**Application to introduce *Paradibolia coerulea* for biological control of *Spathodea campanulata* (African tulip tree) in the Cook Islands**

Prepared by Dr Iain Paterson[1], Guy Sutton[1], Phillippa Muskett[1] and Dr Quentin Paynter[2]

[1]Researcher

Rhodes University

Dept. of Zoology & Entomology

Life Sciences Building
Barratt Complex, African St
Grahamstown
I.Paterson@ru.ac.za

[2]Research Leader
Landcare Research New Zealand Ltd.
231 Morrin Road
St Johns Auckland
New Zealand
Paynterq@landcareresearch.co.nz

On behalf of the Cook Islands Ministry of Agriculture:
Ara Tapu,
Arorangi District,
Cook Islands

DATE: March 2019

# Contents

# 1. Summary

The Cook Islands Ministry of Agriculture seeks approval for the release of the Spathodea flea-beetle, *Paradibolia coerulea* P. Beauv. (Coleoptera: Chrysomelidae), for the control of the alien invasive plant, *Spathodea campanulata* Beauv. (Bignoniaceae).

*Spathodea campanulata* (African tulip tree) is a damaging alien invasive that is indigenous in Central and West Africa but is now widespread throughout the Pacific Region. It is considered one of the 100 worst alien invasive species in the world along with only 30 other terrestrial invasive plants (Lowe *et al*. 2000). It was introduced into the Cook Islands as an ornamental plant but has now naturalised and is a threat to indigenous biodiversity. In other Pacific Islands *S. campanulata* is a destructive alien weed that invades indigenous forests and arable land causing reductions in natural biodiversity and agricultural productivity (Larrue *et al.* 2014; Labrada & Medina 2009). The density and distribution of the *S. campanulata* in the Cook Islands is likely to increase if control measures are not implemented.

Mechanical and herbicidal control of *S. campanulata* is expensive and labour intensive. The plant reproduces asexually by means of root suckers and coppices readily. Slashing, without the use of a cut-stump treatment herbicide, will result in the formation of dense monocultures. The plant also produces vast quantities of seeds that are distributed by wind, so after mechanical and herbicidal clearing has been completed there is a need for long-term follow-up treatments in order to remove seedlings. Biological control will complement other control measures by reducing the plant's growth rate and seed set, making control more feasible. Without the inclusion of biological control in a strategy against *S. campanulata* it will be impossible to effectively control the weed.

*Paradibolia coerulea* is a specialist herbivore that feeds on *S. campanulata* in the native distribution in Africa. It is a leaf-feeding beetle that causes defoliation of the leaves in the adult phase and mines the leaf material in the larval stage. Adult feeding was recorded on some closely related non-target test plant species but none of the close relatives of *S. campanulata* are indigenous in the Cook Islands and the majority of the ornamental species within the family Bignoniaceae that are present on the Islands have been tested without any sign of feeding or

oviposition. Larval development was only possible on two closely related species, neither of which are present in the Cook Islands. Feeding and development was restricted to a closely related clade of the Bignoniaceae, with no feeding possible on test plant species outside of this clade or in other families. The agent is therefore suitably host specific and should not feed on, or oviposit on any other species in the Cook Islands. Any spill-over feeding on other plant species is only expected if all *S. campanulata* in the immediate vicinity has been defoliated by the beetles and this spill-over effect will be temporary as the beetles will not be able to persist on non-target plants.

The release of *P. coerulea* is expected to reduce the density and spread of *S. campanulata* in the Cook Islands, resulting in a reduction in the negative impacts of the weed. Another agent, the Spathodea mite, *Colomerus spathodea,* was released in Cook Islands in 2017 and is now widely distributed in Rarotonga. The combined effect of the two agents is expected to provide a greater level of control than either agent alone. Biological control of *S. campanulata* is considered a sustainable, long-term control method that will compliment other methods of control without any negative impacts on other plant species or indigenous biodiversity in general.

This EIA has been prepared in accordance with Section 36 of the Cook Islands Environment Act 2003 (Box1, below) and section 68 of the Cook Islands Biosecurity Act 2008 (Box 2, below).

| BOX 1. SECTION 36 OF THE COOK ISLANDS ENVIRONMENT ACT 2003 |
|---|
| Environmental Impact Assessment – <br> (1) No person shall undertake any activity which causes or is likely to cause significant environmental impacts except in accordance with a project permit issued under this section. <br> (2) A person who proposes to undertake an activity of the kind referred to in subsection (1) shall apply to the permitting authority for a project permit in respect of the activity in accordance with the procedures (if any) prescribed by regulations. <br> (3) Every application for a project permit shall be submitted to the Service and shall include an environmental impact assessment, setting out details of - <br> (a) the impact of the project upon the environment and in particular - <br> (i) the adverse effects that the project will have on the environment; and <br> (ii) a justification for the use or commitment of depletable or non-renewable resources (if any) to the project; and <br> (iii) a reconciliation of short-term uses and long-term productivity of the affected resources; and <br> (b) the proposed action to mitigate adverse environmental effects and the proposed plan to monitor environmental impacts arising out of the project; and (c) the alternatives to the proposed project. <br> (4) Every application for a project permit shall be accompanied by an application fee prescribed by regulations. <br> (5) The Service shall undertake public consultation for the issuance of the project permit and in so doing – <br> (a) publish details of the project in such a manner that these become accessible to the affected public; <br> (b) make available copies of the environmental impact assessment report prepared by the project developer for review by the public; and <br> (c) receive comments within 30 days from the date of public notice from the general public and other interested parties; <br> (6) The Service shall request comments from any Government department or agency, or person affected by or having expertise relevant to the proposed project or its environmental impact. <br> (7) After the permitting authority has reviewed and assessed the application and all relevant information including the environment impact assessment, it shall, subject to guidelines (if any) prescribed by regulations- |

(a) issue a permit for the proposed project specifying the terms and conditions subject to which the permit is issued; or

(b) request the applicant to submit modifications regarding the proposed project; or

(c) where there are reasonable grounds to do so (taking particular account of the purpose of this Act), refuse to issue a permit for the proposed project and state the reasons for such refusal.

(8) The Service shall immediately convey to the applicant the decision of the permitting authority.

(9) Within 14 days of receiving notice of a refusal under subsection (7)(c) the applicant may by letter to the Minister, request that the Minister consider the permitting authority's decision. The Minister shall review the permitting authority's decision and all information relevant thereto and shall notify the applicant and the permitting authority in writing of the Minister's decision to either -

(a) uphold the permitting authority's decision to refuse a permit for the proposed project; or

(b) direct the Service to request that the applicant submit specified modifications to the Service regarding the proposed project for reconsideration by the permitting authority.

