The ecology and conservation of wild and reintroduced populations of the critically endangered Mauritius olive white-eye *Zosterops chloronothos*

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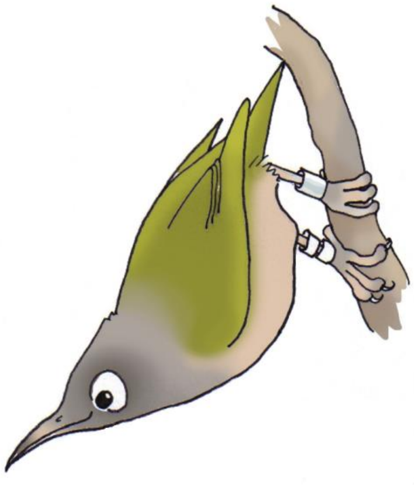
Declaration

I, Gwendolyn Betty Maggs, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Gwendolyn B. Maggs, 10th August 2016



Every endangered species needs a champion, especially if it is a little green one that few have heard of and less have seen. White-eyes are neither sexy nor macho, and all of the usually invoked reasons (by and large preposterous anyway) for preserving endangered species would not seem to apply here (i.e. white-eyes do not cure cancer). The only way that such species are likely to persist is through the action of motivated individuals

Robert J. Craig, 1999

Abstract

The world is facing a biodiversity crisis and nowhere is that more apparent than on oceanic islands with recent research identifying islands as conservation priority areas and so increasing the importance of conservation for island endemics. Despite this some of the most remarkable success stores in the history of conservation have come from island nations with countries like Mauritius among the few to buck the biodiversity loss trend. However, species conservation often requires intensive management to reduce limiting factors and save endangered species from extinction. But with limited resources and knowledge accurately assessing the impact of management techniques is essential to reduce uncertainty and enable effective decision-making.

Here I have developed decision-making tools to identify the role of management for a critically endangered passerine, the Mauritius olive white-eye (*Zosterops chloronothos*), within both a wild and reintroduced population. Specifically I combined field datasets with statistical, economic and social analytical approaches through mixed-effects models, population modelling, knowledge exchange, expert elicitation, population viability analysis and cost-effectiveness analysis to guide efficient long-term management; identifying the role of invasive species management and supplementary feeding.

I quantitatively identified invasive rats as a major limiting factor to the wild olive white-eye population, however, rat management can mitigate this threat increasing annual productivity 5-6 fold and preventing further population decline. These findings identify rat management as a viable option and provide evidence to pursue large-scale, long-term management in the form of a ‘mainland island’. By comparing four rat management techniques I created decision-making tools to identify the area required for a mainland island and the most cost-effective technique against extinction risk; comparing trapping, ground based poisoning, self-resetting traps and predator-proof fencing.

Within the reintroduced population the supplementary feeding (SF) programme is exponentially increasing with olive white-eye population growth. By identifying the mismatch between supply and demand I show that the demand for SF peaks during energetically expensive phases of the breeding cycle, when natural plant resource availability is low, and in the morning. This identifies short-term refinements responding to peaks in demand and a potential long-term exit strategy through the increase of natural plant resource availability, reducing demand over time.

The approaches taken in this study illustrate how the combination of conservation tools can increase our understanding of both the ecology and conservation of highly threatened species focusing on both wild and reintroduced populations of the Mauritius olive white-eye. Here I identify the role of management and create decision-making tools to enable the timely application of robust and viable long-term management while accounting for financial, logistical and epistemic uncertainty.

These findings have a broad relevance for other highly threatened species programmes experiencing similar limiting factors, resource limitations and long-term uncertainty by minimising the risk of decision-making and enabling evidence-based management. This is especially relevant for island endemics where invasive species are one of the biggest threats, intensive management through reintroduction and supplementary feeding is required and actions have to be taken quickly to avert species extinction.

Acknowledgements

I would firstly like to thank my wonderful supervisors Ken Norris, Malcolm Nicoll, Nicolas Zuël and David Murrell for their endless support and encouragement throughout my PhD. Nicolas for helping setup the data collection and supporting my determination to help and save the Mauritius olive white-eye all those years ago. Malcolm for giving me a chance during that first meeting and being there throughout with your continuous patience and detail and the dreaded "but what is the question!". Ken for your vision and helping me develop this research further than I could ever have imagined and for your humour which lightened any stressful meeting. And David for taking on me and my research late in the game but making huge contributions and for always being there with kind words which truly helped me through.

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Chapter 1

Introduction

1.1 Island Species Conservation

The world is facing a biodiversity crisis with declines most obvious on oceanic islands, where native and often highly endemic fauna continue to be susceptible to changes brought by successive waves of human colonists (Jones & Merton 2012). Recent research has identified islands as conservation priority areas for evolutionary distinct and globally endangered (EDGE) species, increasing the importance of conservation for island endemics (Jetz et al. 2014). Historically many large mammals have been the victims of human colonisation with Madagascar loosing dozens of its largest species of lemur and hippopotamus (Diamond 1989). However, modern extinctions, occurring since the 16th century, have had a considerable impact on bird species with 171 bird species becoming extinct and 151 of those were island species from areas such as Hawaii, New Zealand, the Mascarenes and the West Indies (Diamond 1989). The causes of these extinctions are known as the "Evil Quartet" involving (1) overkill (human overexploitation), (2) habitat destruction and fragmentation, (3) impacts of introduced species and (4) secondary extinctions (the extinction of species causing the subsequent extinction of another due to interspecific behaviours) (Diamond 1989). However, there are various approaches used either individually or in combination to avert extinctions and recover endemic populations including re-enforcement and reintroduction, eradication or control of invasive alien species and intensive management (Jones & Merton 2012).

These approaches have been applied successfully throughout the world with hundreds of invasive species eradications (Towns & Broome 2003; DIISE 2015; Russell et al. 2016), endangered species reintroductions (Soorae & Seddon 1998; Ewen et al. 2012) and intensive management actions including captive breeding and release, clutch and brood manipulations, habitat protection and restoration and supplementary feeding; preventing the extinction of some highly threatened species such as the Californian condor (*Gymnogyps californianus*), Hawaiian goose (*Branta sandvicensis*) and black robin (*Petroica traversi*) (Butchart et al. 2006). Numerous examples and quantitative research into the impact of conservation organisations on species status provide evidence that long-term, intensive management really can have significant conservation impact (Hoffmann et al. 2010; Young et al. 2014). Some of the most remarkable success stories in the history of the conservation movement have come from island nations with countries like Mauritius among the few to buck the global biodiversity loss trend (Rodrigues et al. 2014). Given that conservation management approaches are available, and can be successful if used in the right way, the key question then becomes how to make the 'right' decision in a given situation when there is still widespread uncertainty around the effectiveness of conservation investments hindering decision-making (Ferraro & Pattanayak 2006).

For small declining populations, which are at the greatest risk of extinction, decisive and innovative management actions may be crucial to reverse population decline and ultimately avert extinction, however, managers throughout the world struggle to achieve goals due to a poor understanding of systems, risk factors and resource limitations which all impact management decisions (Atkinson 1989; Meek et al. 2015; Smith et al. 2015). It is therefore important to trial management options and conduct research focused on understanding the long-term conservation management of species so managers and decision-makers can make wise use of scare conservation resources while ensuring species survival, bridging the gap between research and management (Cullen et al. 2001; Jones & Merton 2012). Nowhere is this more crucial than in Mauritius where the evil quartet have had a devastating impact on island biodiversity and although intensive management has prevented the extinction of a number of species many conservation projects still face long-term financial, logistical and knowledge uncertainty which is hindering evidence-based and effective decision-making.

1.2 Mauritius

Mauritius (20.25°S 57.5°E) is a small island (1,865 km^2) located in the southern Indian Ocean and is one of three main islands which make up the Mascarene archipelago along with Réunion and Rodrigues. Mauritius is the oldest of the Mascarene Islands forming some 10 mya and is of volcanic origin, therefore, it has never been connected to a continental landmass (Cheke & Hume, 2008). This isolation enabled rich and diverse ecosystems to evolve via temporary island ‘stepping stones’ created through sea-level fluctuations enabling species to reach and colonise these linking islands with some eventually reaching Mauritius; rapid sea-level rises 14,000 years ago drowned most of the islands thus cutting off the avenue (Cheke & Hume 2008). Mauritius after this point remained in isolation until humans arrived in 1598 (Cheke & Hume 2008).

1.2.1 Habitat Loss

Originally the uplands of Mauritius supported lower montane, wet, evergreen forest, scrub and marsh vegetation with palm savanna in the coastal areas of the north and west (Safford 1997b). The first human settlements were established by the Dutch in the 16th century where they exploited the hard woods which covered much of the island lowlands harvesting ebony for exportation, introduced sugar-cane (*Saccharum officinarum L.*) and consumed the endemic palms in great quantities (Parnell et al.

1989; Cheke & Hume 2008). The palm savanna was quickly lost, now remaining only on Round Island and Ile aux Aigrettes, and in the 17th century when the French colonised cereals, coffee and sugar-cane were successfully cultivated with many plants introduced and plantations trialled (Vaughan & Wiehe 1937). When the British colonised in the 18th century the sugar-cane plantations were extensively increased and large areas of native forest were felled so much so that by 1880 forest acreage was reduced by 96% and Mauritius was described as “a picture of doleful ruin” (Thompson 1880) (Figure 1.1; Vaughan & Wiehe 1937). Sugar-cane plantations now cover over 50% of the island and only 5% of native vegetation remains with a majority of this in the south-west of the island now protected by the Black River Gorges National Park (BRGNP) which was established in 1994 and the remaining patches protected by previous legislation (Cheke, 1987b; Safford, 1997).

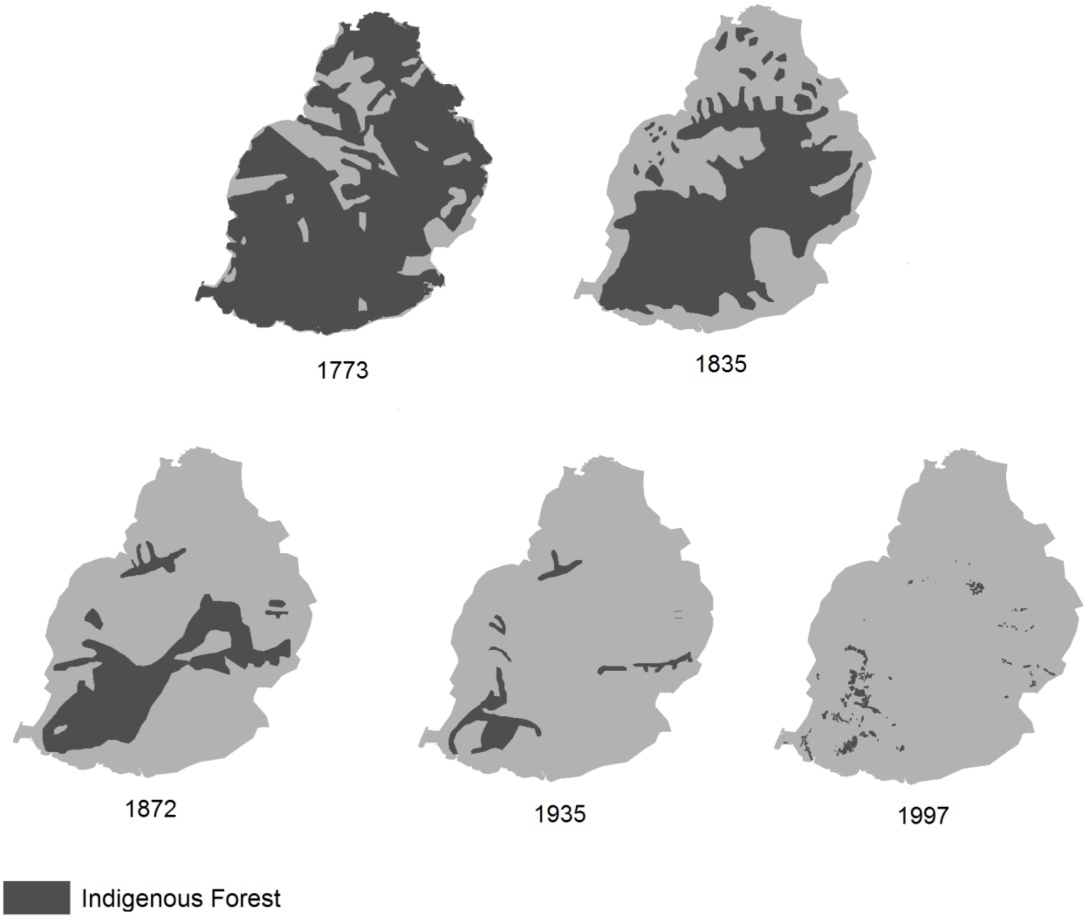

Figure 1.1 An illustration of the mass deforestation of indigenous forest across mainland Mauritius from the 17th century to the present day (Thompson 1880; Vaughan & Wiehe 1937; Page & D’Argent 1997; Safford 1997b)

1.2.2 Invasive Species

Along with the deforestation of indigenous flora invasive animals were also introduced to Mauritius when humans colonised, some accidentally and some purposefully, having devastating effects on the native fauna. Ship rats (*Rattus rattus*) were thought to have reached Mauritius before human settlement in the 16th century, pigs were introduced shortly after, in the 17th century brown rats (*Rattus norvegicus*) arrived on ships while crab eating macaques (*Macaca fascicularis*) and feral cats (*Felis domesticus*) were introduced followed by the small Indian Mongoose (*Herpestes javanicus*) in the 19th century (Cheke & Hume 2008). The house shrew (*Suncus murinus*), tenrec (*Tenrec ecaudat*) and common mynah (*Acridother tristi*) were also introduced and although predators of nestlings, small reptiles and sea birds (Cheke & Hume 2008), the extent of their impact has not yet been fully established. In addition to invasive animals invasive plants were introduced in the 17th century with strawberry guava (*Psidium cattleianum*), rose-apple (*Syzygium jambos*), traveller's palm (*Ravanala madagascariensis*), white popinac ((*Acacia*) *Leucena leucocephele*) and Mauritius hemp (*Furcraea foetida*) being the most invasive, damaging the native forest and preventing regeneration (Cheke & Hume 2008)

1.2.3 Extinct and Extant Species

The mass deforestation of indigenous forest and the arrival of a suite of invasive predators to Mauritius over the last four centuries has had devastating effects causing the extinction of 50% of the endemic fauna and still threatening the remaining species (Cheke, 1987b). Pigs were introduced as a source of food but were thought to have contributed greatly to the demise of the giant tortoise and ground nesting birds such as the iconic dodo (*Raphus cucullatu*) by digging up and predating on eggs (Cheke 1987b). Feral cats were introduced to control the rat populations but whose introduction coincided with the extinction of species such as the flightless red rail (*Aphanapteryx bonas*) along with other vulnerable ground dwelling species (Cheke 1987b). The small Indian mongoose were introduced to try and control rat populations but failed and, although arriving late, would still have impacted large ground dwelling birds and is thought to have caused the extinction of the last remaining Audubon's shearwater (*Puffinus lherminieri*) population soon after arrival by predating on both adult birds and nestlings (Cheke 1987b; Cheke & Hume 2008). For arboreal bird species the crab eating macaque was thought to be a major threat by destroying nests and predating on birds, nestlings and chicks, however, rats were and are by far the biggest threat to reptiles and birds, especially passerines, predating on bird eggs, nestlings and potentially brooding adult birds and adult and juvenile reptiles; both macaques and rats contributed to the extinction of the supposedly flightless raven parrot (*Lophopsittacus mauritianus*) (Cheke 1987b; Cheke & Hume 2008).

Of the 21 known bird species of Mauritius 11 have survived extinction. The Mascarene martin (*Phedina borbonica*) and Mascarene swiftlet (*Collocalia francica*) are not endemic to Mauritius or threatened with extinction globally (Cheke & Hume 2008). The Mauritius kestrel (*Falco punctatus*), pink pigeon (*Nesoenas mayeri*) and echo parakeet (*Psittacula eques*) were by far the most threatened species having all reached less than 20 individuals, however, over the last 40 years the species have been recovered to populations in the hundreds but are still all classed as endangered (Jones et al. 1995; Swinnerton 2001; Malham et al. 2005; IUCN 2015). The remaining six endemic bird species are forest-dwelling passerines. The Mauritius grey white-eye (*Zosterops mauritianus*) is the most abundant of the endemic bird species and is not threatened with an estimated 34,000-68,000 pairs in 1974-75 (Cheke 1987b) which is likely to have remained the same since (Safford 1997a). The Mauritius Cuckoo-shrike (*Coracina typical*) and Mauritius Bulbul (*Hypsipetes olivaceus*) are both currently vulnerable and the endemic sub-species of the Mascarene Paradise Flycatcher (*Terpsiphone bourbonnensis desolata*) is classified as least concern (IUCN 2015), however, all of these populations are thought to be declining (Ormsby et al. 2012). The Mauritius Fody (*Foudia rubra*) was one of the rarest passerines in Mauritius but was down listed to endangered in 2009 following intensive recovery which still continues (Cristinacce et al. 2009; IUCN 2015). Currently the rarest and least known of the Mauritian passerines is the Mauritius olive white-eye (*Zosterops chloronothos*) classed as critically endangered and the focus of this research.

1.3 Mauritius olive white-eye

1.3.1 Species Life History

The Mauritius olive white-eye (here after referred to as the olive white-eye) was classified as a species in 1817 (Vieillot) and is part of an ancient Indian Ocean white-eye lineage with birds colonising Mauritius from Asia prior to the subsequent evolution of the African species (Warren et al. 2006; Cox et al. 2014). The olive white-eye, in the absence of nectivorous competitors evolved the longest bill of all white-eye species making them the most specialised nectar feeder in the *Zosterops* genus (Figure 1.2; Moreau et al., 1969). Based on their specialised morphology it is argued that the olive white-eye colonised the Mascarenes prior to the grey white-eye and being a specialised nectar feeder enabled the ancestors of the grey white-eye to colonise the islands some time afterwards filling an alternative niche; this double colonisation lead to the sympatric co-existence of the white-eye species which is rare (Gill 1971). Based on their unique genetic history the olive white-eye are in the top 10% of the EDGE bird species list (Jetz et al. 2014).

1.3.2 Description

The olive white-eye is a small, elusive passerine with no sexual dimorphism, however, males can be identified by their rambling, mimicking song thought to function in breeding and territoriality (Gill 1971; Safford & Hawkins 2013). They weigh approximately 8g with an average wing length of 52.8mm, tail length of 31mm and bill length of up to 17mm (Safford & Hawkins 2013). They have an olive-grey plumage around the head becoming olive-green on the back, wings and upper tail, a white grey-buff belly and throat, olive-yellow plumage round the vent and a distinct white eye-ring (Figure 1.2; Safford and Hawkins, 2013). They form monogamous pairs and are highly territorial defending territories of around 0.5ha in size against all other bird species, especially grey white-eye (Maggs et al. 2011). They are found in humid forest and scrub which is often highly degraded but in areas where exotic nectariferous plants are abundant specifically rose-apple (Safford & Hawkins 2013). Their general behaviour mimics that of sunbirds *Nectariniidea* rather than the typical *Zosterops* with rapid direct flights, calling abruptly and chasing through the canopy which highlights further their evolutionary distinctiveness (Safford & Hawkins 2013). The olive white-eye is a highly nectivorous species but also feed on invertebrates and fruit with their long bills enabling foraging and probing in foliage as well as flowers.

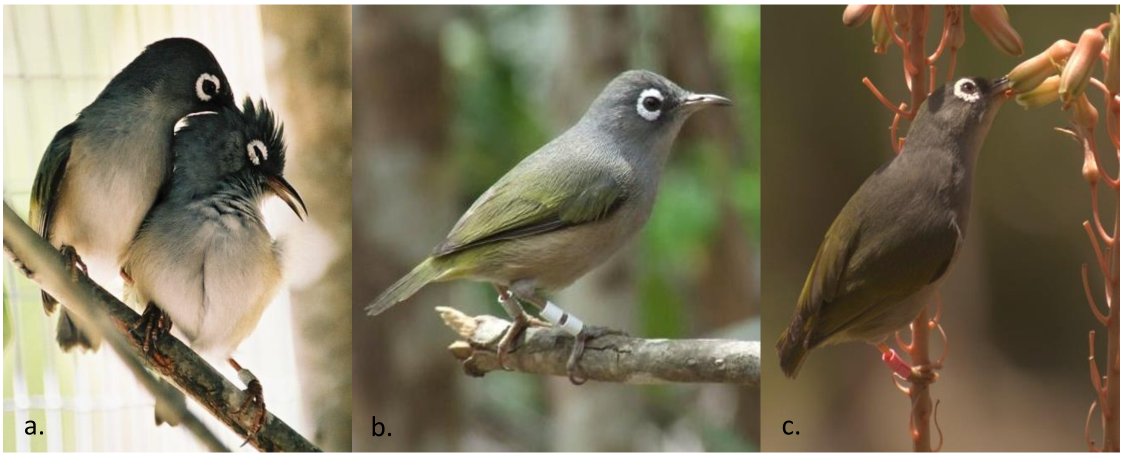

Figure 1.2 The Mauritius olive white-eye (*Zosterops chloronothos*) illustrating (a) a mutually preening pair, (b) adult plumage and (c) their highly evolved bill feeding on the endangered endemic *Aloe Lomatophyllum*; pictures creditted to Ruth Cole (a), Jason Van de Wetering (b) and Megan Whittaker (c)

1.3.3 Breeding Ecology

Prior to 2001 little was known about the olive white-eye with only eight nesting episodes ever recorded; of which only one successfully fledged (Safford 1991; Staub 1993; Nichols et al. 2005a). They are a monogamous, multi-brooded species which indulge frequently in extensive mutual preening during the breeding season (Figure 1.2; Cheke 1987b). The male and female participate equally in all of the nesting stages, building small open cup nests within the upper canopy on small outer branches using various materials such as leaf veins, moss and cobweb and lining them with feathers; unlike the sympatric grey white-eye (Cheke 1987b; Nichols et al. 2005a). Females lay typically 1-3 pale blue eggs, which are then incubated for 12 days by both the male and female; a clutch of four eggs was recorded for the first time in the 2014/15 breeding season (Nichols et al. 2005a; Cole et al. 2007b; Ferrière et al. 2015a). Nestlings are fed invertebrates by the pair for 14 days until fledging after which the juveniles will remain with the adults for 2-8 weeks before reaching independence (Nichols et al., 2005; Safford and Hawkins, 2013). Fledglings are identified by the lack of a tail and eye-ring, the tail developing within 7 days and the eye-ring unfurling between 15-30 days, after which they are indistinguishable from their parents in appearance (Safford & Hawkins 2013). For a full description of the nesting stages and behaviours see Nichols et al. (2005) and Safford and Hawkins (2013).

1.3.4 Population Decline

The olive white-eye has experienced an island wide decline with the main limited factors thought to be habitat loss and degradation and suspected nest predation by invasive rat species (Nichols et al. 2004). There historical range was more extensive occurring in the north and east but by 1975 the population was estimated at 340-350 pairs restricted mainly to the south-west of Mauritius, forest clearing between 1971 and 1975 of 2,800ha within the olive white-eye range for pine plantations would have dispersed a lot of birds and by 1993 they had declined to 200 pairs (Cheke 1987b; Safford 1997a; Safford & Hawkins 2013). Surveys in 2001 recorded further population decline to 93-148 pairs and again in 2012 to an estimated 80 pairs primarily restricted to an area less than 25km^2 in the BRGNP (Figure 1.3; Nichols et al. 2004; Ormsby et al. 2012). The mass deforestation of Mauritius which continued into the 1970s has had a major impact on olive white-eye range and suspected nest predation by rats causes very low productivity (Nichols et al. 2005b) these limiting factors could be a major contribution to the estimated 77% population decline in just 37 years.

