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Large-scale pest control in New Zealand beech forests

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Graeme Elliott *and* ***Josh Kemp*** *work as scientists for the Department of Conservation (Private Bag 5, Nelson 7042, New Zealand; Tel: +64 3 5-463292; Email: gelliott@doc.govt.nz). The project arose as a consequence of large-scale pest control being undertaken in response to pest irruptions following heavy beech seeding.*

Summary In 2014, baits laced with the poison sodium fluoroacetate (1080) were sown over 694 000 ha of mostly native beech forests in New Zealand to control rats, stoats and possums – a landscape-scale pest control programme called 'Battle for our Birds'. This large pest control operation was necessitated by the mast seeding of beech trees which led to irruptions of rodent and stoats which were predicted to lead to decreases in vulnerable native wildlife. In this article, we describe why and how this extensive pest control programme was developed and implemented. We describe the seedfall monitoring that was used to determine the need for large-scale rodent and stoat control and the response of these predators to this control. We also provide a summary of the bird monitoring that was undertaken to demonstrate the effectiveness or otherwise of the programme.

Key words: *1080, Battle for our Birds, possums, rats, stoats, pest control.*

Introduction

Since the arrival of humans in New Zealand about 800 years ago, there has been a dramatic decline in New Zealand's fauna which continues to the present day (Holdaway 1989). The two main waves of colonisation (Polynesian about 800 years ago) and European (about 150 years ago) resulted in the introduction of a suite of mammalian predators to which New Zealand's bird biota was poorly adapted. Predation by introduced Common Brushtail Possum (*Trichosurus vulpecula*), Stoat (*Mustela erminea*) and rats (*Rattus exulans, Rattus norvegicus, Rattus rattus*) has been identified as the main cause of declines amongst birds and continues to be the main threat to New Zealand's avifauna. Today, 41% of New Zealand endemic birds are extinct and 77% of the remaining forest birds are declining or threatened with extinction (Innes *et al.* 2010).

History of pest animal control in New Zealand

Attempts to suppress possums, rats and stoats in New Zealand have occurred in three phases: (i) large-scale possum control was initiated in the 1950s because of the damage they caused to forest trees, and their role as vectors of bovine tuberculosis (Cowan 2005). Control was primarily undertaken by distributing baits laced with sodium fluoroacetate (1080) poison from aircraft, although ground-trapping and hand-laying poisons were also used. (ii) From the mid-1980s, attempts were increasingly made to eradicate introduced mammals, particularly rats, from islands, and these eradication attempts were greatly facilitated by the availability of potent second-generation anticoagulant toxins and the adoption of navigational guidance systems for aircraft laying baits (Towns *et al.* 2013). (iii) Since the 1990s, there has been increasing public acceptance of the importance of predator control to reduce predation of native wildlife (Russell 2014) and an increasing focus on suppressing rats and stoats as well as possums (which are also predators) in mainland forests.

This suppression was initially undertaken using traps and poison laid in bait stations, but pest control has been undertaken over increasingly larger areas by applying 1080 from the air. Although 1080 has been used since the 1950s to control possums, its use to control rodents and stoats as well as possums is more recent. Only recently was it discovered that 1080 is a consistently effective rodenticide when used with prefeed (Josh Kemp, unpublished data, 2007, DOC); and 1080 has also been found to be effective at killing stoats through secondary poisoning when stoats eat poisoned possums and rodents (Murphy *et al.* 1999).

The strategies developed for control of rats, stoats and possums in mainland forests are different to those for island eradications. On the mainland, the focus is on cost-effective control of pests in the face of their inevitable recolonisation, whereas on islands, the focus is on killing the last animal at almost any cost. This difference has led to the widespread use of anticoagulant poisons used at high sowing rates for island eradications (Broome *et al.* 2014), in contrast to widespread use of 1080 with ever-decreasing sowing rates for mainland pest control (Parliamentary Commissioner for the Environment 2011).

Mast seeding in beech forests – and Battle for our Birds

Five species of beech (*Fuscospora cliffortioides, F. fusca*, *F. truncata, F. solandri* and *Lophozonia menziesii*) are important components of at least half of New Zealand's indigenous forests (Wiser *et al.* 2011). Beech trees are mast seeders: in most years, they produce no or very few flowers or seed, but once every 2–6 years, most of the trees in an area flower and produce large quantities of seed (Wardle 1984). As masting is related to climate, seeding amongst trees in an area (a catchment for example) is most often synchronised, but it is sometimes synchronised over much larger areas (e.g. South Island wide) and rarely over most of New Zealand (Wardle 1984).

Riney *et al.* (1959) speculated that mouse, rat and stoat numbers would rise following beech mast (as rodents feed on the seed and stoats prey on the rodents); and that this might lead to high rates of predation on forest birds. King (1983) confirmed that a seedfall–mouse–rat–stoat relationship did exist in beech forests and that higher rates of predation of forest birds resulted from the irruptions of these predators following a mast event. The impact of beech mast-induced rodent and stoat irruptions on forest bird populations became clear in the late 1980s when dramatic declines of Mohua (*Mohoua ochrocephala*) were detected following beech mast (Elliott & O'Donnell 1988; Elliott 1996; O'Donnell 1996). At the same time, the benefits of controlling the full suite of predators (possums, rodents and stoats) on threatened forest birds has also become much clearer (Innes *et al.* 1999; Moorhouse *et al.* 2003; Powlesland *et al.* 2003).

As a result of better understanding, the link between beech mast, rodent and stoat irruptions, and predation on forest birds, the New Zealand Department of Conservation (DOC) decided in 2003 that it was critical to deal with these predator irruptions through active predator control during mast events (Elliott & Suggate 2007). In response to high rat and stoat numbers resulting from a widespread heavy beech mast event in 2014, DOC undertook the largest aerial 1080 operation ever covering 10% of New Zealand's indigenous forests, dubbed 'Battle for our Birds'. This programme involved the aerial spreading of cereal-based baits laced with the poison 1080 over 694 000 ha of mostly beech forest in which irruptions of rodents or stoats were occurring. In this article, we provide an overview of the management approach taken by DOC to the 2014 predator control programme and present a qualitative summary of the effect this had on rat and stoat numbers (the main predators). We provide a summary of the bird monitoring that was undertaken to demonstrate the effectiveness or otherwise of the programme, but detailed data and analyses of bird responses are not provided here as they are being published separately.

Methodological Approach to Large-Scale Pest Control in Response to Beech Mast

Aerial 1080 operations to control rodent and stoat irruptions are best undertaken between July and November (see 'The timing of 1080 operations'). For financial and legal reasons, planning for such operations has to be undertaken as much as 2 years beforehand. That is, where a large number of operations are desirable, DOC may not be able to fund them from within its normal budget and will need to try and secure extra funding: this needs to happen at least a year in advance of any 1080 operations. The legal permissions necessary to undertake 1080 operations can take between 2 months and 2 years to be granted depending on the local authority rules and the degree of public interest in 1080 use at a site. For these reasons, having legal permissions already in place and being able to predict beech seedfall