(10) If the Minister is required to make a decision under subsection (9) in any case where the Minister is the applicant for the permit, or is otherwise directly or indirectly interested in the permit application otherwise than as the reviewing authority, the Minister shall –

(a) with the concurrence of the permitting authority concerned, convene an independent panel to review the permitting authority's decision and submit a recommendation to the Minister; and

(b) follow that panel's recommendation in making the decision under subsection (9); and

(c) make those recommendations public.

(11) Every person commits an offence who, without reasonable excuse or lawful justification, fails or refuses to comply with subsection (1), and shall upon conviction be liable -

(a) in the case of a body corporate, to a fine not exceeding $100,000;

(b) in any other case, to a fine not exceeding $50,000.

(12) In addition to any penalty imposed under subsection (11), the Court may order that the person convicted –

(a) under the supervision and to the satisfaction of a person appointed by the Court, clear up and remove the damage caused to the environment as a consequence of the offence within such period and upon such conditions as may be specified in the order;

(b) pay such amount as the Court may assess in respect of the expenses and costs that have been or are likely to be incurred-

(i) in restoring the environment to its former state (its state immediately before the offence was committed); or

(ii) in removing or cleaning up or dispersing any oil or noxious liquid, or other harmful substance to which the offence relates.

(13) For the purposes of subsection (1), any designation, or issue or re-issue of approval of any land (whether by a Minister or any other public officer or authority, and whether under this or any other Act) for the disposal of any kind of waste is deemed to be an activity that is likely to cause significant environmental impacts.

| BOX 2. SECTION 68 OF THE COOK ISLANDS BIOSECURITY ACT |
|---|
| 68. Beneficial organisms and biocontrol agents – |
| (1) The Secretary[1] may in writing approve the release of beneficial organisms or biocontrol agents that he considers necessary or appropriate for the control or eradication of a particular pest or disease in the Cook islands. |
| (2) An approval under subsection (1) shall identify – |
| (a) the organism or agent; |
| (b) the pest or disease which it is intended to control; |
| (c) the area where it may be released; |
| (d) the period during which it may be released; |
| (e) the person or persons who may release it; and |
| (f) any conditions subject to which the approval is granted. |
| (3) No liability attaches to the Secretary, Director [2] or any public officer in respect of the release of organisms or biocontrol agents in accordance with this section, except on proof of negligence or malice. |
| (4) The Director shall keep a biosecurity register of – |
| (a) the names of any beneficial organisms or biological agents released under this section; and |
| (b) the place of and extent of release of such organisms and agents. |
| (5) In this section, "beneficial organism" and "biocontrol agent" mean a natural enemy, antagonist or competitor of a pest or disease, and any other self-replicating biotic entity used for pest and disease control. |
| [1] Secretary to the Ministry of Agriculture |
| [2] Director of Biosecurity |

# 2. Background and aims of proposal

*Spathodea campanulata* is a large tree of secondary forests and forest edges that is native to Central and West Africa. The species has been widely utilized as an ornamental plant due to the beautiful flowers, fast growth and relative ease of cultivation (Francis 1990). It is used as a shade tree in parks and coffee plantations and is frequently used as living fenceposts (Francis 1990). Widespread cultivation of the plant has led to naturalisation in areas outside of the native range in Africa (Hedberg *et al*. 2006), the Caribbean (Francis 1990; Labranda & Medina 2009) and the Pacific Islands (Meyers 2004). It has become naturalised on many of the Pacific Islands including American Samoa, Commonwealth of the Northern Mariana Islands, Federated States of Micronesia, Fiji, French Polynesia, Guam, Hawaii, Nauru, Malaysia, Marshall Islands, Niue, Palau, Samoa, Tonga, Vanuatu, Wallis and Futuna Islands, and Tahiti (Labranda & Medina 2009, Lowe *et al*. 2000). On some of these islands it has become a destructive weed, invading indigenous forests and severely impacting agricultural production (Larrue *et al.* 2014; Labranda & Medina 2009) (Fig. 1 & 2). *Spathodea campanulata* is in the early stages of invasion in the Cook Islands at present, but the evidence from other Pacific islands suggests that the problem is likely to become much more severe if control measures are not implemented. Within the Cook Islands the weed is currently only common on Rarotonga (Fig. 3), where it is listed as very common on the Cook Islands biodiversity database. Infestations are currently quite scattered through the forested interior of Rarotonga but ‘halos’ of saplings are often present around these isolated trees and small patches indicating that over time, these infestations will become larger and denser. It is also present on Atiu, Mauke, Aitutaki, in the Southern Group and on Manihiki, in the Northern Group. It is likely to spread to other islands if not properly controlled.

Mechanical and herbicidal control of *S. campanulata* is labour intensive and expensive. In Fiji, the difficulty of removing *S. campanulata* from agricultural fields resulted in famers clearing indigenous forest, which is less labour intensive to clear, and abandoning fields infested with *S. campanulata* (Labranda & Medina 2009). To effectively control the plant using mechanical methods requires that the root stock of the plant be dug up because of its ability to grow from suckers and to coppice. Ringbarking is also completely ineffective because only the above-ground parts of the plant are killed (Labranda & Medina 2009). Herbicide application can effectively kill plants using a cut-stump treatment but this method is impractical for large infestations and, because of the large amount of seeds produced by the plant, frequent and long-term follow-up treatments in which seedling and saplings are pulled would be essential. In order to effectively control *S. campanulata* an integrated control strategy is required and biological control is an essential component. Biological control will complement other control methods by reducing the competitive ability, growth rate and reproductive output of the weed.

**Figure 1** An example of the landscape level impact of *Spathodea campanulata* on the island of Viti Levu in Fiji.

**Figure 2** An example of *S. campanulata* in an agricultural setting. The plants have been slashed back but all cut stumps are resprouting. This photograph was taken on a Taro farm in Viti Levu, Fiji.

**Figure 3.** Although it is mainly found in the lowlands of Rarotonga, *S. campanulata* is invading the forested interior as seen here in a photo taken from the Needle on the Cross Island Track.

Surveys for potential biological control agents were conducted in Ghana, West Africa, in 2009, 2014 and 2016. Ghana was deemed a suitable area for collection of biological control agents for *S. campanulata* in the Cook Islands because genetics data suggests that West Africa was the source of the plants that are now invading Rarotonga (Sutton *et al*. 2017a). Several natural enemies were found feeding on *S. campanulata* in Ghana and the two most promising were imported into quarantine at Rhodes University in South Africa for host specificity testing. The first was the Spathodea gall-mite, *Colomerus spathodeae* (Carmona) (Acarina: Eriophyoidea), which was approved for release in the Cook Islands in December 2016, and was successfully established in the field in February 2017. The second natural enemy was the Spathodea flea beetle, *Paradibolia coerulea* P. Beauv. (Coleoptera: Chrysomelidae) (Paterson *et al*. 2017).

