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Challenges for pest management in New Zealand

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Summary

- New Zealand remains under intense pressure from pests which threaten our economy and environment, despite investing heavily in biosecurity and pest management systems. Ongoing targeted investment is needed to protect our native land and aquatic environments and primary production from weeds, vertebrate and invertebrate pests and pathogens.
- Changes in the use of pest management tools have been made in response to public concerns and trade issues around the environment, humaneness standards and food safety. Increasing pest resistance is also making some invertebrate pesticides and herbicides ineffective, while others have been phased out.
- Urgent action is needed to develop new approaches and to improve existing tools to protect the country's environment and economy. New Zealand has already provided leadership in environmentally and socially sensitive pest management but there is an urgent need to do more.
- More emphasis needs to be given to surveillance and pest monitoring to:
  (i) increase the chances of successful eradication of new incursions when pest distributions are still limited; and
  (ii) prevent the recovery of existing pests after control has been applied. To this end:
    - more trained local and central government staff are needed to assist with translating and applying scientific research and new technology.
    - citizen science should play a much stronger role in monitoring and surveillance for pests in New Zealand.
- More species-focused research is needed because many pests are managed with little scientific understanding of their life-cycle or population processes, and New Zealand's unique environment means we cannot presume that the behaviour of species in their native range will be replicated here. As part of this research:
    - more specialist taxonomists are urgently needed so indigenous species can be distinguished from exotic threats, to underpin surveillance and responses, and fundamental biological understanding. The application of next generation genomic sequencing and bioinformatics offer valuable opportunities.
    - Public attitudes to novel pest management tactics need to be explored in advance of use, and ways of improving public engagement developed with social researchers.
    - Greater use of information technology will move pest management towards "real time" control.
    - Better understanding of the biology of pests, their interactions, and their impacts on assets we value, are all required.

Introduction

New Zealand's economy and reputation are closely linked to land and aquatic managed ecosystems and the natural environment, to an unusual extent for an OECD country. New Zealand's productive capacity has flourished through the introduction of hundreds of economically important plants and animals, and the resulting managed ecosystems are critical to the country's economy. However, these ecosystems, and New Zealand's natural indigenous ecosystems, are constantly under pressure from a range of pests, such as weeds, vertebrates, invertebrates and micro-organism pathogens. Reducing the impact of these largely exotic threats has mainly relied on pesticides, sometimes augmented by biocontrol agents. Invertebrate, micro-organism and weed pests in the natural environment for the most part go uncontrolled but, in contrast, intensive campaigns are conducted against vertebrate pests using aerially-applied toxins or ground-based trapping and toxins to protect vital assets including threatened ecosystems and endangered plants and animals. New pest incursions (largely invertebrates, weeds and micro-organisms) occur, sometimes with dramatic impacts on both humans and the natural environment.

The focus of this contribution is to alert interested parties to the on-going changes and increasing complexity in the way New Zealand must deal with its pest management threats. The analysis presented therefore canvasses a number of considerations including the unique nature and inherent instability of New Zealand's pest management situation, the potential for further pest management challenges through biosecurity failure and, in particular, the implications for the decreasing acceptability and availability of certain pest management solutions. The latter is based on both the potential for environmental damage and increased social resistance.

This paper cannot cover all aspects of New Zealand pest management and the material herein therefore does not purport to do so. Rather the topic areas and the pest types and species alluded to are used as examples to illustrate the range of issues New Zealand is facing, rather than in any way seeking to be comprehensive.

Case Study: Island eradications: a blueprint for success?
Invasive mammals have been eradicated from many of New Zealand's offshore islands[1], and as a result New Zealand is regarded as a world leader in such procedures[2]. Eradications have mostly been on relatively small islands and in fenced sanctuaries, but Norway rats (*Rattus norvegicus*) were eradicated from 11,000 ha Campbell Island in 2002[3] and all mammals have now been removed from Rangitoto/Motutapu Islands (3700 ha) in the Hauraki Gulf[4]. Programmes are underway to eradicate stoats (*Mustela erminea*) and red deer (*Cervus elaphus*) from Secretary and Resolution islands in Fiordland (8,100 and 21,000 ha respectively)[5], although re-invasion remains a challenge on such islands, which are within the swimming-range of such pests. New Zealand's 'can do' attitude towards the eradication of vertebrate pests from ever-larger areas is providing impetus for two future challenges: eradication or large-scale suppression of certain mammals on large inhabited islands[6] and the mainland[7], and a long term vision of a 'Predator-Free New Zealand'[8], involving the eventual complete eradication or large-scale suppression of mustelids, possums and rats.

The New Zealand pest threat – impacts and costs

New Zealand has a challenging range of high impact pests and so biosecurity and pest management are crucial to New Zealand's environmental and economic wellbeing:

- New Zealand's unique natural environment is integral to us as a nation and drives our tourism industry.
- New Zealand's commitment to the international Convention on Biological Diversity obliges it to protect its unique natural ecosystems, flora and fauna. Due to habitat loss and predation, many species are endangered with some teetering on the brink of extinction. The incursion and subsequent outbreak of the freshwater diatom didymo (*Didymosphenia geminata*) in South Island streams and the appearance of kauri dieback shows what can happen without effective pest detection and management.
- Agricultural and aquatic ecosystem services are vital to New Zealand's economic performance with this country having the world's fourth largest marine Exclusive Economic Zone and 45% of its land area devoted to primary production.
- Productive ecosystems are threatened by arthropods and micro-organisms affecting economically important species such as *Pinus radiata and Trifolium repens*.
- Natural ecosystems are under pressure, with invasive mammals and micro-organisms threatening keystone species such as kauri and certain podocarps.
- Pests in New Zealand's freshwater systems destabilise aquatic habitats, and modify water flow with negative consequences for drainage, irrigation, power generation, and recreational activities. In the marine environment, invasive species displace native species, modify coastal habitats and affect human health. They also pose threats to aquaculture, commercial fishing and other maritime industries, including recreational pastimes.
- Productivity in our land-based industries is compromised by a wide range of invertebrate pests and weeds. In our native forests, possums, stoats, rats and cats still pose the greatest threat to plants, birds and bats but exotic phytophagous invertebrates have relatively little impact[9].
- Pathogens of plants and animals are often extremely difficult to detect until their presence is noted in diseased organisms. Diseases in New Zealand crops can utilise New Zealand natives in the same family as their hosts. For example the endangered native plant species, *Pachycladon* spp. and Cook's scurvy grass (*Lepidium oleraceum*), are both members of the Brassica family and can become infected with Turnip mosaic virus. Similarly the rare and endangered *Sicyos australis*, New Zealand's only cucurbit species, can be damaged by certain isolates of cucumber mosaic virus and can also be infected by watermelon mosaic virus.

Pests cost the country billions of dollars in lost revenue and control costs. For example:

- Pastoral weeds are conservatively estimated to cost the New Zealand economy $1.2 billion per annum in lost animal production and control costs[10] and there are more than 300 weeds of conservation concern.
- Weeds pose a threat to one-third of all New Zealand nationally threatened plant species, and could potentially degrade 7% of the conservation estate within a decade, corresponding to a loss of native biodiversity equivalent to $1.3 billion[11].
- Invertebrate plant pests in productive ecosystems incur similar levels of cost. Annual

production losses have been estimated to be around $880 million per annum[12] but this does not include the impact of indigenous species that have become pests, nor the multiplier effects of their impact on economic activity connected with this production.

- The costs and averted economic impacts from eradications of forest insect pests in New Zealand over 20 years, have been significant (see examples in Table 1)
- The total direct economic cost of vertebrate pests to the primary sector is estimated at about $1 billion per year[13], but with multipliers included could be as high as $3.3 billion (1.96% of GDP)[14].
- Annual production losses to aquaculture from a single species of sea squirt (*Styela clava*) were estimated at $15 million per annum in 2005[15]. More recent estimates suggest that if *Styela* spreads to Marlborough, production losses over the next eight years could amount to $383 million[16].
- The long term costs of loss of native biodiversity from vertebrate, invertebrate, freshwater and marine and micro-organism pests have not been estimated. Introduced social wasps in beech forests present a case with extreme consequences for native insect and bird diversity and ecosystem services, as well as impacts on tourism and recreation. New methods of control are clearly needed in such cases, and warrant long term government investment.

Organism (Dates of programme)	**Eradication cost (approx. $millions)**	**Estimated economic impact over 20 years ($millions)**	**Approximate averted costs (i.e. economic Impact less cost of eradication) ($millions)**
White-Spotted Tussock Moth - (*Orgyia thyellina*) (1996 –1998)	$11	$23 - $158	$12 - $147
Gum Leaf Skeletoniser (*Uraba lugens*) (1997 – 1998)	$4	$90 - $127	$86 - $123
Painted Apple Moth (*Teia anartoides*) (1999 – 2006)	$58	$52 - $317	-$6 - $259
Fall Webworm (*Hyphantria cunea*) (2003 – 2006)	$6	$17 - $74	$11 - $68
Gum Leaf Skeletoniser (*Uraba lugens*) (2003)	$107*	$90 - $127	-$17 - $20*
Gypsy Moth (*Lymantria dispar dispar*) (2003 – 2005)	$6	$2 - $259[#]	-$4 - $253

Table 1: Costs and averted economic impacts from eradications of forest insect pests in New Zealand[17](* [18] #[19])

Costs of recent invasive alien species incursions

In the marine environment, expenditures on recent incursions ("defensive costs") by biofouling organisms such as the clubbed sea-squirt (*Styela clava*), the Whangamata sea-squirt (*Didemnum vexillum*), and the Mediterranean fanworm (*Sabella spallanzanii)* have been estimated at $2.2 million, $1 million, and $1 million, respectively[20]. However, these amounts represent only the one-off costs to Central Government and/or industry of initial incursion responses and are modest relative to expenditure on incursion responses and management of terrestrial insect pests (see examples in Table 2)[21]. These costs only represent initial costs of incursion response, and if the decision is made that eradication is not feasible, there will be additional costs of on-going management of the populations and their impacts.

No estimates have been made of the impacts of these or other biofouling species on non-market values. However, a "willingness-to-pay" study assessed the dollar value of marginal changes to indigenous marine biodiversity and other attributes of the coastal marine environment associated with a potential incursion by the European green crab (*Carcinus maenas*)[22]. Of the four attributes evaluated in the study (loss of shellfish species, loss of recreational shellfish take, loss of coastal vegetation and the inability of children to paddle at the water's edge) the loss of indigenous (shellfish) biodiversity was valued most by the respondents. Although focused on a single estuary (Pauatahanui Inlet), the study concluded that if comparable impacts were experienced throughout New Zealand, the expected marginal loss to these non-market values could amount to between $325 million to $600 million[23].

Specific emerging pest issues

Invertebrate pests

Managed ecosystems have low plant and invertebrate biodiversity with a lack of inherent biotic resistance that makes them potentially vulnerable to exotic invasive species and the impacts of severe pest outbreaks. Indigenous terrestrial ecosystems have a low endemic diversity of native pest-suppressing species such as parasitoids, generalised predators, and predatory spiders. Particular issues include:

- only half or less of New Zealand's insect fauna has been described[24] but there are an estimated 2,200 established exotic invertebrate species.
- plant breeding in New Zealand has tended to focus on yield rather than pest resistance.
- disease-transmitting invertebrates, particularly mosquitoes and ticks, can be difficult to detect and intercept.