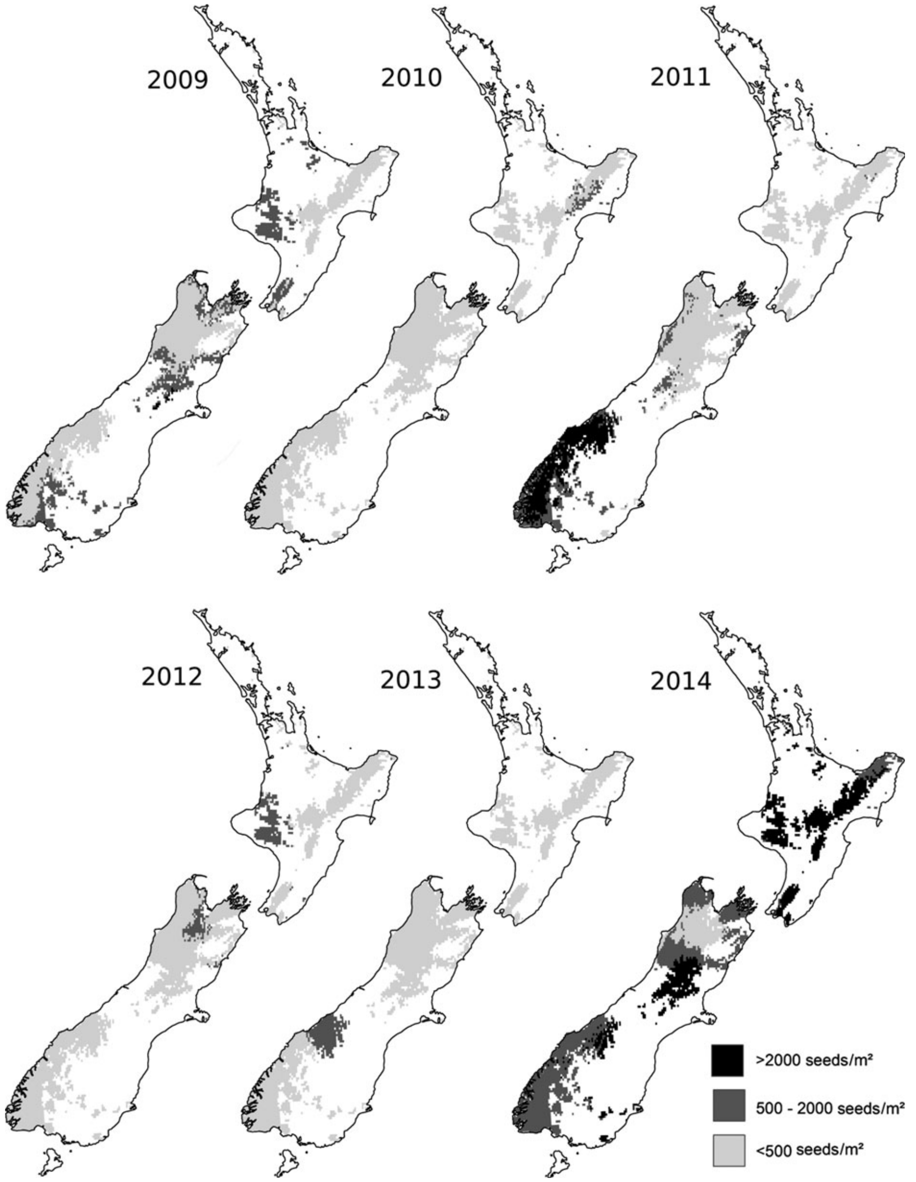

Figure 1. Beech seedfall predictions between 2009 and 2014 based on a modified version of the seedfall model described by Kelly *et al.* (2013).

and subsequent predator irruptions are very important in the planning and implementation of large-scale 1080 operations.

Predicting and measuring beech seedfall

A relationship between beech seedfall and previous summer temperatures has been known since at least 1948 (Poole 1948), and this idea was examined quantitatively by Allen and Platt (1990), Schauber *et al.* (2002), Kelly *et al.* (2013), Allen *et al.* (2014). During the winter of 2013, we used a model to predict the likely seedfall in 2014.

The most recent models of climate and beech seedfall (Kelly *et al.* 2013; Allen *et al.* 2014) are for single species, but as there are no accurate maps of the distribution of the various beech species, we could not use predictions of the seedfall of individual beech species to predict the total seedfall at sites around New Zealand. To make New Zealand-wide seedfall predictions, we therefore modelled the relationship between the total seedfall at sites (all beech species combined) and summer temperatures following Kelly *et al.* (2013). We used seedfall data collected from 51 sites at which seedfall has been collected for between 1 and 42 years and modelled temperature data provided by the National Institute of Water and Atmospheric Research (Tait 2008 and https://www.niwa.co.nz/climate/our-services/virtual-climate-stations) which comprise estimated daily means, minima and maxima for each 0.05° square in New Zealand. We used generalised additive mixed models with normal errors to compare a suite of models involving a random site effect, T_{n-1}, T_{n-2} and ΔT, (where T_{n-1} and T_{n-2} are the summer temperatures in the two summers preceding a beech flowering, and ΔT is the difference between these two summer temperatures), varying combinations of summer months contributing to T_{n-1}, T_{n-2} and ΔT and a smoothed time term. Models were compared using AIC (Burnham & Anderson 2002). The best model included the random site effect, ΔT based on January and February temperatures and a smoothed time term. We used this model to predict seedfall in all beech forests in New Zealand and classified the seedfall predictions as low (<500 seeds/m^2), medium (500–2000 seeds/m^2) or high (>2000 seeds/m^2). Ruscoe *et al.* (2005) found that mouse populations in beech forest were unlikely to increase with seedfalls less than 500 seeds/m^2 and almost certain to rapidly increase when seedfalls were more than 2000 seeds/m^2, and our unpublished data suggest a similar response in rats. Our best model predicted that there would be widespread beech seedfall in the autumn of 2014 (Fig. 1) and therefore likely to be rodent and stoat irruptions in the following winter and spring.

These predictions pinpointed a likely treatment date of between winter (July) and summer (November, 2014) (see 'The timing of 1080 operations') and led to an approach by DOC to central government (in winter, 2013) for funding for the 2014 Battle for our Birds operation. At the same time, applications for the legal permissions necessary to undertake 1080 operations were made.

While climate predictions give an indication of whether or not a beech mast is likely to occur, the predictions are not always accurate (see Kelly *et al.* 2013). To determine whether predicted beech

