Weed eradication on Raoul Island, Kermadec Islands, New Zealand: progress and prognosis

C.J. West[1] *and D. Havell*[2]

[1]*Department of Conservation, P.O. Box 10-420, Wellington 6143, New Zealand. <cwest@doc.govt.nz>.*
[2]*Department of Conservation, Private Bag 68908, Newton, Auckland 1145, New Zealand.*

Abstract During the 45 years that the Raoul Island weed eradication programme has been underway, eleven species have been eradicated. To complete the restoration of Raoul Island's unique ecosystems supporting significant seabird biodiversity and endemic biota, nine further transformer weeds must be eradicated. In this review of progress to date, we examine the feasibility of eradication of these transformers and identify that four species are on target for eradication: African olive (*Olea europaea* subsp. *cuspidata*), yellow guava (*Psidium guajava*), castor oil plant (*Ricinus communis*) and grape (*Vitis vinifera*). However, for four more species more staff resources are required to achieve eradication as currently infestations are establishing faster than they are being eliminated: purple guava (*Psidium cattleianum*), black passionfruit (*Passiflora edulis*), Brazilian buttercup (*Senna septemtrionalis*) and Mysore thorn (*Caesalpinia decapetala*). The ninth species, Madeira vine (*Anredera cordifolia*), is being contained but presents logistical difficulties for effective control – herbicide resistant tubers and cliff locations requiring rope access in unstable terrain. Increasing the resources for this programme now to enable eradication of these transformer weeds will reduce the total long-term cost of the programme. Eradication of rats, the 2006 eruption, recent greater cyclone frequency, increased tourism requiring biosecurity management, and staffing reductions have all impacted progress on weed eradication. Myrtle rust (*Austropuccinia psidii*), confirmed in March 2017 as the latest invasive species on Raoul Island, is establishing on Kermadec pohutukawa (*Metrosideros kermadecensis*), the dominant canopy species. The impact of this species on the weed eradication programme is unknown at this point.

Keywords: conservation, dispersal, eradication feasibility, invasive species, rats, seabirds, seedbank, transformer

INTRODUCTION

Raoul Island, the largest and northernmost of the main islands in the Kermadec Group (29° 15' S, 177° 55' W), was once home to vast seabird colonies. However, the impacts of whalers and settlers from 1800 AD through the introduction of goats (*Capra hircus*), pigs (*Sus scrofa*), cats (*Felis catus*), and Norway rats (*Rattus norvegicus*) extirpated most indigenous seabird species and a number of indigenous land birds (Veitch, et al., 2004). The goats had a major impact on the endemic vascular plants too (Parkes, 1984). Many vascular plant species were introduced for food and animal forage (Sykes et al., 2000). Twenty-five vascular plant species are endemic to Raoul Island (Sykes, et al., 2000), and most of these make up the forest that clothes the island, dominated by Kermadec pohutukawa (*Metrosideros kermadecensis*). The latest invasive species to arrive on Raoul Island is myrtle rust (*Austropuccinia psidii*). This species was first detected in March 2017 and noticed because of canopy die-off of a small area of mature Kermadec pohutukawa in Denham Bay. Myrtle rust has the potential to alter the dynamics of many native and introduced biota on the island by releasing plants from suppression by the pohutukawa canopy and reduced flowering and nectar production which will impact some land birds. Raoul Island is an active volcano, last erupting in 2006, and it is located in the path of seasonal cyclones (December to May).

Because of its unique ecosystems, Raoul Island was declared a Flora and Fauna Reserve (now Nature Reserve) in 1934. The New Zealand government has funded the eradication of all introduced feral mammals: goats were eradicated in 1984 (Sykes & West, 1996), and rats and cats were eradicated in 2002 and 2004, respectively (Broome, 2009). The eradication of goats greatly assisted recovery of endemic plant species, rescuing several from the brink of extinction. As a consequence of the rat and cat eradications indigenous seabirds and land birds are returning to Raoul Island (Veitch, et al., 2011), significantly beginning the recovery of this ecosystem. Several terrestrial birds now occupy extensive areas of Raoul and are likely to have significant impacts on ecosystem dynamics.

However, a small suite of transformer weed species (sensu Pyšek, et al., 2004) currently impedes full restoration of ecosystem functioning on Raoul Island. The vascular plant flora of Raoul Island currently comprises 118 indigenous species and 196 introduced species (of which c.10% are transformer species). A weed eradication programme has been underway since 1972 (West, 2011) and, to date, 11 species have been eradicated (Table 1), the majority of which were transformers (West & Thompson, 2013). New incursions or detection of exotic species are evaluated for impact and eradication potential as per DOC weed-led systems (Owen, 1998). Biosecurity to prevent new incursions is a priority and weed control to protect threatened plant species in non-forested, coastal ecosystems is important.

The eradication programme is now focussed on nine transformer species that have a major impact on forest ecosystems, four of which are vines (Table 2, and see West, 1996 for more background on these species). Given that seabirds are now beginning to return to Raoul Island to breed, it is particularly important to ensure that vines, which can entangle landing seabirds as well as smother native vegetation including forest, are eliminated.

Weed eradication programmes can take a long time, and many have failed (Panetta, 2015). The Raoul Island weed eradication programme has been formally reviewed twice since it began 45 years ago (West, 1996; West & Havell, 2013). Each time, the species being targeted have been evaluated to understand impacts of the species, and effectiveness of the eradication methodology. Both reviews have resulted in changes to the management programme and revised lists of species to focus on for eradication. The latest review restricted the focus to nine species where eradication will have the biggest impact on biodiversity. Changes to staffing were also recommended, so that there would be six months overlap of some experienced staff with new staff. This recommendation has been actioned for the contracted staff but the volunteer programme (six-month term) was discontinued in 2015 and replaced with

In: C.R. Veitch, M.N. Clout, A.R. Martin, J.C. Russell and C.J. West (eds.) (2019). Island invasives: scaling up to meet the challenge, pp. 435–442. Occasional Paper SSC no. 62. Gland, Switzerland: IUCN.

seconded staff (three-month term), effectively halving this additional effort for weed control.

