa (McConnachie et al. 2004). Indeed, this latter project is considered the most effective use of a biocontrol agent against an aquatic weed ever (McConnachie et al. 2004). This shows that biological control of ferns is possible, and gives cause for optimism regarding fern allies such as *S. kraussiana*.

Up until 1978, it was believed that ferns were not generally eaten by insects, but this assumption was shown to be false through research by Balik et al. (1978) who demonstrated that in their study area (in Mexico) ferns were no less attacked than flowering plants (angiosperms). Several fern species have been known for centuries to be highly toxic to both vertebrates and invertebrates and this is why the group was thought likely to be unpalatable to insects. Balik et al. (1978) showed that at least one group of toxins was not as common in ferns as previously thought, and that plenty of insects had ‘overcome the fern’s chemical defence systems to utilise them as food, particularly in the tropics where coevolution proceeds at a more rapid rate’.

When the biological control project for Old World climbing fern began researchers found ‘almost no known insect feeders of *Lygodium* ferns’ (Pemberton 1998). They were not particularly discouraged by this, saying the situation was ‘typical for tropical plants with little economic importance in their native regions’ (Pemberton 1998). In the event, seven years’ worth of survey work resulted in a list of only 18 herbivores associated with *Lygodium* species, and many of the kinds of insects that have been used successfully as biocontrol agents for weeds, such as weevils and leaf beetles, were completely absent (R.W. Pemberton, USDA, Florida, USA, pers. comm.). It is thought that *Lygodium* may be a fern genus that does have particularly potent toxins, and a small project is underway to investigate this possibility (R.W. Pemberton pers. comm.).

Goolsby et al. (2003) were disappointed with the results of their surveys of *Lygodium* species, and they asked researchers who had searched for biocontrol agents for the other three true ferns if they had had similar experiences. 'All indicated that fern herbivores were rarely abundant in their native habitat, and that frequent searches were necessary to assess the species diversity' (Goolsby et al. 2003). This suggests that while it is possible to find good biocontrol agents for ferns, more effort may be required at the survey stage than for flowering plants. The same may, or may not, be true of fern allies such as *S. kraussiana*. A review of the insects recorded as breeding on members of the Lycopsida revealed 16 species from six orders, and all but one of these was from a *Selaginella* species (Mound et al. 1994; Appendix 1). While this is a modest number given the worldwide distribution and diversity of *Selaginella* species, it is a promising start given that no one has actively looked for insects or pathogens on these hosts. The fact that several host-specific pathogens have already been described from the genus also gives cause for optimism.

Prospects are also improved by the lack of close relatives of *S. kraussiana* in New Zealand; potential agents need not be restricted to the target species alone. The lack of close relatives should also reduce the costs associated with host range testing. Non-target plant lists would probably only need to include the 11 members of the Lycopodiaceae that are native to New Zealand and a few representatives of the Isoetaceae, Equisetopsida, Filicopsida and Psilotopsida. It would also be advisable to include the two other naturalised *Selaginella* species, and any others grown as ornamentals in New Zealand, in host range testing. Given the propensity of ornamental *Selaginella* species to naturalise in New Zealand, it would perhaps not be a bad thing if an agent released against *S. kraussiana* were capable of also keeping its closest relatives in check.

5. Conclusions

It is difficult to assess the probability that *Selaginella kraussiana* could be successfully controlled by biocontrol agents in New Zealand. There have been no biological control projects elsewhere in the world against this weed, or indeed any other plant in its class (Lycopsida = fern allies). This is regrettable as there is no body of research for a project in New Zealand to build on, nor is there any strong prospect of financial assistance from other countries.

On the other hand, there are two good reasons for optimism. Firstly, several insects and pathogens that are by nature quite host specific have already been found associated with *Selaginella* species and this suggests that organisms sufficiently specific for use as biocontrol agents may not be uncommon on *S. kraussiana*. Secondly, the genus *Selaginella* is quite taxonomically isolated, being the only genus in the family *Selaginellaceae*, and there are no *Selaginella* species native, or economically important, to New Zealand. This means conflicts of interest with regard to non-target damage from potential agents are likely to be negligible. It should also make host range testing relatively straightforward. In conclusion, an initial survey for prospective agents in the home range of the weed (Africa) is probably justified and after such a survey it should be much easier to assess the prospects for a successful project.

6. Recommendations

- Survey populations of *S. kraussiana* and other *Selaginella* species in Africa with the goal of identifying potential biocontrol agents ($50,000–$100,000 over 2 years).
- On completion of an initial survey in Africa, review the prospects for successful biological control of *S. kraussiana*. If appropriate, prepare a costed programme for consideration by the ARC and/or other interested organisations.
- If a programme is to proceed, survey populations of *S. kraussiana, S. martensii* and *S. moellendorfii* throughout the species' known ranges in New Zealand to determine which invertebrates and pathogens are currently associated with them here. The purpose of this survey would be to eliminate organisms that have already established in New Zealand from consideration as classical biological control agents. The survey should not include looking for a pathogen with potential for development as a mycoherbicide ($50,000–$80,000 over 1 year).
- If an initial survey in Africa did not yield enough agents with good potential for biological control, consider searching for specific organisms that have been found associated with *Selaginella* species elsewhere (e.g. the two smut species known from India/Zimbabwe and Java) ($100,000–$200,000 over 2 years).