Host specificity testing has indicated that *P. coerulea* can feed and develop only on *S. campanulata* and a few close relatives. The few close relatives that were utilised by *P. coerulea* however are not present in the Cook Islands. *Paradibolia coerulea* is therefore safe to release in the Cook Islands and elsewhere in the Pacific Region.

This proposal recommends that a consignment of *P. coerulea* be transported from the quarantine facility at Rhodes University in South Africa to Rarotonga for release on *S. campanulata*.

## 2.1. INFORMATION ON *PARADIBOLIA COERULEA*

### 2.1.1. Taxonomy of *Paradibolia coerulea*

Phylum: Arthropoda
Class: Insecta
Order: Coleoptera
Family: Chrysomelidae
Genus: Paradibolia
Species: P. coerulea

### 2.1.2. Native distribution of *Paradibolia coerulea*

*Paradibolia coerulea* is probably present throughout the native distribution of *S. campanulata*. It is abundant in Ghana, where it was found feeding on about 40% of sites examined during field surveys (Paterson *et al.* 2017). The beetle has also been recorded in Rwanda where it was found feeding on *S. campanulata* during surveys to collect African flea-beetles (M. Biondi, University of L'Aquila, Italy, Pers. Comm.). *Paradibolia coerulea* is a *S. campanulata* specialist that will not feed on any other species of plant besides *S. campanulata* in the native distribution and can therefore only be present where the plant is present. There are no records of the beetle feeding on any other plant species.

Feeding by adult *P. coerulea* results in the removal of leaf material of the host plant leaving feeding scars, while the endophagous larvae of *P. coerulea* mine within the leaf structure, removing large amounts of leaf tissue without breaking the epidermal layers of the leaf. This feeding damage is very similar to that produced by *Uroplata girardi* Pic, which is a highly damaging biocontrol agent that was successfully introduced to control *Lantana camara* in Rarotonga in 1969 (Winston *et al.* 2014).

## 2.2. INFORMATION ON *SPATHODEA CAMPANULATA*

### 2.2.1. Taxonomy of *Spathodea campanulata*

Division: Angiosperms

Clade: Asterids

Order: Lamiales

Family: Bignoniaceae

Genus: Spathodea

Species: S. campanulata

### 2.2.2. Native distribution of *Spathodea campanulata*

*Spathodea campanulata* is native in Central and West Africa. Three subspecies are recognised, *S. campanulata* subsp. *campanulata* is found in West Africa, *S. campanulata* subsp. *nilotica* in Central Africa and *S. campanulata* subsp. *congolana* in the Congo Basin (Fig. 5). The subspecies that is present in the Cook Islands is *S. campanulata* subsp. *campanulata* based on morphological analyses as well as genetic matching studies (Sutton et al., 2017a).

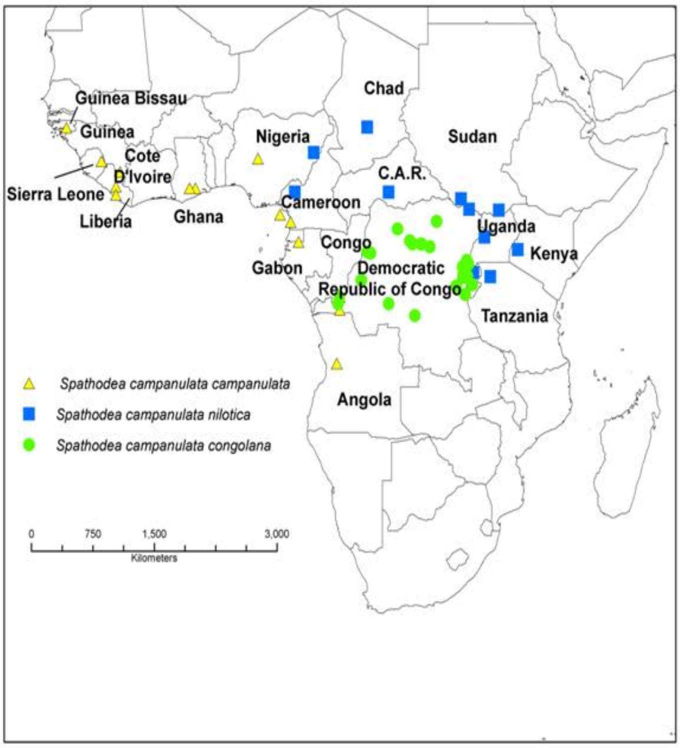


**Figure 5** The native distribution of *Spathodea campanulata* (from Bidgood 1994).

## 2.3. HOST-RANGE TESTING

### 2.3.1. Scientific rationale for determining the host-range of *P. coerulea* in relation to plant species of importance in the Cook Islands

The centrifugal phylogenetic method (Wapshere, 1974) has long been used to determine the host-range of potential biological control agents by sequentially testing plant taxa most closely related to the target weed followed by increasingly distantly related taxa until the host-range has been circumscribed. This approach is supported by recent advances in molecular techniques: for example, host-shifts in lineages of specialist phytophagous arthropods are strongly linked to the evolution of host-plant lineages, and in particular plant chemistry. Such herbivores show a strong phylogenetic conservatism of host associations (Briese, 1996; Briese and Walker, 2002). This pattern of strong phylogenetic conservatism in diet suggests the non-target plants of greatest risk are those closely related to known hosts (Futuyama, 2000), and this has been validated by recent reviews of non-target attack by biological control agents (Briese and Walker, 2002; Louda et al., 2003; Paynter et al., 2004; Pemberton, 2000).

The Web of Science® database and the angiosperm phylogeny website (Stevens, 2001 onwards) were searched for information regarding the taxonomic position of *Spathodea campanulata* and the Cook Islands Natural Heritage Database (McCormack, 2007) were consulted to identify the Cook Islands plant species that are most closely-related to *Spathodea* in order to compile a list of plants for inclusion in host-range testing.

The taxonomy of the Bignoniaceae has recently been revised using molecular techniques (Olmstead *et al*. 2009). Within the Bignoniaceae, *S. campanulata* belongs to the Paleotropical clade (Fig. 7). The most closely-related genera (*Catophractes* and *Rhigozum*) to *Spathodea* are also native to Africa and are absent from the Cook Islands. The most closely-related species that are grown in the Cook Islands (*Tabebuia* spp. and *Crescentia cujete*) are exotic ornamentals that belong to the clade named the *Tabuia* alliance by (Olmstead et al., 2009). More distantly-related species within the "Core" Bignoniaceae include *Tecomaria capensis*, *Tecoma stans* and *Podranea ricasoliana*. While Jacaranda (*Jacaranda mimosifolia*) is even more distantly-related, being outside the "Core" Bignoniaceae (Fig. 7). The most closely-related plant family to the Bignoniaceae that is represented in the Cook Islands native flora is the Lamiaceae (three native species belong to this family: *Leucas decemdentata, Premna serratifolia* and *Vitex trifoliata var. trifoliata*).