In between the two formal reviews, the programme is constantly evaluated in relation to all management on the island. For example, grape (*Vitis vinifera*) was added to the list of target transformer species before rats were eradicated because the two rat species present were preventing fruit development on the grape vines (West and Havell, 2011). The year in which eradication commenced for each of the nine transformer species is shown in Table 3.

The option of eradication of transformer species is more appealing in the long-term than ongoing control to zero-density, as eradication means that financial investment in weed detection and control can cease once the species have been eliminated. To achieve this, sufficient resourcing is required to not only achieve the goal but also reduce total costs (Panetta, 2015). The feasibility of eradication of alien plants from Raoul Island was evaluated 30 years after the programme began (West, 2002). At that time, all necessary conditions (listed in West, 2002) appeared to be met, and application to the task was what was needed.

Preventing reinvasion is entirely achievable for all nine remaining target species, given the remoteness of Raoul Island and the strict biosecurity protocols that are in place. But how well are the species being extirpated and contained within Raoul Island as eradication proceeds? Panetta (2015) describes a model for categorising species in terms of the 'technical' feasibility of eradication by taking into consideration the relative feasibilities of extirpation and containment. He notes that eradication occurs via two processes: (i) extirpation (the elimination of the target in both space and time) and (ii) containment, which is the prevention of further occupancy of space (i.e. spread).

This approach is a useful one to apply to the nine target transformer species on Raoul Island as the work is done and reported on a plot basis, and it is an advancement on the methodology proposed by Holloran (2006) for reporting progress. There are currently 13 weeding blocks comprising 153 plots of varying size (0.1–83.2 ha), covering almost 834 ha which is 28.3% of the total area of Raoul Island (Fig. 1). Plot size varies based on terrain and travelling time; typically each plot can be carefully grid-searched in one day (see West, 2002 for more detail

Table 1 Species eradicated from Raoul Island. For each species, the year eradication began and the year in which the species was last recorded are given. Eradication was formally declared in 2013 by West and Thompson (2013).

Species	Common name	Eradication began	Last recorded
Cortaderia selloana	pampas grass	1984	1993
Ficus macrophylla	Moreton Bay fig	1996	1999
Foeniculum vulgare	fennel	1969	1999
Furcraea foetida	Mauritius hemp	1974	2002
Gomphocarpus fruticosus	swan plant	1979	2002
*Macadamia tetraphylla**	macadamia	1996	2003 (2015)
Phoenix dactylifera†	date	1995	1999
Phyllostachys aurea	bamboo	1996	2001
Populus nigra	poplar	1995	2003
Senecio jacobaea	ragwort	1980	1980
Vitex lucens	puriri	1997	1997

* One macadamia seedling was found in 2015 in the same location as the original small stand of trees.
† Wild dates have been eradicated but the species is still present at two historic sites as apparently non-reproductive individuals.

Table 2 Transformer weeds currently being eradicated on Raoul Island. The juvenile period, seed persistence and dispersal mechanism of each species is used to estimate the feasibility of eradication (Panetta 2015). Species are listed in order of feasibility of eradication: most to least.

Species	Common name	Growth form	Juvenile period	Seed persistence	Dispersal	Feas-ibility	Goal
Olea europaea subsp. *cuspidata*	African olive	Tree	5 years	2.4 years[1]	bird	3	eradicate
Psidium cattleianum	purple guava	Small tree	2–3 years	6–7 months[2]	bird	3	eradicate
P. guajava	yellow guava	Shrub	1–2 years	c. 1 year[3]	bird	4	eradicate
Passiflora edulis	black passionfruit	Vine	9 months	a few weeks[4]	bird	4	eradicate
Ricinus communis	castor oil plant	Small tree	5–6 months	>19 years[5]	explosive*	6	eradicate
Senna septemtrionalis	Brazilian buttercup	Shrub	c. 2 years	>16 years[6]	explosive*	5 or 7	eradicate
Caesalpinia decapetala	Mysore thorn	Vine	4–6 months	>12 years[7]	explosive*	6	eradicate
Anredera cordifolia	Madeira vine	Vine	< 1 year	15 years (tubers)[8]	gravity*	6 or 8	contain
Vitis vinifera	grape	Vine	1 year	5 years[9]	bird	8	eradicate

*Occasional long-distance dispersal by wind, bird, water or accidental-human vectors: for Brazilian buttercup and Madeira vine this occasional longer distance dispersal has resulted in considerable range extension, therefore, two feasibility estimates are given to cover both the normal and not uncommon dispersal events. [1]Cuneo, et al., 2010; [2]Uowolo & Denslow, 2008; [3]CABI, 2017b; [4]CABI, 2017a; [5]Kammili & Jatothu, 2015; [6]Ewart, 1908; [7]no published data: this estimate is from an isolated infestation of known age on Raoul Island; [8]Harden, et al., 2004; [9]no published data found for *Vitis vinifera*: this estimate is for *Vitis aestivalis* (Haywood, 1994).

of the plot-based searching methodology). Using Panetta's model (Panetta, 2015), each plot can be evaluated to see if the species has been extirpated from it, and the distribution of a species among the plots can be evaluated to see if the species is being contained or is expanding its range. Then, the relative relationship between extirpation and containment can be evaluated for each target species to determine if eradication can be achieved (Panetta, 2015).

