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Management in Practice

Knowledge to action on aquatic invasive species: Island biosecurity – the New Zealand and South Pacific story

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This study was contributed in relation to the 20th International Conference on Aquatic Invasive Species held in Fort Lauderdale, Florida, USA, October 22–26, 2017 (http://www.icais.org/html/previous20.html). This conference has provided a venue for the exchange of information on various aspects of aquatic invasive species since its inception in 1990. The conference continues to provide an opportunity for dialog between academia, industry and environmental regulators.

Abstract

New Zealand and Australia are regarded as world leaders in the field of biosecurity, the management of invasive animals and plants including aquatic species. This paper presents an overview of the history and current governance of aquatic invasive species management in New Zealand. Its main focus is the input of biosecurity science, focussing primarily on the proactive management of invasive freshwater plants, and application in Australasia and other Pacific nations. Examples of proactive management actions include; identification of invasive species off-shore to prevent importation, management at the border, mitigation of introduction/dispersal pathways, surveillance for new incursions, incursion response and national eradication programs. Many of these actions are informed and supported by the development and application of risk assessment tools. The success of these initiatives within New Zealand is aided by geographical isolation and a relatively small population size, recognition of the need to protect an economy based on primary production from invasive species, strong effective legislation and biosecurity science directly linked to policy and management.

Key words: alien aquatic invasive species, proactive management, risk assessment of invasive species and dispersal pathways, surveillance, incursion response, eradication

Introduction

The continents of Zealandia (Mortimer et al. 2014) and Australia and a myriad of small Pacific islands are situated on the "empty" side of the globe, each separated from each other and from the highly populated centres and important trading nations of Europe, Asia and the Americas by expanses of open ocean – a major barrier to the introduction of fresh-water and, to a lesser extent, coastal marine species. New Zealand and Australia are regarded as world leaders in the field of biosecurity (Meyerson and Reaser 2002; Simberloff 2014) including freshwater and marine species. This success is founded on biosecurity science (Goldson 2010) and its uptake and utilisation in policy and management, which align with the theme of the 20th International Conference on Aquatic Invasive Species: Knowledge to Action on Aquatic Invasive Species.

This paper reviews the history of aquatic invasive species management in New Zealand, describes current governance and aquatic invasive species research. Case studies of proactive management actions from off-shore prevention strategies to eradication of locally naturalized high-risk invasive species are provided, predominantly focussing on management of invasive freshwater plants. Examples are divided into five sections:

- Keeping future invasive species off-shore;
- Management at the border;

- Surveillance and response;
- Managing dispersal pathways within New Zealand; and
- National eradication programs for established invasive species.

Management of established invasive species to reduce their harmful impacts, where eradication is not deemed attainable, is not considered in this paper.

Finally, the unique set of circumstances and factors that have resulted in effective management of aquatic invasive species and why this proactive approach has, and continues to be, successful in New Zealand are discussed.

History of aquatic invasive species management prior to 1993

The majority of New Zealand and Australian invasive freshwater species were introduced deliberately. Prior to the 1970s, there was an active movement to acclimate non-native species. From 1861, and the formation of the Auckland and Victorian (Australia) Acclimatisation Societies, these efforts were encouraged, with supporting legislation to contribute to the pleasure and profit of the predominantly British colonisers of the 19th Century (Osborne 1991; McDowall 1994). Fortunately, a number of these introductions failed and many renowned invasive species have yet to establish in either country (Champion and Clayton 2000; Champion et al. 2002).

There was a growing appreciation of the environmental and economic harm that could arise from new species introductions (Townsend and Winterbourn 1992) and from the late 1960s, scientists of the day were tasked with the evaluation of risks of potential new introductions such as largemouth bass (*Micropterus salmoides* (Lacepède, 1802)) and channel catfish (*Ictalurus punctatus* (Rafinesque, 1818)), with neither species permitted for importation, because of the perceived risk to introduced salmonid sport fish and native biota (McDowall 1968; Townsend and Winterbourn 1992).

Introduction of most New Zealand and Australian invasive freshwater plants was historically due to their importation in the ornamental pond and aquarium trade (Clayton 1996; Champion and Clayton 2000; Petroeschevsky and Champion 2008). Deleterious impacts caused by invasive freshwater plants included impaired drainage, lowered water quality, reduced hydropower generation, interference with recreational activities and declining native biodiversity (Clayton 1996). In order to prevent the importation of further aquatic weeds the Plants Act (1970) (New Zealand Government 1970), made it illegal to import 132 aquatic plant taxa, including 16 whole genera (Champion et al. 2002).