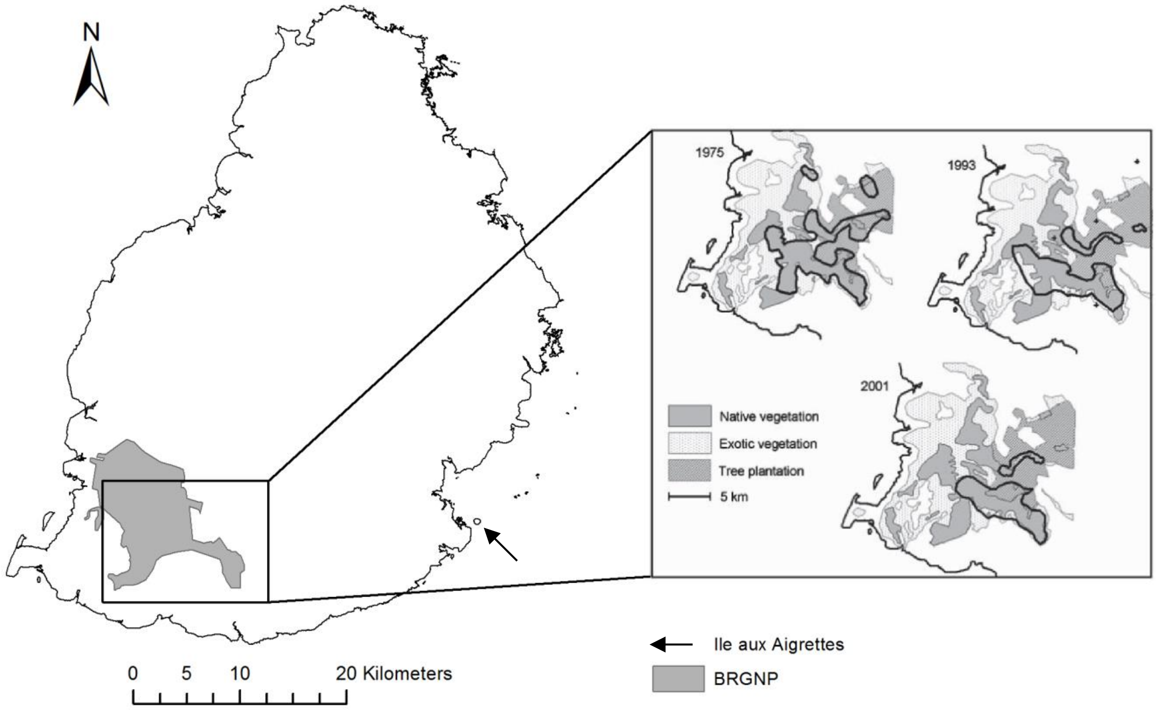

Figure 1.3 Mainland Mauritius (left) illustrating the location of the Black River Gorges National Park (BRGNP) and Ile aux Aigrettes Nature Reserve. Mauritius olive white-eye population range restriction 1975 to 2001 (right) from Nichols et al. (2004)

1.3.5 Species Recovery

In response to the continued population decline of olive white-eye, reported by Nichols et al. (2004), a recovery project was initiated in 2005 by the Mauritian Wildlife Foundation. The aim of the project was to establish a sub-population on the rat-free island Nature Reserve, Ile aux Aigrettes, and monitor a remnant sub-population in the BRGNP controlling rats and increasing our understanding of the species behaviour and breeding biology (Figure 1.3; Cole et al., 2008, 2007; Maggs et al., 2010, 2009).

The techniques applied to the olive white-eye recovery project were adapted from the successful reintroduction of the Mauritius Fody to Ile aux Aigrettes between 2003 and 2006 which combined nest harvesting, captive hand-rearing and marooning techniques (Cristinacce et al. 2008, 2009; Jones & Merton 2012). These nest harvesting and hand-rearing techniques were first applied to the non-threatened grey white-eye in 2004/05 to refine the methods for a *Zosterops* species before implementing them on the critically endangered olive white-eye; these trials were completely successful and paved the way for the olive white-eye recovery project (Cristinacce et al. 2006a).

The first step for the recovery project was to monitor olive white-eye behaviour and breeding biology to increase the knowledge of this least known Mauritian species and to investigate if Ile aux Aigrettes was a suitable release site as the complete historical range of the olive white-eye is unknown. Within the first season of monitoring 19 nesting attempts were found and monitored, only eight had ever been documented prior to this, two of these were harvested and brought to the Gerald Durrell Endemic Wildlife Sanctuary (GDEWS) to determine whether the species were capable of existing in lowland Mauritius; four birds were successfully hand-reared, kept in captivity for a year and all survived (Cristinacce et al. 2006b). Following this success the olive white-eye project was intensified with rigorous monitoring of the wild population (focusing on mapping breeding territories, documenting breeding activity and studying feeding ecology) and localised rat snap-trapping around nest sites to reduce potential nest predation. In total 34 birds were hand-reared to independence and reintroduced to Ile aux Aigrettes between 2007 and 2010 (Cole et al. 2007a, 2008, Maggs et al. 2009, 2010). Due to the lack of historical records of olive white-eye in coastal Mauritius supplementary feed was provisioned to the population following the initial releases to ensure an adequate food supply. This is provided from individual feeding stations distributed across the island with the aim of increasing both survival and productivity. Intensive monitoring of the whole population is conducted throughout the year and there are currently 46 known olive white-eye on Ile aux Aigrettes comprising of 16 breeding pairs (Ferrière et al. 2015b). The long-term goal of the reintroduction is to establish a self-sustained sub-population.

Throughout the 11 years the olive white-eye recovery project has been running detailed monitoring has been conducted in both the reintroduced island population and the mainland wild population, however, the recovery project is now at a crucial stage with two monitored populations under differing management regimes. Whilst detailed data on the demography, feeding ecology and management for each population have been collected (but not yet analysed) our understanding of the ecology of the species remains limited, which is hindering the development of an informed management programme for the species. In particular, there is no understanding of how the olive white-eye responds to management actions and hence there is very limited information to guide the development of cost-effective, long-term management solutions.

1.4 Thesis Structure

Both the mainland and reintroduced populations of olive white-eye are facing difficult management decisions and long-term uncertainty due to the lack of quantitative analysis and scientific evidence. The focus of the research presented in this thesis is to address these uncertainties by combining detailed short-term data, available for both the mainland and reintroduced olive white-eye populations, with analytical tools and population modelling to identify limiting factors, the role of current management techniques and identify long-term, cost-effective management options. These methods create decision-making frameworks which conservation managers can use to assess current and future management scenarios for other island endemics threatened by invasive species, habitat destruction and financial limitations by reducing uncertainty and risk.

Two of the analytical chapters focus on the mainland wild population in the Black River Gorges National Park addressing the threat of invasive species while chapter three focuses on the reintroduced sub-population on Ile aux Aigrettes addressing the role of current management. The thesis has the following structure -

Chapter Two: Can invasive rat management ensure population persistence in a remnant wild population of critically endangered Mauritius olive white-eye?

This chapter demonstrates how small-scale, short-term field experiments in conjunction with demographic models can identify limiting factors and provide an insight into the long-term benefits of controlling nest predators, such as rats, for olive white-eye population persistence

Chapter Three: What factors drive the demand of supplementary feed in a reintroduced population of Mauritius olive white-eye and can identifying these drivers enable management refinement?

This chapter investigates the role supplementary feed plays within the olive white-eye population in regards to environmental seasonality, breeding behaviour, natural plant resource availability and management techniques, illustrating a decision-making framework for identifying the mismatch between supply and demand, to enable the refinement of current *ad libitum* management and devise a potential exit strategy

Chapter Four: What is the most cost-effective, long-term management plan for creating low-predation mainland islands for Mauritius olive white-eye?

This chapter illustrates a decision-making framework incorporating knowledge exchange, expert elicitation, population viability analysis and cost-effectiveness analysis to predict the long-term viability of an olive white-eye population under different large-scale rat management scenarios identifying the most cost-effective technique for establishing a ‘mainland island’; reducing uncertainty and enabling decisive and innovative evidence-based conservation management

Chapter Five: Discussion

This chapter discusses the findings of the analytical chapters and the implications for olive white-eye providing recommendations for future management and research which can be applied to other threatened species facing similar limiting factors globally.

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Chapter 2

Rattus management is essential for population persistence in a critically endangered passerine: Combining small-scale field experiments and population modelling

2.1. Chapter Attribution

This chapter has been published in the scientific journal Biological Conservation:

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I received invaluable advice on the direction of this chapter from my supervisors Prof Ken Norris and Dr Malcolm Nicoll who helped me with R code for calculating the daily nest survival and survival rates and with compiling the biological parameters for the individual-based stochastic simulation model. This simulation model was provided by Dr Patrick J.C White who also gave guidance when parameterising the model. My third supervisor Dr Nicolas Zuël assisted in the experimental design of the data collection and provided comments on the manuscript. Dr Vikash Tatayah and Prof Carl G Jones were key in the management of the Mauritius olive white-eye recovery project while the data was collected and Edward Winfield and Sandra Poongavanan assisted in the field work and data collection.

2.2. Abstract

Invasive species are a major threat for island biodiversity, causing species decline and extinction globally. Of all invasive mammals rats are one of the most detrimental and have been the target of numerous control and eradication programmes. In Mauritius rats have contributed to the extinction of 50% of the island's fauna and are thought to be the main threat to the endemic Mauritius olive white-eye (*Zosterops chloronothos*), a critically endangered passerine. Assessing the impact of rats and suitable control strategies is often problematic in such cases because of the lack of replicate populations for experiments. Here, I illustrate how to overcome this issue by combining a small-scale rat management experiment on olive white-eyes with demographic models that provide estimates of the potential effects of management on vital rates and population growth. I established poison and trapping grids within breeding territories, and show that rat management significantly decreased rat abundance and increased nesting success. An individual-based stochastic simulation model suggested that rat control could produce a 5-6 fold increase in the annual productivity of female olive white-eyes, which in turn would be sufficient to stabilise population growth. In the absence of rat control, my analysis suggests the olive white-eye population will decline by about 14% per annum. By combining low cost field experiments with widely available demographic models I highlight the value of targeted, effective rat management techniques for both short and long-term population management in threatened passerines.

2.3. Introduction

Since the 15th century invasive species have been partly or wholly responsible for the extinction of at least 65 bird species making them the greatest threat to avifauna, especially on islands where predation is a major cause of extinction (Atkinson, 1985; Birdlife International, 2004; King, 1985). Having reached around 90% of all islands rats have been identified as a 'massive' global threat under a new classification system based on the IUCN Global Invasive Species Database with *Rattus rattus* (ship or black rats) having the greatest detrimental effects on island bird populations (Atkinson, 1989, 1985, 1977; Blackburn et al., 2014; Towns et al., 2006).

The eradication of rats from islands is now a widely used conservation tool benefiting numerous taxa (Towns et al., 2006), with 344 successful eradications of ship rats and *R. norvegicus* (brown rats) from islands between 1951 and 2011 (Island Conservation, 2012). In contrast to rat eradications from unpopulated islands, the control of rats in areas on large populated islands remains challenging, however, the local extirpation of rats through the establishment of rat-free areas using poison and trapping is one possible solution. To date these have been implemented with varying degrees of success for many island passerine species threatened by rats where marooning on predator free islands is not an option but the creation of rat-free areas is a viable long-term solution e.g. Cook Islands, Hawaii, New Zealand, Seychelles and Tahiti (Blanvillain et al., 2003; Innes et al., 1999; Rocamora and Baquero, 2007; Robertson et al., 1994; Trent et al., 2008; Vanderwerf and Smith, 2002). However, one of the challenges faced by this approach is quantifying the degree (and duration) to which rat populations can be suppressed (or eradicated) and the apparent benefits of this management to improve the viability of threatened bird populations in both the short and long-term (Innes et al., 1999; James and Clout, 1996; Moorhouse et al., 2003).

Identifying any measurable benefits of management is in itself challenging as it requires observing individuals through whole seasons and individual identification. For multi-brooded passerines this challenge is compounded due to their ecology and behaviour compromising my ability to collect annual individual-based data and accurately assess the benefits (Bottrill et al., 2008; Pease and Grzybowski, 1995). Here I deal with these challenges by combining a small-scale field experiment, investigating the impact of rat management on nesting success, with an individual-based stochastic simulation model to predict annual productivity and a population matrix model to assess the population-level consequences of management. These techniques have been applied successfully for other threatened passerine species investigating species responses to management actions using field experiments spanning numerous years (Brook & Kikkawa 1998; Basse et al. 2003; Armstrong et al. 2006; Fessl et al. 2010). However, here I investigate the impacts of small-scale, short-term management actions combined with demographic models to obtain quick results for species management; which for critically endangered populations is vital.

In the *Zosterops* genus ship rats are considered a threat to 70% of the endangered or critically endangered species all of which are situated on islands (Mauritius, Norfolk Islands, Northern Mariana Islands, Sangehi and Seychelles), they are also thought to be the main cause of the robust white-eye (*Zosterops strenuus*) extinction (Birdlife International 2004; IUCN 2014, 2015). The Mauritius olive white-eye (*Zosterops chloronothos*) (hereafter referred to as the olive white-eye) is one of four white-eye species currently classed as critically endangered and is in the top 10% of the Evolutionary Distinct and Globally Endangered (EDGE) bird species list (IUCN, 2013; Jetz et al., 2014).

Within Mauritius the olive white-eye is the rarest of the remaining nine endemic land bird species, with a limited understanding of its basic ecology (Nichols et al., 2005; Safford, 1991; Safford and Hawkins, 2013; Staub, 1993). The species has experienced an island wide decline due to habitat loss, competition with introduced bird species and suspected nest predation (eggs and nestlings) by ship rats (Nichols et al., 2005; Safford, 1997a; Safford and Hawkins, 2013). Between 1975 and 2001 the population declined from 340-350 pairs to 93-148 and is now primarily restricted to an area less than 25km^2 in the Black River Gorges National Park (Figure 2.1; Cheke, 1987; Nichols et al., 2004). In response to the population decline a recovery project was initiated in 2005, which involved the establishment of a sub-population on a rat-free island nature reserve (Ile aux Aigrettes, 20˚42′S 57˚7′E), the monitoring of a remnant sub-population in the National Park and the control of rats (Cole et al., 2008, 2007; Maggs et al., 2010, 2009).

The recovery project used rat control measures in the mainland population using rat snap-traps around individual nesting sites from 2006 to 2010. However, this sporadic management was unable to identify if rats are a major limiting factor for the breeding population or whether management could effectively control them. Here I examine, using an experimental framework, if rats are a threat to the mainland olive white-eye population and whether the management of rats through poisoning/trapping can reduce their impact by combining a small-scale field experiment with demographic models. Specifically, I examine if (i) the application of poison reduces rat abundance, (ii) the management of rats leads to an improvement in nesting success, (iii) an observed increase in nesting success can significantly improve annual productivity, and (iv) an increase in productivity can have a biological impact on the rate of population change and prevent population decline. Based on my findings I demonstrate how small-scale, short-term field experiments in conjunction with demographic models can provide an insight into the long-term benefits of controlling nest predators such as rats for threatened passerine populations.

2.4. Methods

2.4.1. Study Site and Species

The olive white-eye population has a very restricted range, and within this range, a very patchy distribution with low densities. Combo (20˚46′S 57˚51′E), the chosen study site, is an area of c.5km^2 in the Black River Gorges National Park where the highest density of olive white-eye breeding pairs remain, estimated at 25-30 breeding pairs (Figure 2.1;

Nichols et al., 2004). Combo has a riparian upland forest habitat with degraded vegetation supporting populations of four other endemic bird species (Safford, 1997b).

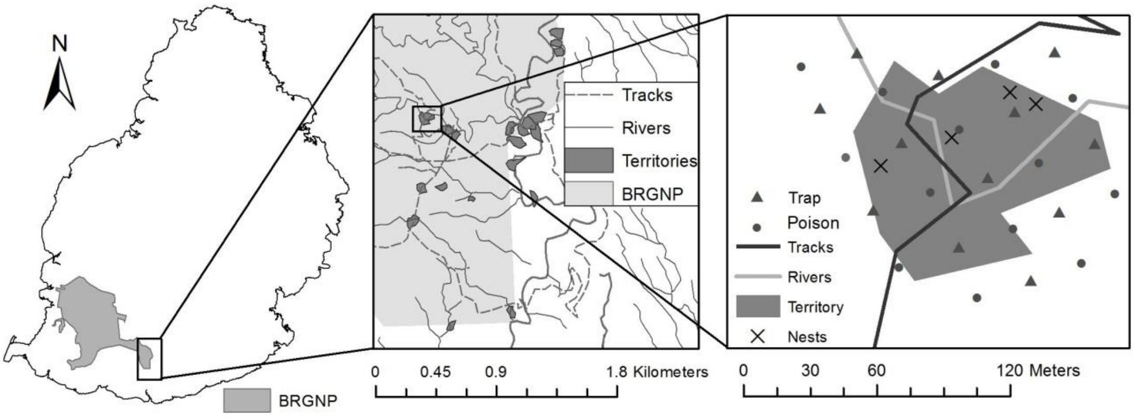

Figure 2.1 The location of the Black River Gorges National Park (BRGNP) in Mauritius (left), Mauritius olive white-eye breeding territories in the Combo region in the south-west of the National Park (middle) and a schematic representation of a poison and trapping grid across an olive white-eye breeding territory (right)

The olive white-eye is part of an ancient Indian Ocean white-eye lineage with birds colonising from Asia prior to the subsequent evolution of the African species (Warren et al., 2006). Prior to 2001 little was known about the olive white-eye with only eight nesting episodes where eggs were laid, ever recorded; of which only one successfully fledged nestlings (Nichols et al. 2005; Safford 1991; Staub 1993). However, through the management and monitoring of the Combo population and the establishment of the Ile aux Aigrettes island sub-population the life-history of the species is now better documented (Cole et al., 2008, 2007; Maggs et al., 2011, 2010, 2009).

Olive white-eye pairs are monogamous and in the wild defend territories of c. 0.5ha (± 0.2, n = 21) which characteristically include running water sources, an area of canopy and open areas (Cole et al., 2008; Maggs et al., 2011; Nichols et al., 2005; Safford and Hawkins, 2013). The breeding season is in the austral summer, typically between August and March. They are a multi-brooded species and will breed continuously throughout the season, regardless of whether their nests succeed or fail; building a new nest with each attempt and reaching up to seven nesting attempts, which may be abandoned before eggs are laid, in one breeding season (Cole et al. 2008; Maggs et al. 2011). The open cup nests take 3-13 days (n=41) to build and are situated high in the canopy on thin outer branches (average nest height of 10m ± 4.5, n = 55), which makes accessing nests logistically challenging and in many cases impossible (Cole et al. 2008; Maggs et al. 2009, 2010, 2011). Females lay 1-3 pale blue eggs, which are then incubated for 12 days by both the male and female (Cole et al., 2007; Nichols et al., 2005). Nestlings are fed invertebrates by the pair for 14 days until fledging after which the juveniles will remain with the adults for 2-8 weeks before reaching independence (Nichols et al., 2005; Safford and Hawkins, 2013).

The remnant wild population is un-ringed and the habitat means that accurate data on breeding biology and survival is difficult to obtain, however, the ringed population on Ile aux Aigrettes provides detailed demographic data which can be applied to the wild population. On Ile aux Aigrettes, where there are no mammalian predators and the population is supplementary fed, the mean egg hatching rate is 1.2 nestlings per nest (n = 47) and the mean nestling fledging rate in successful nests is 1.3 fledglings per nest (n = 14) (Appendix 2.2). Juvenile survival (i.e. first year) is estimated at 0.63 (approx. 95% C.I. = 0.23-0.86) and annual adult survival at 0.81 (approx. 95% C.I. = 0.72-0.87) (Appendix 2.1). Although rats are considered a threat to nesting success in the mainland population, there is no physical or incidental evidence to indicate that adults are predated on the nest. The breeding pairs on the mainland are monitored closely throughout the breeding season and although not ringed their monogamous behaviour allow missing birds to be recorded. Adult olive white-eye have very few natural predators except for possibly the Endangered Mauritius kestrel (*Falco punctatus*) which is not yet found in the Combo region.

2.4.2. Rat Management

Between July 2010 and March 2011 an experiment was conducted to explore the impact of poisoning on rat abundance and the impact of different levels of rat management on olive white-eye nesting success. During this time 24 known olive white-eye breeding territories were present in the Combo region, 21 of which were included in the experiment. Each of the 21 breeding territories were randomly assigned one of three levels of rat management; ‘Control’ (no management) (n = 7), ‘Trap’ (snap-trapping alone) (n = 7) and ‘Poison’ (rat poisoning and snap-trapping) (n = 7). Management techniques were targeted at the two rat species present in Mauritius: ship and brown rats.

Grids were established across breeding territories assigned to Trap and Poison management prior to the breeding season, covering the breeding territory of each individual pair with 25m intersections (Figure 2.1; Vanderwerf et al., 2011). Snap-traps were placed every 50m across the grids and trapping commenced prior to poisoning (July) to identify initial rat abundance. Trapping was then conducted every other month

(Sept, Nov, Jan) to generate an index of rat abundance throughout the breeding season under Trap management (without poison) and Poison management (with poison) to investigate the impact of poison on rat abundance. Snap-traps were set for three consecutive nights and checked and re-set daily following the methods of Cunningham and Moors (1996). In territories under Poison management bait stations were installed every 50m at alternative points to the snap-traps using a ‘hockey stick’ station design (Figure 2.1; Tatayah et al., 2007a). Poison was initiated following the first round of snap-trapping, one month before breeding activity began using 20g Megalon Wax Blocks, a fixed bromadiolone based poison which prevents rats from removing and hoarding poison and encourages consumption (INDIA, 2013). The poison grids were maintained continuously throughout the breeding season and re-baited on a weekly basis. Secondary poisoning is a potential threat when using rat poison but no non-target mammals or birds were observed consuming poison. However, gastropods were observed, but were excluded from the bait stations with the use of copper wire around the entrances (Tatayah et al., 2007b).

2.4.3. Nest Monitoring

Since the initiation of the recovery project in 2005 breeding territories in Combo have been monitored at the start of every season prior to breeding activity in order to identify pairs and define territories. Although the birds are un-ringed missing birds can be identified through the monogamous behaviour of the pairs and the close observations allow us to see gaps in the nesting cycle or breeding behaviour; in the 2010/11 season there were no pair or territory changes. Between August and February 2010/11 all 21 territories involved in the field experiment (Control, Trap and Poison) were monitored for nesting activity with searches commencing prior to the breeding season to find the first attempts; which assisted in subsequent nest finding. Due to the cryptic and elusive behaviour of the breeding pairs and the challenging terrain territories were visited at least twice a week and searched for a maximum of one hour.

If a nest was located, nest habitat data was collected, this included nest characteristics (nest height (m), position in canopy and density of vegetation around the nest) and vegetation structure (understory density and canopy density). Ship rats are known to use the thick canopy and dense understory to move around their home range which could increase the chances of opportunistic predation of nests (Hall, 2003). The nest habitat data enables these additional influencing factors to be investigated against breeding success. Nests were monitored every three days for a maximum of one hour, to determine nest status, until nest outcome. Due to the inaccessible positioning of nests in Combo all activity was recorded through behavioural observation (Nichols et al., 2005). Through these observations and associated searches fledgling rates were obtained; as fledglings stay within a close proximity to the nest for 1-2 days (Safford and Hawkins, 2013). Nests were classed as failed if no breeding activity was seen at the nest for four consecutive nest watches or if a new nest was discovered.

2.4.4. Statistical Analysis

All analyses were conducted in R version 3.0.1 (R Core Team, 2013).

2.4.4.1. Rat Abundance

I wished to assess whether rat poisoning in addition to snap-trapping could significantly reduce rat abundance within olive white-eye breeding territories across a breeding season. To do this, I first calculated the catch per unit effort (CPUE) (for both rat species combined) of snap-traps for each territory under Trap or Poison management during each trapping episode using the methods of Nelson and Clark (1973); which accounts for sprung traps. No absolute control was available for the analysis (which would have to be done with non-lethal monitoring methods, e.g. tracking tunnels) and the territories under Control management, used for monitoring nesting activity, were not included as these had no measure of rat abundance.

Using the CPUE data I tested the impact of poison on rat abundance across the breeding season exploring the month to month variation using a generalized linear mixed-effects model (GLMM) in the package 'lme4' (Bates et al., 2013). The model contained a response variable of CPUE per territory per month, categorical fixed effects of month (July, Sept, Nov, Jan), poison present (Yes/No) and their interaction and random effects of area, a continuous variable (to account for unintended variations in the density of traps and poison stations), and territory, a categorical variable (accounting for repeated data from each breeding territory throughout the breeding season). The model was run with and without the interaction and also with and without area comparing them separately in a two-way analysis of variance to test how the CPUE responded to the presence/absence of poison and variations in the density of treatments. To test for any significant change in the CPUE at two, four and six month intervals following the initiation of poison, individual models were run comparing each post poisoning month (Sept, Nov, Jan) with the pre-poisoning month (July).

2.4.4.2. Nesting Success

A total of 40 nesting attempts, where at least on egg was laid, were monitored and these were evenly distributed across the three rat management treatments; Control (n = 15), Trap (n = 12) and Poison (n = 13). Nests were not monitored on a daily basis and so the nest outcome date was classed as the midpoint between the last and penultimate observation (Mayfield, 1961). Failure dates were rounded up to the nearest day (Hazler, 2004). To compare daily nest survival between rat management treatments I used Mayfield logistic regression (Hazler, 2004) within a GLMM framework (Ludwig et al., 2012). This approach removes bias caused by unrecorded failed nests and the stage at which nests were found (Mayfield, 1975, 1961). I constructed separate models for daily nest survival during the incubation (DNS_I) and nestling (DNS_N) periods because the impact of rat management on nest survival might be stage-specific.