METHODS

On-island weed searching

Details of weed searching and removal are given in West (2002) and Holloran (2006) and here we restate briefly what the annual plan and actions are: that weeding plots should be grid-searched on the ground a minimum of once each year with plots containing the target transformer species to be searched twice. Within plots, known infestations are marked (including GPS coordinates) and specifically searched during grid-searching or between grid-searches. Finds of immature plants outside of infestations are recorded as random finds. New infestations are created when mature, fruiting plants or localised seed banks are found and, if a new infestation is large, a new plot may be created. If no target species have been found at an infestation for the period of the suspected viability of the propagule bank based upon database records, or the site has been destroyed by a landslide or volcanic eruption, the infestation is retired. GPS tracks of grid-searching are downloaded to Arc-GIS and used to identify any gaps in search coverage and to document search effort.

Feasibility of eradication

Data on the factors used by Panetta (2015) to determine feasibility of eradication were compiled from published information and, where necessary or more appropriate, from our observations on Raoul Island. The two key biological factors relevant to extirpation are the length of the juvenile period (i.e. how quickly can plants produce more viable propagules?) and seed persistence (i.e. how long can seed remain viable?). The biological factor that is most relevant to containment is dispersal modes (i.e. is spread likely to be short- or long-distance; predictable – e.g. water or wind – or unpredictable?). Evaluating the data for these three factors enables identification of eradication feasibility on a scale from most feasible (a score of 1) to least feasible (a score of 8 – see Panetta, 2015, p. 232).

Evaluation of progress towards eradication

All data on the number of individuals removed per plot for the nine target weed species from 1 January 1998 to 31 December 2016 were extracted from the Raoul Island weed database. Recording of the number of individuals in three stage classes – seedlings, adolescents (taller than 30 cm but not yet flowering) and mature (flowering and/or fruiting) – began in October 1997, so the database now holds more than 20 years of continuous data.

The number of times each plot was searched per year, from 1998 to 2016 was extracted from the database. Also, the number of active, retired and random infestations in each plot was summarised for the same period. This information was used to interpret the data on number of individuals per target species per plot and per year.

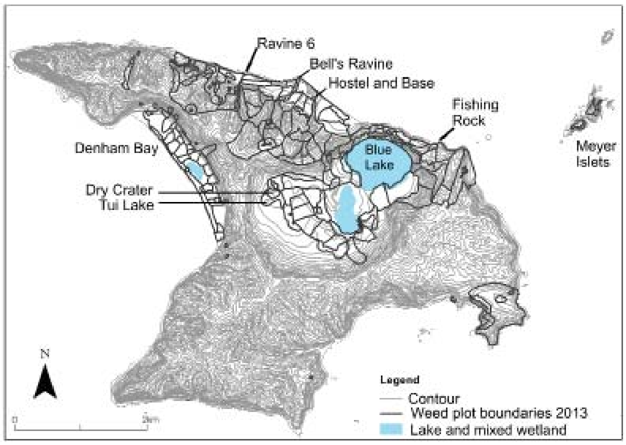

Fig. 1 Raoul Island showing places mentioned and the distribution of weed plots.

RESULTS

On-island weed searching

From 1998 to 2011 the mean number of grid searches per plot exceeded one a year and exceeded two in 2003 (Fig. 2). However, since 2012 the number of plots grid-searched has dropped well below a single search each year culminating in less than one third of plots being grid-searched in 2016.

Feasibility of eradication

The data for the nine transformer species targeted for eradication show a wide range of feasibility (Table 2), from feasible, e.g. African olive (*Olea europaea* subsp. *cuspidata*) and purple guava (*Psidium cattleianum*) to much less feasible e.g. Madeira vine (*Anredera cordifolia*) and grape. Species with long juvenile phase (> 2 years), short seed persistence (< 3 years) and short distance or largely human-mediated propagule dispersal score lower, and are therefore more feasible to eradicate. Conversely,

Table 3 Percentage of plots occupied by each species in 1997–2000 (from West 2002) and 1998–2016 as well as the year in which eradication began.

Species	Common name	Eradication began	% plot occupancy	
			1997–2000	1998–2016
Olea europaea subsp. *cuspidata*	African olive	1973	19.6	13.6
Psidium cattleianum	purple guava	1973	22.4	25.0
P. guajava	yellow guava	1972	11.9	8.6
Passiflora edulis	black passionfruit	1980	32.9	36.4
Ricinus communis	castor oil plant	1990	7.7	6.4
Senna septemtrionalis	Brazilian buttercup	1978	72.0	72.1
Caesalpinia decapetala	Mysore thorn	1974	18.2	20
Anredera cordifolia	Madeira vine	1995	2.1	2.1
Vitis vinifera	grape	1998	8.4	8.6

species with short juvenile phase (< 2 years), long seed persistence (> 3 years) and long distance dispersal score higher. The short juvenile phase means searching has to be more frequent; the long seed persistence means the duration of the programme is longer and is extended every time new seed is added to the soil if a fruiting individual is not found in time; the long-distance dispersal means that a greater area must be searched.

Evaluation of progress towards eradication

All transformer species

The number of active and retired infestations for each species gives a good indication of progress towards achieving eradication (Fig. 3). Five species – African olive, yellow guava (*Psidium guajava*), castor oil plant (*Ricinus communis*), purple guava and black passionfruit (*Passiflora edulis*) – have considerably more retired than active plots. Brazilian buttercup (*Senna septemtrionalis*) and Mysore thorn (*Caesalpinia decapetala*) – the two species with the greatest seed longevity – have proportionally more active plots. Control of grape began later than the other species (Table 3), hence the high proportion of active plots compared to retired. Madeira vine is the only species with more active than retired plots.

The random infestations give an indication of dispersal beyond the immediate vicinity of mature plants (Fig. 3) and the effectiveness of the programme to control weed reproduction. Black passionfruit and purple guava, both bird-dispersed, have a relatively high proportion of random finds. Mysore thorn has the highest proportion of random finds reflecting not its dispersal ability but its highly cryptic nature when growing among the tall ground ferns which grow densely in parts of Denham Bay, and its extensive original distribution.