Organism	Incursion response period	Incursion response cost (NZ$million)
White-Spotted Tussock Moth, (*O. thyellina*) $^{\alpha}$	1996-1998	12
Gum Leaf Skeletoniser (*U. lugens*) $^{\alpha}$	1997-1998	4
Painted Apple Moth (*T. anartoides*) $^{\alpha}$	1999-2006	65
Fall Webworm (*H. cunea*) $^{\alpha}$	2003-2006	7
Hokkaido Gypsy Moth (*Lymantria umbrosa*) $^{\alpha}$	2003-2005	6
Didymo (*D. geminata*) $^{\beta}$	2004-2009	12
Red Imported Fire Ant (*Solenopsis invicta*) $^{\gamma}$	2006-2009	11
Varroa Bee Mite (*Varroa destructor*) $^{\delta}$	2005-2009	20
Clover Root Weevil (*Sitona lepidus*) $^{\delta}$	1996-?	10
Southern Salt Marsh Mosquito (*Ochlerotatus camptorhynchus*) $^{\mu}$	2004-2010	40
Didemnum (*Didemnum vexillum*) $^{\Delta}$	2006-2009	1
Mediterranean Fanworm (*Sabella spallanzanii*) $^{\#}$	2008-2009	1.3

Table 2: **Examples of the costs of recent incursion response campaigns in New Zealand** (α^{25}, β^{26}, γ^{27}, δ^{28}, μ^{29}, Δ^{30}, $\#^{31}$)

- Biological control agents have been successfully introduced against arthropod pests, although there are some biosafety concerns that need consideration[32].
- Responses to incursions have used biopesticides (salt marsh mosquitoes (*O. camptorhynchus*)), and more selective pesticides against targets such as fire ants (*S. invicta*)[33].
- Withdrawal of older broad-spectrum pesticides will leave gaps in control and market access, and New Zealand's small market cannot support the high development costs of replacements.

Pathogenic micro-organisms

Pathogenic micro-organisms, such as those responsible for foot and mouth disease (*Aphthae epizootica*), avian malaria (*Plasmodium relictum*), and the kiwifruit vine disease Psa (*Pseudomonas syringae actinidia*), pose unique threats. New Zealand is currently dealing with: *Phytophthora* diseases (e.g. kauri decline (*Phytophthora* taxon Agathis*)*); cabbage tree die-back; the potential impact of myrtle rust (*Uredeo rangelii*) on pohutakawa trees, and as well as various pine needle diseases. Emerging issues include:

- Some micro-organisms are often wind-borne and spread rapidly and widely. Others, such as livestock diseases, may be rapidly spread through stock movements. Prompt and effective surveillance is needed but, in the case of plant and animal pathogens, this is extremely difficult because symptoms may be non-specific or delayed by latent periods.
- Taxonomy at the species level does not usually account for strains that may have differing pathogenicity. This can lead to complacency if the organism is thought to be already in the country.
- Large, genetically similar monocultures such as radiata pine, kiwifruit, ryegrass /clover pastures and apple plantations are likely to face additional risks.
- Micro-organism pathogens are also a serious threat to animal health and, while diseases like foot-and-mouth (*A. epizootica*) are well understood and monitored, zoonotic diseases that will affect both animals and humans (e.g. bird flu (*Orthomyxoviridae*)) carry additional risks.
- Pathogens such as avian malaria (*P. relictum*), the cause of 'crusty bum' (Cloacitis) in kakapo, and kauri dieback *Phytophthora* can further threaten declining or critically endangered native biota.
- Micro-organisms and pathogens are also a significant concern in the marine environment. The oyster herpes virus (OsHV-1) µvar caused severe mortality of farmed Pacific oysters in 2010, reducing stocks by 60-80% at an annual cost of around $26 million to the industry[34]. In some cases, the diseases, compounded by slow recognition and inadequate response, have decimated fish and shrimp industries[35].

Weeds

Managed ecosystems have low diversity and simple structure and are prone to invasion. Indigenous ecosystems are more resilient but, when modified, may be overwhelmed by plant invaders (for instance, wilding pines) that are better adapted to disturbance or fire. Issues include:

- Garden escapes and live plant imports by gardeners and garden centres are another source of new weeds. Plants present in gardens but yet to establish in the country's broader ecosystems form a huge pool of potential 'sleeper' weeds. Many weeds exhibit extensive time lags, as much as 100 years, between their establishment and spread, suggesting many future weeds might already be here[36]. The risk posed by the 25,000 exotic plant species already present in New Zealand remains poorly understood and research is needed to identify the most likely future weeds among them[37].
- Seeds can be transported into New Zealand by deliberate mail order and as accidental fellow-travellers on clothing and luggage.
- Good progress has been made in New Zealand with biological control of weeds[38], and there are few concerns about non-target effects on plants[39].
- The hybridisation of New Zealand native species with exotic species such that their whakapapa is

compromised is of particular concern for species with Māori heritage values.

Vertebrate pests

There are only two native land mammals in New Zealand (two bat species), the result of 80 million years of geographical isolation. In contrast, 32 species of mammals and 35 birds have become established. New Zealand's native flora and fauna are particularly vulnerable to predation by mammal pests. Rats, mice, weasels and stoats, hares and rabbits, hedgehogs, possums, wild pigs and feral cats all present serious threats. Strenuous efforts are being made to create vertebrate pest-free areas on islands and in predator-fenced sanctuaries. However, these areas are mostly small, and reinvasion is always a risk. Emerging issues include the need for:

- the cost-effective, humane management of vertebrate pests at very large scales;
- larger areas free of mammal pests, and keeping them free by effective monitoring, detection and rapid removal of reinvadors;
- maintenance and more public support for mammal pest control or eradication, especially where this involves toxins (e.g. the Predator Free New Zealand initiative).