Once inside the national border, the spread of aquatic pests is mostly reliant on human-related dispersal, especially long-distance dispersal (Champion et al. 2010). As the majority of freshwater invasive plants were introduced through the aquarium and pond trade, the continued movement of those species through the trade would facilitate their spread throughout populated parts of the country. New Zealand was the first country to stop the spread of invasive species within their national border by nationally prohibiting their sale. In this case six aquatic plants that were naturalised but with limited naturalised distributions, were banned from sale and distribution in 1982 under the Noxious Plants Act 1978, with seven further species prohibited in the late 1980s/early 1990s (Clayton 1996). This was a highly effective way of not only restricting long-distance dispersal, but also reducing the volume of plants spread deliberately (i.e. propagule pressure – Colautti et al. 2006; Champion et al. 2010; Simberloff 2009).

Some locally established aquatic introductions proved to be problematic, with the internationally recognized invasive plant water hyacinth (*Eichhornia crassipes* (Mart.) Solms) was the first aquatic species managed for eradication under the Noxious Weeds Act 1950. Water hyacinth and two additional invasive aquatic plants, *Pistia stratiotes* L. and *Salvinia molesta* D.S. Mitch., were included with two terrestrial species managed for eradication under the Noxious Plants Act. *Pistia stratiotes* is considered eradicated nationally and very few field populations of the other species remain, with over 200 sites eradicated. However, discovery of field populations continue, presumably originating from plants illegally maintained in cultivation (Yamoah et al. 2013; Champion et al. 2014).

Current governance of aquatic invasive species

The Biosecurity Act (1993) (New Zealand Government 1993) clarified, consolidated responsibility and provided the legal framework for New Zealand management agencies to help keep harmful (invasive non-native) organisms out of New Zealand, respond to new incursions across the national border and manage established invasive species. The federal government of New Zealand assigned accountability to the Ministry of Agriculture and Forestry (MAF) (now superseded by the Ministry for Primary Industries – MPI) for the end-to-end management of the biosecurity system. MPI coordinate other federal natural resource management and health agencies (e.g., Department of Conservation, Ministry of Health) to ensure nationally consistent biosecurity management.

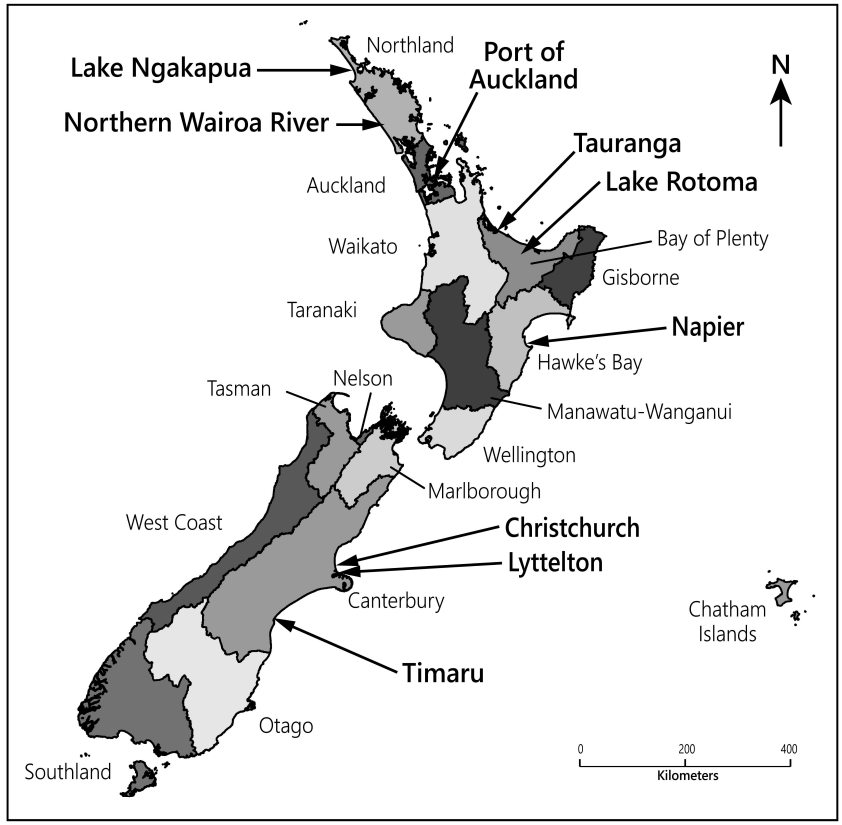

Figure 1. Map of regional council boundaries within New Zealand and specific places referred to in this paper.

While MPI are charged with the responsibility for management of harmful organisms by preventing their entry into New Zealand, intercepting their importation and responding to newly established invasive species populations, much of the management of established invasive species is undertaken by 16 territorial authorities (mostly termed regional councils) managed under regional pest management plans (Figure 1).