African olive

Numbers of this species detected and removed since 1998 are very low (Fig. 4). The last mature individual was removed in 2008, and two adolescent plants from different locations in 2010 and 2011. All of these finds were from within the historic range of this species before eradication commenced and the percentage of active plots for this species has decreased (Table 3).

Purple guava

Numbers of this species were low (West 2002) but began to increase in 2008, increasing an order of magnitude in 2011, and with very high numbers recorded in 2016 (Fig. 4) from just a few infestation plots mostly within the crater around the shores of Blue Lake and Tui Lake. Most of the purple guava detected in 2015 were from new detections in the dry crater near Tui Lake, adjacent to old infestations where purple guava was last detected in 2002. More than half the numbers detected in 2016 were from this infestation. Purple guava infestations are still being found within the known historical range of the species, but the percentage of plots occupied has increased slightly (Table 3). Infestations of purple guava and buffers of up to 100 metres have been intensively searched since 2015, and, subject to resourcing, additional areas within the crater are likely to be checked. Seedlings of this species are very cryptic (look very similar to two of the endemic species) so careful searching is required.

Yellow guava

There is an increased number of yellow guava "seedling" detections since 2011 but overall the numbers are quite low (Fig. 4). The last mature individual detected was in 2008 with no further detections at that site. The seedlings recorded are generally suckers from roots: those recorded in 2011 were suckers from just two plants. A yellow guava shoot was discovered in 2015 in a crack in a concrete path close to the Hostel. This may have originated from root suckers from a relic guava root system in adjacent gardens, as ongoing persistence and lack of other finds indicates. However, it is also possible that an undetected mature plant may be present within the range of local birds. Yellow guava is active in fewer plots within its historical range (Table 3).

Black passionfruit

The number of black passionfruit being detected and removed began to increase markedly from 2004 (Fig. 4), with the biggest number found so far, in 2011, coming primarily from one infestation where eight mature vines had been removed the year before. This site is still very active. To date, despite the increase in numbers detected, black passionfruit has not materially exceeded its historic range. Although it now occupies more plots than previously (Table 3), these are plots within the bounding polygon that describes the historic range of this species.

Castor oil plant

Numbers of this species are low (Fig. 4), with the last mature plants removed in 2003 all from one site. With the exception of three adolescent plants in 2011 and 2012, all other seedlings and adolescents removed since 2004 have come from this site. Castor oil plant has not expanded beyond its historic range and has fewer active plots than previously (Table 3).

Brazilian buttercup

This species has been the most numerous since the eradication programme began. Numbers were declining

Fig. 2 Mean number of grid searches per plot from 1998–2016.

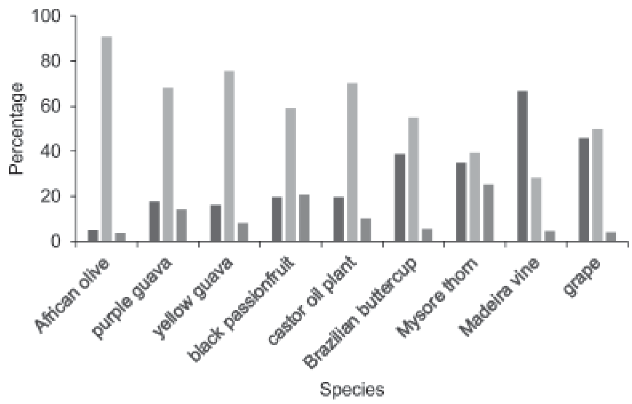

Fig. 3 Percentage of active (black bars), retired (mid grey bars) and random (dark grey bars) infestations within the weeding plots for each transformer species from 1998–2016.