Freshwater aquatic pests

Over 200 freshwater plant and animal species have been introduced to New Zealand and have colonised. Aquatic pests include micro-organisms such as didymo (*D. geminata*), a wide range of freshwater plants, various invertebrates, and a number of pest fish species, some of which continue to be deliberately and illegally spread for recreational fishing. The connectivity of aquatic environments and the flow of water through landscapes create special challenges for the control and management of aquatic pests, as the detection of these in aquatic ecosystems is expensive, and control options are limited.

Marine pests

New Zealand is heavily dependent on maritime trade with thousands of vessels visiting its shores each year. In 2010, a review of non-indigenous and cryptogenic marine species revealed more than 330 non-indigenous species recorded from NZ's marine environments, with just over half of these (178) known to be established here. Another 350 species whose geographic origins are unknown (i.e. they are "cryptogenic") were known to be present in NZ's waters. Marine pests include micro-organisms, large kelp species, and a wide range of invertebrates such as crabs, tubeworms, and sea squirts. Most have arrived with shipping, either attached to the submerged surfaces of vessels and/or marine structures (biofouling) or in the ballast water carried by ships. Pest species are also transported on fishing and marine farming equipment, as well as being spread through aquarium material or introduced deliberately.

Taking action – prioritisation

In the face of such a variety of potential threats, it is important to prioritise research and action. Identification of potential threats before they become uncontrollable is a challenge because of the unpredictable behaviours of threat species across the diverse range of New Zealand ecosystems. Certain risk assessment approaches may bring benefits in preventing the introduction of invasive species but these are not foolproof and depend strongly on knowledge of prior history[40]. Alternative approaches are to prioritise candidate species using life-history traits to identify the likelihood of successful control. For instance, for weeds this approach identified Japanese Honeysuckle (*Lonicera japonica*) as potentially posing a very high risk of accelerated spread when different global clones mingle and set seed[41]. Science, rather than intuition, must therefore inform decision making. The Biosecurity Science Strategy was implemented in October 2007 to assist with prioritisation.

Case Study: Nassella tussock

Nassella tussock (*Nassella trichotoma*), a grass species of low digestibility to sheep, invaded indigenous tussock-grasslands in the eastern parts of the Marlborough and Canterbury regions of New Zealand during their exploitation for pastoral farming from the 1860s. By the early 1900s near monocultures of the weed had developed. Since the renovation of these infested grasslands in the mid 20th century, re-invading plants have been removed annually by digging them out in regionally-coordinated management programmes. This effort has resulted in densities that no longer reduce live-weight gains of sheep and other grazing animals[42]. Whether or not the continuous management of this weed is worthwhile is a topic of intense debate by farmers and scientists. To help inform this debate, the potential range of Nassella tussock in New Zealand has been estimated using a climate model developed from global distribution data, revealing vast tracts of land, particularly in eastern Canterbury and Otago, which are climatically suitable, yet unoccupied by the weed. Regional authorities can now target sites for surveillance that are most at risk of invasion and a computer simulation model is being used to develop a long-term economically optimal strategy for the future management of this weed.

Case Study: Research underpins aquatic weed eradication

New Zealand has a remarkable history of eradication of aquatic weeds. Successes range from national eradication of hornwort (*Ceratophyllum demersum L.*) (the most damaging weed in the North Island)from the South Island and many local eradication successes. These successful projects are underpinned by research aligned with management. An example of this is the control of the world's worst submerged aquatic weed *Hydrilla* *verticillata* (hydrilla). Hydrilla was identified in New Zealand in the early 1960s, fortunately in isolated Hawkes Bay lakes. In the USA a similar limited invasion became a huge problem, with more than US$200M spent managing over 100,000 ha of the weed in Florida alone, and with continued spread to most mainland states. Over 20 years of research into its control in New Zealand has resulted in a Ministry for Primary Industries (MPI) eradication effort in the National Interest Pest Response (NIPR) programme. NIWA aquatic biosecurity team research involved field and laboratory testing of herbicides and the use of herbivorous fish (Chinese grass carp (*Ctenopharyngodon idella*)). The programme, initiated in 2008, has led to the virtual elimination of hydrilla in all water bodies with the risk of escape to other parts of the country now negligible.

Pest management tools and strategies

There are a number of tools of varying effectiveness for eradication or suppression of weeds, pests and diseases.

Pesticides: Pesticides of one form or another have been used in all major pest control or eradication programmes since the 1800s. Early programmes against insects used environmentally hazardous and/or persistent materials that are no longer acceptable, including nicotine and organochlorines such as DDT (dichlorodiphenyltrichloroethane). Similarly, programmes against weeds in the early 1900s used the explosive sodium chlorate to control ragwort and other weeds. Across the spectrum, from new incursions to mitigation of existing pest threats, strategic planning and coordination will be required to apply tools at the appropriate scale and frequency to be effective. This requires a sound knowledge of the biology of each pest species and its impacts, as well as proper integration of tactics.
The trend now is away from broad-spectrum and persistent products towards more selective agents, for example the toxin para-aminopropriophenone (PAPP) for the control of stoats (*M. erminea*). Some insecticides are very short-lived (e.g. biological insecticides which contain living organisms or the toxins produced by them) to improve their environmental safety, but may require repeated applications. Such products may operate through direct contact (e.g. aerosols) or require ingestion while feeding (*Bacillus thuringiensis kurstaki* or Btk), and a few may be acquired systemically through the vascular system of plants (neonicotinoids). Insect Growth Regulators (IGRs) and ecdysone agonists disrupt development through acting on insect endocrine systems. They tend to be very selective and, although some are quite persistent in the environment, their generally low environmental impacts make them attractive for use in sensitive ecosystems.