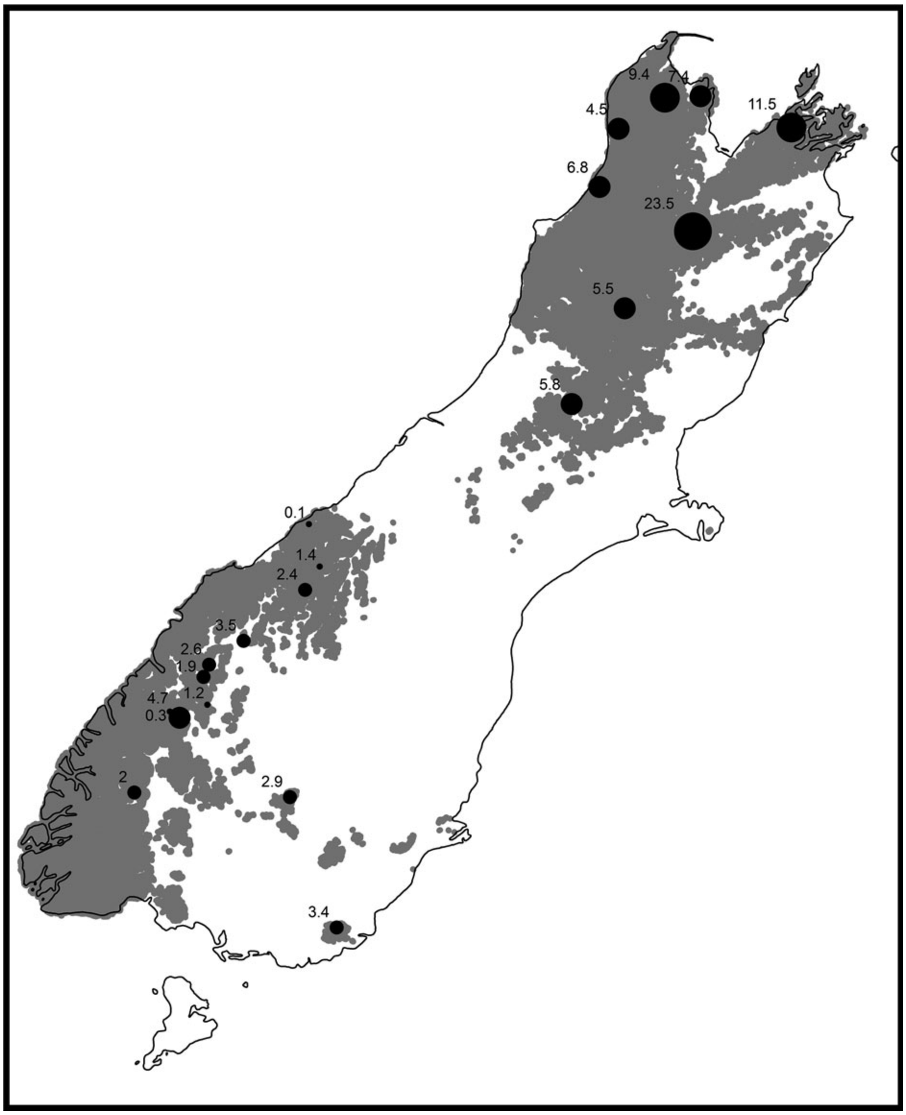

Figure 2. Seed production in beech forests in the South Island of New Zealand in March 2014. Black circles are proportional to the abundance of seeds counted (numbers are the average weight of seeds (grams) per 20 cm branchlet). Shaded areas represent forests with beech trees.

mast was actually occurring, seedfall was monitored in two different ways. Traditionally, beech seedfall has been monitored by placing traps in the forest and collecting the seeds that fall into these (Allen & Platt 1990). Most seed falls between March and May (Wardle 1984), and final seed collection occurs in June once seedfall has finished. The combined litter and seeds that are collected are then dried, and the seeds are separated and counted. Because of the time involved in this, final seed counts are often not available until July or August by which time the first pest control operations ideally should have already been undertaken. Seedfall collected in this way cannot contribute to decisions about implementing 1080 operations in time.

An alternative method has therefore been developed more recently by DOC to obtain an earlier indication of seed production. This involves shooting branches out of trees to count the number of developing seeds. Shooting occurs between January and March when seeds are developed sufficiently so that they can easily be counted, but before they have started to fall. Two branches are shot from each sampled tree, and all the seeds on 20-cm-long branchlets are counted. Based on seed counts obtained by shooting branches, it was confirmed that beech seeding was widespread in the South Island as all of the samples collected in March 2014 contained at least some seeds, with seed production highest in the north (Fig. 2).

Measuring and predicting predator abundance

While the response of mice and stoats to beech seedfall is predictable, their numbers invariably rise (King 1983), the response of rats is much less predictable. Therefore, while a heavy beech seedfall always means there will be a mouse and stoat irruption, there may not necessarily be a rat irruption. Clearly, the desirability of undertaking pest control is greater when mice, rats and stoats irrupt, than it is when only mice and stoats irrupt.

A network of about 10 000 tracking tunnels distributed throughout New Zealand's native forests has been established since 2006 to monitor rodent and stoat abundances. These tracking tunnels are mostly run at quarterly intervals according to the protocol of Gillies and Williams (2007). To predict the likely magnitude of rat irruptions, a model of the growth rates of rat populations has been developed using the tracking tunnel data collected between 2004 and 2013. For modelling purposes, tracking rates (the proportion of tunnels tracked) was transformed to make it (at least theoretically) linearly proportional to rat abundance (Caughley 1977). The model (Fig. 3) assumes that in the absence of 1080 poisoning, rat populations grow at a rate of about 1.2% per day during the period from the start of seedfall in autumn (March) until summer (about the beginning of December) by which time most of the seed has germinated. During the following summer and winter, the growth rates of rat populations are very variable, but on average, they continue to grow at a reduced rate of about 0.09% per day. At some time between June and November (15–20 months after seedfall), most populations crash back to their prebeech seedfall level.

Predictions of the likely peak magnitude of rat irruptions are made in February and May at the time of beech seedfall. Intensive studies of Mohua indicate that only when peak rat tracking rates exceed 30% do mohua populations suffer substantial damage from rat predation (Graeme Elliott and Josh Kemp, unpubl. data, 2016, DOC). As mohua are a particularly vulnerable species to predator irruptions (Elliott & O'Donnell 1988; Elliott 1996; O'Donnell 1996), the predicted rat tracking rate of 30% for Mohua impact is used as a threshold for initiating pest control for most threatened species. A 5% rat tracking threshold is used for the even more vulnerable Orange-fronted Parakeet (*Cyanoramphus malherbi*).

Prioritising sites for management

Biodiversity conservation in New Zealand undertaken by DOC has five objectives (Department of Conservation 2015):

1 A full range of New Zealand's ecosystems is conserved to a healthy functioning state

2 Nationally threatened species are conserved to ensure persistence

3 Nationally iconic natural features and species are maintained or restored

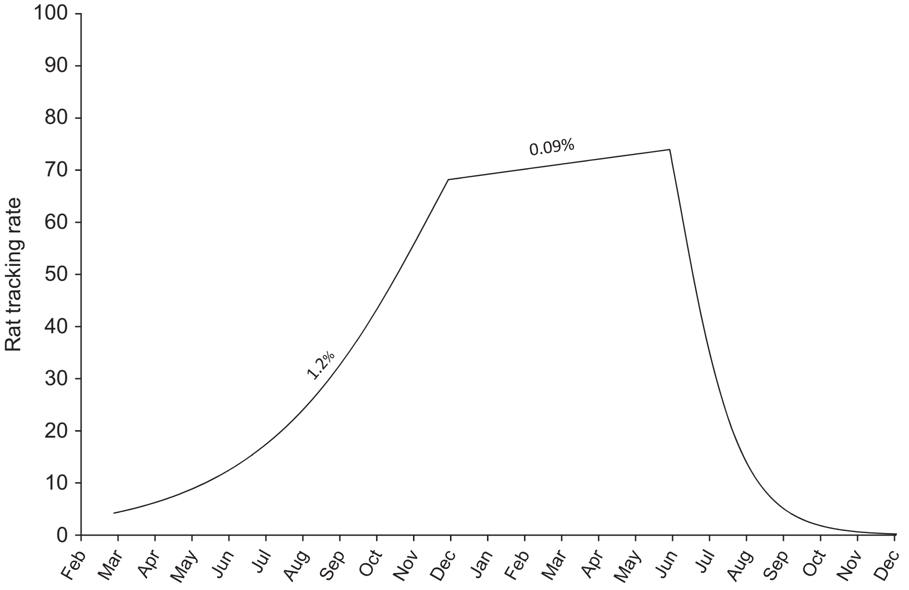

Figure 3. A model of the growth of rat populations in beech forest following beech mast. Rat tracking rate is the percentage of tunnels in which rats are detected. Figures on the graph indicate the daily population growth rate (Graeme Elliott & Josh Kemp, unpublished data, 2016, DOC).