The most closely related species to *S. campanulata* are species with the Paleotropical clade, the majority of which are African species (Fig. 7). Four genera of the Paleotropical clade were tested, although none of these species are present in Cook Islands (Table 2). A representative of each of the 10 genera of Bignoniaceae that are present in the Cook Islands (Table 1), with the exception of *Mansoa* sp., which could not be sourced in South Africa, were also tested. *Mansoa* sp. are not close relatives of *S. campanulata* (Fig. 7), so the inclusion of this genus was not considered essential. In addition to the species listed in Table 1, the only member of the Bignoniaceae that is native in Vanuatu, *Dolichandrone spathaceae*, was included as a test plant species (Table 2). Although this species is not present in the Cook Islands, it is found on other islands in the Pacific region and is a close relative of the target weed. Another exotic, *Catalpa longissima* was introduced to Rarotonga as a possible timber tree. The only known surviving tree was reported to have been chopped down but was recently found to be growing back from the stump. However, the tree has no important significance in Rarotonga and its survival should not prevent the introduction of *P. coerulea* (Gerald McCormack and Joseph Brider, Pers. Comm.).

The inclusion of more distantly related test plant species, such as *Premna serratifolia* and *Vitex trifoliata var. trifoliata*, was not required because the host range of *P. coerulea* was restricted to within the family Bignoniaceae (see Results) and because closely related plant species from the same plant family as *P. serratifolia* and *V. trifoliata* were used as proxies: Seven species from outside the Bignoniaceae were included from families closely related to the Bignoniaceae including representatives from the Verbenaceae, Lamiaceae and Acanthaceae (Table 2). As noted above, the most closely-related plants to *S. campanulata* that are present in the Cook Islands belong to the Lamiaceae, so the representatives from this family that were tested are suitable proxies for the indigenous species (Table 2).

**Table 1** Representatives of the Bignoniaceae in the Cook Islands, listed in order of taxonomic proximity to *Spathodea campanulata*. All species are introduced into the region as there are no indigenous Bignoniaceae in the Cook Islands.

| **Family,** species (common name, if relevant) | Clade | Notes |
|---|---|---|
| **Bignoniaceae** | | |
| *Spathodea campanulata* (African tulip tree) | Paleotropical clade | Target weed |
| *Tabebuia* spp. (*T. aurea* Silver Tabebuia; *Tabebuia donnell-smithii* Gold tree; *Tabebuia heterophylla* Lilac trumpet tree; *Tabebuia rosea* Rose trumpet tree) | Tabuia alliance | Ornamentals native to tropical America |
| *Crescentia cujete* (Calabash tree) | *Tabuia* alliance | Ornamental, fruits used as a container (native to tropical America) |
| *Dollichandra (=Macfadyena) unguis-cati* (Cat's claw creeper) | Bignoniae | Ornamental (native to S America), becoming a serious weed |
| *Mansoa hymenaea* (Garlic-scented vine) | Bignoniae | Ornamental (native to tropical America) |
| *Pyrostegia venusta* (Orange-trumpet vine) | Bignoniae | Ornamental (native to S America) |
| *Podranea ricasoliana* (Pink trumpet vine) | Tecomeae | Ornamental (native to S Africa) |
| *Tecoma stans* (Yellow bells) | Tecomeae | Ornamental (native to Caribbean) |
| *Tecomaria capensis* (Cape honeysuckle) | Tecomeae | Ornamental (native to S Africa) |
| *Jacaranda mimosifolia* (Jacaranda) | Jacarandeae | Ornamental (native to S America) |