For insects, the lure-and-kill tactic combines a pheromone or other attractant with a contact insecticide and a viscous carrier material. The aim is to control the target species by attracting it to large droplets of the formulation causing mortality shortly after contact[43]. It is more acceptable than many other tactics because few species other than the target are likely to contact the pesticide. It is applied at much lower rates than in other applications such as generalised spray application.

Biological control: Biological control is the control of a species through the introduction of a natural enemy, the augmentation of native herbivores, predators or parasites[44], or by bio-pesticides that utilise naturally-occurring pathogens. Cost-effective control has been achieved against invasive invertebrates in New Zealand pastoral ecosystems[45]. While international results from “classical” biological control, involving the release of natural enemies for the suppression of weeds and invasive invertebrates, have been mixed with only about 10% of releases since 1880 being seen as successful worldwide[46], in New Zealand the impact on reducing target weeds is reported to be as high as 50 to 83%[47]. In general, the large number of current and future weed species presents a challenge to biological control programmes relying on highly host-specific agents. Future research needs to help to improve the success rate of biocontrol agents through analysis of 'what worked' in the past, and how biological control can be better integrated with grazing management and chemical and physical control. For example, the efficacy of existing biocontrol agents may be enhanced by ecosystem manipulation[48]. Inundative methods which involve suppression of pests by mass rearing and release of natural enemies are relatively underdeveloped in New Zealand, partly due to the very small market.

In its broader sense, biological control also includes plant host resistance. Exploiting naturally-occurring obligate biotrophic endophytic fungi (*Epichloë*/*Neotyphodium* spp.) to control pests of ryegrass (*Lolium*) and tall fescue (*Festuca arundinacea*) in our pastures has been highly successful[49]. Reducing the impact of diseases such as striped rust in cereals relies on plant resistance, although loss of resistance can be a problem. A major programme is also underway to identify varieties of kiwifruit (*Actinidia deliciosa*) with resistance/and or tolerance to Psa (*P. syringae actinidia*). Traditional breeding methods accelerated by marker-assisted selection (which identify traits rather than modify genes) has also been successfully used to incorporate plant resistance mechanisms but transgenic modification remains a controversial area in New Zealand and also its use is still a barrier for some of our international trade partners. A better understanding of how it works, and its benefits and risks, may assist with acceptance of this technology in New Zealand

Physical methods: Mass trapping[50], shooting[51], or manual removal can be used in reducing the population size of some pests[52].

- Shooting is frequently used to control large species such as red deer, wild pigs, and goats, either by ground-based hunters or from helicopters[53].

- Manual removal of weeds in managed and natural ecosystems is applicable when population densities are low. This approach, termed rogueing, is valuable when targeting specific weeds that pose a specific threat such as the recent incursion of black grass (*Alopecurus myosuroides*) as a result of seed spillage in Canterbury.
- Physical treatment tools have been successfully trialled in the marine environment (e.g. smothering pests with geotextile fabric, polyethylene or dredge spoil[54], as well as heat treatment[55].

Fertility control: Fertility control of vertebrates has been attempted[56] and mating disruption for insects is often used in New Zealand to control moth pests using synthetic pheromone formulations in orchards. Mating disruption technology is now supporting more than $100M of apple exports per annum, using multiple species blends of synthetic pheromones now regulated under a Group Standard[57]. This benign technology can be applied aerially or from the ground.

Case study: Mating disruption in apple orchards supports market access
New Zealand's apple sector is spread across a range of environments each with their own pest and disease pressures. By 2009, 65% of apples produced were grown under the Apple Futures programme which met the phytosanitary requirements of over 65 countries and were either residue-free or with residues below 10% of EU regulatory tolerances. Crop production guidelines now use computer modelling to optimise disease prediction, establish monitoring regimes for insect pests and beneficial organisms, develop pheromone-based mating disruption systems to reduce insect pest populations, and inform targeted spraying of selective pesticides. Pesticide residues on fruit at harvest have been reduced to significantly below regulatory requirements and below even the most stringent levels required by leading European supermarkets. Currently, around 30% of the New Zealand pipfruit industry is using a mating disruption system, resulting in a total saving on pesticides of around $670,000 per year. The pesticide load in the environment has been reduced and pesticide ingredients classified as 'Extremely' and 'Highly Hazardous' to human health have been dispensed with. The New Zealand Institute of Economic Research estimated the Apple Futures programme has preserved up to $113 million of the pipfruit industry's revenue over the last four years. These types of integrated pest management programmes also deliver more ecosystem services, such as higher functional biodiversity against secondary pests[58].

The sterile insect technique (SIT): SIT plays a significant role in containment and eradication programmes for certain pests around the world, such as screw worm (*Cochliomyia hominivorax)*[59]. Area-wide inundative releases of sterile insects can reduce the fertility of a field population but for SIT to be used as an operational method during eradication, several criteria must be met[60]. As with mating disruption, treated areas must be large enough and/or isolated enough so that the effect of immigration from surrounding areas is minimised[61]. The use of SIT as a control tactic has many advantages, including species specificity and compatibility with the use of most other control tactics.