4. Locally treasured natural heritage is maintained or restored in partnerships
5. Public conservation lands, waters and species are held for current and future generations.

The first two objectives aim to prevent extinctions and restore a representative sample of New Zealands' ecosystems, and DOC has developed a rigorous procedure ('Ecosystem Management') based on the software package 'Zonation' (Moilanen 2007) to selected and prioritise sites to meet these objectives. It is DOC's intention to manage these sites intensively. The Battle for our Birds programme is part of the fifth objective which aims to prevent local extinctions and provide some level of protection for threatened biota over as large an area of publically owned land as possible. Site selection procedures for the fifth objective have yet to be developed. Furthermore, the time between the recognition that predator irruptions were likely and the start of large-scale 1080 operations in 2014 was insufficient to allow development of an appropriate rigorous and data-driven selection procedure.

Site selection for the Battle for our Birds programme was undertaken by a committee comprising DOC managers and scientists with expertise in pest control and conservation of threatened species. The committee used their own knowledge, the knowledge of their colleagues and mostly unpublished data to choose sites. The most important criteria for choosing sites (Fig. 4) were as follows: (i) the beech trees at the site were seeding; (ii) rat and mouse tracking indicated that there would be an irruption of stoats and rats and/or mice; (iii) the site supported a population of a bird or bat species that was likely to suffer considerable decline if no attempt was made to suppress rodents or stoats; (iv) the site was highly ranked in DOC's Ecosystem Management system; (v) legal permissions to undertake a 1080 operation at the site had been granted or could be applied for and granted within the available time. In addition, a few further sites were treated with 1080 because they were already subject to regular 1080 control aimed at maintaining low possum densities to protect vegetation values and they were due to be treated again in 2014 anyway.

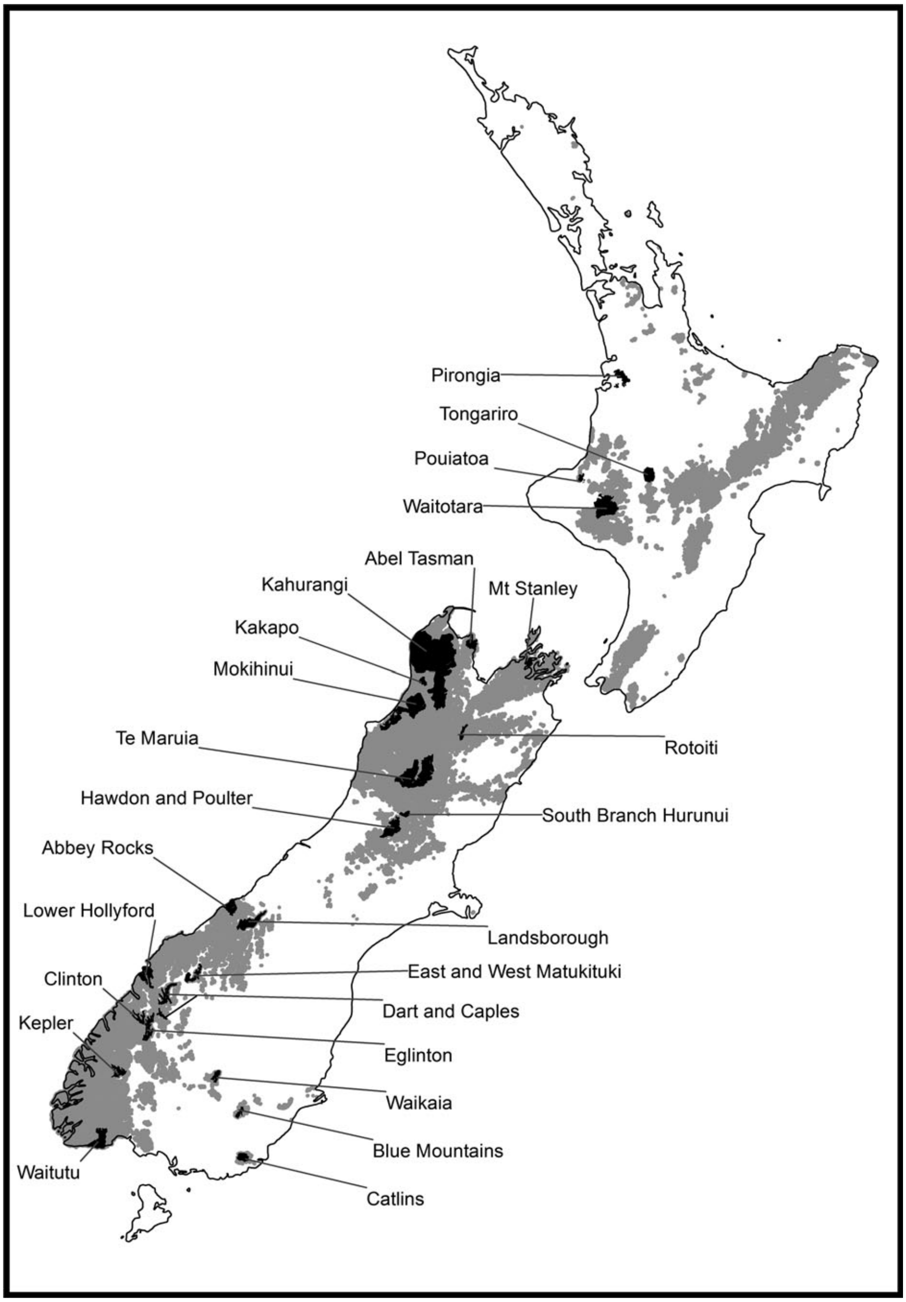

Figure 4. Sites at which 1080 poisoned baits were sown from the air in New Zealand during 2014. Shading indicates the extent of beech forest.

The timing of pest control operations

Ideally, the timing of predator control operations using aerially applied 1080 should be determined by both (i) the need to minimise rat abundance and (ii) logistic, weather and legal constraints. In May 2014, we used the measured tracking rates to predict the likely trajectory of the rat population abundance using our model of rat populations after a beech mast. We then modelled the likely impact of a 1080 operation and any subsequent rat recovery (Fig. 5) for operations carried out a range of times. For each site, this lead to a prediction of the optimum time

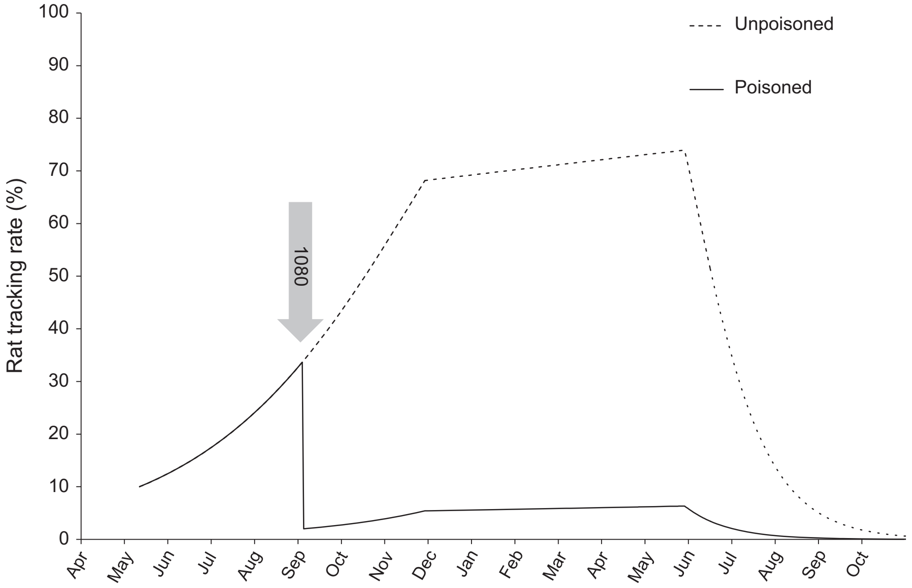

Figure 5. Optimum timing for a 1080 operation to control rats. The dashed line shows the predicted population trajectory for a rat population tracked at 10% on 15 May 2014, and the solid line shows the predicted trajectory for the same population that was poisoned on 7 September 2014 – the date that minimises the area under the rat-time curve.