Additional to the Biosecurity Act, the evaluation of invasive risk and permitting for importation of organisms not known to be present in New Zealand is the responsibility of the New Zealand Environmental Protection Authority (EPA), under the Hazardous Substances and New Organisms (HSNO) Act 1996 (New Zealand Government 1996).

Aquatic invasive species research

Immediately prior to the enactment of the Biosecurity Act in 1992, the New Zealand research structure was reorganised. Research science previously undertaken by the federal government-owned research bodies, primarily MAF and the Department of Science and Industrial Research, was organized into seven sector-based research businesses owned by the Crown, known as Crown Research Institutes (CRIs). Five CRIs provide the research required to support biosecurity management, with the New Zealand National Institute of Water and Atmospheric Research (NIWA) the major provider of marine and freshwater research. The NIWA Freshwater Biosecurity research program approach is structured around a conceptual framework encompassing prevention of introduction, evaluation and prioritised protection, prevention of establishment, control and mitigation tools. Research is aligned to the management aims outlined by the Biosecurity Act, additionally providing feedback of these research areas to policy and management agencies (Figure 2).

The research program is built on research undertaken prior to 1992, with many key NIWA researchers previously employed within MAF. Their research had primarily focussed on survey of water bodies throughout New Zealand for the presence of invasive non-native species, but also assessment of indigenous biodiversity (Figure 2; Goal 2), the development and refinement of control tools (Figure 2; Goal 3) and evaluation of the risks posed by newly established, or potential new introductions of, non-native organisms,

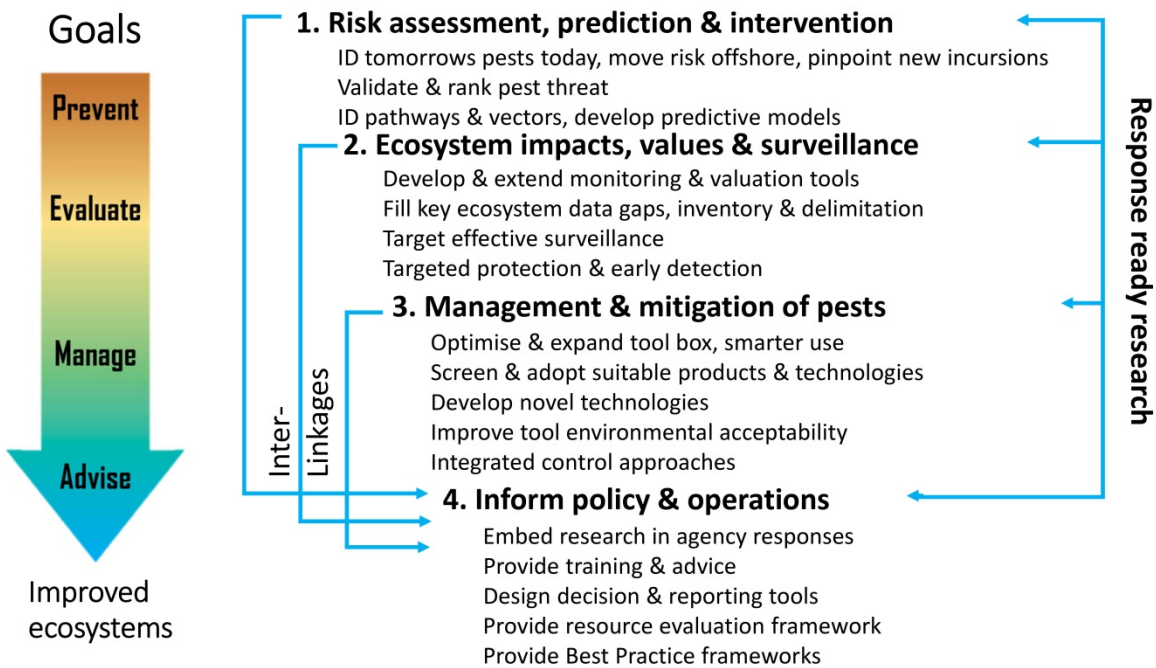

Figure 2. Strategic objectives for NIWA freshwater biosecurity research program.

with advice on their management (Section 2). This research has continued within the NIWA program, especially focussing on developing eradication and control tools and techniques.

A new area of research (Figure 2; Goal 1) undertaken by NIWA was founded on earlier evaluations of introduction risk and was undertaken by government scientists in response to requests to introduce species that had the potential to be invasive (e.g., largemouth bass by McDowall 1968). Townsend and Winterbourn (1992) detailed the required steps to evaluate a new introduction including an environmental impact assessment to review the biology and ecology of the species, invasion history elsewhere in the world, likelihood of escape and establishment in New Zealand, dispersal potential and the ecological consequences of establishment on native and other desirable biota. Daehler and Strong (1993) supported Townsend and Winterbourn's assertion that history of successful invasion and unwanted impacts in other areas outside of the natural range of that species is one of the best indicators of invasion potential. To assist in screening of potential plant invaders, Randall (2017) has collated referenced invasion histories of over 20,000 species, enabling the assessment of plant invasion histories.