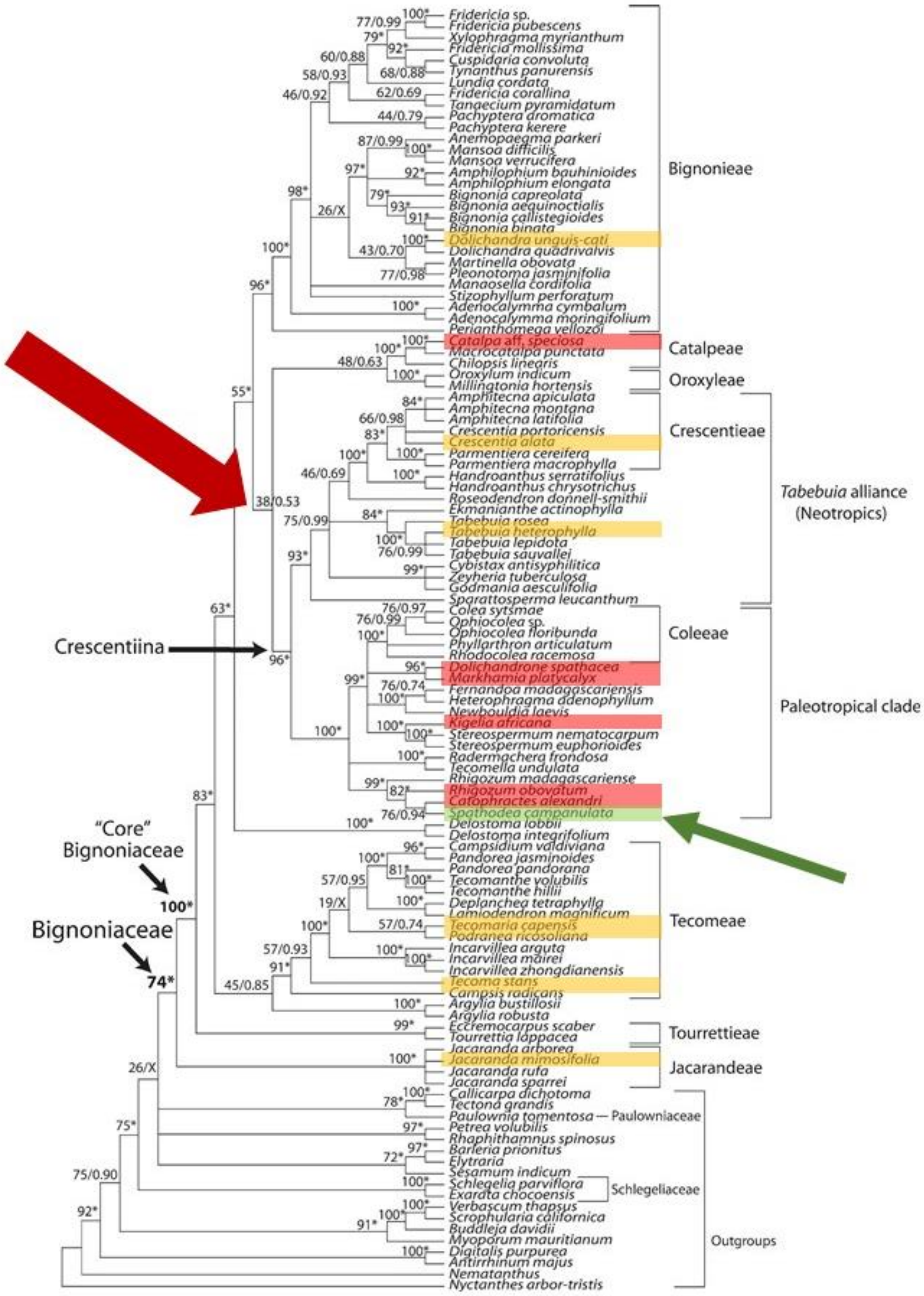


**Figure 7** Phylogeny of the Bignoniaceae (Olmstead et al., 2009). The position of *S. campanulata* is indicated by the green arrow. Test plant genera are shaded: red/dark shading = tested genera that are absent from the Cook Islands; pale/amber shading = genera present in the Cook Islands that were included in testing. Note the genus *Mansoa*, which was not tested, contains one exotic ornamental species in the Cook Islands (garlic scented vine *M. hymenaea*). This genus belongs to the Bignonieae clade, close to *Dolichandra*, which was tested. The tested genus *Pyrostegia*, which is absent from the above phylogeny, also belongs to the Bignonieae (Lohmann, 2006). The large red arrow indicates the base of the clade to which *P. coerulea* is restricted (see 2.3.2 Summary of host specificity testing).

**Table 2** List of test plants included in host specificity testing

| **Family,** species (common name, if relevant) | Clade (if within Bignoniaceae) |
|---|---|
| **Bignoniaceae** | |
| 1. *Spathodea campanulata* (African tulip tree) | Paleotropical clade |
| 2. *Rhigozum obovatum* | Paleotropical clade |
| 3. *Dolichandrone spathaceae* (Mangrove trumpet tree) | Paleotropical clade |
| 4. *Kigelia africana* (African sausage tree) | Paleotropical clade |
| 5. *Markhamia obtusifolia* | Paleotropical clade |
| 6. *Crescentia cujete* (Calabash tree) | Tabuia alliance |
| 7. *Tabebuia heterophylla* (Lilac trumpet tree) | Tabuia alliance |
| 8. *Catalpa speciosa* (Yoke-wood) | Catalpeae |
| 9. *Dollichandra (=Macfadyena) unguis-cati* (Cat's claw creeper) | Bignoniae |
| 10. *Pyrostegia venusta* (Orange-trumpet vine) | Bignoniae |
| 11. *Podranea ricasoliana* (Pink trumpet vine) | Tecomeae |
| 12. *Podranea rosea* (Rose trumpet vine) | Tecomeae |
| 13. *Tecomaria capensis* (Cape honeysuckle) | Tecomeae |
| 14. *Tecoma stans* (Yellow bells) | Tecomeae |
| 15. *Jacaranda mimosifolia* (Jacaranda) | Jacarandeae |
| **Verbenaceae** | |
| 16. *Duranta erecta* (Golden dewdrop) | |
| 17. *Pertrea volubillis* (Purple wreath) | |
| 18. *Verbena peruviana* (Verbena) | |
| **Lamiaceae** | |
| 19. *Salvia splendens* (Scarlet sage) | |
| 20. *Salvia chamelaeagna* (African sage) | |
| **Acanthaceae** | |
| 21. *Acanthus mollis* (Bearsfoot) | |
| 22. *Thunbergia alata* (Back-eyed Susan) | |

### 2.3.2. Summary of host-range testing results

Host specificity testing was conducted using no-choice tests. A pair of sexed *P. coerulea* adults (1 male: 1 female) were taken from the culture maintained in quarantine at Rhodes University, and inoculated onto a single test plant species or a *S. campanulata* control in individual standard insect cages. At least one *S. campanulata* control was included at the same time as all test plant species. The insects were allowed to feed and reproduce until death, after which the extent of feeding damage (number of leaf scars), reproductive output (number of larvae produced) and survival (number of days until death) of each *P. coerulea* pair was recorded. For a proportion of the *S. campanulata* controls (n=8) and for any test plant species that supported oviposition, the number of larvae that developed through to the adult stage was recorded.

*Paradibolia coerulea* could be reared to the adult stage on two of the test plant species, *Catalpa speciosa* and *Dolichandrone spathaceae* (Table 3). These two test plant species are clearly inferior host plants, with much lower numbers of *P. coerulea* surviving to the adult stage compared to on the primary host, *S. campanulata*. Only two eggs were oviposited on *D. spathaceae* and both survived to the adult stage, giving an average of 0.4 adults (S.E. ± 0.4) per plant (Table 3). An average of 6.4 adults (S.E. ± 2.8) emerged from each of the *C. speciosa* replicates, which is significantly less than the 16.0 adults (S.E. ± 1.51) on *S. campanulata* (Table 3). Neither of these test plant species are present in Cook Islands and both are closely related to *S. campanulata* being restricted to a clade which includes the target weed (indicated by the red arrow in Fig. 7). None of the Bignoniaceae, or any other test plant species, that are present on Rarotonga supported development of *P. coerulea.*

Only five of the 21 species that were tested had any feeding damage from adult beetles and these species are all restricted to a closely related clade that includes *S. campanulata* (Fig. 7). Outside of this clade all the beetles died within a few days without feeding and no oviposition was recorded (Table 3). The only plant that is present on Rarotonga that had any feeding damage was the introduced species, *Tabebuia heterophylla,* which had trivial feeding compared to the target weed and is unlikely to be fed on under field conditions.