Each model contained a response variable of daily nest survival, combining ‘trials’ (the days of exposure for each nest) and ‘events’ (0 = success, 1 = failure) using the ‘cbind’ function in R (Hazler, 2004; Ludwig et al., 2012). Rat management was included as a categorical fixed effect and individual olive white-eye territories as a categorical random effect (accounting for repeated data (nesting attempts) from each breeding territory throughout the breeding season). I compared this model with a null model in a two-way analysis of variance to assess the statistical significance of the rat management variable. I also explored models in which rat management treatments were compared separately (Control, Trap and Poison) and combined (Control, Trap + Poison) to assess the statistical evidence for an effect of poisoning alone on nest survival. Formally, my models are based on daily failure rates, so I transformed parameter estimates to visually display DNS_I and DNS_N.

Due to the small sample of nests available for analysis it is possible that an apparent statistically significant effect of rat management on nest survival might be due to other factors in relation to additional nest characteristics or vegetation structure. My small sample size precluded the fitting of complex multivariate GLMMs, so to check for any potential confounding effects I simply compared a range of measures of nesting habitat between rat management treatments. These measures included nest characteristics, nest height (m), position (position in canopy: upper, middle, lower) and density (density of vegetation around the nest: dense, sparse) and vegetation structure, understory (understory density: dense, medium, sparse) and canopy (canopy density: dense, medium, sparse). These additional categorical and continuous measures were run against the rat management categorical factor in individual Chi-squared tests to identify any effect. However, there is a limitation to this approach, if additional effects are identified using this method it will be unclear whether they are independent of any effects found via the GLMM model.

2.4.4.3. Annual Productivity

For demographic projections of management treatments, effects on nesting success needed to be translated to effects on annual productivity (number of fledglings produced per female per season). In multi-brooded species a direct estimate of annual productivity typically requires intensive studies of marked females through an entire season (e.g. Weggler, 2006). Due to the limited number of breeding pairs, the challenges of nest finding, limited staffing and un-ringed individuals a direct estimate of olive white-eye annual productivity in Combo could not be made without creating bias. Instead I took the more frequently used approach of its estimation via a dynamic seasonal productivity model (see review by Etterson et al., 2011).

I used an individual-based stochastic simulation model developed to study predator effects in multi-brooded passerines (White, 2009) based on previous models (Beintema and Muskens, 1987; Powell et al., 1999). The model follows a simulated female on a 'random' walk through a season, selecting randomly from pre-specified distributions of parameters that limit the season (first-egg date, re-nesting probability) or determine breeding success (clutch size, hatching probability, fledging probability, DNS_I, DNS_N), and using temporal duration parameters that determine the length or maximum length (in days) of the seasonal components (nest building, inter-attempt intervals, maximum incubation period, maximum nestling period, maximum number of successful nests) (Table 2.1). All the methods used to generate these parameters can be found in Appendix 2.2.

Table 2.1 Biological parameters and their values used in calculating the mean annual productivity of breeding female Mauritius olive white-eye under differing rat management techniques; Control (No management), Trap (Snap-trapping alone) and Poison (Rat poisoning and snap-trapping)

Parameter		**Value**
Initial first egg date (days)		60
Daily nest survival during incubation	Control	0.942
(DSN_I)	Trap	0.995
	Poison	0.956
Daily nest survival during nestling	Control	0.845
(DNS_N)	Trap	0.925
	Poison	0.977
Building duration (days)		3-13
Maximum number of successful nests		7

Incubation period (days)	12
Nestling period (days)	14
Mean eggs hatching per nest	1.206
Mean nestlings fledging per nest	1.357
Clutch size	1-3
Re-nesting probability following success	Figure A2.2
Re-nesting probability following failure	Figure A2.2

Stochastic simulation models are capable of simulating ‘re-nesting compensation’ which occurs because birds that fail may be able to make more attempts than those that are successful (Grzybowski and Pease, 2005). Re-nesting compensation is expected to dampen the effect of inter-individual or inter-population variation in nest success on seasonal productivity (Nagy and Holmes, 2004). This has important implications for a management study such as this, because it means that apparently large responses observed in nest success may not necessarily translate into biologically significant responses at the level of annual productivity or at the population level. The non-independence of nest success and number of attempts made also means that assuming a fixed number of attempts is ultimately biased (Grzybowski and Pease, 2005). Dynamic models can address the lack of information on number of attempts by constraining the number of attempts individually and indirectly via the inclusion of a re-nesting probability function, which describes the probability at any point in the season that a bird will continue to nest after a failed or successful attempt (Table 2.1; Figure A2.2; Appendix 2.2; Etterson et al., 2009; Mattsson and Cooper, 2007; Pease and Grzybowski, 1995).

For each rat management scenario I simulated 10,000 females and extracted their annual productivity estimates. Model sensitivity testing was carried out using the Control management as a base model with each parameter adjusted by ± 20%. The average effect sizes were estimated along with 95% confidence intervals comparing Poison and Trap management against Control and enabling a comparison of the rat management impact on a biological rather than statistical basis (Corell et al., 2012; Underwood, 1997; White et al., 2013). Replication determines statistical power and so testing statistical significance may be inappropriate for simulation data (White et al., 2013).

2.4.4.4 Population Growth Rate

When investigating the impact of management on population persistence many studies have used population viability analysis (PVA) (Basse et al. 2003; Armstrong et al. 2006;

Fessl et al. 2010). However, with limited data availability a concern is that there is not enough qualitative and quantitative data for a reliable analysis even with expert input (Brook & Kikkawa 1998). A study investigating Capricorn silvereyes (*Zosterops lateralis chlorocephala*) on Heron Island showed that the minimum dataset required to gain an accurate estimate of underlying population parameters was fifteen years and that there is a danger of less costly but seriously deficient management schemes being implemented based on unrealistic or overly optimistic PVA predictions (Brook & Kikkawa 1998). Due to the rarity of the olive white-eye there is still limited data and no understanding of how the key demographic parameters are influenced by environmental conditions and other stochastic events. Therefore, if a PVA was used predictions would be made on inadequate and insufficient data. Instead a population growth rate (λ) was calculated to explore the potential long-term impact of rat management on population growth of the mainland olive white-eye under different rat management treatments.

To calculate the λ, I used a two-stage (yearling, adult) matrix model of a similar form to that developed for Seychelles magpie robins (*Copsychus sechellarum*) (Norris & McCulloch 2003). Stage-specific fecundities were derived from the annual productivity estimates generated by the individual-based stochastic simulation model (section 2.4.4.3). Stage-specific survival rates were estimated from existing data (Appendix 2.1) and assumed equal across the different management treatments as the study was conducted in a small region with the same habitat and environmental conditions. Individuals began breeding at 1 year of age, and I assumed that productivity was similar for yearling and adult females. I assumed survival rates were similar across the rat management treatments as to the best of my knowledge rats do not predate adult olive white-eyes on the nest, so any differences in λ between treatments reflect differences in stage-specific fecundities.

2.5. Results

2.5.1. Rat Management

The results of rat snap-trapping show that the presence of poison had a significant effect on rat abundance in September (χ^2 = 6.9021, d.f. = 1, P = 0.008), two months after poison initiation, with the average CPUE reduced by 23% with Trap management compared with a reduction of 92% with Poison management. Poison had no significant effect on the CPUE across the whole breeding season (χ^2 = 4.6768, d.f. = 3, P = 0.197) or four (χ^2 = 0.2619, d.f. = 1, P = 0.609) and six (χ^2 = 2.1416, d.f. = 1, P = 0.143) months after initiation. Area also had no significant impact on CPUE at two (χ^2 =

0.5136, d.f. = 1, *P* = 0.474), four (χ^2 = 1.5836, d.f. = 2, *P* = 0.453) or six months (χ^2 = 2.6374, d.f. = 2, *P* = 0.268).

2.5.2. Nesting Success

Rat management had a significant effect on DNS_N increasing survival from 85% with Control management to 93% and 98% with Trap and Poison management, respectively (Figure 2.2). The effect of management on DNS_I was not significant, averaging at 97% (± 0.02) across all three rat management techniques. There was no evidence to suggest that either nest characteristics or vegetation structure influenced management and therefore had no impact on its measure of DNS. When combining the rat management treatments to see the impact of poisoning alone on DNS_I and DNS_N no significant difference was found. All model outcomes can be found in Table 2.2.

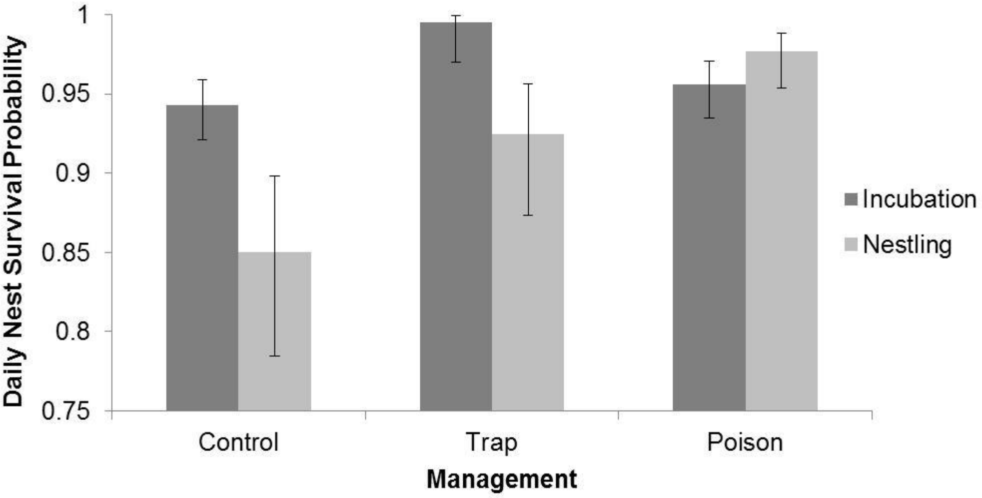

Figure 2.2 Daily nest survival of Mauritius olive white-eye nests in Combo during the incubation and nestling stage in the 2010/11 breeding season under varying rat management techniques; No management (Control), snap-trapping alone (Trap) and rat poisoning and snap-trapping (Poison). Bars represent standard error

Table 2.2 Results using a generalised linear mixed-effects model (GLMM) examining daily nest survival during the incubation and nestling stages (DNS_I/DNS_N) separately in relation to rat management (Management; Control (no management), Trap (snap-trapping alone) and Poison (snap-trapping and rat poisoning)) and investigating rat management as a two and three level factor to assess the impact of rat poisoning alone (Trap + Poison). Also, the results using Chi-squared tests examining the effect of nest characteristics (Nest height (m), Position (position in canopy: upper, middle, lower) and Density (density of vegetation around the nest: dense, sparse)) and vegetation structure measures (Understory (understory density: dense, medium, sparse) and Canopy (canopy density: dense, medium, sparse)) on management to investigate if these factors would impact the influence of management on DNS_I or DNS_N. My small sample size precluded the fitting of complex multivariate GLMMs for these factors

Factor	**Model**	**DNS_I/DNS_N**	**χ^2**	**d.f.**	***P*-value (* < 0.05)**
Management	GLMM	DNS_I	0.2444	2	0.88
		DNS_N	6.8596	2	0.03*
Nest height	Chi-squared	DNS_I	38.3154	36	0.36
		DNS_N	21.6389	24	0.60
Position	Chi-squared	DNS_I	2.7388	2	0.25
		DNS_N	6.3402	4	0.18
Density	Chi-squared	DNS_I	7.749	4	0.10
		DNS_N	4.8431	2	0.08
Understory	Chi-squared	DNS_I	1.2086	4	0.88
		DNS_N	3.9238	4	0.42
Canopy	Chi-squared	DNS_I	2.9256	4	0.57
		DNS_N	4.0212	4	0.40
Trap +Poison	GLMM	DNS_I	0.0554	1	0.81
		DNS_N	0.2034	1	0.65

2.5.3. Annual Productivity

The individual-based stochastic simulation model showed that with the use of rat management the mean annual productivity of females can be increased substantially. Areas without management, i.e. Control management, produced 0.2 fledglings per female per breeding season, whereas Trap and Poison management produced an additional 0.57 (95% C.I. = 0.55 – 0.59) and 0.9 (95% C.I. = 0.88 – 0.92) fledglings, respectively. Sensitivity testing of the model parameters showed all the parameters responded to the changes. However, certain parameters (DNS_N, nestling period and re-nesting probability following success) resulted in a greater change in annual productivity than others (Figure 2.3).

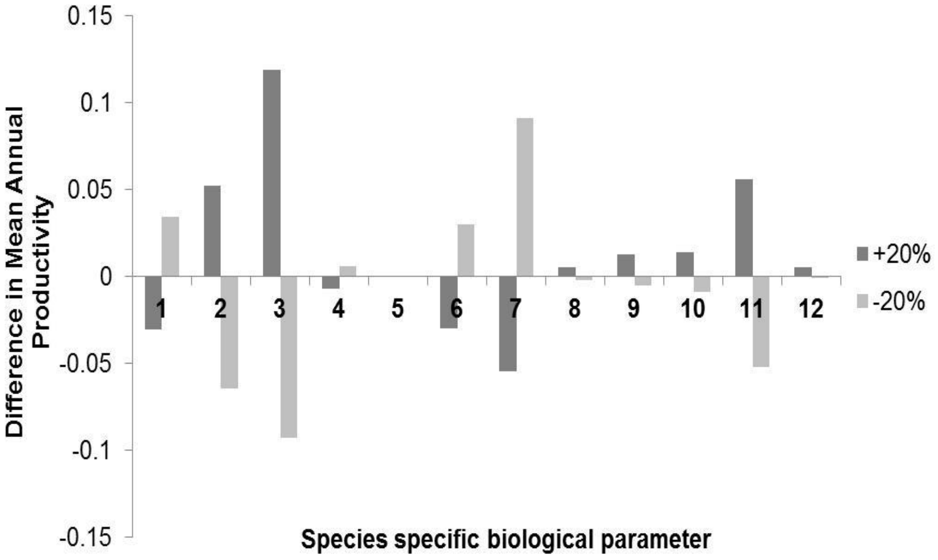

Figure 2.3 Sensitivity testing of the individual based stochastic simulation model illustrating the difference in mean female Mauritius olive white-eye productivity for each parameter adjusted by ± 20%; Initial first egg date (days) (1), Daily nest survival during incubation (2), Daily nest survival during nestling (3), Building duration (days) (4), Maximum number of successful nests (5), Incubation period (days) (6), Nestling period (days) (7), Egg hatching probability (8), Nestling fledging probability (9), Clutch size (10), Re-nesting probability following success (11) and Re-nesting probability following failure (12). Parameter 5 is a fixed value so was not altered. The Control territory parameter values were used as the base model

2.5.4. Population Growth Rate

The two-stage matrix model predicted that the λ increases with the addition of rat management. With Control management the λ is negative with an annual population decline of 14%. With Trap management the PMR becomes positive, with a predicted annual population increase of 1% and with the addition of rat poisoning with Poison management it increases further to 10% per year (Figure 2.4).

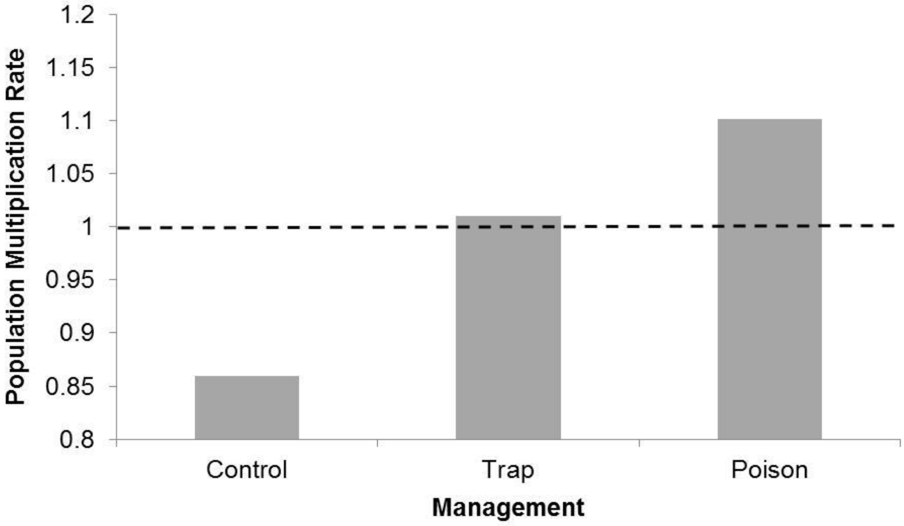

Figure 2.4 The growth rate of the Combo Mauritius olive white-eye population under different rat management techniques; No management (Control), snap-trapping alone (Trap) and rat poisoning and snap-trapping (Poison). Values were generated from a hazard analysis with the dashed line indicating a stable population; values above 1 represent an increase and below 1 a decrease in population growth rate

2.6. Discussion

2.6.1. Rat Management

By using the Nelson and Clark (1973) methodology to generate an unbiased, accurate index of rat abundance my study has shown that the application of rat poison in olive white-eye territories can significantly decrease rat abundance within the first two months of poison application. However, there was no evidence in the subsequent two and four months of a sustained low level of rat abundance, due primarily to fluctuations. One possible explanation for these fluctuations is that poison removes resident rat populations from the area but it is subsequently re-colonised through immigration from the surrounding rat home-ranges. There is evidence to support this from a long-term study of rats on mainland Mauritius (Hall, 2003). A second possible explanation is that there might be natural annual fluctuations in rat abundance in response to rat breeding cycles, stochastic events or environmental factors which could influence the impact of rat poisoning (Alterio et al., 1999; Hall, 2003). However, with relatively small sample sizes and limited short-term data from the study system at Combo these results are preliminary and I am unable to account for these factors in my analyses or explore them in any detail. Therefore, this study should be repeated and these natural fluctuations in rat abundance and the impact of reinvasion should be considered in any future rat management techniques, with rat management implemented during high levels of natural rat abundance (October -December) and periods of peak olive white-eye breeding activity (September-November) (Hall, 2003; Maggs et al., 2011).

The size of the management area and treatment density did not affect the CPUE, however, the olive white-eye territories are small and closely distributed within the Combo region and so there is a risk of rats moving across numerous treatment sites and influencing the impact of management. Territories were allocated treatments randomly to avoid bias and most of the treatment territories were independent of each other. However, some of the territories with Trap management were adjoining which may have influenced the rate of rat re-colonization and underestimated the CPUE, masking the impact of Trap management on an individual territory basis. In Mauritius the home range of rats vary between 0.3 – 0.4ha (Hall 2003) which is less than the average olive white-eye breeding territory (0.5ha) and rat home range sizes are not found to change in response to poisoning (Hall, 2003). It is therefore unlikely that rats would travel across numerous territories or alter their territorial behaviour in response to management and influence the impact of the treatment.

Other studies investigating the impact of management on rat abundance, in relation to threatened passerine populations, have found that the use of rat poison can decrease rat abundance however, these studies also encountered reinvasion effects indicating that small scale management may not be the most effective method over prolonged periods (Blanvillain et al., 2003; Rocamora and Baquero, 2007; Vanderwerf and Smith, 2002).

2.6.2. Nesting Success

Analysis of DNS has shown that the use of rat management can significantly increase DNS_N through rat poisoning and snap-trapping or snap-trapping alone. As suggested by Nicoll and Norris (2010) by conducting a robust field experiment which involved the simultaneous monitoring of both prey and predator species I have gained compelling evidence that there was a concurrent decline in rat abundance and improvement in DNS_N during periods of rat management. Although there were fluctuations in rat abundance across the breeding season the periods of low CPUE overlapped with the peak in nesting attempts at nestling stage (October; Figure. A2.3), which could account for the impact on DNS_N. However, rat management failed to increase nesting success during incubation. This could be due to the secretive and elusive behaviour that olive white-eye display during the incubation period causing rats to overlook the nests. Once the nestlings have hatched the pairs become far more vocal and active around the nest as well as vocalization by the nestlings. Therefore, rats are potentially more likely to find the nests during this period causing a higher rate of predation and hence a positive impact of management.

A small proportion of territories with Trap management in the study were adjoining, potentially reducing the rate of rat reinvasion into the territories and causing the impact of Trap management on DSN_N to be overestimated. However, as previously discussed rat home-range sizes in Mauritius are on average smaller than olive white-eye breeding territories and do not change in response to rat management and so it is unlikely that they would travel across numerous territories in one evening and influence the impact of the treatment (Hall 2003).

As with the rat abundance data the sample sizes for this analysis are relatively small and due to logistical and financial restraints the nesting data only represents one breeding season. Although small-scale field experiments can assist in understanding the response of nesting attempts to different levels of management they are preliminary and cannot directly predict the population level or long-term implications, which are essential when designing more cost-effective management (Hiraldo et al., 1996; Pease and Grzybowski, 1995). Therefore, population-level impact and annual variation were not accounted for through direct field observations but instead predicted using demographic models. The impact of rat management on DNS_N indicates that rats are a major limiting factor to the mainland population, highlighting the positive impact rat management can have on olive white-eye nesting success. Other studies investigating the effect of rat management on nesting success in threatened passerine species support my findings having also found that it can increase nesting success thus, providing further evidence that rats are a global limiting factor for threatened island passerine populations (Fessl et al., 2010; Innes et al., 1999; Robertson et al., 1994).

2.6.3. Annual Productivity

By using an individual-based stochastic simulation model, as opposed to a simple scalar model for example (Etterson et al., 2011), I have shown that the increase in nesting success is large enough to improve annual productivity of the olive white-eye population with both Trap and Poison management in spite of any effect of re-nesting compensation.

The results of the models are based on parameters collected from two olive white-eye populations in contrasting habitats under different management and monitoring regimes; a mainland population and a supplementary fed, reintroduced sub-population on a rat-free island nature reserve. This is due to the rarity of the olive white-eye and limited life history data available for the mainland population; a problem encountered by other projects studying declining, data deficient species (Fessl et al., 2010). However, sensitivity testing conducted on the model found the only parameters sensitive to change were those derived from the mainland study population; DNS_N, length of nestling period and re-nesting probability following success. This indicates that the island derived parameters do not have the greatest impact on the model and are therefore less influential.

Previous studies, calculating annual productivity, support my findings, yet the combination of DNS analysis and simulation models is seldom used for passerine populations yet is necessary in generating accurate annual productivity values for multi-brooded species and investigating the population level consequences of management (Fessl et al., 2010; Paradis et al., 2000; Pease and Grzybowski, 1995; Thompson et al., 2001; White, 2009).

2.6.4. Population Growth Rate

The results of the two-stage matrix model show that without rat management the population decline is predicted to continue however, this can be prevented through the application of rat management within breeding territories. Trap management (snap-trapping alone) can lead to a population increase however the λ remains close to 1 making it susceptible to negative impacts elsewhere or errors in parameterisation. In territories with Poison management (poison and snap-trapping) the λ is substantially higher than 1 leading to an increased more robust population, preventing population decline and potential localised extinction. These results highlight the importance of investigating both the short and long-term impact of rat management techniques, as the addition of poison in territories had large implications for the long-term viability of the population; a factor which may have been overlooked on a small-scale.

Due to the design of the experiment, management sites differed in density where territories with Poison management (25m spacing's between snap-traps and poison stations) were twice the density of those with Trap management (50m spacing's between snap-traps). This design enabled rat abundance to be monitored at the same density and the impact of additional poison to be investigated, a method which has been used in other studies (Vanderwerf et al. 2011). However, if rat snap-trapping was conducted at 25m instead of 50m to match the density of Poison management I may have seen an increase in its effect. The application of these management techniques should be investigated further, applying them at the same density and investigating the impact of poisoning alone. This could enable the most effective technique to be identified, biologically, logistically and financially and allow further studies to be trialled e.g. investigating large-scale against small-scale or increasing the intersection lengths.

Studies researching threatened species tend to focus on the short-term impact of management and on a small, localised scale and so the long-term effects are less understood or misinterpreted (Baillie et al., 2000; Paradis et al., 2000). Therefore, hazard analysis using population matrix-models could be an important conservation tool for predicting the long-term implications of conservation management based on accurate short-term data, specifically the impact of rat management on threatened passerine populations (Armstrong et al., 2014; Norris and McCulloch, 2003).