In the past twenty years, species risk assessment models have been used primarily to screen the importation of animals and plants for potential invasive species. These models are generally trait-based identifying characters that correlate with those of known invasive species. The first terrestrial-based models used to assess invasive plant risk were developed in Australia (e.g., Pheloung et al. 1999) and are used to screen potential plant imports there and in New Zealand. The Pheloung et al. (1999) model did not adequately separate the impacts of major invasive aquatic plants from less invasive or non-invasive plants. Gordon and Gantz (2011) independently assessed the performance of the Pheloung et al. (1999) model on aquatic plants and confirmed that this model concludes all major aquatic plants pests are invasive, but it also categorized 83% of the non-invasive species as potential major invaders.

The Aquatic Weed Risk Assessment Model (AWRAM) (Champion and Clayton 2000) was designed to characterize functional traits relevant to alien aquatic plant invasion e.g., ability to displace other species, reproductive output and dispersal mechanisms, along with assessment of environmental and economic impact and ease of management (Champion and Clayton 2000). Species are assigned

a score for each undesirable trait with a maximum theoretical score of 100. Gordon et al. (2012) tested AWRAM for potential application in the USA using 130 plant species variously assigned as major, minor or non-invaders. They found that major invaders were distinguished from non-invaders with 97% accuracy at the threshold score of 32. This study has shown that AWRAM can be used to accurately separate potential invasive aquatic plants from those species unlikely to cause unwanted impact. In New Zealand AWRAM assessments (Supplementary material Table S1) has been used to inform not only aquatic plant importation and sale but also management of established species.

Rowe and Wilding (2012) proposed a risk assessment model for the introduction of non-native fish into New Zealand. This scored the potential risk of establishment and likely impact of introduced freshwater fish species in New Zealand, based on data for 21 species that occur there with an additional eight species not present. Highest ranked species included the Notifiable and Unwanted Organisms discussed in Section 2, with additional high-risk fish including *Perca fluviatilis* (Linnaeus, 1758), *Misgurnus anguillicaudatus* (Cantor, 1842) and brown bullhead catfish (*Ameiurus nebulosus* (Le Sueur, 1819)). Like AWRAM, the model provides a potentially useful decision support tool for assessing risks posed by importation of a new species and species with limited current distribution within New Zealand.

Additional to species-based risk assessment, research to predict the risk of invasive species spread within New Zealand and introduction to new unimpacted water bodies (pathway risk) has been undertaken. Johnstone et al. (1985) demonstrated the dispersal of submerged invasive plants that solely relied on asexual reproduction was significantly correlated to recreational boating and fishing. More recently, two studies using boosted regression tree modelling, one on submerged invasive plants (Compton et al. 2012), the other on invasive fish (Leathwick et al. 2016), used invasive species distribution data correlated with a number of biotic and abiotic variables to identify at risk sites, showing that human population density, roading network and lake size were well correlated with current distribution of species spread by human activity. Conversely, the distribution of a plant species predominantly spread by waterfowl, *Utricularia gibba* Lam., was best correlated to higher temperatures (Compton et al. 2012).

When the stalked diatom *Didymosphenia geminata* (Lyngbye) M. Schmidt was first detected in New Zealand in 2004 (Southland Region), MPI commissioned a wide range of studies to understand the biology, ecology, impacts potential distribution and control options to guide management responses for this species. This was almost certainly a new incursion, originating from the Northern Hemisphere (Kilroy and Novis 2018). Prior to growth studies on this species, Kilroy et al. (2007a) modelled potentially suitable habitats based on observations that the important environmental variables favouring *D. geminata* colonisation and blooms are: high lake influence; stable, hard substrates; low flow variability; longer time since a flood; and large seasonal temperature differences. Modelling indicated that culturally and economically important trout fisheries in the central North Island were vulnerable to invasion and helped prompt containment measures to prevent spread from the South Island including inspections at major points of departure. It has still not been detected in the North Island of New Zealand. Subsequently, data showing that this species requires very low dissolved reactive phosphorus concentrations for bloom formation has meant that most North Island waters are now thought to be unsuitable for nuisance growths of this species (Kilroy and Larned 2016).

In New Zealand, the research described above has been used to support management agencies and policy development (Figure 2; Goal 4); relating to importation, regulation of sale, incursion response and surveillance, prioritizing control and informing the legal status of aquatic plants (Champion et al. 2014) discussed in the following sections of this review. Additionally, tools such as AWRAM has been applied to assess invasive aquatic plants elsewhere in the Pacific; in Australia (Petroeschevsky and Champion 2008) and Micronesia (United States Department of the Navy 2015).