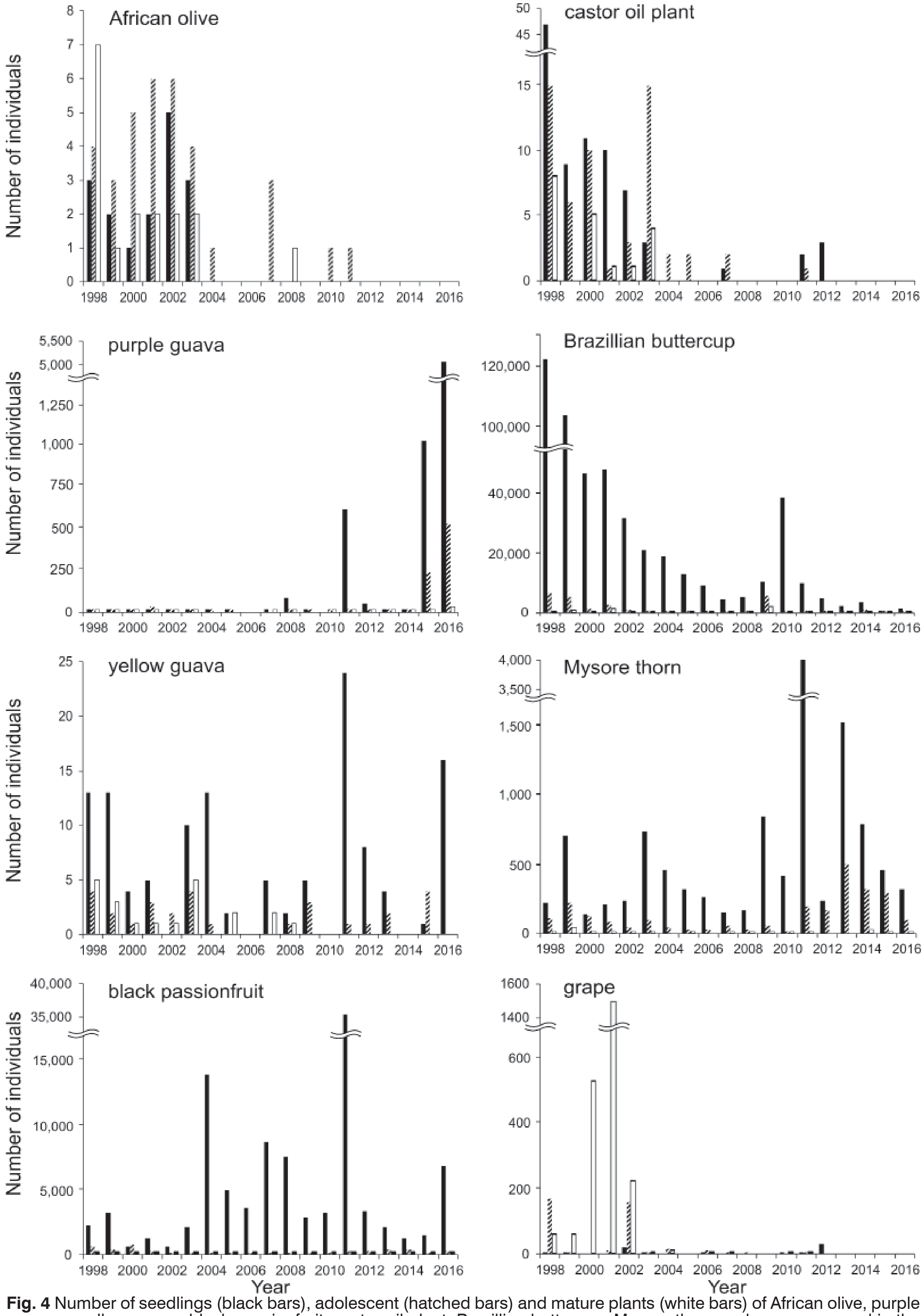

Fig. 4 Number of seedlings (black bars), adolescent (hatched bars) and mature plants (white bars) of African olive, purple guava, yellow guava, black passionfruit, castor oil plant, Brazillian buttercup, Mysore thorn and grape removed in the period 1998–2016 from Raoul Island. For Brazilian buttercup the data for the same period are for removal from Raoul Island and the Meyer Islets: this is the only one of the target species found on these islets that are c. 1 km NE of Raoul Island.

effectively until 2008 when they began to increase, reaching a new peak in 2010 – primarily seedlings (Fig. 4). In 2009, the significant increase in mature and adolescent plants is due to the discovery of three outlier populations that extended the range of this species beyond its historic range. Two of these sites – the westernmost weed plot (see Fig. 1) and a plot on the cliffs at the southern end of Denham Bay were found during helicopter surveillance. The other site, below bluffs at the northern end of Denham Bay was found during a routine search of a nearby plot at the back of the bay. Brazilian buttercup is also on North and South Meyer Islets and is the only one of the target species found off Raoul Island. This species occupies a marginally greater percentage of plots than previously (Table 3): the new plots described above have been virtually cancelled out by the retirement of some plots due to slips and the 2006 eruption.

Mysore thorn

Mysore thorn numbers have fluctuated through time but reached a new peak in 2011 as a result of the high number of mature vines found in 2010 (Fig. 4): the highest number of mature plants recorded since 2001 (Fig. 5). Mysore thorn is confined to Denham Bay now that an infestation at the head of Ravine 6 has been eradicated. Within Denham Bay, however, this species' range has increased slightly, with helicopter surveillance in 2002 and 2009 leading to the detection of two sites on the cliffs above the bay, including the southernmost site known (see Fig. 1). However, it is not these newly discovered infestations that are contributing the higher numbers of all size classes since 2010, it is a number of the historic plots on the flat and towards the cliffs north of Denham Bay swamp. Mysore thorn occupies a slightly higher percentage of plots than previously (Table 3).

Madeira vine

The weight of tubers removed in 1998 was not recorded but a file note halfway through that year mentions 60 sacks of tubers had been removed. The amount of tubers removed is overall less in the past decade than in the previous one (Fig. 6) as the more accessible plots are controlled. Various methods for killing the tubers have been trialled and used, including composting (in black bins using an accelerant), burning, desiccation followed by burning of the desiccated tubers, and freezing (the current method). Madeira vine has not expanded beyond its historic range of two locations and has the same percentage plot occupancy as previously (Table 3). Madeira vine has almost been eradicated from Bell's Ravine with only small finds in 2015.

Grape

Grape vines are now in very low numbers, with no new sites since 2012 (Fig. 4). Most of the infestation sites are in Denham Bay and three are in old settlement areas on the north side of Raoul Island, reflecting past human occupancy. The percentage plot occupancy for grape has increased very slightly (Table 3), reflecting a single mature vine found in 2011 during grid-searching in Denham Bay.

DISCUSSION

Panetta's model (Panetta, 2015) is a very useful framework to evaluate eradication feasibility but when using it, we have been very conscious of the lack of accurate data on seed longevity in the soil in Raoul Island's environmental conditions. We have observed that some of the transformer species being targeted on Raoul Island have seedling banks, e.g. African olive and black passionfruit, and others have the ability to resprout from underground roots, e.g. yellow guava and grape. It could be useful for these mechanisms to be added to the model, perhaps as propagule persistence (replacing seed persistence) given that resprouts can appear more than three years after any other stem material has been present above-ground, and seedlings can remain in a seedling bank for more than three years until a light gap is created allowing the seedlings to rapidly grow to into mature plants.

The graphs of species abundance through time (Figs 4 & 5) combined with life history data indicating feasibility of eradication (Table 2) as well as plot occupancy (Table 3) and the number of active, retired and random infestations (Fig. 3) indicate that eradication is very achievable for four species: African olive, yellow guava, castor oil plant and grape. Note that species differ in their life history traits so therefore have different eradication feasibility scores (Table 2). Grape has the highest score (least feasible) but is eradicable because the biomass of all grapes was reduced to essentially zero before the rats were eradicated (West & Havell, 2011). Dispersal of this species has not been possible because all resprouts are found and destroyed before fruits are formed.