2.7. Conclusion

My findings have confirmed rats as a major limiting factor for the mainland population of olive white-eye. However, I have demonstrated that the application of rat management in breeding territories can significantly decrease rat abundance and significantly increase DNS_N. At a population level the use of rat management can increase annual productivity, leading to apparent population stability or increase. This highlights the immediate need for rat management in the mainland olive white-eye population to ensure their continued survival. With growing numbers of species on the verge of extinction and limited resources accurately assessing the impact of management techniques is essential (Bottrill et al., 2008). Here I demonstrate a conservation tool which enables the assessment of short-term management techniques and predicts its long-term impact allowing management to be refined and conservation resources to be allocated effectively to prevent potential localised extinction.

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Appendix 2.1

Stage specific-survival rates

To estimate stage-specific survival rates, hazard models were used based on individually marked (in the nest), wild fledged birds born into the released, supplementary fed, island population from 2006 to 2013 (Ferrier et al. 2013; Hotopp et al. 2012; Maggs et al., 2009, 2010, 2011). This population is monitored on a daily basis, 365 days a year, providing continuous re-sighting data. Daily survival rates for both juveniles and adults were calculated in separate hazard models using the ‘Survival’ package in R version 3.0.1 with the function ‘survreg’ to account for censored data (R Core Team, 2013; Therneau and Lumley, 2014). I fitted separate models with exponential or Weibull error distributions to explore both constant and age-specific variation in hazard. These null models were then compared using a two-way analysis of variance and the error distribution with the lowest residual deviance was used. The parameter estimates from the chosen models were then transformed to generate the daily survival rate; these rates were then calculated to the power of 365 to generate annual survival for both juveniles and adults.

The hazard models were run using the Weibull error distributions due to the low residual deviance. Juvenile survival (i.e. first year) was estimated at 0.63 (approx. 95%

C.I. = 0.23-0.86, n=32) and annual adult survival at 0.81 (approx. 95% C.I. = 0.72-0.87, n=16).

Survival data used, although from the same species, were derived from the supplementary fed, rat-free, island population, which may have generated higher survival rates than those seen in the mainland population. Nonetheless, the increase in the population multiplication rate remains comparable as the same survival rates were applied to each rat management treatment.

Appendix 2.2

Individual-based stochastic simulation model biological parameters

The model was parameterised from existing olive white-eye data collected between 2007 and 2011; available from internal reports (Cole et al., 2008; Maggs et al., 2009, 2010, 2011). These data were derived from studies on both the mainland population in the Combo region, an un-ringed remnant population which is monitored during the breeding season (August-March), and the reintroduced island population on Ile aux Aigrettes (20˚42′S 57˚7′E) which is ringed and monitored on a daily basis throughout the year.

Daily nest survival during nestling and incubation (DNS_I and DNS_N)

The DNS_I and DNS_N of nests during the 2010/11 experiment were generated from the described Mayfield logistic regression generalised linear mixed-effects model (GLMM), extracting the parameter estimates and standard errors from the model output for Control, Trap and Poison management (section 2.4.4.2).

Mean initial first egg date

The mean and standard deviation was estimated using the mainland population data in 2010/11. The first nesting attempts of known breeding pairs were used, calculating the number of days from the start of the season (1st August as day one) until the first day of incubation. Observations are not taken on a daily basis so all values were rounded up to the nearest day.

Duration of nest building

This was measured using the mainland population data from 2007 to 2010. Only nests which were found during early nest building and which reached incubation were included as breeding pairs are known to abandon nests during the building stage and after completion. Nests are not observed daily and so all values were rounded up to the nearest day.

Hatching and fledging probability

Due to the inaccessibility of nests in the mainland population the hatching and fledgling probability was calculated using the island population nesting data from 2007 to 2010. This provided accurate clutch and brood sizes along with hatching and fledging rates. These rates were used to calculate the hatching and fledging probability of eggs and chicks with a GLMM framework run in the package 'lme4' using the analytical package R version 3.0.1 (Bates et al., 2013; R Core Team, 2013). A hatching or fledging rate binomial response variable was used with a survive numerator (number of eggs/nestlings hatching/fledging) and a fail denominator (number of eggs/nestlings failing to hatch/fledge) created using the 'cbind' function in R with no fixed effect and territory as a categorical random effect (to account for repeated nests from the same pairs). This generated the mean number of eggs hatching and nestlings fledging per nest without a rat predation risk.

Clutch size

Due to the inaccessibility of nests in the mainland population, nesting data from the island population were used from 2007 to 2010. Using the mean clutch size from the island nesting data, randomised clutch size values were generated for the parameter rounding up all values to the nearest integer.

Maximum number of successful nests

Most *Zosterops* species average two nesting attempts per season (Bennett & Owens 2002) and this would also be the case for the olive white-eye if they were successful. However, the maximum number of successful nests was set at seven as this was the maximum number of nesting attempts reached by individual breeding pairs in the 2010/11 season. This was set to prevent the simulation model allowing females to re-nest to unrealistic levels. A negligible amount of simulated females reached this value; less than 1% under each management treatment.

Maximum incubation and nestling periods

These values were taken from existing literature (Nichols et al. 2005).

Re-nesting probability

Re-nesting probability functions of mainland olive white-eye breeding pairs following a failed or successful nesting attempt were estimated from all nests in the mainland population which reached incubation during the 2010/11 breeding season using a GLMM framework run in the package 'lme4' using the analytical package R version 3.0.1 (Bates et al., 2013; R Core Team, 2013). Whether a pair re-nested following a nesting attempt was the binomial response variable (1 = yes, 0 = no), with the day of the nest outcome as a continuous fixed effect (in days from the 1st August) and territory as a categorical random effect (to account for repeated data from the same breeding pairs). Separate models were run for successful and failed nests and the parameter estimates for re-nesting and day were back transformed to calculate the daily re-nesting probability for each day of the season (211 days).

The daily re-nesting probabilities generated for pairs following a successful nesting attempt indicate that the activity of successful pairs declines steadily throughout the breeding season, whereas for pairs that fail the probability of re-nesting declines more sharply leading to a shorter breeding season (Figure A2.2).

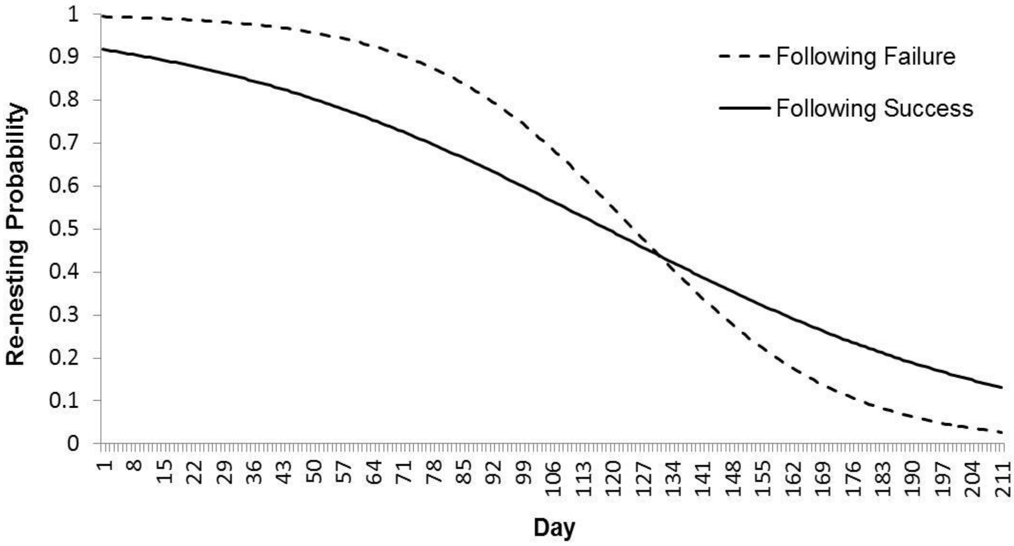

Figure A2.2 Re-nesting probability of Mauritius olive white-eye breeding pairs at Combo, following a successful or failed nesting attempt in the 2010/11 breeding season. The season is measured in days from 1st August and only included nesting attempts which reached incubation

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Appendix 2.3

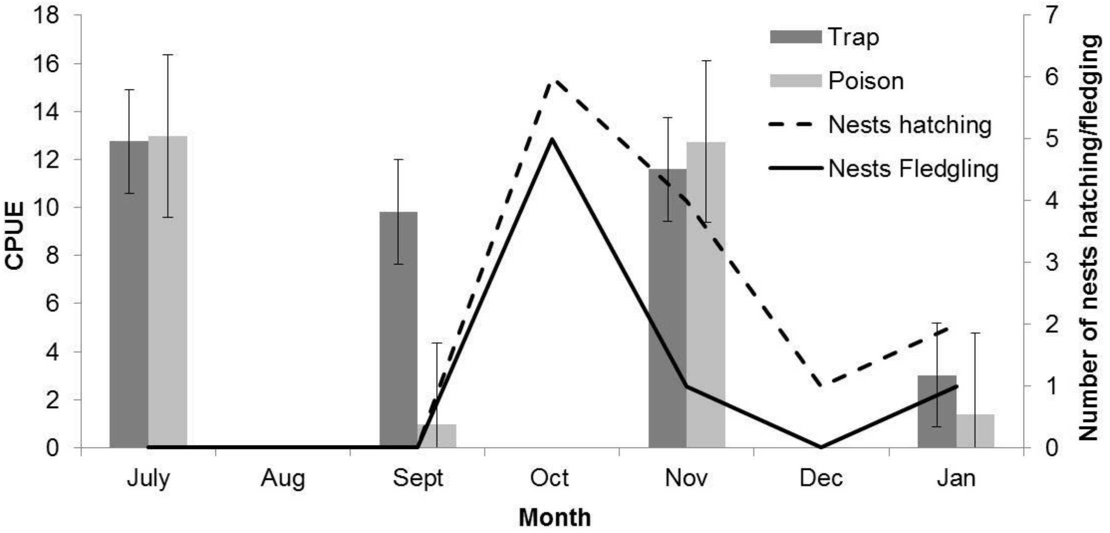

Figure A2.3 Average rat catch per unit effort (CPUE) after accounting for sprung traps in Mauritius olive white-eye territories under different rat management techniques; snap-trapping only (Trap) and rat poisoning and snap-trapping (Poison). This is plotted against the number of Mauritius olive white-eye nests which hatched or fledged one or more nestlings in 2010/11. Bars represent standard error.

Chapter 3

Supplementary feeding in endangered species recovery programmes – reducing the mismatch between supply and demand to refine management and devise an exit strategy

3.1 Chapter Attribution

I received invaluable advice on the direction of this chapter from my supervisors Prof Ken Norris, Dr Malcolm Nicoll and Dr David Murrell who also helped me with R code for the generalised linear mixed-effects model and hierarchical clustering. My fourth supervisor Dr Nicolas Zuël assisted in the experimental design of the data collection and provided additional data throughout analysis. Dr John Ewen provided advice on the focus and interpretation of the chapter.

3.2 Abstract

Supplementary feeding (SF) is a widely used management tool in endangered species recovery. Typically, food is provided *ad libitum* and without a planned exit, which over time can be costly in terms of conservation resources. Quantifying the use of SF is therefore important in order to understand the relationship between supply and demand. By understanding this relationship and identifying any mismatch managers could potentially refine SF practices both in the short and long-term; reducing costs through *ad libitum* management refinement and devising potential exit strategies.

Here I use a novel dataset of factors affecting the consumption of SF by a reintroduced population of critically endangered passerine to identify the mismatch between supply and demand and short and long-term management options. Specifically, I investigated how daily consumption rates are driven by seasonality, natural plant resource availability, breeding behaviour and management techniques.

I show that the demand for SF peaks during energetically expensive phases of the breeding cycle, when natural plant resource availability is low, and in the morning. I suggest, for short-term management, refining supply in response to demand during certain breeding stages and times of day. For long-term management I suggest increasing natural plant resource availability through the planting of key species in order to improve natural food continuity and reduce demand over time.

This study illustrates a first step to understanding the role SF plays within a species recovery programme. I have identified drivers in demand and by exploring both natural plant resource availability and SF supply I have identified management options for current and future ecosystem restoration programmes. These options could lead to the reduction or removal of SF as a conservation action and provide an exit strategy for endangered species management. This has been achieved through the combination of my novel dataset and the quantification of supply and demand which provides scientific evidence for the effective allocation of finite conservation resources. My framework could have broad relevance for species recovery programmes experiencing similar resource limitations and long-term uncertainty by minimising the risks of decision making.

3.3 Introduction

Species conservation often requires intensive management to reduce population limiting factors and save endangered species from extinction (Blanco et al. 2011; Jones & Merton 2012). The reintroduction of endangered species has been an effective intensive management technique for many decades with the ultimate goal of creating self-sustained populations (Soorae 2011; Jones & Merton 2012; IUCN/SSC 2013). In cases where critically endangered species are reintroduced to alternative habitats or habitats which are undergoing restoration it is difficult to know if a viable population can be sustained; especially when small populations are vulnerable to stochastic events (Shaffer 1981; Armstrong & Ewen 2001; Chauvenet et al. 2012). Providing a population with supplementary feed (SF) can buffer the impacts of environmental stochasticity and limited natural resource availability (Houston & Piper 2006; Rodriguez-Hidalgo et al. 2010; Correia et al. 2015).

Providing SF is a well-established conservation tool but has had varying degrees of success (Boutin 1990; Ruffino et al. 2014). Studies investigating the effect of SF on bird populations have found it can induce earlier laying dates and longer breeding seasons, increase egg size, clutch size and quality, fledgling success and survival (Robb *et al.* 2008); but can also cause increased aggression, create ecological traps, chick sex-bias and reduced health (Robertson et al. 2006; Robb et al. 2008; Blanco et al. 2011; Oro et al. 2013).

In most, if not all, conservation management programmes SF is provided *ad libitum* and without an exit strategy. As classified by the International Union for Conservation of Nature (IUCN) Guidelines for Reintroductions and Other Conservation Translocations, an exit strategy is an integral part of any reintroduction plan and enables a defensible and orderly exit when investing further resources is no longer justifiable or if the reintroduction is thought unsuccessful (IUCN/SSC 2013). In most cases exit strategies are planned in the event of a failed reintroduction but for successful reintroductions they are often not planned and therefore SF can expand exponentially alongside population growth and become costly in terms of conservation resources.

For conservation management programmes, with finite resources, providing costly SF without an exit strategy could be unsustainable both logistically and financially (Chauvenet et al. 2012; Ewen et al. 2015). It is therefore important, when implementing management, that it is assessed in order to understand the role it plays within a population and what factors can drive its demand. Identifying drivers of demand can allow conservation managers to understand the relationship between supply and demand and identify any mismatch, which could enable management cost reductions and highlight long-term management strategies.

Here I illustrate how to identify the mismatch between supply and demand using a novel dataset of factors affecting the consumption of SF by a reintroduced population of the critically endangered Mauritius olive white-eye (*Zosterops chloronothos*). Specifically, I examine if the daily consumption rates of individual birds are impacted by environmental seasonality, breeding behaviour, natural plant resource availability and management techniques to enable the refinement of current *ad libitum* management and devise a potential exit strategy.

3.4 Materials and Methods

3.4.1 Study Site and Species

The study site, Ile aux Aigrettes (IAA; 20˚42′S 57˚7′E), is a 26 hectare coralline limestone island situated 0.7km off the south-east coast of Mauritius and is one of the last surviving and best examples of the endemic coastal forest of Mauritius (Figure 3.1; Parnell et al., 1989). The island has experienced high levels of deforestation, however, this ceased following the initiation of a conservation programme by the Mauritian Wildlife Foundation in 1985 after which habitat restoration commenced (Parnell et al. 1989). IAA was eradicated of ship rats *Rattus rattus* and feral cats by 1991 which allowed the island to be used to establish communities of endemic Mauritian plants, reptiles and birds (Jones & Merton 2012).

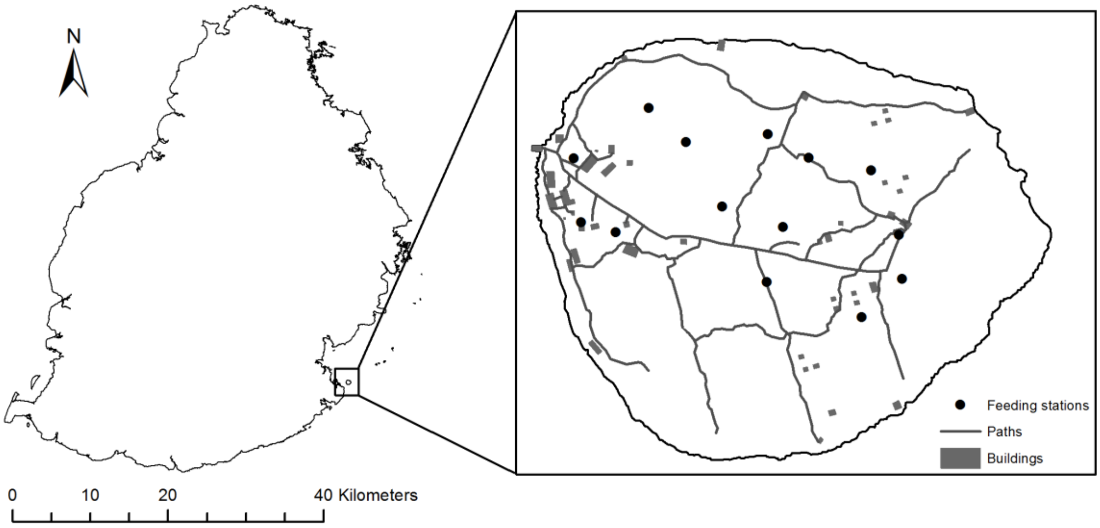

Figure 3.1 Mainland Mauritius (left) illustrating the location of Ile aux Aigrettes (IAA) in south-east Mauritius. IAA (right) showing the distribution of Mauritius olive white-eye feeding stations in relation to paths and buildings across the 26ha island

The Mauritius olive white-eye (hereafter referred to as the olive white-eye) is a critically endangered, evolutionary distinct passerine species endemic to Mauritius (IUCN 2014;

Jetz et al. 2014). The species is part of an ancient Indian Ocean lineage having evolved from Asia prior to African species and have the longest bill of all white-eyes making them the most specialized nectar feeder in the *Zosterops* genus; being referred to in evolutionary terms as “functional sunbirds” (Moreau et al. 1969; Warren et al. 2006). Currently the rarest of the nine remaining endemic land bird species of Mauritius they have experienced a continued population decline, currently estimated at less than 150 pairs, and a restricted range to less than 25km^2 in the Black River Gorges National Park (Nichols et al. 2005). A limiting factor causing this island wide decline is thought to be habitat loss (Nichols et al. 2004) but nest predation by invasive rat species *R. rattus and Rattus norvegicus* has been proven as a major limiting factor causing an estimated annual population decline of around 14% (Chapter 2; Maggs et al. 2015).

In response to continued population decline a recovery project was initiated in 2005 by the Mauritian Wildlife Foundation to establish a sub-population on IAA (Cole et al. 2007, 2008, Maggs et al. 2009, 2010). SF was provided to the reintroduced population to increase survival and productivity. As the population established and due to the monogamous, territorial behaviour of breeding pairs, multiple feeding stations were established across the island in strategic locations to prevent intraspecific aggression (Figure 3.1). As the population continues to grow and additional breeding pairs establish, more feeding stations have to be installed, thereby increasing the cost of management.

3.4.2 Supplementary Feeding Programme

Three types of SF are provided to the olive white-eye population to replicate their omnivorous natural diet; Aves® commercial nectar, fresh fruit (grapes) and insectivorous mix (commercial insectivorous mix, grated boiled egg, grated carrot and finely chopped apple). The population is provided with *ad libitum* feed which is replaced once in the morning (AM feed; approx. 6am) and once in the early afternoon (PM feed; 12-1pm) throughout the year. The SF is provided from specially designed feeding stations which exclude all other bird species (Figure 3.2). The feeding equipment is sterilised daily to prevent disease risks.

3.4.3 Supplementary Feed Consumption

In order to understand what factors drive the use of SF by olive white-eye the consumption of food from all feeding stations was recorded 2-3 days a week for three consecutive years (January 2010 to March 2013). Consumption of each food type provided was recorded; fruit and mix were weighed using digital scales (g) and nectar was measured using a syringe (ml) before and after each AM and PM feed, with the difference in these values representing the consumption. A control feeding station, which excluded olive white-eye, was established at the start of the study to account for daily natural fluctuations in food weight caused by evaporation or saturation. These control values were subtracted from the individual feeding station values to gain the NET consumption. Due to the lack of controls at all individual feeding stations the NET consumption values can only act as an index due to potential individual feeding station variation caused by microhabitat conditions; however, variation is thought to be minimal.

To ensure that all individuals within the population both had access to, and used the SF, individually ringed birds were monitored on a daily basis enabling us to monitor and understand its use at an individual and population level. Monitoring feeding station visitation rates (see section 3.4.6) in addition to consumption also ensured that there were no individuals monopolising the feed and causing bias in the consumption rates.

3.4.4 Factors Affecting the Consumption of Supplementary Feed

Here I am testing various hypotheses that relate to the consumption of SF in a reintroduced population which will allow periods of high and low food demand to be identified and any mismatch in supply and demand to be addressed. Specifically, I ask if the consumption of SF is significantly impacted by (i) environmental seasonality, (ii) breeding behaviour, (iii) natural plant resource availability, (iv) population density, (v) feeding station design or (vi) time of feed (section 3.4.3). Combining these factors in a novel dataset can identify these periods of demand and could enable either the refinement of current *ad libitum* management and thereby saving conservation resources, or replace SF with alternative, natural plant resources creating a potential management exit strategy.

3.4.4.1 Environmental Seasonality

Environmental seasonality can impact the survival of small songbirds through draught (Newton 2013) and was investigated to identify how SF consumption responds to environmental change throughout the study period. Average rainfall (mm) and mean temperature (°C) were measured throughout the study period and collected on a monthly basis by the Mauritius Meteorological Service from the Sir Seewoosagur Ramgoolam International Airport, the closest sampling point, approximately 6km from IAA.

3.4.4.2 Breeding Behaviour

The implementation of SF within bird populations can have positive impacts of reproductive success (Newton 2013; Ruffino et al. 2014), however, although large impacts are easy to observe subtle changes are more difficult to identify (Ruffino et al. 2014). The impact of individual bird behaviour is rarely investigated in SF studies but can aid in identifying subtle changes in the demand of SF due to breeding behaviour (Boutin 1990). However, when SF is provided *ad libitum* or over whole areas it is difficult to identify which bird is using it making assessing the impact difficult (Ruffino et al. 2014). Here the impact of the breeding behaviour of individual birds was investigated alongside SF consumption using detailed breeding data and FS visitation rates to identify the subtle impact of separate breeding stages on the demand for SF within a population.

Data on breeding behaviour was collected on a daily basis for all pairs throughout the breeding period identifying key stages; non-breeding period, nest building, incubation, nestling, fledgling and periods between nesting attempts. To investigate the impact of breeding behaviour on SF consumption feeding stations were assigned a dominant breeding pair based on feeding station visitation rates; this is made possible by the high territoriality of the olive white-eye breeding pairs. Visitation rates were obtained through 30-60 minute observations of individual birds conducted twice a month at all feeding stations throughout the study period; dominant breeding pairs accounted for a minimum of 58-89% of visits at the feeding stations and were therefore considered the main consumer of the supplementary feed. Based on the dominant pair, breeding stage was assigned to daily consumption rates of the relevant feeding station using detailed breeding data. Across IAA there are “floaters” which are either juvenile or single adult birds which also use SF; the proportion of floaters within the population is around 8% (± 7) but varies throughout the year in response to the breeding period. The use of SF by floaters is consistently low and should therefore not influence the impact of breeding behaviour from dominant pairs on the daily consumption rates. During periods when feeding stations do not have a dominant pair the abundance of floaters increases, these periods are classed as ‘no breeding pair’ so that they are not associated with the breeding stages.

3.4.4.3 Natural Plant Resource Availability

Few studies investigate natural resource availability simultaneously to SF consumption and so cannot understand their relationship (Boutin 1990). However, this could be vital as SF may not have a continuous impact on a populations demographics due to fluctuations in natural resource availability but could be crucial at certain times (Robb et al. 2008). Here the availability of natural plant resources was investigated alongside SF consumption using the seasonal flowering and fruiting phenology patterns of key plant species to identify periods when SF could buffer against low natural food supply.

Natural plant resource availability was calculated using plant phenology data collected across IAA on a monthly basis throughout the study period. The flowering and fruiting of plants was recorded binomially (present/absent), with 10-20 plants monitored per species. Due to the variation in sample sizes across the study period the percentage of the plants flowering or fruiting per month was calculated for each species to make them comparable.