Table 1. Sites and dates at which 1080-poisoned baits were sown from the air in New Zealand during 2014

Site	Area (ha)	Optimum date	Date of operation
Pirongia	16 040	–	22 Aug 2014
Pouiatoa	3965	–	8 Sept 2014
Tongariro	14 965	–	25 Aug 2014
Waitotara	52 000	–	8 Sept 2014
Abel Tasman	11 291	9 Aug 2014	24 Aug 2014
Mt Stanley	3932	21 Jul 2014	23 Nov 2014
Oparara (part of Kahurangi)	61 061	14 Jul 2014	8 Nov 2014
Gouland (part of Kahurangi)	55 959	–	15 Oct 2014
Anatoki (part of Kahurangi)	39 754	13 Jul 2014	11 Oct 2014
Cobb (part of Kahurangi)	50 067	3 Aug 2014	7 Nov 2014
Leslie (part of Kahurangi)	20 693	13 Aug 2014	26 Augu2014
Wangapeka (part of Kahurangi)	44 290	2 Aug 2014	14 Oct 2014
Kakapo	5728	14 Nov 2014	7 Nov2014
Rotoiti	13 714	14 Jul 2014	3 Dec 2014
Te Maruia – North	42 824	13 Jul 2014	22 Oct 2014
Te Maruia – South	36 977	13 Jul 2014	14 Oct 2014
Hawdon, Poulter, Hurunui	22 866	9 Nov 2014	1 Dec 2014
Abbey Rocks	15 390	16 Jun 2014	7 Nov 2014
Waikaia	6816	2 Oct 2014	27 Aug 2014
Catlins	10 089	14 Oct 2014	23 Nov 2014
Blue Mountains	4618	14 Oct 2014	2 Dec 2014
Landsborough – upper	25 572	22 Nov 2014	6 Nov 2014
Iris Burn	11 158	11 Sept 2014	25 Aug 2014
Clinton	9022	6 Nov 2014	21 Oct 2014
Dart – Caples	19 444	14 Sept 2014	31 Aug 2014
Eglinton	10 346	3 Sept 2014	12 Dec 2014
Hollyford – Lower	18 873	–	5 Nov 2014
Matukituki – West and East	7090	–	2 Dec 2014
Waitutu	29 360	18 Sept 2014	24 Aug 2014

for a control operation which would minimise rat numbers (Table 1). However, in practice, these predictions had only a small effect on the timing of operations, which were unfortunately constrained more by the availability of helicopters to spread the bait, the lateness of some legal permissions and weather.

Aerial treatments carried out

Cereal baits containing 0.15% 1080 were sown by helicopter over 694 000 ha of mostly native beech forests (Fig. 4) between 22 August and 12 December 2014 (Table 1). At most sites, 6 g non-toxic baits were sown at the rate of 1 kg/ha, and then, approximately 2 weeks later, identical toxic baits were sown at the same rate. Baits were distributed from hoppers slung under helicopters which spread bait in swaths between 150 and 220 m wide depending on the hopper. Flight paths are controlled by GPS to achieve complete coverage except that water supplies, large lakes and rivers, and areas of high human use are avoided.

The effectiveness of aerial control operations were assessed by:

1. Monitoring predators – that is comparing pre- and postcontrol rat tracking rates and stoat tracking rates in areas with and without control.
2. Monitoring birds – that is monitoring some vulnerable bird species to assess their productivity and survival.

Preliminary outcomes of the aerial control

Predators

Based on pre- and post-1080 control rat tracking rates at 25 South Island sites, rat abundances were substantially reduced in all the 1080 operations (Fig. 6). However, it was our aim to reduce rat tracking rates to less than 5% so that they cannot recover to the threshold level (30% at most sites). This was achieved at 72% of sites. The sites where rat tracking rates were not reduced to below 5% were mostly in the northern South Island (e.g. Mt Stanley, Te Maruia, Gouland, Leslie, Wangapeka, Rotoiti) and mostly at sites at which 1080 was sown much later than was optimal and at which tracking rates had risen to very high levels before the poison was sown. However, at some sites in the northern South Island with very high pre-1080 control rat tracking rates (i.e. Oparara, Anatoki and Cobb), tracking rates were reduced to near zero levels so any relationship between pre-1080 tracking rates and the effectiveness of 1080 rat control is not deterministic and we cannot be sure that high tracking rates necessarily mean low rat control success.

At most sites, only post-1080 tracking for stoats was undertaken because stoat populations vary less than rodent populations and stoat tracking is more expensive (it takes 3 days rather than 1 day per track line). We therefore assessed the operation's effectiveness at killing stoats by comparing the post-1080 control stoat tracking rates at sites where 1080 was used with sites where it was not (Fig. 7). Tracking rates at treated sites were lower than at untreated sites, but there were a few sites where post-1080 control stoat tracking rates appeared to be high. At some of these sites, weasels (*Mustela nivalis*) were caught in kill traps continuously run in the area at higher rates than they had previously been caught. It is difficult to distinguish stoat and weasel footprints in tracking tunnels, and weasels are much less abundant in New Zealand than are stoats (King 2005). It is possible that at some of the sites which appeared to have high post-1080 stoat tracking rates, they were actually weasel tracking rates. Distinguishing stoat and weasel footprints and assessing the effectiveness of 1080 at killing weasels will be foci of future research.

It is beyond the scope of this article to present more than a brief account of the recovery or otherwise of rodent and stoat populations following the 1080 operations. At some lowland podocarp–broadleaved forest sites and some upland beech forests sites, there was a disappointing and rapid recovery of rodents within a few months of the 1080 operations, while at other upland beech forest sites, there has been no rodent recovery at all. Stoat populations have typically been suppressed for at least a year post-1080 (Josh Kemp, unpublished data, 2016, DOC).

Birds

Only a summary of bird and bat responses to the 2014 1080 control operation is included here as the bird data and their analyses form the focus of other publications that are in preparation. As part of the Battle for our Birds programme, several indigenous bird and bat species were intensively monitored both to detect any mortality resulting from aerially applied 1080 poison and any increases in productivity that might occur because of a reduction in predation rates caused by a reduction in predator densities. Preliminary analysis of the bird and bat monitoring undertaken as part of the programme suggests an unequivocally positive response for several species monitored to date.