**Table 3.** Performance of *Paradibolia coerulea* on test plant species and *S. campanulata* controls. Feeding scars were those produced by the adult pair that was inoculated onto each plant. The number of larvae and the number of individual that survived to the adult stage (eclosion of adults) are the offspring of the pair inoculated onto each plant. Adult survival is the length of time that the pair of adults survived for.

| Plant species | Replicates | Insect performance (mean ± se) | | | |
|---|---|---|---|---|---|
| | | Feeding scars | Larvae | Eclosion of adults | Adult survival (days) |
| *Spathodea campanulata* | 15 | 940 ± 176 | 19.5 ± 5.4 | 16.0 ± 1.5 (n=8) | 48 ± 10 |
| *Rhigozum ovobatum* | 5 | 45 ± 32 | 0 | 0 | 22 ± 16 |
| *Dolichandrone spathacea* | 5 | 86 ± 38 | 0.4 ± 0.2 | 0.4 ± 0.4 | 25 ± 11 |
| *Kigellia Africana* | 5 | 0 | 0 | 0 | 8 ± 3 |
| *Markhamia obtusifolia* | 5 | 7 ± 3 | 0 | 0 | 4 ± 2 |
| *Crescentia cujete* | 5 | 0 | 0 | 0 | 3 ± 1 |
| *Tabebuia heterophylla* | 5 | 54 ± 24 | 0 | 0 | 3 ± 1 |
| *Catalpa speciosa* | 5 | 704 ± 315 | 17.0 ± 7.0 | 6.4 ± 2.8 | 106 ± 47 |
| *Dolichandra unguis-cati* | 5 | 0 | 0 | 0 | 5 ± 2 |
| *Pyrostegia venusta* | 5 | 0 | 0 | 0 | 4 ± 2 |
| *Pandorea rosea* | 5 | 0 | 0 | 0 | 3 ± 1 |
| *Podranea ricasoliana* | 5 | 0 | 0 | 0 | 3 ± 1 |
| *Tecoma capensis* | 5 | 0 | 0 | 0 | 4 ± 2 |
| *Tecoma stans* | 5 | 0 | 0 | 0 | 7 ± 3 |
| *Jacaranda mimosifolia* | 5 | 0 | 0 | 0 | 4 ± 2 |
| *Acanthus mollis* | 5 | 0 | 0 | 0 | 2 ± 1 |
| *Duranta erecta* | 5 | 0 | 0 | 0 | 3 ± 1 |
| *Petrea volubillis* | 5 | 0 | 0 | 0 | 2 ± 1 |
| *Salvia chamelaeagna* | 5 | 0 | 0 | 0 | 3 ± 1 |
| *Salvia splendens* | 5 | 0 | 0 | 0 | 2 ± 1 |
| *Thunbergia alata* | 5 | 0 | 0 | 0 | 2 ± 1 |
| *Vebena peruviana* | 5 | 0 | 0 | 0 | 2 ± 1 |

These data provide strong evidence that *P. coerulea* is a *S. campanulata* specialist. The only known host in the native distribution is *S. campanulata* and no-choice testing has indicated that feeding and development is restricted to *S. campanulata* and one or two closely related species within a single clade of the Bignoniaceae. None of these close relatives are present in the Cook Islands and *P. coerulea* would therefore poses no threat to any indigenous or commercially important plant species should it be released.

## 2.4. ALTERNATIVE CONTROL OPTIONS

### 2.4.1. No control

The extensive damage that is caused by infestations of *S. campanulata* in Fiji and other Pacific Islands is an indication that the negative impacts in the Cook Islands are likely to increase if no control measures are imposed. *Spathodea campanulata* is a serious threat to indigenous biodiversity and agriculture in the Cook Islands and control measures should be implemented.

### 2.4.2. Mechanical and chemical control

An integrated control strategy, including mechanical, chemical and biological control, is likely to be required in order to control *S. campanulata*. A cut-stump application of glyphosate or 2,4 D + dicamba is effective at killing trees (Labrada & Medina 2009) and should be used whenever possible and appropriate. This treatment should be followed by manually pulling seedlings at regular intervals (Labrada & Medina 2009). The ability of the plant to coppice, the density and scale of some infestations, as well as the high quantity of seeds that are produced, makes mechanical and chemical control exorbitantly expensive and ineffective without the inclusion of biological control. Biological control will complement other control methods, increasing the efficacy of control and reducing costs.

### 2.4.3. Other biological control options

The gall-mite, *Colomerus spathodeae* (Eriophyidae), was shown to be host specific (Paterson et al. 2017) and was subsequently released in Rarotonga in 2017. The mite is now widely established across the island on *S. campanulata* trees. It is too soon to quantify the impact of the mite, but it is expected that the agent will reduce the spread and density of the weed by reducing seed set and stunting or killing seedling and saplings.

*Paradibolia coerulea* has a very different mode of damage to the galling mite. The mite deforms the growing tips and leaves of *S. campanulata* while the flea-beetle feeds internally on the leaves as larvae and then externally as adults. Based on observations in the native range, as well as in quarantine in South Africa, the flea-beetle will avoid feeding and oviposition on parts of the plant that are infected with the mites but will feed and develop normally on other parts of the same plant. The combined effect of the damage from both agents is likely to result in cumulative stress to the plant and will therefore provide a better level of control if the two agents are used in combination rather than either of the agents alone.

There are several other potential agents that have been identified in the native distribution of *S. campanulata* (Paterson *et al.* 2017). The mite that has already been released and *P. coerulea* are considered the two most promising of all the natural enemies based on their modes of damage and observations in the native range. Other agents, including seed attacking agents, could be considered in future, and there is no evidence to suggest that the release of *P. coerulea* could have any negative implications to the efficacy of these future agents should they be considered for release.

# 3. Environmental consequences

It is unlikely that the introduction of *P. coerulea* could be reversed. It is, therefore, important to determine the potential environmental consequences of its introduction.

- No action will result in continued invasion and a range of negative impacts such as costs to, native species, medicinal plants, aesthetic values and agricultural productivity.
- Chemical and mechanical control methods are both labour intensive and very costly. Acceptable levels of control are unlikely to be achieved without the inclusion of biological control.
- Biological control, if successful, will result in a reduction in growth and reproductive output (seeds and suckers).
- Permanent reductions in *S. campanulata* biomass could result in replacement by other invasive species (but note that the current MFAT-funded project has targeted other major weed species, many of which are now under control).
- Permanent reduction in *S. campanulata* biomass will result in better protection of indigenous biodiversity and agricultural land.

## 3.1. UNCERTAINTIES

### 3.1.1. Risk of non-target attack

Non-target impacts of weed biological control are very rare: The vast majority of agents introduced for classical biological control of weeds (>99% of 512 agents released) have had no known significant adverse effects on non-target plants thus far (Suckling and Sforza, 2014). Moreover, the few cases where significant non-target attack has occurred (e.g. *Rhinocyllus conicus* on native thistles; *Cactoblastic cactorum* on native cacti) were predictable from host-range testing and these introductions would not be permitted today (Suckling and Sforza, 2014). The only significant non-target effects that have been recorded from biological control agents are therefore non-target effects that were deemed acceptable at the time of release (Delfosse 2005). No significant and unpredicted non-target effects have ever been recorded from a biological control agent released to control an invasive alien plant.