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Appendix 1 Organisms recorded worldwide associated with *Selaginella* species

Organism	Taxonomy	Selaginella host/s	Other host/s	Source (reference)	Damage or insect guild	Distribution
Pathogens						
Leucocoprinus straminellus	Fungi: Basidiomycota: Agaricaceae	*Selaginella* sp.	Saprobe found often in glasshouses. Associated mainly with mulch, soil and compost	(Anon. 2004a)	No damage	England, Scotland, Wales, Italy. Range could be wider than this but no further details available
Melaniella oreophila	Fungi: Basidiomycota: Ustilaginomycetes: Melaniellaceae	*S. chrysocaula, S. chrysorrhiza, S. delicatula, S. tenera* and *Selaginella* sp.	-	(Bauer et al. 1999), PDD 63545	Spore pustules (sori) on leaves forming irregular black spots 0.1–1.5 mm in diameter, sometimes comprising the whole leaf. Rarely, sori also occur on stems. Tissues near sori appear yellow and unhealthy	Known only from Zimbabwe and India, but 'probably more widespread but overlooked' (Bauer et al. 1999)
Melaniella selaginellae	Fungi: Basidiomycota: Ustilaginomycetes: Melaniellaceae	*Selaginella* sp.	Known only from type collection	(Bauer et al. 1999)	Lead-coloured spore pustules (sori) up to several centimetres long on young stems of host	Java, known only from type collection
Uredo vetus	Fungi: Basidiomycota: Uredinales	*Selaginella* spp.	Known only from two collections	(Hennen 1997)	Rust pustules, no other symptoms given	China, including Hong Kong
Invertebrates						
Acrophtalmia artemis	Insecta: Lepidoptera: Nymphalidae	*S. delicatula*, *S. fenixii*, *S. uncinata* (reared indoors on the latter species)	-	(Mound et al. 1994)	Butterfly	Philippines
Aleurotulus pteridophytae	Insecta: Homoptera: Aleyrodidae	*S. eurynota*	Oligophagous, has been found on several ferns (Filicopsida)	(Mound et al. 1994)	Whitefly	Costa Rica

Boreus reductus	Insecta: Mecoptera: Boreidae	*Selaginella* sp.	Larvae of *Boreus* species have only ever been collected from amongst the rhizoids of mosses and *Selaginella* species (Penny 1977)	(Mound et al. 1994)	It is not clear if *Boreus* larvae feed on living or decaying tissues (Penny 1977)	Washington, USA
Echinothrips selaginellae	Insecta: Thysanoptera: Thripidae	*S. eurynota*	Known only from collection/s on *S. eurynota*	(Mound et al. 1994)	Thrips	Costa Rica
Encarsia sueloderi	Insecta: Hymenoptera: Chalcidoidea	*S. eurynota*	Attacks insects, not plants	(Mound et al. 1994)	Parasitoid reared from white fly (*Aleurotulus pteridophytae*, see above). Would not have harmed plant	Costa Rica
Euptychia fetna	Insecta: Lepidoptera: Nymphalidae	*Selaginella* spp.	-	(Savela 2004)	Butterfly	Mexico
Euptychia jesia	See above	*S. horizontalis*	?	(Mound et al. 1994)	Butterfly	Costa Rica
Euptychia mollina	See above	*Selaginella* spp.	-	(Savela 2004)	Butterfly	Costa Rica, Colombia
Euptychia mollis	See above	*S. horizontalis*	?	(Mound et al. 1994)	Butterfly	Costa Rica
Euptychia picea	See above	*Selaginella* sp.	?	(Carlton & Tishechkin 2000; Savela 2004)	Butterfly	Ecuador, Amazon, Peru, Surinam
Euptychia rubrofasciata	See above	*Selaginella* sp.	?	(Savela 2004)	Butterfly	North-west Mexico
Euptychia westwoodi	See above	*S. arthritica*	?	(Mound et al. 1994)	Butterfly	Costa Rica
Phenacoccus solani	Insecta: Homoptera: Pseudococcoidae	*Selaginella* sp.	Highly polyphagous, recorded from hosts in at least 15 families of flowering plant	(Mound et al. 1994)	Mealybug	California, USA (on *Selaginella*). Also (on other hosts) Africa, Canada, Central America, Europe, South America, USA
Ragadia luzonia	Insecta: Lepidoptera: Nymphalidae	*S. delicatula*, *S. fenixii*, *S. uncinata* (reared indoors on the latter species)	-	(Mound et al. 1994)	Butterfly	Philippines

Unidentified cecidomyid 1	Insecta: Diptera: Cecidomyidae	*Selaginella pentagona*	?		(Mound et al. 1994)	Single gall	Europe
Unidentified cecidomyid 2	Insecta: Diptera: Cecidomyidae	*Selaginella* sp.	?		(Mound et al. 1994)	Bud gall	New Guinea
Unidentified sawfly larvae	Insecta: Hymenoptera: Symphyta	*S. horizontalis*	?		(Mound et al. 1994)	Sawfly	Trinidad