Mortality of some bird species during 1080 operations is known to occur (Veltman & Westbrooke 2011; Morris *et al.*

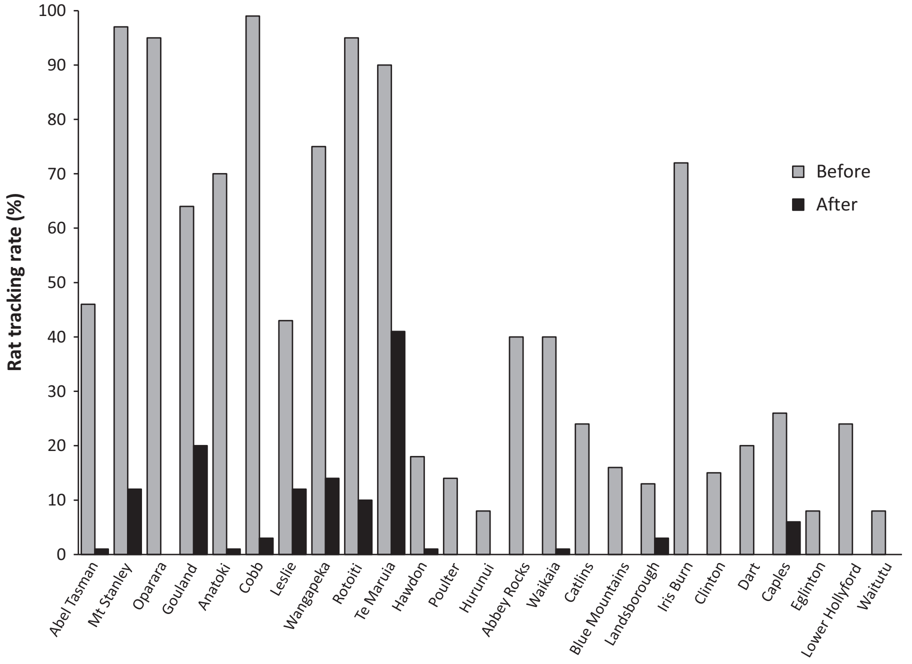

Figure 6. Rat tracking rates before and after the 2014 1080 operations at 25 sites in the South Island. Sites are arranged from north (on the left) to south (on the right).

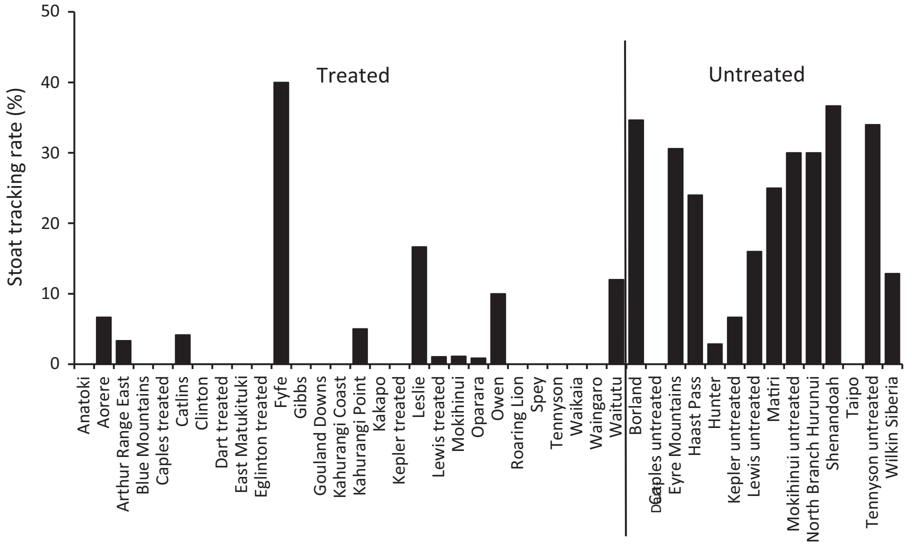

Figure 7. Stoat tracking rates at sites included in the 2014 1080 control operations and comparable sites that were untreated.

2016), but more importantly, productivity increases after 1080 operations (Powlesland *et al.* 1999, 2000, 2003). The aim of the bird monitoring programme was to collect mortality and productivity data associated with 1080 operations for some species not previously monitored and to collect mortality and productivity data for species that had not been monitored during 1080 operations for more than 5 years: there have recently been substantial changes in 1080 sowing rates (Veltman & Pinder 2001; Veltman & Westbrooke 2011) and the use of prefeed (Warburton *et al.* 2009).

Preliminary data analysis from six of the nine bird and bat species monitored during Battle for our Birds showed that some Kea (*Nestor notabilis*) were killed by 1080, and some Rock Wrens (*Xenicus gilviventris*) disappeared soon after the application of 1080 (although the cause of the latter is uncertain). No mortality was detected in five species: Whio (*Hymenolaimus malacorhynchos*), South Island Robin (*Petroica australis*), Morepork (*Ninox novaeseelandiae*), Rifleman (Acanthisitta chloris) and South Island Weka (*Gallirallus australis*). Furthermore, there were substantial increases in productivity in four species (Rock Wren, Mohua, South Island Robin and Rifleman) after the 1080 operations (Fig. 8). More detailed analysis of these data is the focus of several studies that are currently underway.

Implications for future large-scale 1080 control operations

Aerially applied 1080 has been used in New Zealand for over 60 years to control possums; and the effects of possum-focussed 1080 use on forest birds have been mostly positive (Byrom *et al.* 2016). However, it is only in the last 10 years that aerially applied 1080 has been routinely used to kill rats and stoats as well as possums with the aim of protecting forest birds. The increase in its use as a multipest control tool results from increasing urgency about the status of many of New Zealand's native animals, and from recent discoveries that it could reliably be used to control rats and stoats.

During the 2014 Battle for our Birds programme, 1080 was aerially sown over more than twice the land area over which it had been sown in the previous 6 years (Environmental Protection Authority 2015). Although aerially applied 1080 has been used previously to control localised beech mast-induced rat and stoat irruptions, 2014 was the first time that aerially applied 1080 had been used when beech masts and irruptions were widespread. Large-scale use of aerially applied 1080 is likely to be undertaken in future whenever beech mast and predator irruptions are widespread, so research that improves the timing and efficacy of 1080 operations could have substantial cost and logistic benefits for future conservation management. Three issues were identified during the 2014 operation that are the focus of current and future research. These issues are as follows: by-kill; achieving high rat kill rates; and the rate of rodent and stoat population recovery following 1080 application.

By-kill

Some bird and bat species are killed by 1080, but many species have increased productivity resulting from a reduction in predator abundances. For any species killed by 1080, it is vital to determine whether or not any increased productivity outweighs the losses. There are a suite of species including Kiwi (*Apteryx* spp.), Whio, Mohua, Yellow-crowned Parakeet (*Cyanoramphus auriceps*), Kea, Rock Wren and Kaka (*Nestor meridionalis*) that are declining because of predation for which aerially applied 1080 is likely to be the only practical management tool over most of their remote and inaccessible range. For these species, it is important to determine whether or not regular predator control using 1080 is enough to secure their future.