Management examples

Keeping future invasive species off-shore

The Biosecurity (Notifiable Organisms) Order 2016 (New Zealand Government 2016) lists a number of aquatic organisms that have either never been recorded in New Zealand, or that have been eradicated. These organisms must be reported by anyone either finding them or suspecting their presence in risk goods. They include 8 diseases affecting crustacea (e.g., *Aphanomyces astaci* Schikora), 10 diseases affecting molluscs (e.g., *Xenohaliotis californiensis*), 15 diseases affecting fish (e.g., koi herpesvirus), 15 mosquito species (e.g., *Aedes camptorhynchus* (Thomson, 1869)), 3 freshwater animals (two species of freshwater crayfish or marron (*Cherax* spp.) and channel catfish) and 7 marine taxa (e.g., *Caulerpa taxifolia* (M.Vahl) C. Agardh, *Carcinus maenus* (Linnaeus, 1758)).

The only freshwater plants listed on the Notifiable Organisms Order are five species already present in New Zealand that are all managed under national eradication programs (Table S1). Formerly, 11 aquatic plants not known to be in New Zealand were also listed as Notifiable Organisms (see Champion et al. 2014), but are now designated as Unwanted Organisms under the Biosecurity Act (MPI 2018), effectively still preventing their importation (Table S1).

Additional freshwater fish listed as Unwanted Organisms in New Zealand include all members of the pike family (Esocidae), *Cyprinus carpio* Linnaeus, 1758, *Gambusia affinis* (Baird and Girard, 1853), all members of the genus *Gasterosteus* and gudgeon (*Gobio gobio* (Linnaeus, 1758)). Of these species, only Esocids and *Gasterosteus* have yet to be found in New Zealand.

These Notifiable and Unwanted Organism form a list of freshwater organisms prohibited from importation (Champion et al. 2014).

Border management

The New Zealand border is well defined with limited access for overseas goods and passengers. There is only one entry point for mail (Auckland International Mail Centre), six international airports (Auckland and Christchurch are the largest) and 25 ports/harbours (World Port Source 2018). Tauranga, Auckland, Lyttleton and Napier are the largest ports (Figure 1).

All mail is inspected by soft x-ray in order to detect any living material. Passengers are required to declare any biosecurity risk goods and are frequently inspected by Ministry for Primary Industries (MPI) officials. Imported containers and international vessels are also inspected by MPI under the Biosecurity Act. This Act also requires that imported risk goods (e.g., seeds for sowing, food items) are subject to Import Health Standards and any living material must undergo post-entry quarantine (PEQ) to enable inspection by MPI officers for the detection of any hitch hiker pests and diseases.

Any organism not listed as present in New Zealand (New to New Zealand) must be evaluated by EPA. The onus is on the importer to demonstrate that the new species doesn't pose an unacceptable risk to New Zealand's economy, ecology or human health – in the form of a detailed risk assessment based on an EPA protocol. The importer also has to pay the costs of processing the application. If approval is attained, anybody can import the organism provided all Biosecurity Act requirements are followed. Unsurprisingly, no new aquatic plants and fewer than 100 organisms have been processed by the EPA since the inception of HSNO, effectively halting the legal importation of new aquarium or pond plants (Champion et al. 2014). This appears to have led to illegal importations, with 27% of aquarium plant species in trade in 2000 apparently entering New Zealand illegally (Champion and Clayton 2001). Australia who operate similar stringent import processes as New Zealand have also reported the likelihood of illegal aquarium fish imports (Morrisey et al. 2011).

Critically, illegal imports miss Biosecurity Act import requirements such as PEQ screening for hitch hiker species. For example, a number of new to New Zealand invertebrates have been detected amongst species collected from aquarium tanks (Duggan 2010). A total of fifteen species of naturalized invertebrates are likely to have been imported through the aquarium trade in New Zealand (Duggan et al. 2006, 2012; Champion et al. 2013; Burns et al. 2017), but not were detected by PEQ protocols.

Early detection/rapid response (EDRR)

Once an invasive species has entered the country across the national border (Transport sensu Kolar and Lodge 2000) then a range of management activities can be undertaken to prevent naturalization of organisms evaluated as potentially invasive (Establishment sensu Kolar and Lodge 2000). These activities have been termed incursion detection and response, or early warning (or detection)/rapid response (EDRR sensu Simberloff 2014).

Many new incursions have been detected by researchers or management agency staff undertaking field work, or through information received by the public. MPI have created a Pest and Disease hotline telephone number for the public to report any new or unusual organisms or disease symptoms (MPI 2017a).