Both endemic/native and exotic plant species act as natural plant resources for the olive white-eye on IAA, however, the phenology data only includes endemic and native species. Therefore, I were unable to investigate the impact of exotic plant species fruiting and flowering on the use of SF. Opportunistic feeding observations of olive white-eye, collected on IAA between 2007 and 2013, show that exotic plant species make-up a small proportion of the nectar, fruit and invertebrate feeding observations at 11%, 1% and 7% respectively, this is due partiality to reduced availability following intensive weeding of exotic plants across IAA between 1985 and 1997 (Cole et al. 2008; Maggs et al. 2009, 2010, 2011; Hotopp et al. 2012; Ferrière et al. 2013). It can therefore be assumed that the endemic/native plant phenology data would indicate an accurate rate of natural plant resource availability throughout the year for the population.

Using the opportunistic feeding observations of olive white-eye, fifteen endemic/native plant species were identified as natural plant resources across IAA. These plants are all available within the breeding territories of olive white-eye (except *Ficus rubra* which was absent from three territories) but are utilised in different proportions with some equating to only 1% of observations; the rarity and low abundance of some species across the island could account for fewer observations. Nonetheless, these could be important natural plant resources and so all endemic/native species, where phenology data is available, were included in the analysis to prevent bias (Appendix 3.1); the only plant species for which phenology data were unavailable was *Aloe Lomatophyllum*.

3.4.4.4 Population Density

Population density was included as a factor in the dataset to investigate if an increase in population size impacted the consumption of SF in regards to both adult and juvenile birds. An increase in SF consumption would indicate an increase in demand for the current supply and that the number of FS available is inadequate to support the population; suggesting the need for additional FS’s.

Adult (>365 days old) and juvenile (≤ 365 days old) densities were included as separate variables to investigate how these two life stages would impact SF consumption. The values were taken from monthly population sizes calculated from daily sightings of individually ringed birds on IAA throughout the study period.

3.4.4.5 Feeding Station Design

The feeding station design was altered during the study period in October 2012, changing two sides of the feeding station from wire mesh to wooden slats (Figure 3.2). This change allowed an easier exit for olive white-eye and was put into place to reduce fatalities of floating and juvenile olive white-eye (Ferrière et al. 2013). This has been included as a variable to observe any change in the use of the feeding stations prior and post modification and observe how design may impact the consumption of SF.

Figure 3.2 Mauritius olive white-eye supplementary feeding station. Original wire mess design (left) which excludes all other bird species and the modified wooden slat design (right) which allows an easier exit for olive white-eye while still excluding other bird species. This was put into place to reduce fatalities of floating and juvenile olive white-eye in October 2012

3.5 Statistical Analysis

All analysis was conducted in R version 3.1.2. (R Core Team 2015)

3.5.1 Plant Phenology Hierarchal Clustering

To minimise the number of explanatory variables within the final analysis plant species identified as the natural plant resources (section 3.4.4.3) were clustered based on seasonal patterns of their flowering and fruiting phenology over the three year study period; clustering flowering and fruiting patterns separately. These were included separately to investigate the impact of natural nectar and fruit resources on the consumption of SF. For each plant species the percentage of monthly flowering and fruiting plants were calculated (section 3.4.4.3) and separate matrices created.

Hierarchical cluster analysis was then conducted on the matrices using Ward’s minimum variance method, this method aims to form hierarchical groupings of mutually exclusive subsets each of which has members which are maximally similar with respect to specific characteristics; which in this study is flowering and fruiting phenology patterns (Ward 1963). The primary goal of cluster analysis is to identify natural groupings of objects and hierarchical clustering is the most commonly used approach in bioinformatics and is appropriate due to the simplicity of the dataset being used which has little noise which can be created by outliers (Chen et al. 2015).

The hierarchical clustering method grouped plant species based on their squared Euclidean distance using an agglomerative approach with the ‘dist’ and ‘hclust’ functions and the default complete linkage method. The final cluster groupings used for the plant phenology explanatory variables were displayed in a dendrogram and highlighted with borders using the ‘cutree’ function. A key species from within the final clusters was identified using feeding observations and the data for these species used to represent the clusters in the final analysis (Appendix 3.1). All of the plant phenology clusters were included in the analysis of nectar, fruit and insectivorous mix consumption as the nutritional content of natural plant resources and how the olive white-eye use supplementary feed to substitute these nutrients is not yet understood.

3.5.2 Generalized Linear Mixed-effects Model

To investigate what factors drive the consumption of SF a generalized linear mixed-effects model (GLMM) was used to allow for fixed factors and account for repeated data, via random factors. The GLMM was run with the function lme from the package ‘nlme’ (Pinheiro et al. 2016) with a Gaussian family for normal errors and restricted maximum likelihood. Separate models were run for the different types of SF to understand what drives the use of the different food groups. All the models had a response variable of NET consumption index (nectar, fruit or insectivorous mix), fixed factors included breeding stage (non-breeding season, nest building, incubation, nestling, fledgling, between nesting attempts and no breeding pair), other SF consumption (to investigate the impact of different food type consumptions), feeding station design (old/new), time of feed (AM/PM), environmental factors (mean temperature (°C) and average rainfall (mm)) and plant flowering and fruiting phenology clusters (Figure 3.3); with a random factor of feeding station number. The latter accounted for repeated data from feeding stations and spatial autocorrelation due to the lack of controls at individual feeding station sites.

3.6 Results

Hierarchal clustering of plant phenology data identified six clusters of seasonal flower phenology and eight clusters of seasonal fruit phenology (Figure 3.3). The clusters were determined using the chosen height criterion of 1, there is no definitive answer to where to set the height criterion as cluster analysis is essentially an explanatory approach. The height criterion selected here was chosen based on where the branches are short, and therefore more highly correlated, and where the clustering's are biologically meaningful. Due to fluctuations in data collection and inconsistency of flowering and fruiting events within the plant phenology data two species were removed from the analysis, *Morinda citrifolia and Dracaena concinna* as they prevented model convergence. These plant species combined equated to 2% of feeding observations by olive white-eye on IAA and do not impact the results.

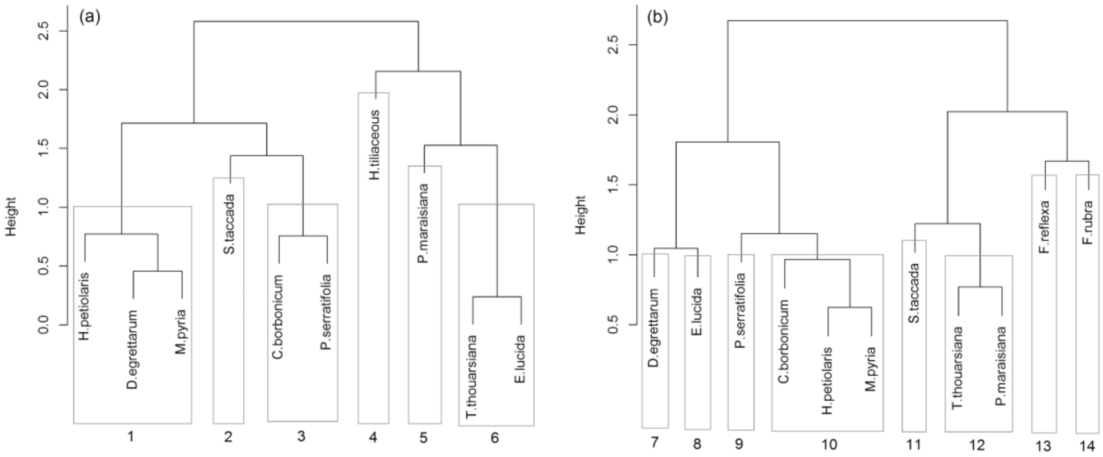

Figure 3.3 Hierarchical clustering dendrogram illustrating clusters of endemic/native Mauritian plant species based on their seasonal flower (a) and fruit (b) phenology patterns on Ile aux Aigrettes, January 2010 to March 2013. Grey boxes indicate clusters and the numbers correspond with the fixed factors used in the generalized linear mixed-effects models

In the south-east region of Mauritius there is clear environmental seasonality with the peak mean temperatures coinciding with the peak average rainfall creating a hot/wet season (November-April) and a cool/dry season (May-October) (Appendix 3.2). SF nectar and fruit consumption significantly decrease during wet periods while fruit and mix consumption significantly increase as temperatures rise (Table 3.1).

Breeding stage was identified as a major driver for the consumption of all three food types. During the non-breeding period consumption of SF is consistently low and even during the early breeding stage such as nest building consumption does not significantly increase. Nectar consumption only significantly increases during the fledgling stage, fruit significantly increases during the incubation and fledgling stages and insectivorous mix significantly increases throughout the breeding period, between first egg date and last fledgling (Table 3.1; Figure 3.4). In addition, fruit consumption significantly decreases when there is no breeding pair at the feeding station.

Nectar and fruit consumption significantly increased with each other; however, the consumption of insectivorous mix was not impacted by the other SF types.

I found the flowering and fruiting of certain endemic/native plant species across IAA significantly decreased the consumption of SF indicating key plant species and periods of low natural plant resource availability (Table 3.1). Other plant species significantly increase the consumption of SF, this indicates that although certain plant species are used by olive white-eye they may not fulfil their energy or nutrient requirements and therefore they rely on SF to boost their intake.

The consumption of SF is influenced by population density but the two life stages differ in their impact. An increase in adult density significantly decreases nectar and fruit consumption but does not impact insectivorous mix. Alternatively, an increase in juvenile density significantly increases nectar and insectivorous mix consumption but does not impact fruit consumption (Table 3.1).

There is a significant difference between the morning (AM) and afternoon (PM) feed, with the consumption of all three SF types significantly decreasing during the PM feed (Table 3.1). Results also show the feeding station design significantly impacts SF consumption with higher consumption for all three food types with the old feeding station design (Table 3.1).

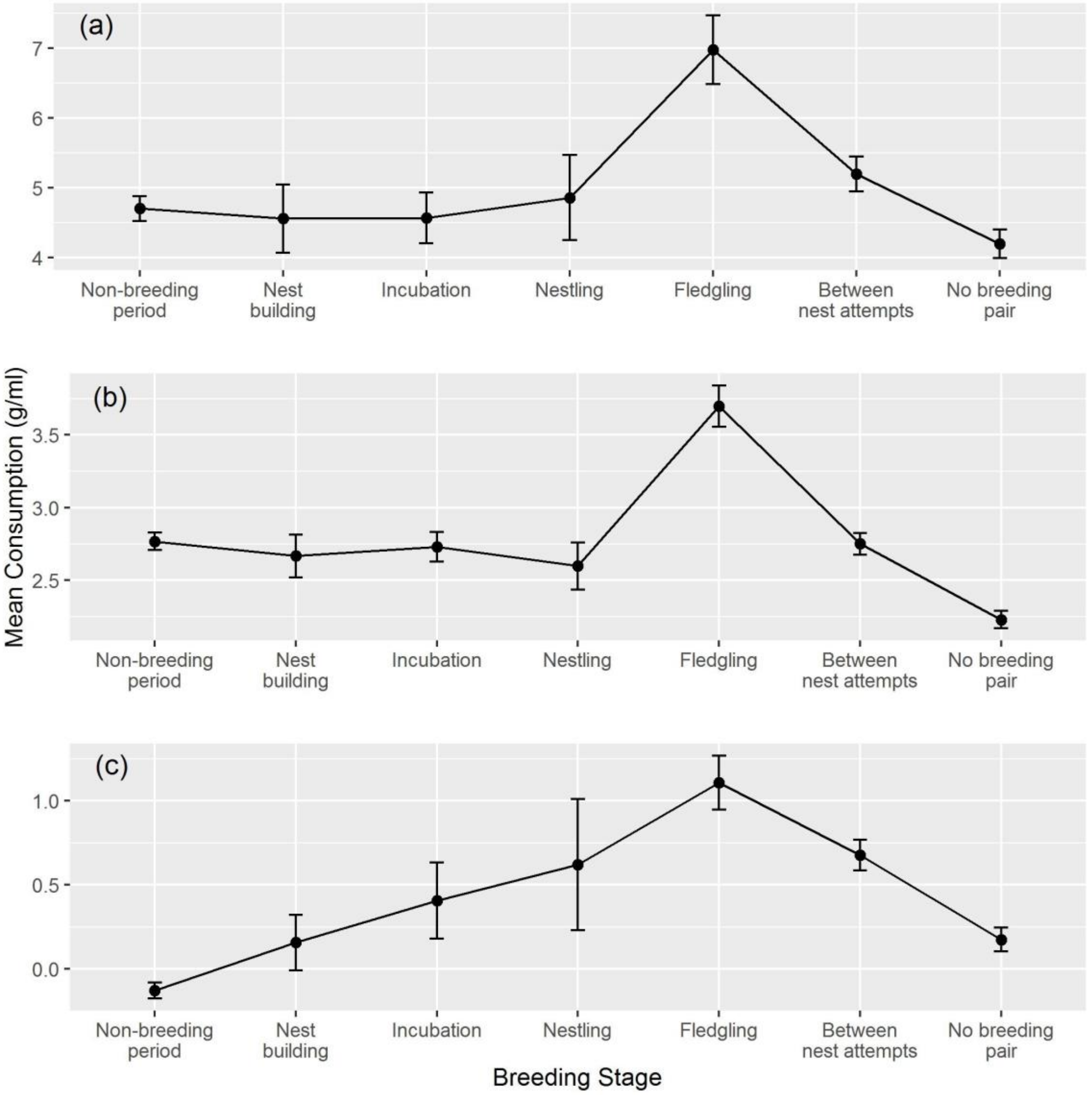

Figure 3.4 Mean consumption of nectar (a; ml), fruit (b; g) and insectivorous mix (c; g) by Mauritius olive white-eye during different breeding stages; Ile aux Aigrettes, January 2010 to March 2013. Bars represent standard error

Table 3.1. Global generalised linear mixed-effects model (GLMM) output examining Mauritius olive white-eye daily consumption rates of supplementary feed (SF) (nectar, fruit and insectivorous mix) on Ile aux Aigrettes, January 2010 to March 2013. Investigating SF consumption in relation to breeding stage, management techniques, other SF consumption, population size, environmental impacts and the phenology of endemic/native plant species; plant species are clustered based on their seasonal flowering and fruiting phenology. Values in bold are significant (P = <0.05) (n = 3774)

		Nectar			**Fruit**			**Insectivorous Mix**		
Fixed Effects		Value	Standard Error	*P*-value	Value	Standard Error	*P*-value	Value	Standard Error	*P*-value
Breeding Stage	Non-Breeding period (Intercept)	18.253	5.762	**0.001**	5.062	1.965	**0.01**	-6.149	2.439	**0.01**
	Nest building	-0.178	0.48	0.711	0.152	0.164	0.354	0.174	0.203	0.392
	Incubation	0.374	0.38	0.322	0.269	0.13	**0.038**	0.393	0.16	**0.014**
	Nestling	-0.034	0.51	0.947	0.018	0.175	0.917	0.060	0.216	**0.005**
	Fledgling	1.033	0.415	**0.01**	0.54	0.142	**<0.001**	0.623	0.175	**<0.001**
	Between breeding attempts	0.386	0.312	0.216	0.033	0.106	0.760	0.294	0.132	**0.025**
	No breeding pair	-0.089	0.384	0.816	-0.475	0.119	**<0.001**	-0.069	0.138	0.318
Management techniques	Feed – PM	-4.448	0.177	**<0.001**	-0.273	0.065	**<0.001**	-0.995	0.08	**<0.001**
	Feeding station design – Old	8.092	1.106	**<0.001**	1.64	0.38	**<0.001**	3.107	0.469	**<0.001**
SF types	Mix consumption	0.065	0.038	0.09	0.011	0.013	0.39	-	-	-

	Fruit consumption	0.3	0.047	**<0.001**	-	-	-	0.017	0.02	0.387
	Nectar consumption	-	-	-	0.037	0.006	**<0.001**	0.012	0.007	0.074
Population size	Juvenile density	0.675	0.256	**0.008**	-0.066	0.0877	**<0.001**	0.786	0.108	**<0.001**
	Adult density	-0.937	0.177	**<0.001**	-0.535	0.06	0.451	-0.044	0.075	0.557
Environmental impacts	Mean temperature	-0.062	0.193	0.749	0.251	0.066	**<0.001**	0.214	0.082	**0.009**
	Average rainfall	-0.013	0.002	**<0.001**	-0.002	0.001	0.047	-0.001	0.001	0.301
Plant Phenology	Cluster 1	0.025	0.013	**0.04**	0.033	0.004	**<0.001**	-0.008	0.005	0.118
	Cluster 2	-0.072	0.022	**<0.001**	0.01	0.007	0.174	-0.031	0.009	**<0.001**
	Cluster 3	0.036	0.021	0.089	-0.044	0.007	**<0.001**	0.033	0.009	**<0.001**
	Cluster 4	0.006	0.014	0.644	0.022	0.005	**<0.001**	-0.008	0.006	0.159
	Cluster 5	0.112	0.033	**<0.001**	0.048	0.011	**<0.001**	-0.03	0.014	**0.034**
	Cluster 6	-0.117	0.018	**<0.001**	-0.025	0.006	**<0.001**	-0.041	0.008	**<0.001**
	Cluster 7	0.119	0.021	**<0.001**	0.0041	0.007	**<0.001**	0.047	0.009	**<0.001**
	Cluster 8	-0.11	0.017	**<0.001**	-0.055	0.006	**<0.001**	-0.043	0.007	**<0.001**
	Cluster 9	-0.027	0.022	0.217	0.004	0.007	0.617	0.042	0.009	**<0.001**
	Cluster 10	-0.066	0.032	**0.036**	-0.026	0.011	**0.016**	-0.077	0.013	**<0.001**
	Cluster 11	0.06	0.016	**<0.001**	0.025	0.005	**<0.001**	0.03	0.007	**<0.001**

Cluster 12	-0.027	0.026	0.294	0.02	0.009	**0.028**	-0.056	0.011	**<0.001**
Cluster 13	-0.179	0.031	**<0.001**	-0.063	0.011	**<0.001**	-0.101	0.013	**<0.001**
Cluster 14	-0.055	0.016	**<0.001**	-0.044	0.006	**<0.001**	-0.043	0.007	**<0.001**

3.7 Discussion

By combining demographic, environmental and management factors with SF consumption within a GLMM this study has conducted a robust analysis with a novel dataset and successfully quantified the supply and demand of SF within a reintroduced population of olive white-eye. Choosing to interpret the results using the global model output has enabled me to identify the impact of all of the explanatory variables, whether significant or not, and interpret the results as a whole on a biological as well as statistical basis. This has identified the mismatch between the supply and demand of SF which can guide the refinement of current *ab libitum* management and long-term management strategies by creating a self-sustained population and potential exit strategy through ecosystem restoration.

3.7.1 Factors Influencing Demand for Supplementary Feed

Incorporating plant flowering and fruiting phenology with environmental seasonality illustrates that natural plant resources have clear environmental drivers. These environmental drivers do not directly impact the consumption of SF but prompt an increase in natural plant resource availability which decreases the demand for SF. These findings suggest that the supply of SF buffers periods of low natural plant resource availability, which has been seen in other studies, and could be vital during periods of high demand such as breeding stages (Elliott et al. 2001; López-Bao et al. 2010). In this study natural invertebrate availability was not included, instead the flowering and fruiting of native/endemic plants on IAA was assumed to indirectly impact the consumption of insectivorous mix SF by increasing invertebrate density around the plant species and increasing the availability of invertebrate prey. Further research is required to investigate the impact of invertebrate availability alone on the demand for SF, specifically insectivorous mix.

The demand for insectivorous mix during the breeding period is supported by past research which found that protein consumption in many bird species increases during breeding activity (Meijer & Drent 1999). The increased demand for all three food types when fledglings are present indicates high energy requirements during this breeding stage; therefore, SF could be essential for post fledging survival. Other studies investigating the impact of SF on nesting success have also found a high demand during the nestling and fledging periods (Schoech et al. 2008; Heath et al. 2008; Ruffino et al. 2014). Consumption of nectar and insectivorous mix is also seen to significantly increase with juvenile density indicating that SF could also be important for first year survival, also recorded in other species (Piper et al. 1999).

As discussed the consumption of SF significantly increases during the breeding period highlighting periods of demand such as the fledgling stage; however, throughout these periods of demand an increase in natural plant resource availability simultaneously decreases demand indicating contradictory results. When plotted together it can be seen that during these contradictory periods there are two phases, high and low natural plant resource availability (Figure 3.5). This indicates that for the olive white-eye natural plant resources take preference over SF, however, SF plays a vital role during periods of demand when these natural pant resources are low, buffering the impact of low food availability; patterns which have been observed in other studies (Elliott et al. 2001; Siriwardena et al. 2008).

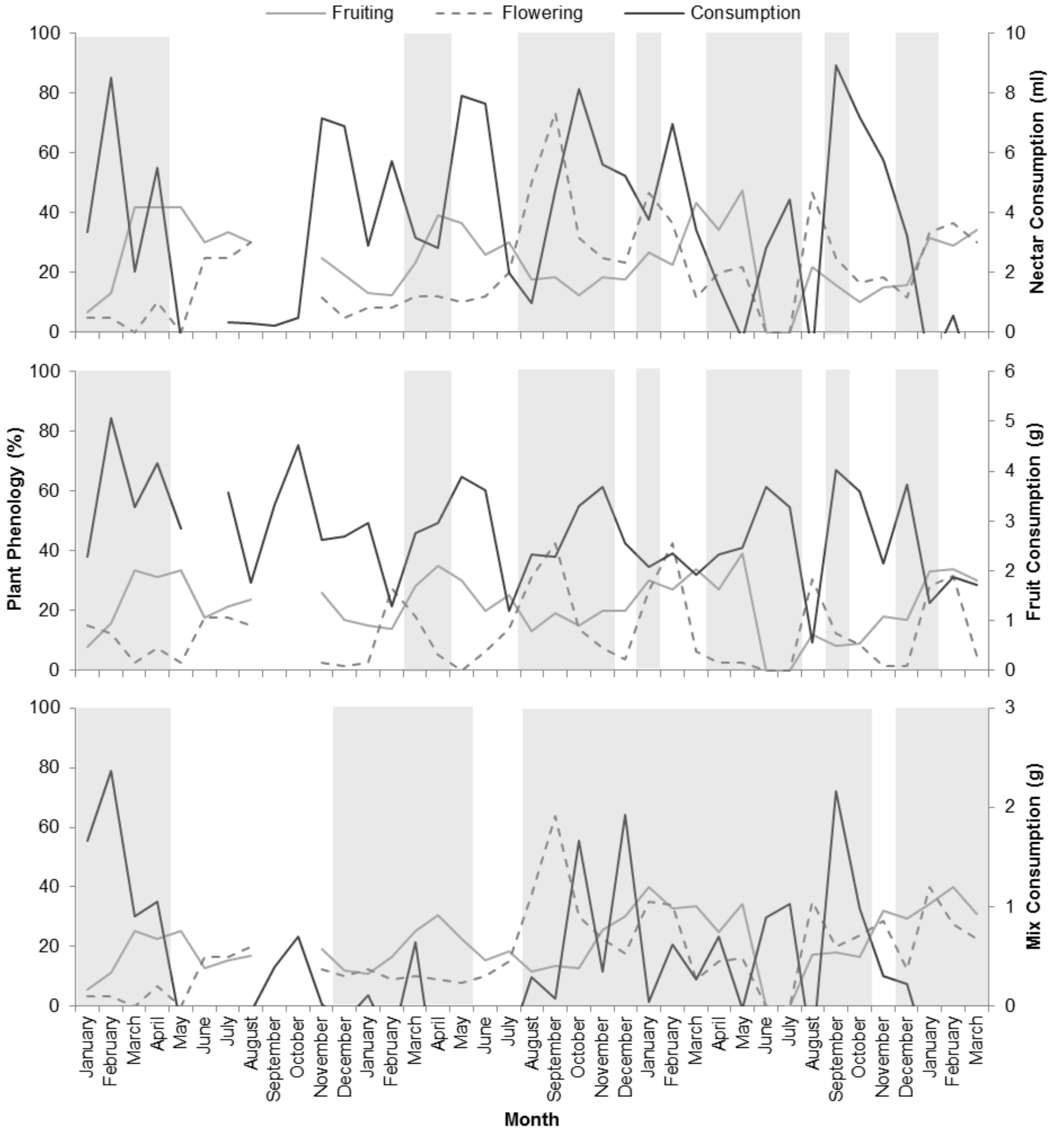

Figure 3.5 Mean consumption of nectar, fruit and insectivorous mix by Mauritius olive white-eye in relation to the flowering and fruiting of key natural plant resources and breeding stages when demand for each food type significantly increases (grey areas); Ile aux Aigrettes, January 2010 – March 2013. The graph illustrates how supplementary feed buffers periods of low natural plant resource availability during periods of increased demand throughout the significant breeding stages

Investigating SF consumption at different times of day has highlighted the morning as a period of demand for all three food types supplied. This supports findings from Hansen et al. (2002) who found that olive white-eye on mainland Mauritius are most active during the early morning; behaviour which is seen in other nectar feeding passerines (Paton 1993). Feeding station design also influenced the use of SF with the new design decreasing demand, supporting the changes made. Currently the number of feeding stations available can support the population as adult density does not significantly increase consumption, however, with consumption significantly increasing with juvenile density the instalment of new feeding stations with population growth is paramount in potentially assisting first year survival.