Appendix 2 Organisms recorded in New Zealand associated with hosts in the class Lycopsida (genera *Isoetes, Huperzia, Lycopodiella, Lycopodium, Phylloglossum* and *Selaginella*)

Organism	Taxonomy	Lycopod host/s	Other host/s	Source (reference)	Damage	Distribution
Pathogens						
Phytophthora cinnamomi	Chromista: Oomycetes: Pythiaceae	*Lycopodium deuterodensum*	Host range very broad: recorded from at least 88 genera in NZ	(Pennycook 1989; Anon. 2004c)	Well-known pathogen, can be highly damaging	Africa, North, Central and South America, South-East Asia, Australasia (including both islands of NZ), Europe, UK
Terriera minor	Fungi: Ascomycetes: Rhytismataceae	*Lycopodium* sp.	Found on fallen leaves of a wide range of plants including at least 24 spp.	PDD 46137 (Anon. 2004c)	Mostly on fallen leaves, so not associated with disease symptoms	Both islands of New Zealand, Chile, Venezuela
Trichoglossum walteri	Fungi: Ascomycetes: Geoglossaceae	*Lycopodium* sp.	Mostly found on the ground or rotting litter	PDD41112 (Anon. 2004c)	Growing as a saprobe on debris amongst *Lycopodium*, not on the plant itself	Native, but not endemic, to New Zealand
Invertebrates						
Paracoccus glaucus	Insecta: Hemiptera: Pseudococcidae	*Huperzia varia* (reported under synonym of *Lycopodium billardieri*)	Mealybug, Polyphagous	(Cox 1987)	?	New Zealand, known only from type collection

Appendix 3 Ferns (Pteridophyta: Filicopsida) targeted by biological control, and the agents released against them

Exotic Weed (taxonomy)	Weed origin	Agent/s (taxonomy)	Agent/s origin	Place (date) of introduction	Reference/s
Azolla filiculoides (Azollaceae) = red water fern or fairy fern	South America	*Stenopelmus rufinasus* (Coleoptera, Curculionidae, Weevil)	Florida (USA)	South Africa (1997) Berkshire, England (2004)	(Hill & Cilliers 1999; Fitter 2004; McConnachie et al. 2004)
Lygodium microphyllum (Schizaeaceae or Lygodiaceae) = Old World climbing fern	Wet tropical and subtropical Africa, Asia, Australia, and the Pacific islands	*Austromusotima (Cataclysta) camptozonale* (Pyralidae, moth)	Australia	Florida (permission to release granted August 2004, release to begin October 2004) NB: Non-target plants tested for susceptibility to this moth included three *Selaginella* species. There was no larval development on any of them (Buckingham et al. 2003, 2004)	(Pemberton 1998; Hutchinson et al. 2004; Yen et al. 2004; R.W. Pemberton pers. comm.)
		Floracarus perrepae (Eriophyidae, gall mite)	Asia and Australasia	Florida (petition to release filed Feb 2004)	
		Neomusotima conspurcatalis (Pyralidae, moth)	Asia and Australasia	Florida (petition to release was probably submitted Oct/Nov 2004)	
		Several other agents from Asia (a pyralid moth, *Ambia* sp., a leaf mining buprestid beetle, *Endelis bakerianus*, and a leaf-feeding sawfly, *Neostrombocerus abicomus*) are still being considered			
Pteridium aquilinum (Dennstaedtiaceae) = bracken fern	Cosmopolitan, occurring everywhere except in glacial and periglacial climates	*Conservula consigna* (Moth), Several other agents (a moth, *Panotima* sp., and an Eriophyid mite from South Africa, and a fungal pathogen from the UK, *Ascochyta pteridis*) are still being considered	South Africa	UK. (permission granted for release in large field cages in 1992)	(Burge & Kirkwood 1992)

Salvinia molesta (Salviniaceae) = water fern or Salvinia	South America	*Cyrtobagous salviniae* (Coleoptera, Curculionidae, weevil)	Brazil, South America	Australia (1980), Papua New Guinea (1982), India (1983), Namibia (1984), South Africa (1985), Sri Lanka (1986), Malaysia (1989), Kenya (1990), Zambia (1990), Fiji (1991), Zimbabwe (1992), Ghana (1996)	(Forno 1987; Cilliers 1991; Julien & Griffiths 1998)
		Cyrtobagous singularis (Coleoptera, Curculionidae, weevil)	Trinidad	Botswana (1971), Zambia (1971), Fiji (1975)	
		Paulinia acuminate (Orthoptera: Pauliniidae)	Trinidad and Uruguay	Zimbabwe (1969), Kenya (1970), Zambia (1970), Botswana (1971), Sri Lanka (1973), India (1974), Fiji (1975)	
		Samea multiplicalis (Pyralidae, moth)	Brazil and Trinidad	Zambia (1970), Botswana (1972), Fiji (1976), Australia (1981)	