Achieving high kill rates

Another important focus for research is to determine whether 1080 operations can

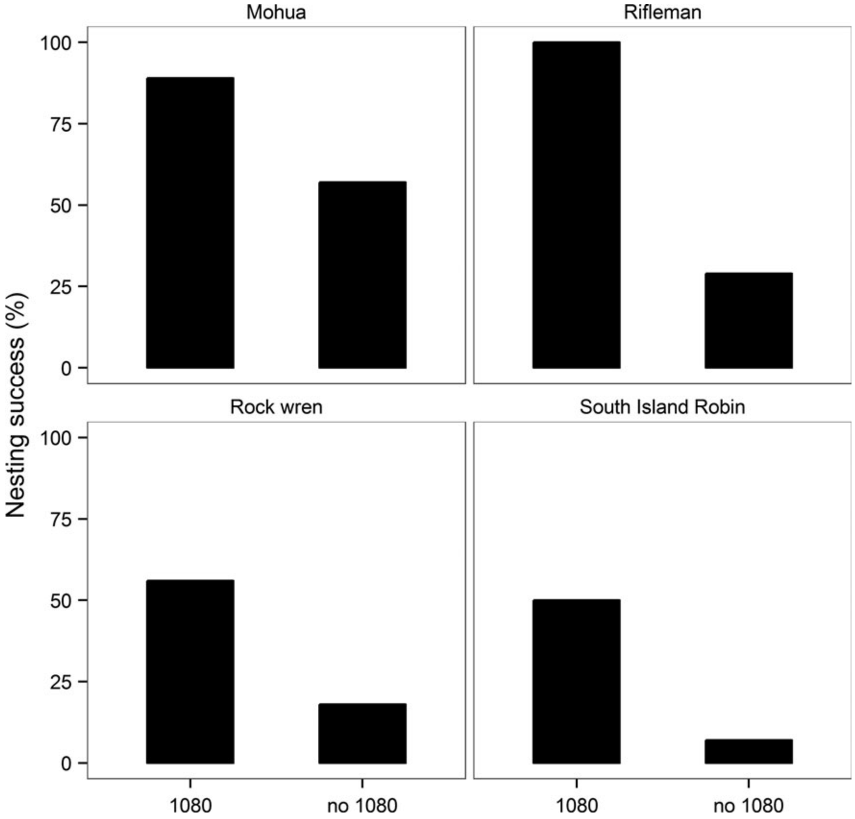

Figure 8. Response of four bird species to 1080 application. Nesting success at sites before and after 1080 was used to reduce predator abundance.

be modified to reliably kill a high proportion of rats, even when they occur at high densities. Many of the 1080 operations that did not meet their 5% postcontrol rat tracking targets were carried out much later (due to operational constraints) than the model predicted was optimal (see Table 1 and Fig. 6), when rats had already reached very high densities. 1080 operations need to be undertaken at the optimal time. Where operations cannot be carried out at the optimal time, it becomes important to ensure that a high proportion of rats can be killed even when they are abundant. An obvious possible explanation for the relative lack of success of rat control at high rat abundances is that insufficient bait was laid to kill all the rats. However, some of the 1080 operations carried out at high rat densities were very successful while others were not, yet bait was sown at the same density in all the operations. A preliminary examination of the patterns of bait spread suggests that uneven bait spread (e.g. due to wind, height above the ground, complexity of the terrain) might be the cause of the relatively low rat kill at some sites. This will be the focus of future research.

Rate of predator recovery

The effectiveness of a single short-lived predator control operation such as an aerial 1080 application depends, to at least some extent, on the duration of suppressed predator abundances. Innes *et al.* (1995) found that rats recovered to precontrol levels in 3–6 months following 1080 operations in podocarp–broadleaved forests and Ruscoe *et al.* (2011), Sweetapple and Nugent (2007), also working in podocarp–broadleaved forests, reported that rat numbers rose to even higher levels than pretreatment when possums as well as rats were killed. In contrast, in upland beech forests, rodents are often very rare between beech masts and their numbers can remain low following pest control for several years until the next beech mast (Elliott & Suggate 2007 and Graeme Elliott, unpublished data, 2014, DOC). Prior to Battle for our Birds, we assumed that rapid rodent recoveries might be confined to lowland podocarp–broadleaved forests, and that rodent recovery would always be slow until the next beech mast in upland beech forests. Rodent tracking since 2014 reveals that the distinction is not so clear. After the Battle for our Birds 1080 operations, some rodent populations both in podocarp–broadleaved forests at lower altitudes and in upland beech forests recovered quickly, while in some upland beech forests, their numbers have remained low. Identifying the factors that determine the rate of rodent recovery post-1080 operations will be a focus of future research.

In New Zealand, the aerially applied 1080 operations require two sets of permissions from local government which often impose conditions on the timing and extent of 1080 operations. The speed with which local governments dealt with applications for 1080 operations and the conditions they impose varied considerably from place to place in 2014, and this was one of the main reasons why many operations were not carried out at their optimum times. Improving the speed of granting permissions and the consistency of conditions imposed is an important focus for future aerial 1080 operations.

Conclusions

Despite recent positive reviews of its effectiveness and safety of 1080 (Environmental Risk Management Authority 2008; Parliamentary Commissioner for the Environment 2011), the use of aerially applied 1080 continues to be controversial (Russell 2014). An important function of the monitoring undertaken as part of the Battle for our Birds programme was to test whether 1080 delivers useful reductions in pest abundances and increases in productivity of native wildlife without unacceptable by-kill. The rat and stoat tracking results demonstrate marked reductions in pest abundances following the use of 1080, but they also identify areas where improvements could be made.

The 2014 Battle for our Birds 1080 programme was undertaken in response to widespread beech mast and predicted rodent and stoat irruptions. While localised beech mast is a frequent event, widespread beech mast is much less common, and conservation managers assumed that another beech mast predator irruption would not occur for at least a few years. This has proved not to be the case. There was almost no beech seeding in 2015, but during 2016, there was another widespread beech mast of similar magnitude to the one in 2014. At the time of writing, DOC is planning for another 1080 response to predator irruptions of an even larger scale than the one undertaken in 2014 and this will build on some of the lessons learnt in the 2014 operation. While the scientific data to confirm the biodiversity benefits of the 2014 Battle for our Birds programme are still being analysed, the vast majority of conservation research in New Zealand (see Byrom *et al.* 2016 for a meta-analysis) suggests that without management operations such as this, New Zealand's unique native biodiversity will continue to decline.

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References

Allen R. B. and Platt K. H. (1990) Annual seedfall variation in *Nothofagus solandri* (Fagaceae), Canterbury, New Zealand. *Oikos* **57**, 199–206.

Allen R. B., Hurst J. M., Portier J. and Richardson S. J. (2014) Elevation-dependent responses of tree mast seeding to climate change over 45 years. *Ecology and Evolution* **4**, 3525–3537.

Broome K., Cox A., Golding C., Cromarty P., Bell P. and McClelland P. (2014) *Rat Eradication*

Using Aerial Baiting: Current Agreed Best Practice Used in New Zealand (Version 3.0). New Zealand Department of Conservation internal document, Wellington, New Zealand. http://www.doc.govt.nz/Documents/conservation/threats-and-impacts/pest-control/other-technical-documents/rat-eradication-using-aerial-baiting.pdf

Burnham K. P. and Anderson D. R. (2002) *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*. Springer Verlag, New York.

Byrom A. E., Innes J. and Binny R. N. (2016) A review of biodiversity outcomes from possum-focused pest control in New Zealand. *Wildlife Research* **43**, 228–253.

Caughley G. (1977) *Analysis of Vertebrate Populations*. John Wiley and Sons, London.

Cowan P. E. (2005) Brushtail Possum. *In*: *The Handbook of New Zealand Mammals*, 2nd edn (ed. C. M. King) pp. 56–80. Oxford University Press, Melbourne.

Department of Conservation. (2015) Department of Conservation Statement of Intent 2015–2019. http://www.doc.govt.nz/Documents/about-doc/role/publications/statement-of-intent-2015-2019.pdf

Elliott G. P. (1996) Mohua and stoats: a population viability analysis. *New Zealand Journal of Zoology* **23**, 239–247.