3.7.2 Addressing the Mismatch in Supply and Demand

For some conservation programmes the supply of SF cannot meet the demand of the species or the supply meets demand but any reduction causes a decrease in survival (New et al. 2012; Correia et al. 2015). The entire reintroduced olive white-eye population use SF and it plays an important role, but by investigating the use of SF in relation to various factors, I have identified key drivers in demand. These findings can enable a more flexible approach to the implementation of SF minimising any mismatch in the short and long-term, whereby *ad libitum* SF more closely tracks demand over time and overall demand is reduced through the continuity and increased abundance of natural plant resources.

Tracking demand over time can be achieved through a responsive management approach, optimising the timing of supply in response to species requirements and reducing management without jeopardising species recovery; as seen in other species (Robertson et al. 2006). However, the overall aim for most, if not all, reintroductions are to establish a self-sustained population. Although the incorporation of responsive management could reduce short-term costs its long-term viability as a conservation action and the role it plays in population restoration remains a challenge. By exploring the link between natural plant resource availability and the demand for SF I have identified specific plant species which could be incorporated into ongoing ecosystem restoration programmes which in turn could provide continuous natural plant resources and a potential exit strategy.

3.7.3 Conservation Recommendations

Short-term responsive management should focus on bird behaviour, responding to their feeding times and breeding activity. Supply should be reduced in response to time of day, removing the afternoon feed based on significantly higher demand for all three food types during the morning period; providing enough feed in the morning to meet demand throughout the day. With demand for SF also peaking during energetically expensive phases of the breeding cycle, the supply of all three food types should be further reduced in response to dominant pair breeding activity and whether a dominant pair is present. Insectivorous mix could be greatly reduced when pairs are not breeding, nectar could also be reduced greatly when breeding pairs do not have fledglings and fruit when pairs are not incubating and do not have fledglings, potentially removing it completely when there is no dominant pair. These management alterations in response to demand could significantly reduce the supply of *ad libitum* SF and conservation resource costs. However, any alterations made to current management should be carried out using an adaptive management approach, conducting continuous monitoring and evaluation to identify any potential negative impacts of management changes and reduce management uncertainty (Armstrong et al. 2007; Westgate et al. 2013).

Due to the variable seasonality of plant phenology, caused by environmental stochasticity, using a responsive management approach based on natural plant resource availability would be difficult and potentially damaging to the population. Instead focus should be put into habitat manipulation, planting additional key plant species across IAA, increasing the availability of natural plant resources and reducing olive white-eye dependency on SF over time. Plant species found to decrease demand for SF provide continuous resources throughout the year, however, their availability fluctuates and plant abundance may not currently be high enough to support the whole population (Figure 3.6). Therefore, current habitat restoration work on IAA should focus on increasing the abundance of these key plant species to support the population and enable food continuity. The incorporation of habitat restoration into the long-term management of reintroduced species enables the integration of SF management into wider ecosystem restoration programmes and provides a potential exit strategy for successful reintroductions by creating a self-sustained population.

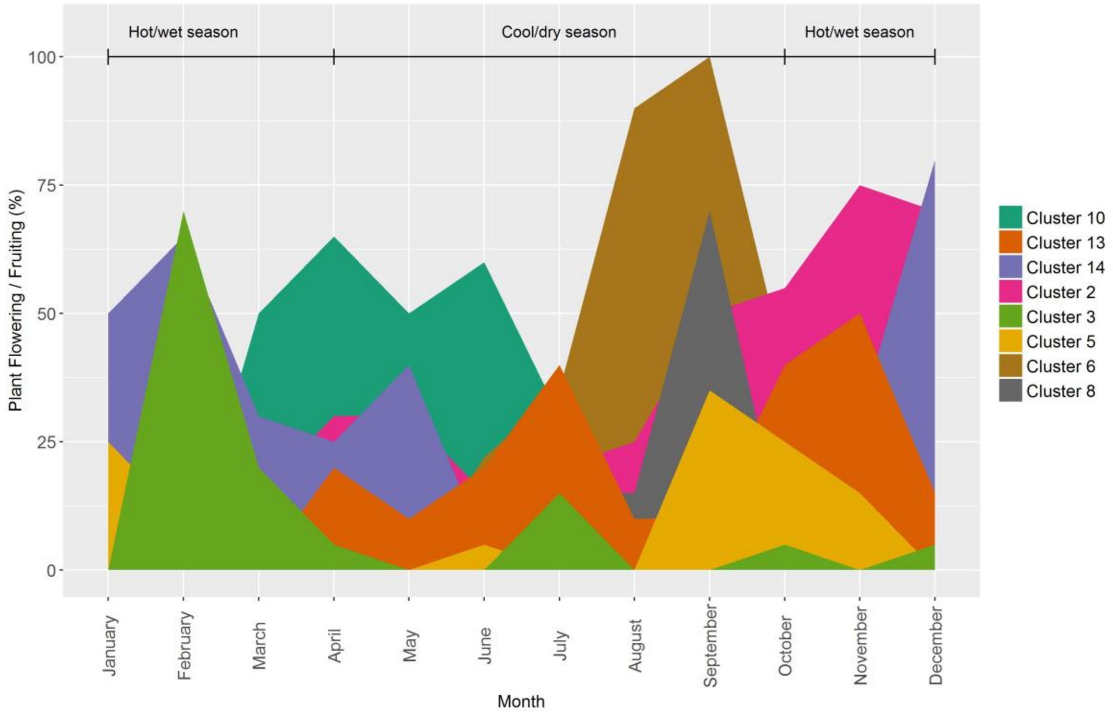

Figure 3.6 The annual phenology cycle of key plant species which significantly decrease demand for supplementary feed by the Mauritius olive white-eye; Ile aux Aigrettes, January - December 2012. Key plant species are clustered based on seasonal flowering and fruiting patterns. The graph illustrates the continuity of natural plant resources and fluctuations in availability for olive white-eye in regards time of year and environmental seasonality (hot/wet and cool/dry seasons)

3.8 Conclusion

Conservation programmes often have to utilise all the tools and resources at their disposal to recover populations from the brink of extinction, but this level of effort may not be sustainable in the long-term (Komdeur 1996; Heath et al. 2008), therefore refining management actions in the long-term is a priority. SF is often viewed as a key tool in the recovery of threatened species but can be costly in terms of conservation resources. My study illustrates an approach to quantifying the use of SF by a reintroduced population and how this use is shaped by a range of factors including breeding activity and seasonal fluctuations in natural plant resources. By exploring the link between various factors and SF supply I am able to identify management options which can refine current *in-situ* management techniques and be incorporated into ongoing and future ecosystem restoration programmes. Potentially, these options could allow the effective allocation of finite conservation resources and lead to the reduction or even removal of SF as a conservation tool, providing an exit strategy for successful threatened species management; something which has been rarely studied.

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Appendix 3.1

Table A3.1 Endemic/native plant species identified as natural plant resources for the Mauritius olive white-eye through opportunistic feeding observations on Ile aux Aigrettes between 2007 and 2013. Plant species have been grouped using hierarchical clustering based on their seasonal flowering (FL) and fruiting (FR) phenology. All fourteen clusters were used in the generalised linear mixed-effects models, * indicates the plant species which represents the cluster in the analysis, identified as a key plant species based on olive white-eye feeding observations

Hierarchical Cluster	Endemic/native Plant Species
Cluster 1	*Hilsenbergia petiolaris FL.**
	Diospyros egrettarum FL.
	Maytennus pyria FL.
Cluster 2	*Scaevola taccada FL.**
Cluster 3	*Coptosperma borbonicum FL.**
	Premna serratifolia FL.
Cluster 4	*Hibiscus tiliaceous FL. **
Cluster 5	*Polyscias maraisiana FL. **
Cluster 6	*Turraea thouarsiana FL. **
	Eugenia lucida FL.
Cluster 7	*Diospyros egrettarum FR. **
Cluster 8	*Eugenia lucida FR. **

Cluster 9	*Premna serratifolia FR. **
Cluster 10	*Hilsenbergia petiolaris FR. **
	Maytennus pyria FR.
	Coptosperma borbonicum FR.
Cluster 11	*Scaevola taccada FR. **
Cluster 12	*Turraea thouarsiana FR. **
	Polyscias maraisiana FR.
Cluster 13	*Ficus reflexa FR. **
Cluster 14	*Ficus rubra FR. **

Appendix 3.2

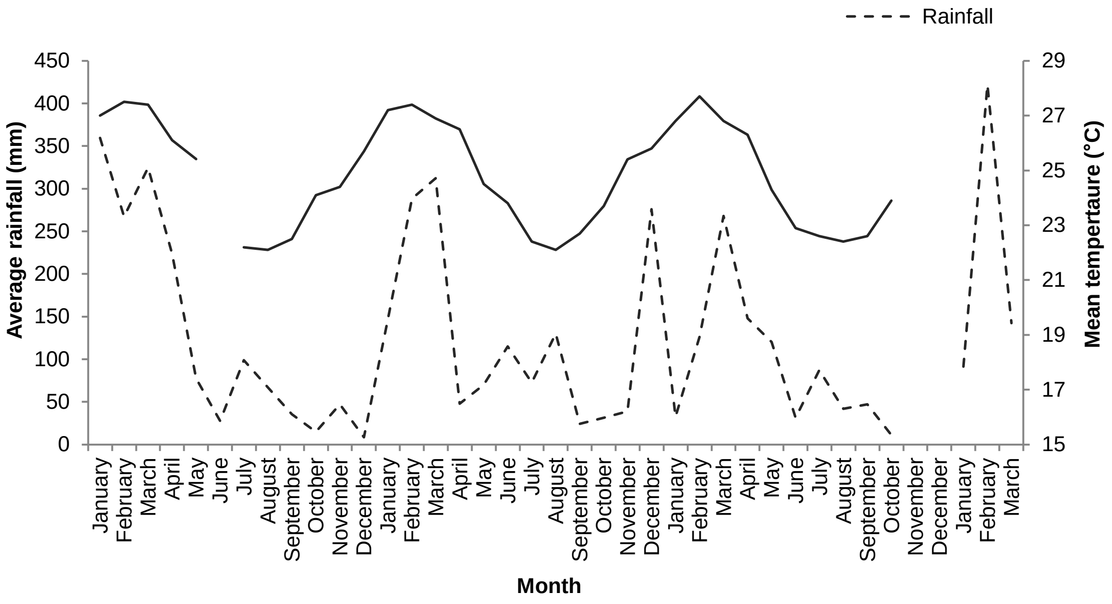

Figure A3.1 Average rainfall and mean temperature in south-east Mauritius illustrating the annual seasonality on Ile aux Aigrettes, January 2010 to March 2013; cool/dry season (June-Oct) and hot/wet season (Nov-May)

Chapter 4

A decision-making framework for identifying long-term, cost-effective conservation management in the face of extinction risk

4.1 Chapter Attribution

I received invaluable advice on the direction of this chapter from my supervisors Prof Ken Norris, Dr Malcolm Nicoll and Dr David Murrell who also provided advice on the parameterisation of the Vortex 10 model. My fourth supervisor Dr Nicolas Zuël assisted with the costing, providing detailed pricings of all the materials which could be sourced in Mauritius, project running costs and the labour involved. Dr John Ewen provided advice on expert elicitation and questioning methods for the online questionnaire and along with Dr Steffano Canessa provided advice on cost-effectiveness analysis.

4.2 Abstract

Recent research has identified islands as conservation priority areas increasing the importance of conservation for island endemics. For many island endemics invasive species are a major threat and are considered one of the biggest drivers of biodiversity loss on oceanic islands. Of all invasive species rats are one of the most detrimental having reached around 90% of all islands they are a major threat and are notorious for devastating bird populations, especially passerines. Small declining populations are at the greatest risk of extinction and although the eradication of rats from islands is a successful conservation tool, for populations restricted to mainland sites invasive species management remains a challenge. Large-scale rat management areas known as 'mainland islands' have been successfully developed in New Zealand, however, large-scale management is a long-term investment and decision-makers face difficult decisions due to high levels of uncertainty caused by limited resources, time and knowledge.

Here I illustrate decision-making tools which address these difficult management decisions and uncertainties and enable a robust evaluation of the rat management techniques available to establish a mainland island for the critically endangered Mauritius olive white-eye (*Zosterops chloronothos*). The decision-making tools address four main questions (1) what rat management options are available, (2) how effective are these options in controlling rat populations, (3) what potential impact might these options have on population viability and (4) what option is likely to be most cost-effective. By combining knowledge exchange, expert elicitation, population viability analysis and cost-effectiveness analysis I have illustrated how to break down these questions and the challenging decisions into clear quantitative decision-making tools. This enables an organisation to evaluate and assess each management possibility on a site and species specific basis and in regards to both the scale of management required and the capital expenditure and recurrent costs minimising uncertainty and enabling the effective and swift allocation of finite conservation resources to ensure threatened species survival.

4.3 Introduction

Recent research has identified islands as conservation priority areas for evolutionary distinct and globally endangered (EDGE) species increasing the importance of conservation for island endemics, however, managers throughout the world struggle to achieve goals due to a poor understanding of systems, risk factors and resource limitations which all impact decisions (Jetz et al. 2014; Smith et al. 2015). For small declining populations, which are at the greatest risk of extinction, decisive and innovative management actions may be crucial to reverse population decline and ultimately avert extinction but with high levels of uncertainty caused by limited resources, time and knowledge making long-term management decisions can be challenging, therefore, rigorous evaluation needs to be conducted to provide powerful reasoning (Atkinson 1989; Cullen et al. 2001; Meek et al. 2015).

Success is not easily achieved in biodiversity protection, and hard decisions over where to allocate available resources are inevitable. It is therefore important to trial management options and conduct research focused on understanding the long-term conservation management of species so that programme managers and decision-makers can make wise use of scarce conservation resources while ensuring species survival (Cullen et al. 2001; Jones & Merton 2012). There are numerous tools available to tackle the problems encountered by conservation decision-makers, knowledge exchange and expert elicitation can overcome knowledge gaps (Martin et al. 2012), cost-effectiveness analysis can assist in effectively allocating limited resources (Shwiff et al. 2013) and population viability analysis can compare potential management options based on long-term population persistence (Reed et al. 2002), all of which can identify and mitigate threats to island endemics.

Since the 16th century 171 bird species have become extinct and 151 of those were island species from areas such as Hawaii, New Zealand, the Mascarenes and the West Indies (Diamond 1989). A major threat facing island endemics is invasive species which account for half of island bird extinctions and of all invasive species rats are one of the most detrimental; having reached around 90% of all islands they are a major threat to island biodiversity and are notorious for devastating bird populations, especially passerines (Cheke 1987; Diamond 1989; Towns et al. 2006). Currently invasive species are considered one of the biggest drivers of biodiversity loss on oceanic islands (Rodrigues et al. 2014).

The eradication of rats from islands is an effective, well-established conservation tool having been used globally for many decades (Towns et al. 2006; DIISE 2015). However, these typically small islands averaging at 191ha (DIISE 2015) cannot contain all or even the majority of threatened, endemic species and excludes species with no island equivalent of their habitat so it is equally as important to manage and restore mainland sites (Saunders & Norton 2001; Reardon et al. 2012). In the 1990s island eradication techniques were applied to mainland areas across New Zealand not for eradication but to control invasive species at low densities (Gillies et al. 2003). These trials paved the way for the establishment of predator control areas, known as ‘mainland islands’, to protect threatened species and ecosystems from invasive species, these ranged in size depending on various factors including the target species, habitat availability, geographic location, management technique and management resources available (Saunders & Norton 2001). For example Harataunga Kiwi Project combines numerous projects together to manage 30,000ha using trapping to control stoats, ferrets, weasels, hedgehogs and rats and protect the brown kiwi (*Apteryx mantelli*) and Mokomoko Dryland Sanctuary uses a predator-proof fence to protect the Otago skink (*Oligosoma otagense*) over 0.3ha which excludes all invasive mammals (Butler et al. 2014).

For the Mauritius olive white-eye, a critically endangered passerine endemic to the island of Mauritius and in the 10% of the EDGE bird species list, (Jetz et al. 2014; IUCN 2015), invasive rat species are a major threat causing an estimated annual population decline of 14% (Chapter 2; Maggs et al., 2015). Rat control can ensure population persistence by increasing annual productivity and therefore a mainland island would be a viable option for the species. However, with limited conservation resources, time and knowledge, due to the rarity of the species, project managers face difficult decisions on long-term, large-scale management mainly (1) what area should the mainland island cover to ensure population viability, (2) what is the most cost-effective rat management option in regards to both establishment and long-term management and (3) with the species facing extinction and with limited time how do we obtain life-history data to enable decisions. Uncertainty around these decisions can stem from the fact that funding for recovery programmes of rare species is finite and so must be carefully applied to maximise the positive impact on the species but even with the most competent managers and conservation teams decisions can be made which are unsuccessful (Engeman et al. 2003; Meek et al. 2015; Regan et al. 2005).

The value of decision-making is familiar to many conservation biologists and is now more widely recognised, however, classical decision theory used expert opinion rather than data analysis to estimate the probability of different outcomes (Harwood 2000). Decision analysis is a broad field which can address the problem of resource allocation when faced with many alternatives by formalising the value judgements inherent in any decision in an effort to improve the quality of decision-making (Guikema and Milke 1999). The methods around environmental decision-making have progressed and there are a number of approaches to decision analysis, however, all these approaches involve certain steps from gathering information, to outlining objectives, discussion and implementation (Clark and Brunner, 2002; Gregory et al. 2012). Here I illustrate an approach to creating decision-making tools through robust scientific data to reduce uncertainty and risk by providing detailed information to assist in the decision-making process.

Specificially, I illustrate decision-making tools which enable a robust evaluation of the rat management techniques available to establish a mainland island which accounts for limited resources, time and knowledge. This novel approach to long-term threatened species management combines numerous conservation tools to answer four main questions - (1) what rat management options are available? Here a systematic literature review is conducted through a qualitative synthesis to allow an informal evaluation of results combining general and scientific databases, cited literature and knowledge exchange with subject experts (Pullin et al. 2006); (2) how effective are these options in controlling rat populations? Here anecdotal evidence was obtained through expert elicitation to generate a rat management effectiveness score which was combined with existing data to predict the effectiveness of non-field tested methods; (3) what potential impact might these options have on Mauritius olive white-eye population viability? Here a population viability analysis is used to predict the long-term viability of a population using different rat management options; and (4) what option is likely to be most cost-effective? Here cost-effective analysis is used to compare the long-term costs of establishing and running each rat management option across a mainland island area. Combining these questions through decision-making tools can guide decisive and innovative evidence-based conservation which accounts for uncertainty to ensure the effective allocation of conservation resources and population persistence for highly threatened island species

4.4 Methods

4.4.1 Study Site and Species

This research is being conducted on the island of Mauritius, the second largest of the Mascarene islands, which has been severely degraded since the colonisation of humans in the 1600s and the subsequent introduction of invasive flora and fauna (Cheke & Hume 2008). The study site, Combo, is within the Black River Gorges National Park where the highest densities of Mauritius olive white-eye breeding pairs remain; 25 – 30 pairs (Figure 1; Nichols et al., 2004). Combo has a degraded, riparian habitat approximately 9m in height (n=37, Maggs et al., 2010) with small open grassland fragments situated on a peninsula of the National Park surrounded by agricultural land producing sugar cane and private lands for deer hunting; which contain large grasslands and forest. There is clear seasonality within the area with a cool/dry season between March and August and a warm/wet season between September and February.

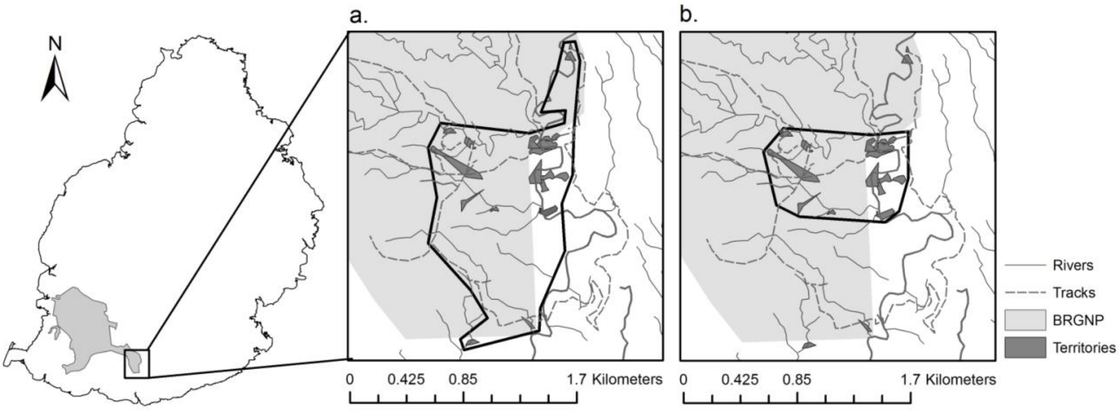

Figure 4.1 Mainland Mauritius (left) illustrating the location of the Black River Gorges National Park (BRGNP) and the location of the Combo region (right) illustrating the distribution of Mauritius olive white-eye defended territories, 2012-13. Territory distribution was used to calculate both low (a) and high (b) population density

The Mauritius olive white-eye (here after referred to as the olive white-eye) is the rarest of the nine remaining land bird species of Mauritius, with less than 150 pairs remaining, and is part of an ancient white-eye lineage having evolved from Asia prior to the African species (Nichols et al. 2004; Warren et al. 2006; IUCN 2015). They are a monogamous, multi-brooded species defending territories of approximately 0.5ha in size (Maggs et al. 2011). The male and female participate equally in all of the nesting stages, building small open cup nests within the upper canopy on small outer branches; females lay 1-3 eggs (Safford & Hawkins 2013). Rats are a major limiting factor to the species (Chapter 2; Maggs et al., 2015) but habitat restriction and degradation is also thought to be a threat contributing to the restricted and fragmented range of the remaining population (Safford & Hawkins 2013).

4.4.2 Rat Management Options

4.4.2.1 Knowledge Exchange

Evidence suggests that decision-makers rely on individual experience or other secondary resources of knowledge in isolation from scientific evidence when formulating decisions, potentially compromising the effectiveness of their decisions (Cvitanovic et al. 2015). As a result ‘knowledge exchange’ has emerged, focused on identifying and overcoming the barriers to knowledge exchange among scientists and decision-makers (Cvitanovic et al. 2015). When devising potential invasive rat management scenarios and investigating their effectiveness and cost it is vital that the data and information used is as robust as possible to enable reliable analysis and realistic results.

In Mauritius a mainland island has never been established and the rat management techniques used for the olive white-eye have been limited to localised snap-trapping and ground based-poisoning (Chapter 2; Maggs et al., 2015). It was therefore vital to gain expert knowledge into the demands and practicalities of running and maintaining large-scale rat management to incorporate into the analyses. The managers of eight mainland islands across New Zealand participated in a knowledge exchange to discuss the logistical and financial implications of trapping, poisoning, self-resetting traps and predator-proof fencing. The knowledge obtained from personal experience and ‘grey literature’ supplied information into labour demands, equipment required, improvements made and problems encountered (Appendix 4.1).

4.4.2.2 Rat Management Techniques

Both ship and brown rats (*Rattus rattus* and *Rattus norvegicus*) are present in Mauritius and will both be the target of the mainland island rat management. A long-term study of the rat species in Mauritius found that rat management through poisoning can remove resident rat populations but the areas are subsequently reinvaded from the surrounding rat home-ranges (HR) which vary in size between 0.3 – 0.4ha (Hall 2003). This area does not vary between males and females and is not found to change in response to poisoning but rat densities do fluctuate annually with high levels of rat abundance between September and December (Hall 2003). These fluctuations may be due to natural annual fluctuations in response to rat breeding cycles, stochastic events, environmental factors or human activity with rats emigrating into the National Park when the surrounding agricultural fields are harvested between June and December (Hall 2003). Fluctuations in rat densities and reinvasion have been addressed in the discussion of this chapter.

The four rat management scenarios were selected based on the techniques applied across New Zealand, the leaders in mainland island management. There are around 111 mainland island areas across New Zealand of which 72% target invasive rat species, of these 37.5% use trapping, 22.5% use predator-proof fencing, 20% use trapping plus poisoning, 17.5% use poisoning alone and 2.5% use self-resetting traps (Butler et al. 2014). The rat management materials and methods proposed for a mainland island within this study have been based on an extensive literature review of numerous mainland islands and rat management projects from throughout the world incorporating reports, published research and the information acquired through the knowledge exchange with mainland island managers (Appendix 4.1). The management techniques identified through the literature review and the proposed management scenarios have been outlined in detail in Appendix 4.2.