No-choice tests are considered the most conservative tests in predicting the host-range of biological control agents (Withers & Mansfield 2005). The results produced by these tests are frequently false positives, defined as the use of a plant during the test which will not be utilised under realised, field conditions (Cullen 1990). Many biological control agents that have fed or developed on non-target plants during no-choice tests have been shown to be host specific in choice tests and have subsequently been released with no non-target feeding being recorded under field conditions. For *P. coerulea*, choice tests were not deemed necessary as previous work has indicated that female beetles select host-plants by responding to olfactory cues (Sutton et al., 2017b), which may confound any oviposition recorded during choice tests. *Paradibolia coerulea* is as specific as many biological control agents, many of which have had significant positive impacts in reducing alien plant densities and none of which have had any substantial non-target effects.

The risk of non-target attack from *P. coerulea* to any other species on the Cook Islands is therefore minimal, but the risks associated with not controlling the target weed are very high.

## 3.2. PROPOSED PROTOCOL FOR INTRODUCTION OF *PARADIBOLIA COERULEA*

*Paradibolia coerulea* collected from Ghana in May 2016 has been reared for multiple generations in the Rhodes University Biological Control Quarantine Facility, Grahamstown, South Africa.

1. *Paradibolia coerulea* has been identified by an expert taxonomist, so the identity of the insect has been confirmed.
2. The population of *P. coerulea* has been housed at Rhodes University since 2016 over multiple generations, so any parasitoids that may have been present have been reared out of the culture.
3. A small population of about 50 *P. coerulea* adults will be transported from quarantine in South Africa to quarantine in New Zealand, with a small amount of *S. campanulata* leaf tissue for food, in a sealed container.

4. In quarantine in New Zealand, all remaining leaf tissue will be destroyed and the *P. coerulea* population so that the beetles can be shipped free of vegetation.
5. *P. coerulea* will be in a sealed container without any *S. campanulata* tissue for transportation to Rarotonga.
6. The consignment will be transported to Rarotonga where it will be released directly into the field.

### 3.2.1. Procedure for field releases and monitoring

Field releases and monitoring will be done by Cook Islands Ministry of Agriculture staff, with assistance of Guy Sutton (who will accompany the first shipment of *P. coerulea*).

Monitoring will be done on a hierarchical basis. Initially, signs of establishment will be looked for by visually searching for adult feeding damage, adult beetles and larval mines within the leaves of plants growing near to the release sites. If establishment is confirmed, then regular searches will be conducted along transects from the release site to investigate the rate of spread and permanent quadrats will be set up to investigate the impact of *P. coerulea* on *S. campanulata* percentage cover, growth rates and biomass accumulation.

### 3.2.2. Summary of roles and responsibilities

*Paradibolia coerulea* will be reared at Rhodes University until a consignment is transported by a staff member of Rhodes University to Rarotonga. Rhodes University will ensure that:

(1) All relevant permits are obtained;
(2) That the consignment to be shipped to Rarotonga has been correctly identified and is free from contaminants.

Guy Sutton (Rhodes University) will accompany the first shipment and assist/train Cook Islands Ministry of Agriculture Staff in how to release and monitor the agent.

Landcare Research staff will assist/train Cook Islands Ministry of Agriculture Staff in how to set up monitoring plots to observe the spread and impacts of *P. coerulea*.

The Cook Islands Ministry of Agriculture, together with Landcare Research, shall ensure that the general public is made aware of the project, through media releases and public consultation.

The National Environment Service is responsible for ensuring that the EIA is followed as described within this document.

The Technical Advisory Group, which consists of representatives from Landcare Research; Cook Islands Ministry of Agriculture; Cook Islands Natural Heritage Project; and the Cook Islands National Environment Service will help coordinate biocontrol release and monitoring activities and deal with operational problems that may arise.

#### 3.2.3. Areas where releases will be made

Release sites on Rarotonga will be selected by the Cook Islands Ministry of Agriculture, in consultation with land owners and the Technical Advisory Group, if required. It is anticipated that releases will commence within two months after the Environmental Impact Assessment permit has been granted.

### 3.3. EDUCATION AND AWARENESS

It is recommended that some form of education and awareness programme be undertaken prior to and during the release of *P. coerulea*, awareness beyond just the EIA to inform the public of the Ministry's intent to introduce. Education is important to inform the public of the expected impacts on *S. campanulata* and the expected consequences. Although EIA are advertised in stores, libraries and online and notification of the availability of EIA for viewing is made in local papers, not everybody actually picks up and reads an EIA.

To this end, the weed biocontrol project against *P. rubra* and other major weeds in the Cook Islands has already been extensively publicised on Cook Islands Radio, Television and in the Cook Islands News. For example, the selection of target weeds, including *S. campanulata*, was publicised in the Cook Islands News (http://www.cookislandsnews.com/item/12777-weeds-list-highlights-biological-control/12777-weeds-list-highlights-biological-control).

### 3.4. ECONOMIC CONSIDERATIONS

No formal cost-benefit analysis has been done for the introduction of *P. coerulea* in the Cook Islands because economic data regarding the cost of *S. campanulata* control in the Cook Islands are lacking. In Fiji, on average, surveyed households in Fiji spent 3.7 hours/week (about 24 days/year) clearing the *S. campanulata* from their land (with annual control costs, in Fiji dollars amounting to approximately $2000/ha). To put this figure in perspective, the average household surveyed spends about 35 hours a week managing their crops, of which about 10% of that time is used specifically to control this invasive species (Daigneault et al., 2013). Moreover, some 36% of villages surveyed reported that some farmers had stopped growing crops altogether in severely impacted fields because they could not keep up with the African tulip tree's aggressive spreading (Daigneault et al., 2013). As noted in section 2.4.2, attempts to eradicate *S. campanulata* without the inclusion of biological control are likely fail to bring the plant under acceptable control and would be extremely expensive. Biological control will, at the very least, reduce the costs of controlling *S. campanulata*.

# 4. Conclusion

*Spathodea campanulata* is a serious threat to indigenous biodiversity and the agricultural sector of the Cook Islands. Without biological control it will not be possible to reduce densities of *S. campanulata* to acceptable levels. If successful, biological control will reduce the negative impacts of the weed, prevent the spread of the weed on Rarotonga where it is already present, and reduce the chances of the weed spreading to other islands.

The risks of introducing *P. coerulea* as a biological control agent are minimal and the potential benefits to native biodiversity and agriculture are substantial.

# 5. Acknowledgements

Esther Mostert, Ongezwa Mpekhula and Mzi Ncuba are thanked for technical assistance in quarantine. Prof Martin Hill is thanked for scientific advice and mentorship. Dr Stefan Neser is thanked for mentorship and knowledge of natural enemies of *S. campanulata* in Ghana. Dr Felix Akpaby is thanked for assistance in field work in Ghana and for acquiring permits. Dr Sarah Dodd is thanked for assistance conducting fieldwork in Ghana.