Other methods: Fences[62], and grazing and manipulation of plant competition will become more important if reliance on herbicides declines and herbicide resistance becomes more widespread. Breeding for pest resistance is one of the main techniques for plant disease control, but such programmes rely on the ownership and availability of suitable germplasm, making this tactic rather specialised and more useful in the long-term to reduce disease pressure.

Pressures on pest management tools

Pressures on pest management tools remain a major policy challenge. With pesticides, for example, pressures arise due to changes in public and environmental acceptability, the development of behavioural or biochemical resistance to control techniques, and the incursion of pests without any apparent means to deal with them.

Evolved resistance
There are now many cases of evolved resistance to chemical pesticides where formerly useful pesticides are now no longer effective against their target pest, which has led to the development of resistance management strategies[63]. The evolution of genetic resistance in Norway rats to anticoagulant poisons has caused great concern in Europe[64], while New Zealand has examples such as resistance of apple Black Spot (*Venturia inaequalis*) to the current fungicide regime. Anthelmintic resistance is also a significant issue in New Zealand livestock. A possible risk might also come through the loss in efficacy of biocontrol agents due to co-adaption as a result of selection pressure[65]. Pesticide resistance management strategies are vital to ensure the sustainability of current pesticides, and this requires research to find alternative mode-of-action synthetic chemical pesticides and other non-chemical approaches. A 'toolbox' of options is needed that can be used in a rotational manner to reduce selection for resistance in pest populations. For example, New Zealand agriculture benefits from having relatively few herbicide resistant weeds but should the recent appearance of glyphosate resistance become more widespread, the annual cost to the arable sector could be NZ$25-50 million[66] and the wider spread of herbicide resistant giant

buttercup could cost NZ dairy farmers $750 million in lost milk solids revenue[67].

Controversy arising from differing human values and perceptions

Millions of pest animals are killed annually and control programmes, especially those focusing on vertebrates, often generate strong, negative public reactions[68]. Even classifying certain animals as pests is controversial. Some species (e.g. deer and trout) are considered pests by some but a resource by others[69]. Proposed control of species such as cats generates a great deal of heated debate, because while domestic cats are companion animals, cats (both domestic and feral) are also a major predator in New Zealand ecosystems. The 'cat debate' flares occasionally in the media, and the ensuing furore often results in a greater awareness of the potential impacts of such species on native fauna. Aerial delivery of toxins such as sodium fluoroacetate (1080) still occasions vehement protest[70]. While the risks and benefits of 1080 have been well documented[71], opposition to aerial poisoning continues.

In New Zealand the conservation estate (i.e. wilderness) is clearly distinguished from farmlands. This is in contrast to the UK where the British public regard their farms and surrounding areas as (effectively) their national parks and centres of biodiversity. This delineation creates a rather different dynamic between users of farms and conservation areas in New Zealand when it comes to pest management. There is also a contrast in New Zealand attitudes to the use of chemical treatments in the marine environment as opposed to productive terrestrial ecosystems. For example, few mussel farmers use chemicals to control biofouling in New Zealand, although in other countries, chemicals have been used to eradicate or manage marine pests such as the Black Striped Mussel (*Mytilopsis sallei*) in Darwin[72] and 'Killer Algae' (*Caulerpa taxifoli*a) in southern California[73].

Animal welfare

The welfare impacts of pest control are increasingly scrutinised in New Zealand[74], and this needs to be taken into account when assessing the overall costs and benefits of pest control operations[75]. Considerable attention has been given to improving and assessing the relative humaneness of traps[76] and poisons[77]. New Zealand is at the forefront of incorporating ethical and welfare principles internationally[78], but if the country's use of a wide range of pest control tools is to be maintained, vigilance will be required in terms of international trends in this area.

Potential new tools

There is a need to develop new approaches and improve the use of existing tools, in part to counter the loss of older and less acceptable pest management tools, including pesticides, and to have a range of tools to cover different species and different situations. Pesticides are likely to continue to have a role for the foreseeable future, but the rising costs of development and increasing demands for sustainability will continue to limit their flow into New Zealand.

Develop fertility and biological control methods

In response to growing concerns about the lethal control of animal pests, there has been a concerted effort to develop fertility control methods for possums and marine biofouling pests[79]. Recent advances include the potential use of Vaccinia virus as a delivery mechanism for fertility control agents[80] and more recently, the Trojan female technique[81] which aims to produce infertile males through the female mitochondrial line. No successful option for self-disseminating fertility control of small mammals such as rodents has been developed for broad-scale application anywhere in the world[82], although much research has be done on this approach for invasive fish such as carp[83], and research is being undertaken on developing transgenic strains of insect pests carrying genetic systems that are lethal to females under certain conditions[84].

In response to increasing need for additional pest management technologies, research continues on the use of biocontrol methods for rabbits (specifically, rabbit haemorrhagic disease)[85], but not for any other vertebrate pests. There is also research being done on encouraging sea urchin (*Evechinus chloroticus)* populations for the biocontrol of biofouling organisms[86], and on the development of koi herpes virus for managing that species in lakes and streams. The use of pheromones and other attractants for beneficial insects offers some promising leads, in areas such as weed and insect classical biological control[87], as well as in aquatic environments for some invertebrate species, including paddle crabs.

Identification of new weed control agents

Microbially-based biopesticides show great promise although currently lacking reliability and effectiveness, and work is continuing on improving them and their cost-effectiveness (e.g. their shelf-life)[88]. Biological control in broadacre agriculture is particularly important because scale prevents the extensive use of pesticides. The identification and development of classical biological control solutions is also a promising area for development because of its strategic alignment with trends towards residue-free production for export. Arthropod biological control agents are hard to deploy successfully, and require detailed long-term research including consideration of non-target impacts. However, some candidates have no New Zealand relatives, and non-target impacts are less of an issue. Importation of generalist biological control agents for release in glasshouse crops may present challenges to regulators as these agents can be expected to have wider ecological consequences outside the glasshouse.