4.4.2.2.1 Trapping

For the trapping management scenario DOC150 traps have been selected; these traps have been specially designed by the Department of Conservation (DOC). They meet the guidelines as humane traps for stoats, rats and hedgehogs by the National Animal Welfare Advisory Committee (NAWAC) in New Zealand and have been approved for use in England to catch grey squirrels, rats, stoats and weasels (DEFRA 2007). These standards prove the humaneness of the trap which should be a priority when planning large-scale rat management. The traps are made from stainless steel which ensures longevity and due to the reinforced spring and frame does not warp with use, requiring far less maintenance and ensuring much higher reliability. The traps are very strong, however, there is a setting tool available to enable the operator to set the trap without having direct contact and they have an easy to set mechanism which makes the process very quick and efficient.

The DOC150 traps would be placed in boxes built to the specifications of the DOC to protect non-target species and prevent miss-sprung traps (DOC 2014) and placed over a 50m x 50m grid with perimeter traps at 25m spacing’s. There would be an initial ‘knock out’ phase when all traps would be checked daily and baited with peanut butter and oat mix for at least two weeks after which, ensuring rat trapping rates had decreased, they would be checked fortnightly and baited with hen eggs as a longer lasting bait.

4.4.2.2.2 Poisoning

For the poisoning management scenario plastic ‘Novacoil’ drainage tubes have been selected as bait stations as they are an effective low cost technique recommended by the DOC for targeting both ship and brown rats (Spurr et al. 2006, 2007). Although research in Mauritius has identified the hockey stick design as the most efficient method the equipment for this design is expensive, however, the results of the study would be applied and poison would be fixed within the drainage tubes which should prevent poison hoarding by rats (Tatayah et al. 2007). Based on literature from both tropic and temperate regions, a 50m x 50m grid would be used and the stations checked fortnightly, however, this frequency could be adapted depending on poison consumption.

There are numerous types of poison available for rat management including non-anticoagulant rodenticides, and first and second-generation anticoagulant rodenticides, all with both advantages and disadvantages (see Eason and Ogilvie, 2009). The type of poison proposed here would be varied to avoid rats becoming immune to the bait and first-generation anticoagulants would be used to reduce bioaccumulation through the food-web and secondary poisoning. Diphacinone would be the primary poison used across the mainland island; additional poisons such as pindone could also be used to alternate across years but this shall not be discussed here. Diphacinone is a first-generation rodenticide and the most toxic which is rapidly eliminated from the prey and therefore has a lower tendency to cause secondary poisoning compared to second-generation rodenticides (Eason & Ogilvie 2009). It has been successfully applied across rat management areas both in New Zealand and Hawaii and in the USA is the only registered rodenticide which can be used for long-term rat management (Vanderwerf 2001; Vanderwerf & Smith 2002; Gillies et al. 2006; Eason & Ogilvie 2009; Young et al. 2013).

4.4.2.2.3 Self-Resetting Traps

Self-resetting traps have been developed by Goodnature®, the A24 rat trap has been designed to humanely kill rodents without any secondary impacts and reduced labour costs and have been selected for the self-resetting trap management scenario. They meet the guidelines of the NAWAC New Zealand and are supported by the New Zealand DOC (Jansen 2011; Ross 2015). They have the potential of reducing labour costs as the self-resetting mechanism and long-life, auto pump lure reduce trap checks to every 6 months depending on rat densities (Appendix 4.2.3; Goodnature, 2015). These traps are being used in more than 15 countries including New Zealand, Hawaii, the Caribbean and the UK (Goodnature 2014).

A 100m x 50m grid would be established with the Goodnature® A24 traps based on projects which have already successfully implemented the technique in both tropical and temperate regions and best practice guidelines (Gilles & Williams 2005; Franklin 2013; Goodnature 2014; DOC 2015a). They would be baited with the newly designed auto pump lure which remain stable within a tropical environment and maintains fresh lure across 6 months (Goodnature 2015). They would be checked monthly when first established to monitor the CO^2 canisters after which checks would be reduced to every 6 months to change both the lure and CO^2 canister following Goodnature® guidelines.

4.4.2.2.4 Predator-Proof Fencing

Predator-proof fences have been successfully developed in New Zealand to create predator-free areas and protect threatened species. All fences have the same basic design with mesh fencing, an underground skirt (to prevent burrowing) and a curved hood (to prevent climbing). Xcluder™ are the main company who build fences and have done so throughout the world including a trial in Mauritius (Tatayah et al. 2005) and so there fence design will be used for the predator-proof fence management scenario. Having conducted a trial in Mauritius it was identified that all the equipment required would be available in country except high quality galvanised mesh which would need to be imported (Day 2004). Fences are extremely effective when maintained and require less labour once built, however, they are vulnerable to invasions and therefore surveillance and maintenance is paramount and continuous.

The predator-proof fence would be erected around the perimeter of the mainland island area. Once the fence is complete the initial eradication of rats would be conducted following the ground-based rat poisoning technique (section 4.4.2.2.2) and using second-generation anticoagulant rodenticide brodifacoum based on its high effectiveness and the short-term, singular use. A predator-proof fence is a multi-species technique and therefore small Indian mongoose (*Herpestes auropunctatus)* and feral cats (*Felis catus*) would also be targeted (for detailed methods see Appendix 4.2.4).

The fence would be checked weekly for breaches in any of the materials, within the fence permanent trapping and poisoning would be in placed along the inner fence perimeter with 50m spacing's for rat poison bait stations, 100m spacing's for mongoose trapping and 200m spacing's for cat live traps, these would be checked monthly (cat live traps set and checked for one night per month); brodifacoum remains palatable to ship rats for up to 12 months within stations so monthly checks are more than adequate (Morriss et al. 2008). The 50m x 50m rat poison grid established across the area for the initial eradication would remain in place in the event of reinvasion in which case the grid can be activated.

4.4.2.3 Monitoring Rat Abundance

The tracking tunnel method has been selected for monitoring rat abundance in the mainland island and was first described by King and Edgar (1977). They are a simple design with bait and an ink pad in the centre of the tunnel and sheets of card either side which record rat prints as they pass through the tunnel (Gilles & Williams 2005; Gillies 2013). This method, for indexing small mammals, in preferred over kill-trapping as they are non-destructive and do not impact the target population, do not threaten to non-target species, can detect rats at low densities and are less labour intensive as the tunnels can remain in the field; this also reduces rat neo-phobia (Gilles & Williams 2005; Gillies 2013). Tracking tunnels can only provide a coarse index of rat abundance and are best suited to providing simultaneous comparisons of relative abundance, which in this study would be gross changes in relative abundance over time at a single site (Gilles & Williams 2005).

Black Trakka™ tunnels and cards would be used across all the potential management techniques on a 100m x 100m grid at opposite points to the management grid points to avoid biased detection due to management baits (Gilles & Williams 2005). The best practice for tracking tunnels recommends lines of tunnels positioned randomly across the management area (Gilles & Williams 2005), however, grid positioning would be used in order to monitor rat reinvasion rates and patterns into the mainland island area over time to observe rat behaviours and identify reinvasion ‘hot spots’. The tracking tunnel grid would be activated monthly for one fine night baited with peanut butter (Gilles & Williams 2005).

4.4.3 Rat Management Effectiveness

4.4.3.1 Expert Elicitation

In an ideal world information to parametrise models would be available but for many management decisions such empirical data are scarce and cannot be obtained before the decision needs to be made, therefore, it is becoming increasing common to rely on expert elicitation; this may be the only credible source of information and can be replaced with data when it becomes available (Runge et al. 2011; Martin et al. 2012; Doherty & Ritchie 2016). An expert is someone with subjective knowledge on a particular topic that is not widely known by others which may result from training, research, skills and personal experience (Martin et al. 2012).

Incorporating expert knowledge in decision-making and conservation planning, in a quantitative rather than qualitative way, is a new concept and is growing but with no set way or formal method (Martin et al. 2012; Metcalf & Wallace 2013). Here I use expert elicitation to identify the effectiveness of numerous rat management scenarios at reducing rat abundance to a desired level to generate a rat management effectiveness score; similar effectiveness scores have been created in other studies investigating the impact of rat management techniques but using existing data not expert elicitation (Norbury et al. 2014). The rat management techniques being compared include the four from this study plus trapping with snap-traps and snap-trapping plus poisoning which were trialled in a past study and for which olive white-eye annual productivity values are available (Chapter 2; Maggs et al., 2015).

To elicit the expert opinion an online questionnaire was designed in SurveyMonkey® (Appendix 4.3) and sent to 20 large-scale rat management experts from various backgrounds including academic researchers and mainland island managers from both temperate and tropical regions identified through published literature and the knowledge exchange, this variation reduces bias caused by individual experience or incentives (Cullen et al. 2001); ethical approval was granted for this questionnaire by the Zoological Society of London Ethics Committee. Within the questionnaire the 4-step elicitation process was used which collects expert opinion while accounting for overconfidence by combining their best guess, lowest likelihood, highest likelihood and their confidence in their answer (Speirs-Bridge *et al.* 2010). Using the following four questions each of the six rat management techniques were rated where 0 is the lease effective and 10 is the most effective –

1. Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

2. Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

3. Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

4. Rate how confident you are that the true likelihood that the threshold of <10% rat tracking indices is achieved would lie between your lowest and highest guesses

The target of <10% rat tracking indices was used as a base line for the experts to compare the management techniques against and was based on existing literature and olive white-eye behaviour. In past research it has been identified that olive white-eye can breed successfully with a suppressed rat population which indicates that complete eradication is not necessary (Chapter 2; Maggs et al., 2015). For similar passerine species in New Zealand it has also been found that populations can persist if rat tracking indices from tracking tunnels are reduced to 20 or 50%, however here indices below 10% have been set assuming olive white-eye will require minimal rat abundance and based on management targets set by other passerine projects (Armstrong & Davidson 2006; Armstrong et al. 2006; Bogardus 2015).

The data received from experts were recalibrated to account for overconfidence, the higher and lower range of each expert were re-scaled to 100% confidence using the methods of Speirs-Bridge *et al.* (2010) expanding the experts range and illustrating what their range would be if they were 100% confident which standardises the results and makes them comparable. All experts with a confidence less than 50% were removed from the analysis as these responses were nonsensical (i.e. this means they believed the true result was more likely outside their range), and any rescaled values which fell outside the range given in the questionnaire of 0-10 were capped so they remained within the desired range.

The calibrated expert elicitation results for each of the six management techniques were then aggregated across the experts and converted to a beta-PERT distribution using the “rpert” function from the package mc2d using the default shape of 4 in the statistical package R version 3.2.5 (Pouillot et al. 2016; R Core Team 2016). The PERT distribution is frequently used, with the triangular distribution, to translate expert estimates of the lowest (average lowest likelihood), highest (average highest likelihood) and most likely (the average of the best guesses) of the random variable in a smooth parametric distribution (Pouillot et al. 2016). These values represent the rat management effectiveness score (0-10) at reducing rat densities to the desired level of <10% rat tracking indices.

4.4.3.2 Annual Productivity Probabilities

The effectiveness scores, generated from the expert elicitation beta-PERT distributions, were then plotted against the known annual productivity of olive white-eye under control (control, no management, was included assuming 0 effectiveness), trapping with snap-traps and trapping plus poisoning management taken from previous research (Chpater 2; Maggs et al., 2015). The “geom_smooth” function was used to plot the variables in the package ggplot2 with model=lm for a linear regression in the statistical package R version 3.2.5 (R Core Team 2016; Wickham et al. 2016). I assumed a linear relationship and not asymptotic based on the annual productivity rates achieved within a reintroduced olive white-eye population free from mammalian predators where breeding pairs can produce up to five fledglings per breeding season, this could also be feasible on the mainland under rat management and in the right conditions (Maggs et al. 2010). It is therefore assumed that olive white-eye would not reach a cut off point for productivity within this analysis. The linear regression line does not go through 0 as olive white-eye can fledge under control management but there is a very low probability (Chapter 2; Maggs et al., 2015).

The linear regression equation ($y=a+bx$) was used in R version 3.2.5 (R Core Team 2016) to predict the annual olive white-eye productivity probability using the x axis value, rat management effectiveness score, to calculate the y axis value, annual olive white-eye productivity, for the unknown rat management techniques; trapping with DOC150 traps, poisoning alone, self-resetting traps and predator-proof fencing. These annual productivity values represent the effectiveness of the four rat management techniques at increasing annual olive white-eye productivity which can be incorporated into individual population viability analyses to predict their effectiveness at reducing population quasi-extinction risk.

4.4.4 Rat Management Impact on Population Viability

4.4.4.1 Population Density

For a population viability analysis the initial population size has to be set, in this study that is the number of olive white-eye territories which can be supported within a set mainland island area within the Combo region. However, due to the critically endangered status of the olive white-eye the population density is far below carrying capacity within the Combo region and so the potential population size for a ‘restored’ stable population in each mainland island area must be estimated. Detailed olive white-eye territory data in the Combo region were used from the 2012-13 breeding season to estimate the number of territories per hectare at a low and high density based on field observations and bird ringing (Figure 1; Ferrière et al., 2013). Density was calculated based on defended territories rather than breeding territories so not to underestimate the density of birds in the area and only included parts of the Combo region where monitoring was conducted.

Using the defended territory GPS data in ArcMap 10.2.2 the density of defended territories per hectare was calculated and multiplied by two to account for both females and males. These densities were calculated from areas which match the habitat type of the whole Combo region and so can be applied to the whole area when predicting mainland island size.

4.4.4.2 Population Viability Analysis

Population viability analysis (PVA) is a powerful and widely used modelling tool to predict population change and determine extinction risk of wildlife (Brook & Kikkawa 1998; Reed et al. 2002; Volampeno et al. 2015). Demographic models are being used increasingly to predict how management may influence population growth or viability and PVA was a major development guiding conservation efforts and decision making (Norris & Mcculloch 2003; Armstrong & Davidson 2006). It allows one to predict the likelihood that the population under study will persist for a given time into the future and determine population decline under different scenarios subject to demographic, genetic and environmental stochasticity (Akçakaya & Sjögren-Gulve 2000; Armstrong et al. 2006; Volampeno et al. 2015). Population viability analysis can be used to bring together information to highlight gaps in knowledge, to assist in determining the number and size of protected areas, help identify limiting factors, compare management scenarios and help formulate a mitigating management strategy for species facing short-term, driven extinction (Armstrong et al. 2006; Flather et al. 2011; Volampeno et al. 2015).

Although PVA has progressed, when using them for threatened rare species where there is little data caution should be taken into the accuracy of the explicit quantitative predictions (Brook & Kikkawa 1998). There is not yet a minimum number of years which a population must be monitored to allow accurate predictions of extinction risk, a minimum dataset of 15 years was estimated for the Capricorn silvereye (*Zosterops lateralis chlorocepha*) but other studies claim at least 5 years of data is needed for a PVA; however, data from different populations can be used and the model updated when the data becomes available (Brook & Kikkawa 1998; Reed et al. 2003; Armstrong & Davidson 2006). For endangered species where only limited datasets are available it is more reliable to run PVA over short time periods as limited datasets cannot capture demographic rates, stochasticity, dispersal rates or catastrophes which creates uncertainty (Beissinger & Westphal 1998; Brook & Kikkawa 1998; Akçakaya & Sjögren-Gulve 2000; Armstrong et al. 2006; Flather et al. 2011). In addition, the quasi-extinction risk should be calculated, as the risk of decline below a critical population level, not complete extinction to one sex remaining (Akçakaya & Sjögren-Gulve 2000).

The stochastic simulation model Vortex 10 was used in this study to run a PVA (Lacy & Pollak 2015), this programme is widely used for endangered species conservation, both species specific and meta-analyses, and by the International Union for Conservation of Nature (IUCN) (IUCN 1994; Reed et al. 2003; Fessl et al. 2010; Volampeno et al. 2015). The Vortex model was used to predict the population quasi-extinction risk of olive white-eye over 50 years across different mainland island areas comparing the four rat management scenarios; trapping, poisoning, self-resetting traps and predator-proof fencing. In order to predict population viability for a mainland island area a 'recovered' population was simulated presuming the starting population was at carrying capacity with the aim of maintaining a stable population over 50 years. The values in the four rat management models were fixed with only annual productivity changing to illustrate the effectiveness of rat management (Table 4.1) and density independence was assumed; if density dependence is included when there is no clear evidence to do so extinction risk could be greatly overestimated, which for management purposes could be detrimental (Ginzburg et al. 1990; McCallum et al. 2000). All the methods used to generate the parameters can be found in Appendix 4.4. Control management (no management) was included using the annual productivity value from Maggs et al. (2015; Chapter 2) to illustrate the fate of the olive white-eye population if no management action is taken.

Each rat management scenario was simulated 1000 times for each mainland island area from 50-350ha in 25ha increments and 350-1000ha in 50ha increments. Model sensitivity testing was carried out to address uncertainty in the model parameters and identify life-history stages which have the greatest impact on population growth (McCarthy et al. 1995; Reed et al. 2002; Norris 2004). For this the trapping with snap-traps scenario was used as a baseline model using the annual productivity value from Maggs et al. (2015; Chapter 2), representing a relatively stable population growth rate ($\lambda = 1.07$), adjusting each parameter ±50%.

Some of the parameters within the Vortex model are based on empirical data generated from detailed management and monitoring or quantitative analysis but others, due to the rarity of the olive white-eye, are based on sparse data or expert opinion. Those parameters based on sparse data and expert opinion, with large sensitivities, were explored when running the models under the different rat management scenarios. Rather than running a sensitivity analysis for each rat management technique varying each parameter in turn the PVA was run under the baseline scenario (input parameters as they are), a best-case scenario (most optimistic values) and a worse-case scenario (most pessimistic values) based on the parameters highlighted in the sensitivity analysis and those which are not based on empirical data (Table 4.1). These parameters were varied by ± 20%, except environmental variation (EV), correlation between reproduction and survival, which was set at 0.5 for the worst-case scenario and male/female survival which was set at 15 years old for the best-case scenario, to reflect the level of uncertainty. Additional runs that explore how sensitive the results are to the less reliable parameters can help map out the boundaries of uncertainty in the results e.g. is predator-proof fencing always better no matter what, or only better under certain conditions.

Table 4.1 Biological parameters and their values used in the population stochastic simulation model Vortex 10 calculating the population quasi-extinction risk of a wild olive white-eye population under differing rat management scenarios; trapping, poisoning, self-resetting traps and predator proof fencing. * indicates the parameters most sensitive to ± 50% alteration in the values. Parameters in bold highlight those included in best and worst-case scenarios based on both their high sensitivity and data source; sparse data or expert opinion. Empirical data has been generated from detailed management and monitoring or quantitative analysis. The source of the data and whether if it is from the wild population (Combo) or the reintroduced, supplementary fed population (Ile aux Aigrettes; IAA) has also been indicated

	Parameter	Value	Status of data
1	Number of interactions	1000	-
2	Number of years	50	Literature
3	Duration of each year (days)	365	-
4	Extinction definition - critical size *	60	Literature
5	**EV correlation between reproduction and survival**	**0**	**Expert opinion**
6	Age of first offspring – females *	1	Empirical data – IAA
7	Age of first offspring – males *	1	Empirical data - IAA
8	**Max age of female reproduction ***	**10**	**Sparse data - IAA**
9	**Max age of male reproduction ***	**10**	**Sparse data - IAA**
10	Maximum lifespan *	10	Empirical data - IAA
11	Maximum number of broods per year	1	-

12	Maximum number of progeny per brood	9	Empirical data - Combo
13	Sex ration at birth (% of males) *	50	Empirical data – IAA and Combo
14	**% of adult breeding females ***	**90**	**Expert opinion – IAA**
15	**SD in breeding females due to EV**	**10**	**Expert opinion - IAA**
16	0 Broods *	0	Empirical data – IAA and Combo
17	1 Broods *	100	Empirical data – IAA and Combo
18	Mean distribution of offspring per female per brood *		
	Trapping	1.16	Empirical data - Section 4.4.3.2
	Poisoning	1.14	Empirical data - Section 4.4.3.2
	Self-resetting traps	1.24	Empirical data - Section 4.4.3.2
	Fencing	1.64	Empirical data - Section 4.4.3.2
19	SD	0	-
20	**Mortality of juvenile females ***	**24**	**Sparse data - IAA**
21	**SD**	**10**	**Expert opinion**
22	**Mortality of adult females ***	**18**	**Sparse data - IAA**
23	**SD**	**5**	**Expert opinion**
24	**Mortality of juvenile males ***	**24**	**Sparse data - IAA**
25	**SD**	**10**	**Expert opinion**
26	**Mortality of adult males ***	**18**	**Sparse data - IAA**
27	**SD**	**5**	**Expert opinion**
28	**% males in breeding pool ***	**90**	**Expert opinion - IAA**
29	Initial population size	-	-
30	Carrying capacity *	-	-
31	**SD due to EV**	**10**	**Expert opinion**

4.4.5 Rat Management Cost-Effectiveness

With high conservation expenditure and finite resources conservation managers and decision-makers must be able justify the allocation of resources and degree to which conservation projects produce success, however, assessing the success of conservation projects is difficult and there are few guidelines on how to conduct analysis on the economic efficiency of wildlife conservation projects (Shwiff et al. 2013). A number of methods have been developed to identify project economic efficiency with the most common methods being cost-effectiveness analysis (CEA) and cost-benefit analysis (CBA), improvements and innovations of these methods have led to the development of other methods such as cost-utility analysis (CUA), threat-reduction assessment (TRA) and conservation output protection years (COPY) (see review by Shwiff et al., 2013).

CBA is used when the output of conservation projects can be assigned a monetary value (Engeman et al. 2002, 2003; Becker et al. 2009), whereas CEA and CUA are used when the conservation impact can be quantified but not monetised (Shwiff et al. 2013). CEA quantifies the impact of the conservation project by measuring an increase in units e.g. eggs, birds etc. (Laycock et al. 2009; Canessa et al. 2014) and CUA, having been derived from the health sector, measures the increase in ‘health’ status per monetary unit spent (Cullen et al. 2001; Shwiff et al. 2013). TRA is the measure of conservation success in terms of a reduction in the threat to biodiversity instead of measuring project success e.g. number of threats to a bird population before and after management implementation; cost can be added (cost-TRA) by calculating the cost per unit of threat reduction (Salafsky & Margoluis 1999; Shwiff et al. 2013). COPY is again derived from the medical sector and is the time-weighted measure of improvement in species status, the COPY estimates from different conservation plans can be compared giving an indication of their efficiency; cost-COPY can be incorporated by calculating cost per increase in conservation output projection per year (Cullen et al. 1999; Laycock et al. 2011; Shwiff et al. 2013).

Here CEA is used to quantify the impact of large-scale rat management techniques on population quasi-extinction risk as cost can be assigned to the measurable increase in annual productivity. Effectiveness in this study is measured by the quasi-extinction risk of an olive white-eye population and how effective the four rat management techniques are over various mainland island areas at increasing population persistence. Cost was derived as the cost of management over the set mainland island areas, incorporating both capital expenditure (acquiring and replacing fixed assets) and recurrent costs (regular costs incurred repeatedly; labour), across 50 years. The values are then plotted to illustrate the cost-effectiveness patterns for both a low and high population density under the best, baseline and worst-case scenarios. This process was then repeated for capital expenditure and recurrent costs separately to investigate the different elements of cost-effectiveness. This illustrates how effective the rat management techniques are based on different aspects of cost as cost type can impact conservation funding opportunities and therefore influence decision-making.

To enable the costings of the large-scale rat management techniques to be as accurate and as applicable as possible information was gathered from a number of sources including the knowledge exchange with mainland island managers, published literature, grey literature and direct contact with the olive white-eye project manager and suppliers in Mauritius, New Zealand and the UK. All equipment purchased outside Mauritius had a 15% import tax applied and was converted from GBP or NZD to MUR, based on the exchange rate on the 21/06/16 and 03/07/16 respectively, also an annual inflation rate of 2% was applied to the long-term costs (including both equipment and labour) based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016a). All of the rat management techniques were costed directly through suppliers except for predator-proof fencing. Due to the complexity of building a predator-proof fence this was costed based on the cost per km from Scofield, Cullen & Wang (2011) for Sanctuary Mountain Maungatautari and Rotokare Scenic Nature Reserve; these fenced mainland islands, visited during the mainland island knowledge exchange, have the high specifications required in Mauritius and so illustrate the level of costs required. These were both built around 2006 and so an inflation rate of 2.1% was added based on inflation rates reported by Statistics New Zealand (Trading Economics 2016b). Labour costs were based on the daily cost of a team of five containing two staff and three volunteers.