Staff of the federal agency responsible for invasive freshwater fish management, Department of Conservation (DOC) discovered three invasive species, the Unwanted Organisms *Cyprinus carpio* and *Gambusia affinis*, and also rudd (*Scardinius erythrophthalmus* (Linnaeus, 1758)) in the South Island (Nelson/Tasman) in 2000. Distribution surveys for these species were undertaken throughout the South Island, with *Cyprinus carpio* and *Gambusia affinis* deemed to be targets for eradication (Elkington and Maley 2005). It is likely that eradication of *C. carpio* has been achieved, and most *Gambusia affinis* sites are eliminated (Collier and Grainger 2015).

A member of the public reported a sighting of a large freshwater crayfish next to a road in Auckland Region (Gould 2005). The crayfish was identified as the Notifiable Organism marron (*Cherax tenuimanus* Smith, 1912) and a coordinated response by central and regional government agencies led to the

discovery of a nearby property with large tanks containing this species, but also European gudgeon, an introduced European fish hitherto unknown in New Zealand and regarded as an illegal introduction. No further specimens of these species were trapped as part of surveillance of waterbodies proximate to the discovery site, but an investigation arising from the original response led to the discovery of a second pond within Auckland Region containing both species. Eradication of both organisms was achieved (Gould 2005). In addition to reliance on reports of suspicious organism/diseases by the public, there are a number of targeted surveillance programs instigated by federal or regional management agencies. These target sites deemed to be at high-risk of secondary spread of established invasive organisms, with target areas either decided by expert panel or using pathway modelling approaches (Section 4).

MPI lead a marine surveillance program that annually take over two thousand samples across New Zealand's 11 most heavily used ports and marinas. Sites are checked twice a year through a combination of trapping, underwater searches and shore searches (Woods et al. 2017). This program has been running since 2010, with 351 non-indigenous species identified (187 now established). Between 2010 and 2015, 33 species new to New Zealand were recorded including the Notifiable Organism *Sabella spallanzanii* (Gmelin, 1791).

Sabella spallanzanii was first detected in Lyttleton, New Zealand in 2008. Culling by divers as part of a Government response to this invasive species largely eliminated it in Lyttelton (Read et al. 2011), but it was subsequently found in the Auckland Region and MPI now consider that eradication from New Zealand is not feasible. One successful marine incursion response was achieved following the discovery of the invasive laminarian alga *Undaria pinnatifida* (Harv.) Suringar on the hull of a recently sunk fishing trawler by DOC in 2000 in coastal waters off the Chatham Islands, approximately 800 km east of Canterbury. As this was the only recorded occurrence of this species from the Chatham Islands, the then Ministry of Fisheries (now incorporated into MPI) undertook an eradication response (Wotton et al. 2004). This was achieved by heat-treatment of the entire hull, either by water heated to at least 70 °C or a underwater flame torch for hard to access areas.

A total of eight invasive freshwater plants have been eradicated nationally from New Zealand. These include *Butomus umbellatus* L., *Eichhornia paniculata* (Spreng.) Solms, *Menyanthes trifoliata* L., *Nymphoides peltata* (Gmel.) Kuntze, *Pistia stratiotes* L., *Potamogeton perfoliatus* L., *Typha latifolia* L., and *Zizania palustris* L. In these cases, eradication was achieved by early detection, rapid assessment that these species posed a high risk and expedient control. Mechanical and manual removal was used in all but three cases where herbicides were used in association with physical removal. In the case of *N. peltata*, long-lived seed continued to germinate on the only known site, a small 300 m^2 farm pond, despite the pond being covered by opaque weedmat. Finally, the water body was destroyed (permanently filled) and a new dam constructed.

Invasive freshwater plant surveys are also undertaken annually in many of New Zealand's regions, especially those with a substantial risk of invasive plant invasion (Compton et al. 2012). For example, Northland Regional Council undertakes submerged invasive plant surveillance in six high-value uninvaded sites. Likely sites of introduction (e.g., boat ramps and commonly used beach access points and anchorage areas such as favoured fishing areas and sheltered bays) were intensively searched over the depth range supporting submerged vegetation, predominantly by scuba divers either on boat tows, or underwater scooters (Champion and Wells 2014). Several invasive freshwater plant detections have been intercepted and managed as discussed in the following sections.

To increase the likelihood of new invasive freshwater plant incursion detections, Bay of Plenty Regional Council have constructed weed cordons at boat access points in several of their high-value water bodies. These are buoyed cordon panels supporting purse seine net "curtains" that create a physical barrier to reduce the likelihood of the movement of invasive plant fragments out of the cordon and into the main body of the lake (Lass 2012). They create a much smaller search area for surveillance. Recent detections include viable fragments of *Ceratophyllum demersum* L. and *Egeria densa* Planch. from Lake Rotoma. Neither species has established in that lake (H. Lass, Bay of Plenty Regional Council, pers. comm.).