With no detections of African olive since 2011 and estimated seed persistence of 2.4 years, it is theoretically possible to declare this species eradicated now. However, given the cryptic nature of this species and seedling persistence, our preference is to wait until at least 2021 before making this claim (if there are no further detections). Yellow guava persists as occasional suckers in just three accessible locations, presumably from relict root systems, so should be eradicable with annual checks of the locations although the timeframe is difficult to estimate. Castor

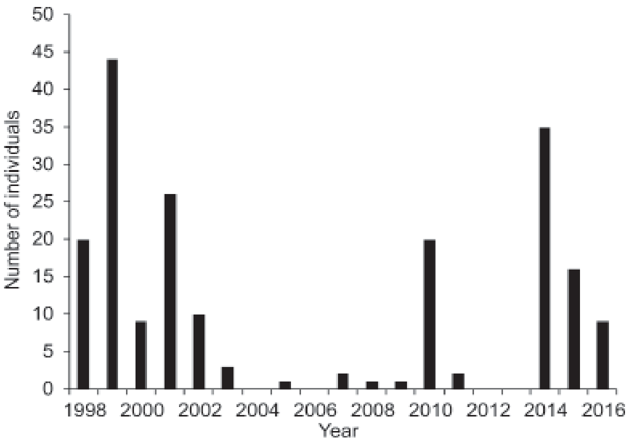

Fig. 5 Number of mature plants of Mysore thorn removed in the period 1998–2016 from Denham Bay, Raoul Island.

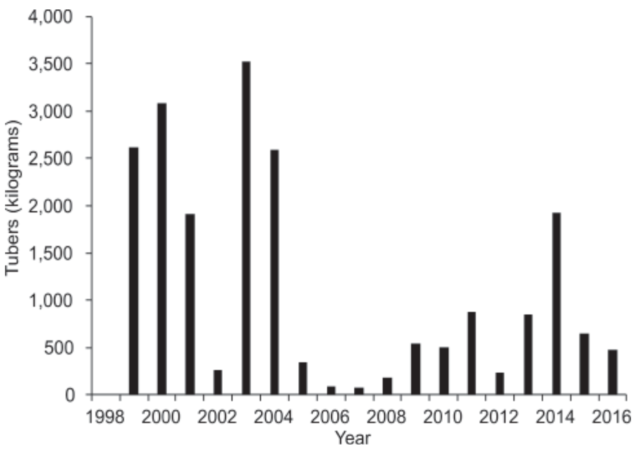

Fig. 6 Quantity (kg) of Madeira vine tubers (aerial and ground) removed in the period 1998–2016 from Raoul Island.

oil plant has seed longevity of >19 years so with the last detection of this species in 2012, and assuming no further detections, it could be deemed to have been eradicated by 2040. All grapes detected on Raoul Island so far have been resprouts from persistent root systems. Given the low feasibility of eradicating this species if it were reproducing by seed (Table 2) it is vital that fruit are never produced. All plots containing grape must be searched a minimum of once a year, ideally twice, given the short juvenile period possible for resprouts.

The feasibility of eradication for purple guava and black passionfruit is relatively high (Table 2), however, both species have been recorded in highest numbers in recent years (Fig. 4) and have a relatively high proportion of random finds (for black passionfruit there have been more random finds than there are active plots). The trend for both species indicates that the current search effort (Fig. 2) of less than one plot search per year, and the current area searched, is not sufficient to prevent seed dispersal. Black passionfruit is known to produce fruit within one year on Raoul Island, and the development of mature plants and purple guava seedlings may have occurred in the dry crater in the three years between 2012 and 2015. At the moment, both species have still been found within their historic range but, since they are bird dispersed, it is quite possible that these two species could be spreading to areas outside the current extent of searched plots (Fig. 1). All of these results indicate that grid searching for both purple guava and black passionfruit must continue until suppression of reproduction in these species is clearly demonstrated. Searching needs to be undertaken within the known range of these species and be extended into surrounding areas to detect any new infestations from bird-dispersed seeds. Uowolo and Denslow (2008) suggest the most effective time for purple guava control is at least three months after the fruiting season when the majority of seeds have germinated or died, given the short seed persistence. Another risk is the potential of large purple guava plants to sucker and reproduce rapidly after long periods of quiescence. A weed detection dog is being trained to focus on black passionfruit, both guava species and grape but is not yet ready for deployment.

Brazilian buttercup is the most widespread of the target species (Table 3). Range extensions of this species, discovered in 2009, plus its occurrence on the Meyer Islets indicates this species has rare long-distance dispersal, possibly by birds (although human dispersal can't be ruled out). In order for this species to be eradicated, detection methods need strong focus (Holloran, 2006). Any opportunities for helicopter surveillance should be taken, particularly when these coincide with the flowering period.

Although Mysore thorn is confined to Denham Bay, too many individuals are being missed in plot searches allowing considerable seed set e.g. the very high numbers of seedlings recorded in 2011 (Fig. 4). Seed germination in 2011 could also have been aided by two cyclones that affected Raoul Island in February (Atu) and March (Bune), with the latter resulting in widespread treefalls and stripping of foliage from trees. Given the rapid growth rate of Mysore thorn (Table 2) and the high proportion of random finds, the plots in Denham Bay need to be searched a minimum of twice each year and possibly with a closer spacing between observers than in the past (we suggest a minimum of 2 m). The short juvenile period plus the long seed persistence time make this species less feasible for eradication. However, because long-distance dispersal is very rare, this species is eradicable if seed banks and fruiting can be eliminated (as demonstrated by the eradication in Ravine 6). Of all the transformer species, Mysore thorn poses the greatest threat to ecosystem recovery, as shown by historic photographs and reports of Mysore thorn smothering the Kermadec pohutukawa canopy in Denham Bay (West, 1996). Landing seabirds can get entangled in vegetation: vines provide greater opportunities for entanglement and thorny vines (like Mysore thorn) less opportunity for safe escape (Arcilla, et al., 2015).