Elliott G. P. and O'Donnell C. F. J. (1988) *Recent Declines in Yellowhead Populations*. Science and Research Internal Report No. 29, Department of Conservation, Wellington, New Zealand. http://www.doc.govt.nz/upload/documents/science-and-technical/SRIR29.pdf

Elliott G. and Suggate R. (2007) *Operation Ark Three Year Progress Report*. Southern Regional Office, Department of Conservation, Christchurch. http://www.doc.govt.nz/Documents/conservation/land-and-freshwater/land/operation-ark-report.pdf

Environmental Protection Authority (2015) *Annual Report on the Aerial use of 1080 for the Year Ended 31 December 2014*. Environmental Protection Authority, Wellington, New Zealand. http://www.epa.govt.nz/Publications/2014_Annual_Report_webready.pdf

Environmental Risk Management Authority (2008) Environmental Risk Management Authority Decision. Application for the Reassessment of a Hazardous Substance under Section 63 of the Hazardous Substances and New Organisms Act 1996. Name of Substance(s): Sodium Fluoroacetate (1080) and Formulated Substances Containing 1080. Application Number: HRE05002 Environmental Protection Authority, Wellington, New Zealand. http://www.epa.govt.nz/Publications/1080-Decision-document-with-amendments.pdf

Gillies C. and Williams D. (2007) DOC tracking tunnel guide V.2.5.1. Unpublished report. OLDDM-118330 Research Development & Improvement Division, Department of Conservation, Hamilton, New Zealand.

Holdaway R. N. (1989) New Zealand's pre-human avifauna and its vulnerability. *New Zealand Journal of Ecology* **12**(Supplement), 11–25.

Innes J., Williams D., Speed H., Warburton B. and Bradfield P. (1995) Large-scale poisoning of ship rats (*Rattus rattus*) in indigenous forests of the North Island, New Zealand. *New Zealand Journal of Ecology* **19**, 5–17.

Innes J., Hay R., Flux I., Bradfield P., Speed H. and Jansen P. (1999) Successful recovery of North Island kokako *Callaeas cinerea wilsoni* populations, by adaptive management. *Biological Conservation* **87**, 201–214.

Innes J., Kelly D., Overton J. M. and Gillies C. (2010) Predation and other factors currently limiting New Zealand forest birds. *New Zealand Journal of Ecology* **34**, 86–114.

Kelly D., Geldenhuis A., James A. *et al.* (2013) Of mast and mean: differential-temperature cue makes mast seeding insensitive to climate change. *Ecology Letters* **16**, 90–98.

King C. M. (2005) Weasel. In: *The Handbook of New Zealand Mammals*, 2nd edn (ed C. M. King), pp. 287–94. Oxford University Press, Melbourne.

King C. M. (1983) The relationships between beech (*Nothofagus* sp.) and populations of mice (*Mus musculus*), and the demographic and dietary responses of stoats (*Mustela erminea*), in three New Zealand forests. *Journal of Animal Ecology* **52**, 141–166.

Moilanen A. (2007) Landscape Zonation, benefit functions and target-based planning. Unifying reserve selection strategies. *Biological Conservation* **134**, 571–579.

Moorhouse R., Greene T., Dilks P. *et al.* (2003) Control of introduced mammalian predators improves kaka *Nestor meridionalis* breeding success: reversing the decline of a threatened New Zealand parrot. *Biological Conservation* **110**, 33–44.

Morris G. A., Nugent G. and Whitford J. (2016) Dead birds found after aerial poisoning operations targeting small mammal pests in New Zealand 2003–14. *New Zealand Journal of Ecology* **40**, 361–370.

Murphy E. C., Young J. B., Robbins L. and Dowding J. E. (1999) Secondary poisoning of stoats after an aerial 1080 poison operation in Pureora Forest, New Zealand. *New Zealand Journal of Ecology* **23**, 175–182.

O'Donnell C. F. J. (1996) Predators and the decline of New Zealand forest birds: an introduction to the hole-nesting bird and predator programme. *New Zealand Journal of Zoology* **23**, 213–219.

Parliamentary Commissioner for the Environment (2011) Evaluating the use of 1080: Predators, poisons and silent forests. Parliamentary Commissioner for the Environment, Wellington. http://www.pce.parliament.nz/media/1294/evaluating-the-use-of-1080.pdf

Poole A. L. (1948) The flowering of beech. *New Zealand Journal of Forestry* **5**, 422–427.

Powlesland R. G., Marshall I. S. J. and Knegtmans J. W. (1999) Costs and benefits of aerial 1080 possum control operations using carrot baits to North Island robins (*Petroica australis longipes*), Pureora Forest Park. *New Zealand Journal of Ecology* **23**, 149–159.

Powlesland R. G., Knegtmans J. W. and Styche A. (2000) Mortality of North Island tomtits (*Petroica macrocephala toitoi*) caused by aerial 1080 possum control operations, 1997–98, Pureora Forest Park. *New Zealand Journal of Ecology* **24**, 161–168.

Powlesland R. G., Wills D. E., August A. C. L. and August C. K. (2003) Effects of a 1080 operation on kākā and kereru survival and nesting success, Whirinaki Forest Park. *New Zealand Journal of Ecology* **27**, 125–137.

Riney T., Watson J. S., Bassett C., Turbott E. G. and Howard W. E. (1959) Lake Monk expedition. An ecological study in southern Fiordland. *Department of Scientific and Industrial Research Bulletin* **135**, 1–75.

Ruscoe W. A., Elkington J. S., Choquenot D. and Allen R. B. (2005) Predation of beech seed by mice: effects of numerical and functional responses. *Journal of Animal Ecology* **74**, 1005–1019.

Ruscoe W. A., Ramsey D. S. L., Pech R. P. *et al.* (2011) Unexpected consequences of control: competitive vs. predator release in a four-species assemblage of invasive mammals. *Ecology Letters* **14**, 1035–1042.

Russell J. C. (2014) A comparison of attitudes towards introduced wildlife in New Zealand in 1994 and 2012. *Journal of the Royal Society of New Zealand* **44**, 136–151.

Schauber E. M., Turchin P., Kelly D. *et al.* (2002) Masting by eighteen New Zealand plant species: the role of temperature as a synchronizing cue. *Ecology* **83**, 1214–1225.

Sweetapple P. J. and Nugent G. (2007) Ship rat demography and diet following possum control in a mixed podocarp-hardwood forest. *New Zealand Journal of Ecology* **31**, 186–201.

Tait A. (2008) Future projections of growing degree days and frost in New Zealand and some implications for grape growing. *Weather and Climate* **28**, 17–36.

Towns D. R., West C. J. and Broome K. G. (2013) Purposes, outcomes and challenges of eradicating invasive mammals from New Zealand islands: an historical perspective. *Wildlife Research* **40**, 94–107.

Veltman C. J. and Pinder D. N. (2001) Brushtail possum mortality and ambient temperatures following aerial poisoning using 1080. *Journal of Wildlife Management* **65**, 476–481.

Veltman C. J. and Westbrooke I. M. (2011) Forest bird mortality and baiting practices in New Zealand aerial 1080 operations from 1986 to 2009. *New Zealand Journal of Ecology* **35**, 21–29.

Warburton B., Clayton R., Nugent G., Graham G. and Forrester G. (2009) Effect of prefeeding on foraging patterns of brushtail possums (*Trichosurus vulpecula*) about prefeed transects. *Wildlife Research* **36**, 659–665.

Wardle J. A. (1984) *The New Zealand Beeches: Ecology, Utilization and Management*. New Zealand Forest Service, Wellington, New Zealand.

Wiser S. K., Hurst J. M., Wright E. F. and Allen R. B. (2011) New Zealand's forest and shrubland communities: a quantitative classification based on a nationally representative plot network. *Applied Vegetation Science* **14**, 506–523.