Once a new incursion is detected, the following stages of incursion response are recommended: delimitation to ascertain the extent of the incursion, evaluation of control options, containment of the incursion to prevent further expansion, control program and monitoring to measure control effectiveness and any follow-up control required (Champion and Wells 2008). As an example, the invasive freshwater plant *Lagarosiphon major* (Ridley) Moss was detected in a Northland dune lake (Lake Ngakapua) in October 2014 as part of the Northland Regional Council annual surveys. Delimitation was undertaken and established fragments were found in approximately 10% of the southern lake basin, adjacent to emergent macrophyte beds. As the lake was essentially

contained, with no inflow or outflow, containment was not attempted. The best eradication option was considered to be the herbicide endothall, which had been used to eradicate this species from other water bodies in New Zealand (Wells et al. 2014). Permissions to use this product were granted and herbicide was applied in April 2015 to areas where *L. major* was found in a second delimitation survey. Subsequent monitoring every six months has failed to detect any living plants of *L. major*, with no impact on indigenous biota, and eradication will be declared should no plants be found for three consecutive years.

Managing dispersal pathways inside New Zealand

Deliberate spread

As discussed in Section 2, prevention of sale and distribution of six aquatic previously popular aquarium/pond plants in 1982 was a highly effective way of not only restricting long-distance dispersal, but also reducing the volume of plants spread deliberately. More recently, MPI (2006) used this approach to manage the trade of over 130 plant taxa using the National Pest Plant Accord (NPPA) to legally prohibit their sale, propagation and distribution. The agreement not only includes regional and national management agencies, but also plant growers (New Zealand Plant Producers Incorporated NZPPI). This list includes 29 aquatic species listed in Table S1. All commercial nurseries, pet and aquarium shops are regularly inspected by regional council staff to ensure compliance (Champion et al. 2014).

The rationale for inclusion on the NPPA list is that invasive plants of limited distribution within New Zealand would be prevented from further distribution, where deliberate distribution by human activities would increase their potential range and level of impact. The process used to determine these species is discussed in Newfield and Champion (2010).

Accidental spread

Not all invasive aquatic species were introduced deliberately. *Didymosphenia geminata* is likely to have been introduced in contaminated fishing equipment imported from the Northern Hemisphere. Subsequent spread, is thought to have occurred via human mediated spread. MPI initiated a management response and in 2005, developed a campaign to "Check Clean Dry" for freshwater users to prevent the spread of this and other aquatic invaders between water bodies (MPI 2017b). This involves the visual check of gear after use, treating gear with various options including detergent, bleach, hot water and freezing (Kilroy et al. 2007b). These decontamination methods have recently been tested for a range of other freshwater invasive animals and plants (Burton 2017), with hot (55 °C) water the most efficacious.

Eradication of established invasive species

Eradication of species that have already established extensive self-sustaining naturalized populations requires a greater management effort (both in spatial and temporal scale) than EDRR and is dependent on a greater understanding of the level of impacts the invasive species will have (to justify and secure long-term government investment) and the development of selective eradication tools that will have a reduced/ acceptable non-target impacts on invaded ecosystems. There are examples of successful eradications in New Zealand.

New Zealand became the first country in the world to eradicate a saltmarsh mosquito nationally. In June 2010, MPI declared that the Notifiable Organism *Aedes camptorhynchus* had been eradicated, after its first detection in 1998 (Yard 2011). As this mosquito is capable of transmitting Ross River virus, the eradication program was initially run by the Ministry of Health. In total, eleven populations, all but one in the North Island, were detected. Eradication was achieved by aerial and ground-based application of S-methoprene and *Bacillus thuringiensis israelensis.* Additionally, surveillance for mosquito larvae and adults was carried out to monitor for successful control and check available habitat. The program was transitioned to MPI in 2002. The total cost of the eradication program was approximately NZ$70 M.

MPI initiated six National Interest Pest Response programs to eradicate invasive freshwater plant species in 2008, based on risk assessment and management options advice provided by NIWA (e.g., Champion and Hofstra 2006). In four cases, the aim was national eradication, with two of those species, *Eichhornia crassipes* and *Salvinia molesta*, already already under management with the goal of eradication (see Section 2). The other two species were *Phragmites australis* and *Hydrilla verticillata*. Additionally, *Zizania latifolia* was targeted for eradication outside of its main centre of distribution (50 km of the Northern Wairoa River – Figure 1)), whereas *Ceratophyllum demersum* was targeted for eradication from the South Island. These species were the five highest ranked invasive freshwater plants using AWRAM (Champion and Clayton 2000), while *S. molesta* was ranked New Zealand's 11th highest ranked species.

Ceratophyllum demersum eradication from the South Island was declared in 2013, achieved with only one application of endothall at 5 ppm over affected areas of the single, small water body near Timaru (Wells et al. 2014).