Case Study: Increasing effectiveness of biological control of weeds
With a pool of 25,000 exotic plants in New Zealand, some 2500 of which are naturalised, control of weeds of concern to both the environmental and production sectors is paramount. Classical biological control offers a tried-and-true means of large-scale suppression of ineradicable weeds, with no cases of biocontrol agents having a negative effect on indigenous biota for over 50 years in New Zealand. The next big challenge for weed biological control is to achieve a higher rate of success of agents at a landscape scale. Wide-host-range bioherbicide fungi may have a future role at this scale[89] as may herbivorous insects[90]. For example, New Zealand has no native plants and virtually no economic plants in the "thistle" family, a group that makes up 25% of all pastoral weed species in New Zealand. Biocontrol agents that feed widely across this group could be introduced that would potentially control many of New Zealand's most damaging thistle weeds and potentially prevent garden thistles from becoming a problem in the future.

Improving existing tools for vertebrate pests

Vertebrate toxic agents (VTAs) and control devices for mammal species such as possums, stoats, rabbits, feral cats, and rodents[91], are currently being developed. Recent innovations under development include a self-resetting trap (the 'GoodNature' trap[92]) and species-selective, multi-dose devices that spray toxins (such as Para-aminopropiophenone (PAPP) or sodium nitrite) directly onto the fur of pests such as possums or stoats. Such tools hold promise for use in less accessible areas. Other research has optimised use of existing traps and shown the circumstances under which several single-capture kill-traps deployed at one location may be more cost-effective than multiple-capture traps[93]. Recent significant improvements in the use of VTAs mean the same kill rates can be achieved with a fraction of the amount of toxic bait used in the 1970s to 1990s[94]. The use of synergists acting in tandem with the toxicant to either speed up the animal's metabolism, leading to more rapid death, or as analgesics to minimise suffering, will significantly improve the humaneness of these methods[95]. Food-based lures are currently used to attract pests to control devices, but pheromone-based lures may increase the effective search area of control devices and the probability of animals interacting with them[96].

Non-target risks of VTAs have encouraged a shift from the use of broad-spectrum VTAs to species-selective VTAs[97]. New Zealand has led the way in this area, with development of the first new rodenticide with enhanced efficacy for the genus *Rattus* since the formulation of brodifacoum 25 years ago[98]. Species-selective VTAs show great promise because they are designed to have no impacts on non-target species, so can be used on areas of mainland New Zealand, such as farmland or urban areas, where broad-spectrum VTAs pose risk to domestic animals. So far, research and development efforts have been restricted to rats, but the concept would be readily extendable to a range of small mammal pests such as rabbits, possums and mice. A key issue that urgently needs to be addressed with the development of new vertebrate pest control tools is the extremely long time frame between development of the product, its registration for field use, and hitting the market shelves (sometimes it can take 20 years[99]).

Developing and maintaining biosecurity tools for aquatic weed management

The options to manage aquatic weeds are severely limited, with most emphasis put on prevention of spread, and surveillance for early detection. Until 2005, only two herbicides were registered for use in aquatic areas and these proved ineffective against a range of high-impact species including *Spartina anglica* and *S. alterniflora* (spartina), *Alternanthera philoxeroides* (alligator weed) and hydrilla. After extensive research, three new herbicides are now available for aquatic use and two other highly selective herbicides were permitted under previous permissions from the Pesticides Act (1979). Through this work, the impact of these highly invasive species has been successfully reduced. Use of four of these herbicides under aquatic situations was recently reassessed by the New Zealand Environmental Protection Agency (EPA) for 'hard to control' weed species in marginal edges of aquatic systems. New options for biocontrol of aquatic weeds are also being actively pursued. These initiatives have expanded the aquatic weed control toolbox, providing management agencies with effective selective control options and permitting improved biosecurity.

Monitoring and surveillance

Early detection is an essential prerequisite for successful pest incursion eradication[100], as it enables action to be taken while the distribution of an invader is still contained. The availability of lures increases the probability of invertebrate pest eradication by more than 20-fold but are simply not available for many pests. Models of potential pest or weed distributions enable territorial authorities to target their surveillance operations to sites where pests or weeds new to the region are most likely to establish.

New approaches

Unless a pest is highly conspicuous it can be extremely difficult to find the first few invaders, re-invaders, or the last few survivors[101], and this is particularly difficult for incursions of micro-organisms, such as plant pathogens. Increasingly, Bayesian inference is used to assess uncertainties to assist managers in the interpretation of surveillance data[102]. New technologies are also being employed to help with this effort including the use of information technology to move pest management towards "real time" control[103]; and the use of pheromones and other odorants to uncover the presence of an invader[104], determine its geographical distribution, and monitor its population, all of which are critical elements of eradication and pest management programmes. Sex pheromones are now available for about thirty horticultural and other insect pests[105]. The development of a Group Standard for moth pheromones under the HSNO Act (1996) supports innovation in pheromone technology for control, although pheromones for all other insects are still regulated individually[106].

Techniques such as environmental DNA sampling in waterways can also improve aquatic monitoring and surveillance, with research needed to improve the ability of environmental DNA methods to detect unwanted organisms[107]. More trained local and central government staff (e.g. regional council and fisheries officers), are needed to assist with translating and applying scientific research and these new technologies to this effort.