Madeira vine is the most difficult species to control on Raoul Island (West, 2002). It was last detected in its original location in Bell's Ravine in 2015 but because it can grow from tiny aerial tubers and subterranean tubers, it may still occasionally resprout in that location. However, at the main location east of Fishing Rock, this species grows on steep, unstable cliffs so tubers can be removed only from the most accessible sites and places that can be reached by abseiling safely. Herbicide is still used to knock back foliage when necessary to gain access to the herbicide-resistant tubers so they can be removed. Until a control method is developed that can kill tubers on the inaccessible cliffs, this species can only be contained rather than eradicated. Management so far has successfully contained Madeira vine.

It has been stated frequently in the literature that eradications are unlikely to succeed if the area occupied is large (Panetta, 2015). Howell (2012) identified that the only successful eradications of environmental weeds in New Zealand were those where the initial extent was < 1 ha, noting that there were other eradications of similar extent that were unsuccessful. On Raoul Island, four species currently have distributions of < 1 ha: African olive, yellow guava, castor oil plant and grape although the area to be grid-searched in the plots within which they occur ranges from 6 ha (castor oil plant) to 80 ha (grape). The area to be searched for the more abundant species – purple guava, black passionfruit, Brazilian buttercup and Mysore thorn ranges from 60 ha (Mysore thorn) to 550 ha (Brazilian buttercup).

However, Panetta's (2015) model of extirpation and containment indicates that African olive, yellow guava, castor oil plant and grape are all currently being extirpated (the rate of extirpation of managed infestations exceeds the rate of establishment of new ones) and contained, and could be eradicated with the current level of resourcing. As indicated above, breakthroughs in methodology are needed for extirpation of Madeira vine to become a reality. For the other four species, there have been more new infestations leading to greater numbers and, for Brazilian buttercup, range extension in recent years. The current level of resourcing is not sufficient to enable eradication as, based upon GPS track logs, not all known and potential areas are able to be searched within the time it takes for each species to fruit. There is also insufficient resourcing to analyse records of infestation within the Raoul Island weed database, and therefore plan the work more effectively.

There are many factors that have led to this situation. Rats (*Rattus norvegicus* and *R. exulans*) are no longer eating flowers, seeds and seedlings of plants. This effect can be seen in the results for several species, e.g. Mysore thorn, black passionfruit and yellow guava. No access to the crater was permitted for two years after the eruption in 2006 resulting in mature plants of purple guava and Brazilian buttercup, with dispersal of the former and seed added to the seed bank for the latter. Cyclones have been frequent in the past decade, resulting in large areas of windfallen trees within weed control sites that stimulates germination (good for reducing the seed bank) but also impedes access and slows down the rate of grid-searching, making weed removal harder. A formal process for retiring plots is not in place and this may have resulted in a lack of focus on areas that need more regular checking.

Health and safety requirements and biosecurity management are the factors that have most influenced the drop in the mean number of plots grid-searched (Fig. 2). Staff effort has been directed towards biosecurity management as the number of visitors to the island (including organised tour groups) has increased over the years. Health and safety requirements have increased considerably since 2006: permission must be sought to enter the crater to search the plots (the granting authority is the Operations Manager based on advice from the Institute of Geological and Nuclear Sciences which monitors seismic activity on the island); weed plots that must not be searched after heavy rain or during seismically active periods and those that require climbing gear have been identified. Staff numbers have been reduced since 2015 when deployment of volunteers for six-month periods was replaced by seconded staff for three-month periods.

These factors, combined with the lack of assistance from rats, reduced staff resourcing, plus the increased number of cyclones, has led to the increase in weed abundance, particularly for purple guava, black passionfruit, Brazilian buttercup and Mysore thorn. Health and safety standards should never be compromised but need to be compensated for by increased resourcing for the eradication of transformer weeds to be successful. The current budget for the programme is $555,000, reduced from $566,000 in the previous year. This needs to be increased to $850,000 to provide sufficient staff time to check all plots once a year plus an additional check of all plots with known Mysore thorn, grape and black passionfruit infestations (two checks a year, minimum). Madeira vine plots should be checked at the current rate of one day per week. As Panetta (2015) states "Despite the best of intentions and the highest level of professionalism, an eradication effort will not succeed if it is not adequately resourced". Increasing the budget is a wise move given that Cacho, et al., (2007) showed that total cost of weed eradication is high when low search effort was involved, but falls rapidly with increasing search effort because a more intense search effort would reduce the number of reproductive plants. This is currently the sticking point for four of the nine transformer species in the Raoul Island weed eradication programme. Whereas the bulk of the budget should be spent on Raoul Island (staff, infrastructure, materials), the off-island support resourcing is also vital and must be set at the optimal level. Remote island-based programmes require huge logistical support from dedicated teams both on and off the island.

The preceding discussion describes a number of factors that need to be considered when budgeting for success in this programme and the results described are all influenced by these. However, myrtle rust, whose impact is yet to be felt by Raoul Island ecosystems, is the latest agent of change that will need to be considered. Monitoring plots have been established to provide early indications of how this disease will affect Kermadec pohutukawa and what the flow-on effects will be. It is possible that the dynamics of the transformer weeds in this eradication programme will change, just as they have following eradication of rats and cyclones.

ACKNOWLEDGEMENTS

Thanks to staff on Raoul Island, and those on the mainland associated with the weed eradication programme for providing information for this paper. Thanks to Geoff Woodhouse, Paul Rennie and Clayson Howell for their comments on an earlier draft of this paper. A special thanks to the staff who undertake the arduous task of weed eradication on the island. Thanks, also, to the anonymous reviewers who improved this paper and to Dick Veitch for improving the figures.