# 6. References

Barton, J., 2004. How good are we at predicting the field host-range of fungal pathogens used for classical biological control of weeds? Biological Control 31, 99-122.

Bidgood, S., 1994. Infraspecific variation in Spathodea campanulata (Bignoniaceae). Proceedings of the XIIIth Plenary Meeting AETFAT, Malawi. Seyani, J.H., Chikuni, A.C. (Eds) 1:327-331.

Briese, D.T., 1996. Phylogeny: can it help us to understand host-choice by biological control agents? In: Moran, V.C., Hoffmann, J.H., (Eds.), Proceedings of the 9th International Symposium on Biological Control of Weeds. University of Cape Town, South Africa, pp. 63-70.

Briese, D.T., Walker, A., 2002. A new perspective on the selection of test plants for evaluating the host-specificity of weed biological control agents: the case of Deuterocampta quadrijuga, a potential insect control agent of Heliotropium amplexicaule. Biological Control 25, 273-287.

Cullen, J.M., 1990. Current problems in host specificty screening. In: Delfosse ES (Ed.). Proceedings of the VII International Symposium on Biological Control of Weeds. 6-11 March 1998. Rome, Italy. Instituto Sperimentale per la Patologia Vegetale, MAF, Rome.

Daigneault, A., Brown, P., Greenhalgh, S., Boudjelas, S., Mather, J., Nagle, W., Aalbersberg, B., 2013. Valuing the Impact of Selected Invasive Species in the Polynesia-Micronesia Hotspot.

Delfosse, E.S. (2005) Risk and ethics in biological control. Biological Control 35, 319–329.

Francis, J.K., 1990. Spathodea campanulata Beauv. African tulip tree.Bignoniaceae. Bignonia family. SO-ITF-SM-32.

Futuyama, D.J., 2000. Potential evolution of host-range in herbivorous insects. In: Van Driesche, R.G., Heard, T., McClay, A.S., Reardon, R., (Eds.), Host-specificity testing of exotic arthropod biological control agents: the biological basis for improvement in safety. USDA Forest Service Bulletin, Morgantown, West Virginia, USA, pp. 42-53.

Heard, T. A. Van Klinken, R.D. 1998. An analysis of the design for host range tests of insects for biological control of weeds. Pest Management – Future Challenges, Sixth Australasian Applied Entomology Research Conference, Vol. 1: 539-546. Brisbane, Australia.

Hedberg, I., Kelbessa, E., Edwards, S., Demissew, S., Persson, E., 2006. Flora of Ethiopia and Eritrea Volume 5. Addis Ababa. Ethiopia.

Labrada, R., Medina, D.A., 2009. The invasiveness of the African Tulip Tree, Spathodea campanulata Beauv. Biodiversity 10, 79-82.

Larrue, S., Daehler, C., Vautier, F., Bufford, J.L., 2014. Forest invasion by the African Tulip Tree (Spathodea campanulata) in Hawaiian Islands: Are seedlings shade tolerant? Pacific Science 68, 1-27.

Lohmann, L.G., 2006. Untangling the phylogeny of neotropical lianas (Bignonieae, Bignoniaceae). American Journal of Botany 93, 304-318.

Louda, S.M., Pemberton, R.W., Johnson, M.T., Follett, P.A., 2003. Nontarget effects - the Achilles' heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Annual Review of Entomology 48, 365-396.

Lowe, S., Browne, M., Boudjelas, S., De Poorter, M., 2000. 100 of the World's Worst Invasive Alien Species: a selection from the Global Species Database. Invasive Species Specialist Group (ISSG) a specialist group of Species Survival Commission (SSC) of the World Conservation Union (IUCN). Aliens 12, 1-12.

McCormack, G., 2007. Cook Islands Biodiversity Database, Version 2007.2. Cook Islands Natural Heritage Trust, Rarotonga. Online at http://cookislands.bishopmuseum.org. Accessed 9 December, 2013.

Meyers, J.Y., 2004., Threats of invasive alien plants to native flora and forest vegetation of eastern Polynesia. Pacific Science 58, 357-375.

Olmstead, R. G., Zjhra, M. L., Lohmann, L. G., Grose, S. O., Eckert, A. J., 2009. A molecular phylogeny and classification of Bignoniaceae. American Journal of Botany 96, 1731-1743.

Paterson, I.D., Paynter, Q., Neser, S., Akpabey, F.J., Orapa, W. Compton, S.G. 2017. West African arthropods hold promise as biological control agents for an invasive tree in the Pacific Islands. African Entomology. 25:244-247.

Paynter, Q.E., Fowler, S.V., Gourlay, A.H., Haines, M.L., Harman, H.M., Hona, S.R., Peterson, P.G., Smith, L.A., Wilson-Davey, J.A., Winks, C.J., Withers, T.M., 2004. Safety in New Zealand weed biocontrol: A nationwide survey for impacts on non-target plants. New Zealand Plant Protection 57, 102-107.

Pemberton, R.W., 2000. Predictable risk to native plants in weed biological control. Oecologia 125, 489-494.

Stevens, P. F. (2001 onwards) Angiosperm Phylogeny Website. Version 12. http://www.mobot.org/MOBOT/research/APweb/. Accessed 16 September, 2013.

Suckling, D.M., Sforza, R.F.H., 2014. What magnitude are observed non-target impacts from weed biocontrol? PloS one 9, e84847.

Sutton, G.F., Paterson, I.D., Paynter, Q., 2017a. Genetic matching of invasive populations of the African tulip tree, Spathodea campanulata Beauv. (Bignoniaceae), to their native distribution: Maximising the likelihood of selecting host-compatible biological control agents. Biological Control 114: 167-175.

Sutton, G.F., Paterson, I.D., Compton, S.G., Paynter, Q., 2017b. Predicting the risk of non-target damage to a close relative of a target weed using sequential no-choice tests, paired-choice tests and olfactory discrimination experiments. Biocontrol Science and Technology 27: 364-377.

Wapshere, A.J., 1974. A strategy for evaluating the safety of organisms for biological weed control. Annals of Applied Biology 77, 201-211.

Winston, R.L., M. Schwarzländer, H.L. Hinz, M.D. Day, M.J.W. Cock and M.H. Julien, Eds. 2014. Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds, 5th edition. USDA Forest Service, Forest Health Technology Enterprise Team, Morgantown, West Virginia. FHTET-2014-04. 838 pp.

Withers, T.M., Mansfield, S., 2005. Choice or No-Choice Tests? Effects of experimental design on the expression of host-range. In: Hoodle M (Ed. ) Proceedings of the 2nd International Symposium of Biological Control of Arthropods. USDA Forest Service, Morgantown, West Virginia, USA.