Organisation and coordination

The division of resources between monitoring and surveillance activities versus eradication and control activities is a challenge. There is a need for an agreed set of priorities across the various levels of government. These may include issues such as who it is that provides monitoring, where this should be carried out, and why. Decisions also have to be made with regard to the duration and rigour, and after discovery, what happens next. For example, there is a clear agreement on what to do when foot and mouth disease (*A. epizootica*) or new Psa-V infections of kiwifruit are detected as there are strong economic drivers to respond. The action required when dealing with natural ecosystems is not clear, and pest control responses can vary. An example of this is the marine Mediterranean fanworm, a major pest of shorelines, which can reduce native biodiversity and has significant indirect effects on nutrient cycling in marine environments. It was detected in Lyttelton Harbour in Christchurch in 2008 and in Waitemata Harbour in Auckland in 2009. Soon after its discovery in Lyttelton, an attempt was made to eliminate it, and its density was reduced to less than 3% of its original level. Conversely, no action was taken in the Waitemata, and the population there has since undergone rapid radiation throughout the harbour, with new satellite populations now detected in Whangarei, Tauranga and Nelson[108].

When eradication attempts are carried out, monitoring and surveillance need to continue for sufficient time to ensure eradication success. It can be difficult to find equal enthusiasm for funding on-going control versus targeting funding on new eradication elsewhere. This was a hard learned lesson for the Animal Health Board (now TBFree New Zealand) in its efforts to control bovine Tuberculosis (TB) via reduction of possum numbers (possums being the primary wildlife vector of the disease). The re-emergence of TB in livestock in the 1980s and early 1990s occurred as a result of reduced funding for possum control[109]. In spite of such evidence, convincing stakeholders that it is worth the extra effort to achieve full eradication (of a disease or pest) remains an ongoing challenge[110].

In undertaking monitoring and surveillance, there are opportunities for Citizen Science in empowering local enthusiasts to look after local areas and waterways. For example, botanical societies have engaged with wilding pine removal and old man's beard (*Clematis vitalba*) control. A recent survey assessed whether there were on-going monitoring activities being carried out around New Zealand that could be harnessed for a national surveillance programme for 'new-to-New Zealand-species'. The results identified a widespread and diverse range of habitats that were regularly monitored and sampled, based on a diversity of technical skills and taxonomic capabilities that could be harnessed for national surveillance programmes[111].

Need for specialist taxonomic and ecological expertise

Biosystematics is the scientific discipline that classifies and names the diversity of life, provides a conceptual framework for understanding the relationships of species, and is underpinned by national collections of biological specimens. The names of, and relationships between, organisms provide a critical entry point into databases and existing knowledge to discriminate native from non-native organisms.

Improving the ability of border biosecurity and pest management to distinguish native from exotic species requires significant action. The first requirement is that there is a good understanding of the native flora and fauna. For many groups of organisms in New Zealand the discovery and documentation of the native biota is significantly incomplete and distributed across multiple databases found in various agencies. Often there are no adequate reference materials or descriptions of key groups of native organisms related to potential exotic pests. Second, identification requires that the target organism can be recognised as being of interest. This requires front-line staff to be very familiar with the local flora and fauna and able to distinguish unusual specimens. Third, there is a need for experts with a broad knowledge of the particular groups of organisms of interest. The experts need to be familiar not only with New Zealand species, but also with specialists worldwide and their associated networks, who can rapidly undertake comparative analyses to determine if the target organism is foreign. New Zealand lacks critical skills and biosystematics infrastructure to identify many major groups of organisms that include pests. Overseas expertise is already employed to identify organisms in a number of groups, but there are significant risks in not having resident expertise which gives a capacity for continuing surveillance, and the ability to provide rapid answers and information.

Conclusion

This contribution has highlighted the inescapable importance of effective pest management in New Zealand under changing circumstances. Considerations include on-going arrival of invasive species, declining effectiveness of existing control, changing land use and climate change. Accentuating these is growing political and social concern about some existing pest management technologies, and the growing demands of international trade for quality assurance. Doing nothing is not an option because of New Zealand's unique dependence on its environment and need to maintain its reputation for high quality, residue-free and ethical primary production.

New Zealand's natural environment also poses unique challenges particularly regarding control of vertebrate pests. Pest management in aquatic environments presents its own set of challenges and difficulties not the least because of a lack of political and public awareness.

The inherent limitations of existing pest management approaches underline the need for either new technologies or on-going refinement of existing methods. In particular there needs to be a trend away from the use of pesticides to more knowledge-intensive, biologically based control systems. This being the need, undoubtedly there is a need for intensification and integration of existing research effort. This applies equally to microbial, plant, invertebrate and vertebrate pest management but also beyond the organisms to ecosystem function. Furthermore, as pest management becomes more sophisticated, a higher level of expertise will be required of all parties involved.

In addition to scientific research there is real opportunity for more citizen involvement, particularly in the area of biosecurity surveillance. New Zealand is fortunate to have a motivated population concerned about the quality of the environment. Additionally it will be necessary to engage early with the public over novel pest control tactics or risk losing the battle for control of pests.

Finally, the increasingly sophisticated nature of pest management and biosecurity surveillance inevitably requires improved linkages and integration of pest management science and central and local government operational agencies. This is an area where already excellent progress has been made.

Further information

This paper was authored by a Royal Society of New Zealand panel chaired by Dr Matt McGlone FRSNZ. The Panel members were: Dr Graeme Bourdôt, Dr Andrea Byrom, Professor Mick Clout FRSNZ, Dr Stephen Goldson FRSNZ, FNZIAHS, Dr Wendy Nelson FRSNZ, Dr Alison Popay, Dr Max Suckling FRSNZ, and Dr Matt Templeton.

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For further information, please contact info@royalsociety.org.nz, or go to the Royal Society of New Zealand web pages: www.royalsociety.org.nz/pestmanagement.

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