REFERENCES

Arcilla, N., Chang-Yong, C., Kiyoaki, O. and Lepczyk C.A. (2015). 'Invasive species and Pacific island bird conservation: a selective review of recent research featuring case studies of Swinhoe's storm petrel and the Okinawa and Guam rail'. *Journal of Ornithology* 156 (Suppl. 1): S199–207.

Broome, K.G. (2009). 'Beyond Kapiti – a decade of invasive rodent eradications from New Zealand islands'. *Biodiversity* 10: 7–17.

Cacho, O.J., Hester, S.M. and Spring, D. (2007). 'Applying search theory to determine the feasibility of eradicating an invasive population in natural environments'. *Australian Journal of Agricultural and Resource Economics* 51: 425– 433.

Cuneo, P., Offord, C.A. and Leishman, M.R. (2010). 'Seed ecology of the invasive woody plant African olive (*Olea europaea* subsp. *cuspidata*): implications for management and restoration'. *Australian Journal of Botany* 52: 342–348.

Ewart, E.J. (1908). 'Vitality of seeds'. *Proceedings of the Royal Society of Victoria* 2: 1–203.

Harden, G.J., Fox, M.D. and Fox, B.J. (2004). 'Monitoring and assessment of restoration of a rainforest remnant at Wingham Brush, NSW'. *Austral Ecology* 29: 489–507.

Haywood, J.D. (1994). 'Seed viability of selected tree, shrub, and vine species stored in the field'. *New Forests* 8: 143–154.

Holloran, P. (2006) 'Measuring performance of invasive plant eradication efforts in New Zealand'. *New Zealand Plant Protection* 59: 1–7.

Howell, C.J. (2012). 'Progress toward environmental weed eradication in New Zealand'. *Invasive Plant Science and Management* 5: 249–258.

CABI, (2017a). *Passiflora edulis* (passionfruit). In: Invasive Species Compendium. Wallingford, UK: CAB International. <www.cabi.org/isc>.

CABI, (2017b). *Psidium guajava* (guava). In: Invasive Species Compendium. Wallingford, UK: CAB International. <www.cabi.org/isc>.

Kammili, A. and Jatothu, J. (2015). 'Differential longevity of castor (*Ricinus communis* L.) germplasm conserved under uncontrolled storage conditions across extended periods'. *Journal of Crop Improvement* 29: 706–719.

Owen, S-J. (1998) *Department of Conservation Strategic Plan for Managing Invasive Weeds*. Department of Conservation, Wellington.

Panetta, F.D. (2015). 'Weed eradication feasibility: lessons of the 21st century'. *European Weed Research Society* 55: 226–238.

Parkes, J.P. (1984). 'Feral goats on Raoul Island II: Diet and notes on the flora'. *New Zealand Journal of Ecology* 7: 95–101.

Pyšek, P., Richardson, D.M., Rejmánek, M., Webster, G.L., Williamson, M. and Kirschner, J. (2004). 'Alien plants in checklists and floras: towards better communication between taxonomists and ecologists'. *Taxon* 53: 131–143.

Sykes, W.R. and West, C.J. (1996). 'New records and other information on the vascular flora of the Kermadec Islands'. *New Zealand Journal of Botany* 34: 447–462.

Sykes, W.R., West, C.J., Beever, J.E. and Fife, A.J. (2000). *Kermadec Islands Flora - Special Edition: A Compilation of Modern Material about the Flora of the Kermadec Islands*. Lincoln, Canterbury, N.Z.: Manaaki Whenua Press.

Uowolo, A.L. and Denslow, J.S. (2008). 'Characteristics of the *Psidium cattleianum* (Myrtaceae) seed bank in Hawaiian lowland wet forests'. *Pacific Science* 62: 129–135.

Veitch, C.R., Gaskin, C., Baird, K. and Ismar, S.M.H. (2011). 'Changes in bird numbers on Raoul Island, Kermadec Islands, New Zealand, following the eradication of goats, rats and cats'. In: C.R. Veitch, M.N. Clout and D.R. Towns (eds.) *Island invasives: eradication and management,* pp. 372–376. Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

Veitch, C.R., Miskelly, C.M., Harper, G.A., Taylor, G.A. and Tennyson, A.J.D. (2004). 'Birds of the Kermadec Islands, south-west Pacific'. *Notornis* 51: 61–90.

West, C.J. (1996). Assessment of the weed control programme on Raoul Island, Kermadec Group. *Science & Research Series no 98*. Department of Conservation, Wellington.

West, C.J. (2002). 'Eradication of alien plants on Raoul Island, Kermadec Islands, New Zealand'. In: C.R. Veitch and M.N. Clout (eds.) *Turning the tide: the eradication of invasive species,* pp. 365–373. Occasional Paper SSC no. 28. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK.

West, C.J. (2011). 'Consideration of rat impacts on weeds prior to rat and cat eradication on Raoul Island, Kermadecs'. In: C.R. Veitch, M.N. Clout and D.R. Towns (eds.) *Island invasives: eradication and management,* pp. 244–247. Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

West, C.J. and Havell, D. (2011). 'Plant responses following eradication of goats and rats from Raoul Island, Kermadecs'. In: C.R. Veitch, M.N. Clout and D.R. Towns (eds.) *Island invasives: eradication and management,* p. 535. Occassional Paper SSC no. 42. Gland, Switzerland: IUCN and Auckland, New Zealand: CBB.

West, C.J. and Havell, D. (2013). *Raoul Island Review – Phase 2 Part 1: Review of Biodiversity programme.* Unpublished internal report, DOCDM-1157983. Department of Conservation.

West, C.J. and Thompson, A.M. (2013). 'Small, dynamic and recently settled: responding to the impacts of plant invasions in the New Zealand (Aotearoa) archipelago'. In: L.C. Foxcroft, P. Pyšek, D.M. Richardson and P. Genovesi (eds.) *Plant Invasions in Protected Areas: Patterns, Problems and Challenges*, 7: 285–311. Invading Nature – Springer Series in Invasion Ecology.