The *H. verticillata* program relied on two decades of eradication research which included experimental verification of the invasion potential of this species (Hofstra et al. 1999), a lake trial using grass carp (*Ctenopharyndogon idella* (Valenciennes, 1844)) (Clayton et al. 1995) and herbicide trials using endothall (Wells and Champion 2010). NIWA also coordinated an application to EPA for the registration of endothall in New Zealand to allow its use as an eradication tool. After the stocking of grass carp in all Hawkes Bay lakes containing *H. verticillata* in 2008, no plants of this species have been seen since 2015.

The programs for the other species are also making good progress towards their eradication goals.

Conclusions

Why is proactive aquatic pest management successful in New Zealand?

Simberloff (2014) regarded the New Zealand biosecurity system as world leading in areas of interdiction at points of entry (the border) and EDRR.

New Zealand is isolated with a relatively small population and separated from trading partners by expanses of open ocean – a major barrier to the introduction of freshwater and, to a lesser extent, coastal marine species. There are also restricted points of access as discussed in Section 5.2. New Zealand is highly reliant on primary production and many of the population are familiar with the concept of biosecurity and the importance of the need to protect primary industries, environment and public health from weeds, pests and diseases (Goldson 2010). Freshwater is a hugely valued resource and a large number of New Zealanders are concerned about the degradation of our waters (Hughey et al. 2016).

New Zealand has strong effective legislation protecting the importation and spread of potential biosecurity threats and also enabling their management under the Biosecurity Act. Effective management results from good federal and regional interagency collaboration and engagement of other affected parties.

Finally, the strategic focus of proactive management is science driven, with direct uptake of research by management and policy agencies. In the case of invasive freshwater plant management, a long-term research program with experienced research practitioners has worked alongside management agencies providing tools to achieve effective proactive management. Additional to the long-term research program, members of the team had historically been part of the decision-making process prior to the segregation of science from federal government departments. Since the formation of CRIs, links with management agencies have been retained through membership of advisory panels (e.g. NPPA and NIPR programs) and contracted advice on, for example, management options assessments for national eradication programmes (e.g., Champion and Hofstra 2006).

Mack et al. (2000) outlined some of the enormous challenges facing invasive species management once strategies to exclude them fail. These included:

- Identification of invasive attributes of species being inconclusive.

The Pheloung et al. (1999) model and AWRAM have shown good predictive power to separate major invaders from non-invaders and have been used to inform management both in New Zealand elsewhere.

- Prediction of likely invasion locales seems very problematic.

Niche modelling used to identify susceptible habitats (Kilroy et al. 2007a) and BRT spread models (e.g., Compton et al. 2012) have assisted the selection of surveillance sites for new freshwater incursions.

- Eradication successes are rare and rely more on the level of commitment and diligence than the efficacy of the control method.
- Long-term ecosystem-wide strategies are likely to be more effective than targeting individual invaders.

Risk assessment tools have played an important role in justifying long term commitment and expenditure. In addition, the NIWA invasive freshwater plant research program and research elsewhere is developing highly selective herbicide methods and optimising their use on target species with reduced environmental impacts. By comparison, New Zealand eradication methods for invasive freshwater fish and marine organisms have not majorly advanced over the past two decades, but still EDRR programs have been effective on these invasive species.

- Prevention is much more cost efficient than post-entry control

This is very much the reality and New Zealand biosecurity system is world leading in areas of interdiction at points of entry (Simberloff 2014). In addition, proactive risk screening where the onus is placed on the importer to demonstrate organism safety has successfully limited new importations, but may have led to some illegal importation.

The recommendations for US policy and management of biological invasions by Lodge et al. (2006) mirror the New Zealand approach, with improved pathway management to mitigate the transport of invasive organisms, risk analysis for potentially harmful species, increased active surveillance and funding of EDRR, protection of high value uninvaded systems and centrally coordinated management of invasive species.

New Zealand has an unparalleled success with national eradication of aquatic species that have already established extensive naturalized populations. Simberloff (2014) identifies five (or six) features that are critical to successful eradications:

- Clearly identified management goals of the program
- Sufficient resources to complete the program, with elimination of the last few individuals increasing costly
- Ensure the cooperation of all parties affected by the program
- Know the life histories of target organisms and identify their vulnerable life stages
- Identify the likelihood of reinvasion
- Expect surprises (unintended consequences of a program).

New Zealand is well positioned to meet those criteria due to its isolation, inclusive management approach with supporting legislation and integration of adaptive research as part of` the eradication program.

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Supplementary material

The following supplementary material is available for this article:

Table S1. New Zealand problem and potential problem invasive freshwater plants, showing Aquatic Weed Risk Assessment score and management status.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2018/Supplements/MBI_2018_Champion_Table_S1.xlsx