For each of the rat management techniques the costs were calculated for (1) establishing the mainland island grid points, (2) installing rat management including both the equipment and labour involved, (3) installing, running and maintaining a tracking tunnel grid across the rat management for monitoring purposes over 50 years and (4) maintaining and running the rat management techniques over 50 years. A breakdown of the management phases, equipment and the type and source of costs can be found in Table 4.2. The only cost which was not accounted for was transport costs of equipment to Mauritius, however, all the rat management techniques require some equipment to be imported and so this will not impact the overall results.

Table 4.2 The management phases (indicated in bold) for establishing a mainland island outlining the equipment required, type of cost, both capital (acquiring and replacing fixed assets) and recurrent (regular costs incurred repeatedly; labour), and the source of the estimated costs. For a detailed breakdown of all the costs see Appendix 4.5

Equipment	Type of cost	Source of cost
Establishing grid		
Grid lines	Capital	Knowledge exchange Mauritius suppliers
Grid markers	Capital	Knowledge exchange Mauritius suppliers
Labour costs	Recurrent	Knowledge exchange Mauritian Wildlife Foundation
Installation of rat management equipment		
DOC 150 traps	Capital	New Zealand supplier
Trap boxes	Capital	Grey literature Mauritius supplier
Poison bait stations	Capital	Knowledge exchange Mauritius supplier
Goodnature® A24 self-resetting traps	Capital	New Zealand supplier
Xcluder™ predator-proof fencing	Capital	Published literature Knowledge exchange
Labour costs	Capital	Olive white-eye project manager
Tracking tunnel grid		
Black Trakka™ tunnels	Capital	New Zealand supplier
Black Trakka™ cards	Capital	New Zealand supplier
Labour costs	Recurrent	Olive white-eye project manager
Maintaining and running		
Equipment replacement	Capital	Assuming all equipment will need replacing every 15 years except predator proof fence every 25 years
Black Trakka™ tunnels		
DOC 150 traps		
Trap boxes		

Poison bait stations		
Goodnature® A24 self-resetting traps		
Xcluder™ predator-proof fencing		
Bait	Capital	
Hen eggs		Mauritius supplier
Diphacinone poison		New Zealand supplier
Goodnature® lure and CO^2 canisters		New Zealand supplier
Brodifacoum		Mauritius supplier
Labour costs	Recurrent	Olive white-eye project manager

4.5 Results

In total 11 responses were received from the questionnaire including experts from different regions, both an academic and management background and with knowledge in all of the rat management techniques being investigated; preventing any bias towards certain management techniques. Of all six rat management scenarios proposed to experts, predator-proof fencing was scored the most effective followed by self-resetting traps. Trapping with DOC150 traps, poisoning and poisoning plus snap-trapping were all within 0.2 of each other and poisoning and poisoning plus snap-trapping had only a 0.05 difference indicating that the addition of bi-monthly snap-trapping had no additional impact on poisoning effectiveness; the least effective was trapping with snap-traps (Table 4.3). This hierarchy was repeated for the annual productivity probability when plotting the effectiveness scores against known annual productivity values with a linear regression (Figure 4.2 and Table 4.4).

Table 4.3 The effectiveness scores of six large-scale rat management techniques derived from expert elicitation and beta-PERT distribution. * indicates the management techniques being considered for implementation across a mainland island and the remaining two used to predict annual productivity values using existing data. The effectiveness score is between 0-10 where 0 is the least effective and 10 is the most effective

Rat Management Technique	Effectiveness Score
Trapping – snap-traps	3.31
Poisoning and snap-trapping	5.8

Poisoning *	5.85
Trapping – DOC 150 *	6
Self-resetting Traps *	6.5
Predator-proof Fencing *	9.05

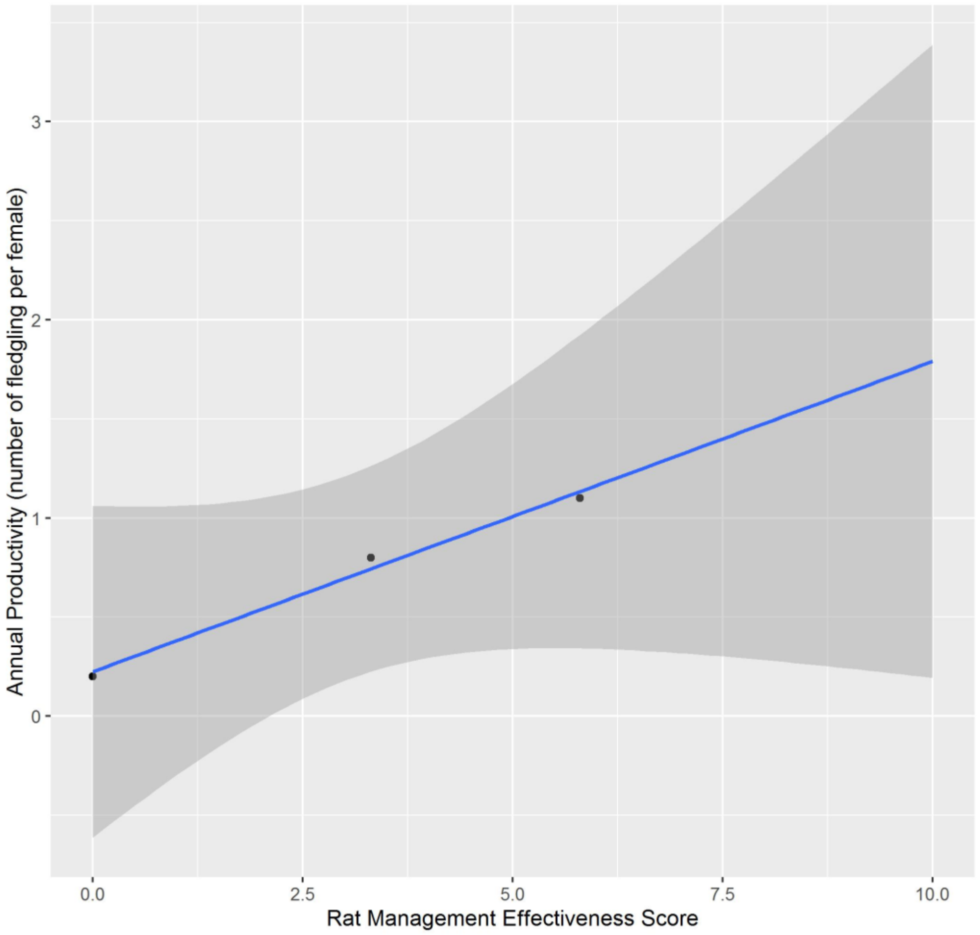

Figure 4.2 Rat management effectiveness score generated through combined expert elicitation calibrated to 100% confidence and converted with a beta-PERT distribution plotted against the annual productivity of female olive white-eye in the mainland population under control (no management), trapping with snap-traps and trapping plus poison management. The blue line represents a linear regression enabling the calculation of annual productivity under rat management techniques with different effectiveness scores. The dark grey area represents the 95% confidence interval. The lm model is very close to significant (P = 0.07)

Table 4.4 Expected annual productivity probability (y), (number of fledglings per female per year), for wild Mauritius olive white-eye breeding pairs under different rat management scenarios calculated using a linear regression ($y=a+bx$) where a is the intercept, b is the slope and x is the rat management effectiveness score generated through expert elicitation. *

indicates the management techniques being considered for implementation across a mainland island

Rat Management	***a***	***b***	***x***	***y***
Trapping snap-traps	0.22465	0.15657	3.31	0.74
Poison and trapping	0.22465	0.15657	5.8	1.13
Poisoning *	0.22465	0.15657	5.85	1.14
Trapping DOC150 *	0.22465	0.15657	6	1.16
Self-resetting traps *	0.22465	0.15657	6.5	1.24
Fencing *	0.22465	0.15657	9.05	1.64

Using the defended territory data of the Combo olive white-eye population, 2012/13, the density of defended territories per hectare was calculated as 0.154 territories per hectare at a low density and 0.263 territories per hectare at a high density.

Sensitivity testing of the Vortex model parameters found parameters associated with reproduction, mortality and population size were the most sensitive (Figure 4.3). As long-term monogamists both females and males play an important role in quasi-extinction risk and are equally important in population persistence, because of this altering the age of first reproduction, the maximum age of reproduction, the percentage of males and females in the breeding pool and creating a sex bias within the population all altered the population quasi-extinction risk. Decreasing the reproductive rates in regards to percentage of breeding pairs which have 1 brood, the number of progeny per female per year and increasing mortality rates also had a large impact. In regards to population size, increasing the carrying capacity above the initial population size and increasing the extinction threshold both decreased and increased quasi-extinction risk respectively. All of the environmental variation standard deviation parameters had little impact on the quasi-extinction risk indicating that they do not have a major influence on the model output (Figure 4.3 and Table 4.1).

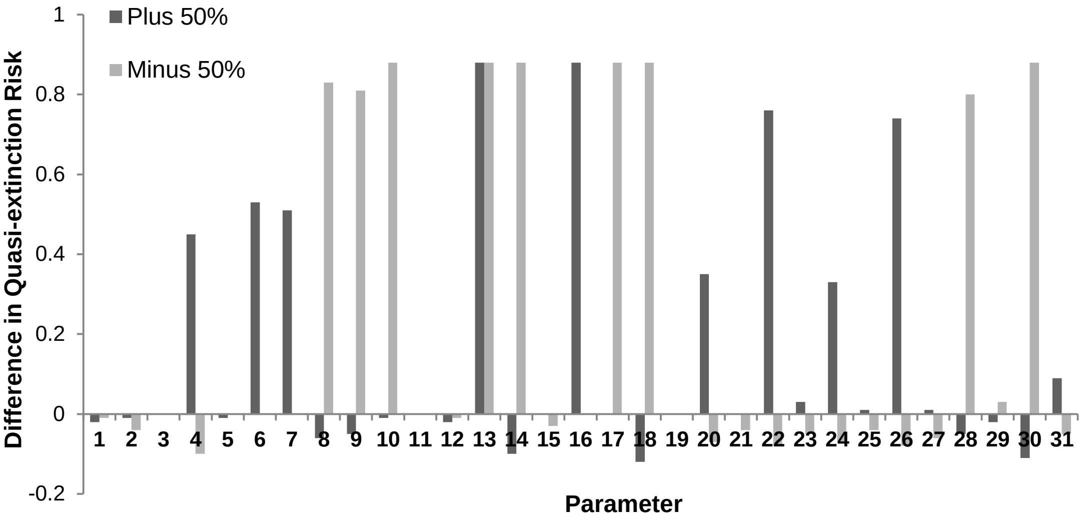

Figure 4.3 Sensitivity analyses of the Vortex model parameters illustrating the difference in quasi-extinction risk of a wild Mauritius olive white-eye population for each parameter adjusted ±50%. The numbers correspond to the parameters in Table 4.1. The annual productivity value under snap-trapping management was used from a previous study to simulate a stable population (λ=1.07; Chapter 2; Maggs et al., 2015)

When the annual productivity values derived from the rat management effectiveness scores were imputed into the Vortex simulation models the quasi-extinction risk over the different mainland island areas varied little between the management techniques. If the quasi-extinction risk threshold is set at 0.01 for a 99% chance of population persistence over 50 years the mainland island area required only varied by 25ha at both a high and low population density (Figure 4.4). Under a low population density the minimum mainland island area required is 275ha for all the rat management techniques except poisoning at 300ha and under a high population density 175ha for all of the rat management techniques except predator-proof fencing at 150ha. The population quasi-extinction risk under control management is 1, predicting that over 50 years the population will become extinct regardless of population density or scenario (Figure 4.4).

The results of the baseline scenario in the Vortex model are very close to those under the best-case scenario with only 25 hectares between those and the baseline and with very little variation between the rat management techniques. However, when modelling the worst-case scenario the mainland island areas increase greatly and rat management technique has a big impact. Although there is an overall increase in hectares the magnitude is reduced the more effective the rat management technique is suggesting that smaller mainland island areas are more viable under the more effective managements in a worst-case scenario (Figure 4.4).

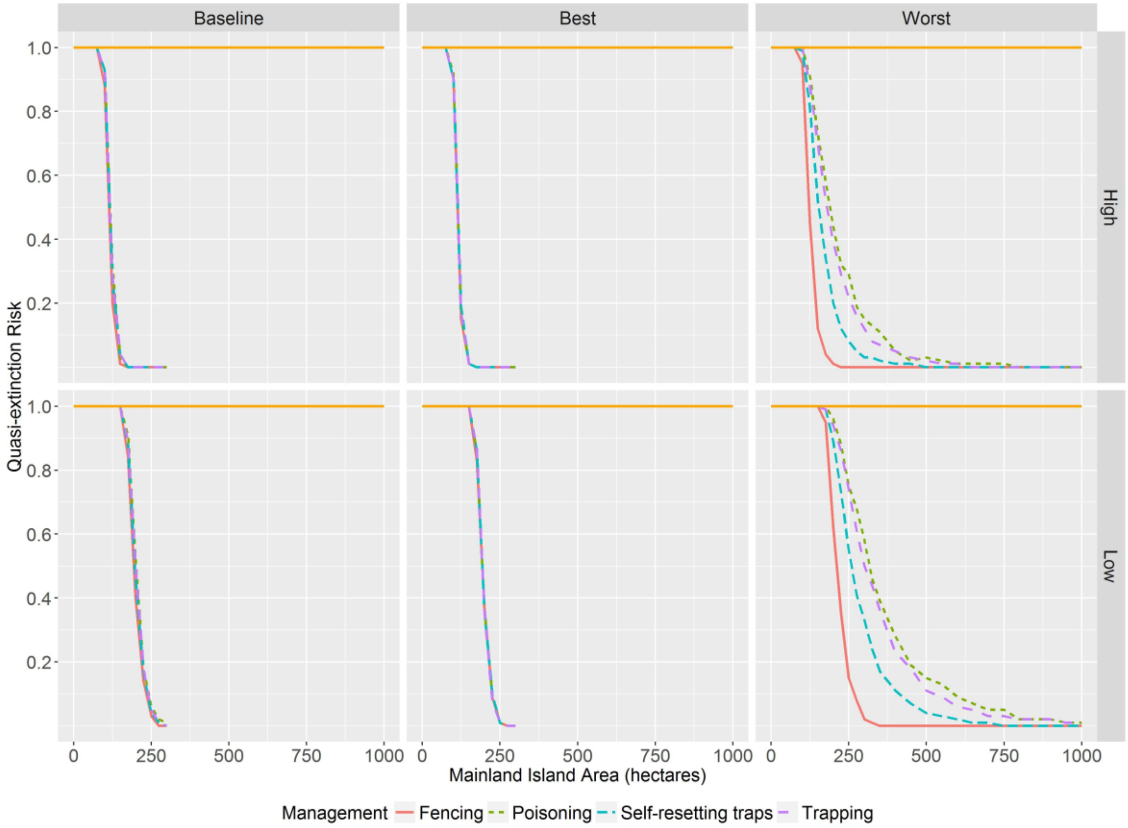

Figure 4.4 The quasi-extinction risk of a wild Mauritius olive white-eye population, at a high and low population density, under a best, baseline and worst-case scenario over 50 years across various mainland island areas under different large-scale rat management techniques; trapping with DOC150 traps, ground-based poisoning using Diphacinone, Goodnature A24 self-resetting traps and Xcluder™ predator-proof fencing. The orange line is control management (no management) using annual productivity data from a previous study to illustrate the fate of the olive white-eye population if no management action is taken

The cost-effectiveness analysis, combining the quasi-extinction risk with management costs, shows more distinction between the rat management techniques compared to mainland island area. If the quasi-extinction risk threshold is set at 0.01 for a 99% chance of population persistence over 50 years the most cost effective management, in both a high and low population density under the baseline scenario, is rat trapping with DOC150 traps at £1.24 and £2.94 million, respectively, followed by Goodnature® A24 self-resetting traps at £1.65 and £3.82 million respectively. At a low population density predator-proof fencing is the next most cost effective technique at £5.7 million and finally poisoning at £7.93 million, however, for a high population density this switches to poisoning at £2.76 million and finally predator-proof fencing at £2.88 million (Figure 4.5). When modelling the best and worst-case scenarios the best-case is very similar to the baseline with the same hierarchy of cost-effectiveness, however, the worst-case scenario finds predator-proof fencing to be the most cost-effective followed by self-resetting traps, trapping and finally poisoning with both a high and low population density (Figure 4.5).

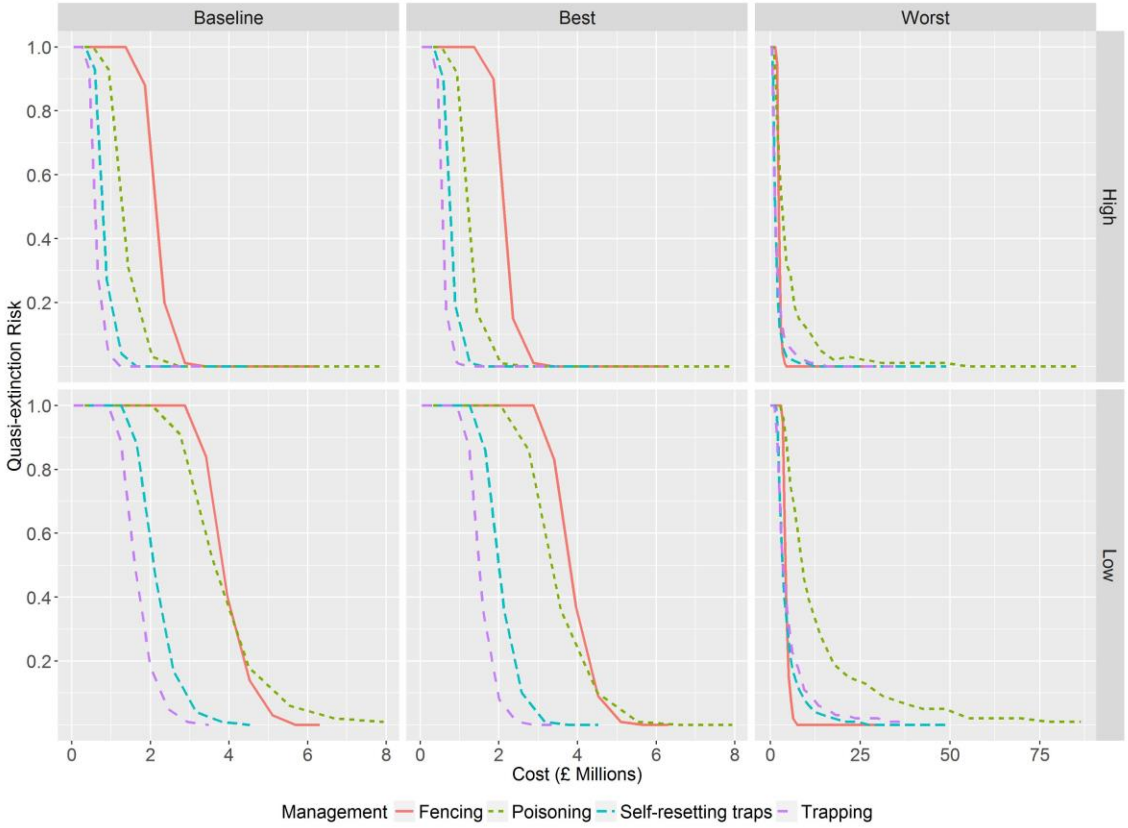

Figure 4.5 The cost-effectiveness of large-scale rat management techniques comparing cost, capital expenditure (acquiring and replacing fixed assets) plus recurrent costs (regular costs incurred repeatedly; labour), with quasi-extinction risk over 50 years for both a high and low density population of wild Mauritius olive white-eye under a best, baseline and worst-case scenario comparing trapping with DOC150 traps, ground-based poisoning using Diphacinone, Goodnature® A24 self-resetting traps and Xcluder™ predator-proof fencing

Investigating capital expenditure and recurrent costs separately highlights clear differences in the cost distribution of the rat management techniques and their cost-effectiveness. Capital expenditure, which includes acquiring and replacing all fixed assets, has exactly the same cost-effectiveness pattern as the combined costs based on a quasi-extinction risk threshold of 0.01 for a 99% chance of population persistence over 50 years in both a high and low population density and under the best, baseline worst-case scenarios (Figure 4.6). However, for recurrent costs, which are regular costs incurred repeatedly (labour), the pattern of cost-effectiveness is altered. If the quasi-extinction risk threshold is set at 0.01 for a 99% chance of population persistence over 50 years the most cost-effective management, under the baseline and best-case scenarios, is Goodnature® A24 self-resetting traps. Under the baseline scenario this is followed by predator-proof fencing, poisoning and finally trapping. Under the best-case scenario this is followed by predator-proof fencing, poisoning and trapping with a low population density, at a high density predator-proof fencing and poisoning are an equal cost followed by trapping. Under the worst-case scenario the most cost-effective management is predator-proof fencing followed by self-resetting traps, poisoning and trapping (Figure 4.7). The differences between the recurrent costs show that in most scenarios Goodnature® A24 self-resetting traps are the most cost-effective technique averaging at £0.84 million, followed by predator-proof fencing at £1.13 million, poisoning at £6.92 million and trapping at £15.31 million making trapping by far the least cost-effective of all the scenarios.

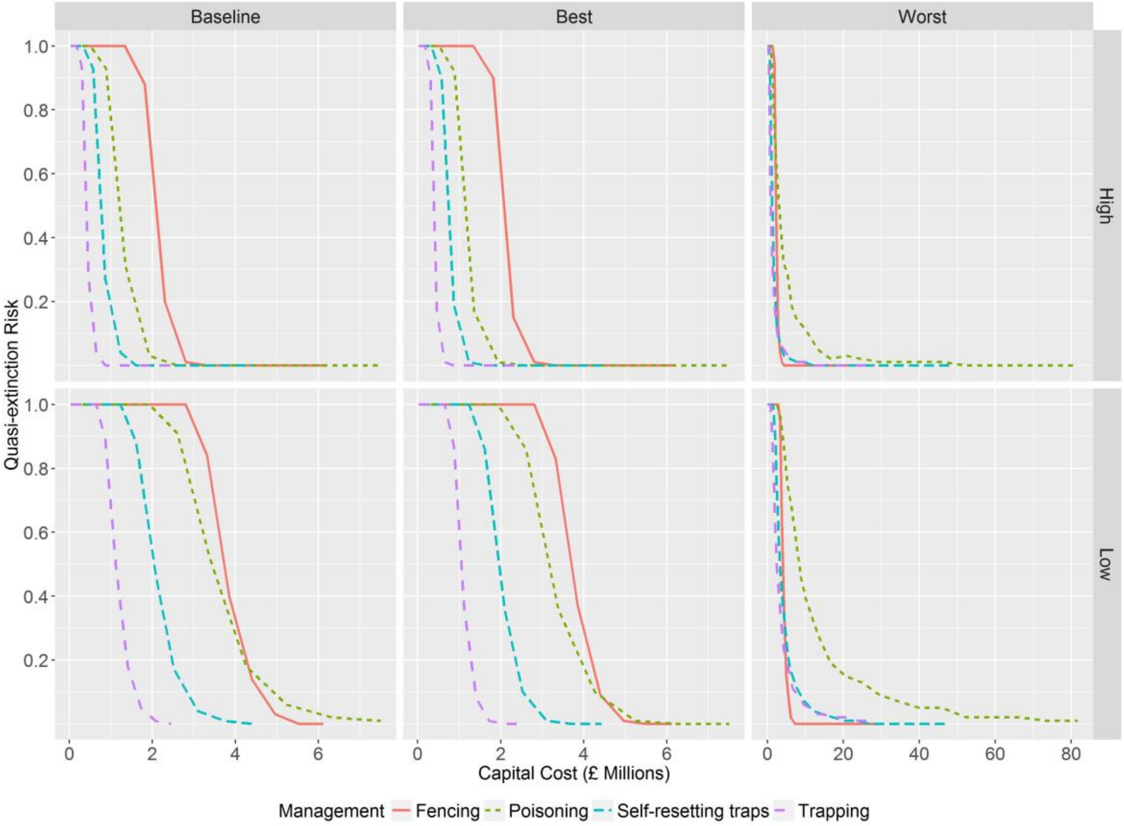

Figure 4.6 The cost-effectiveness of large-scale rat management techniques comparing capital expenditure costs (acquiring and replacing fixed assets) with quasi-extinction risk over 50 years for both a high and low density population of wild Mauritius olive white-eye under a best, baseline and worst-case scenario comparing trapping with DOC150 traps, ground-based poisoning using Diphacinone, Goodnature® A24 self-resetting traps and Xcluder™ predator-proof fencing

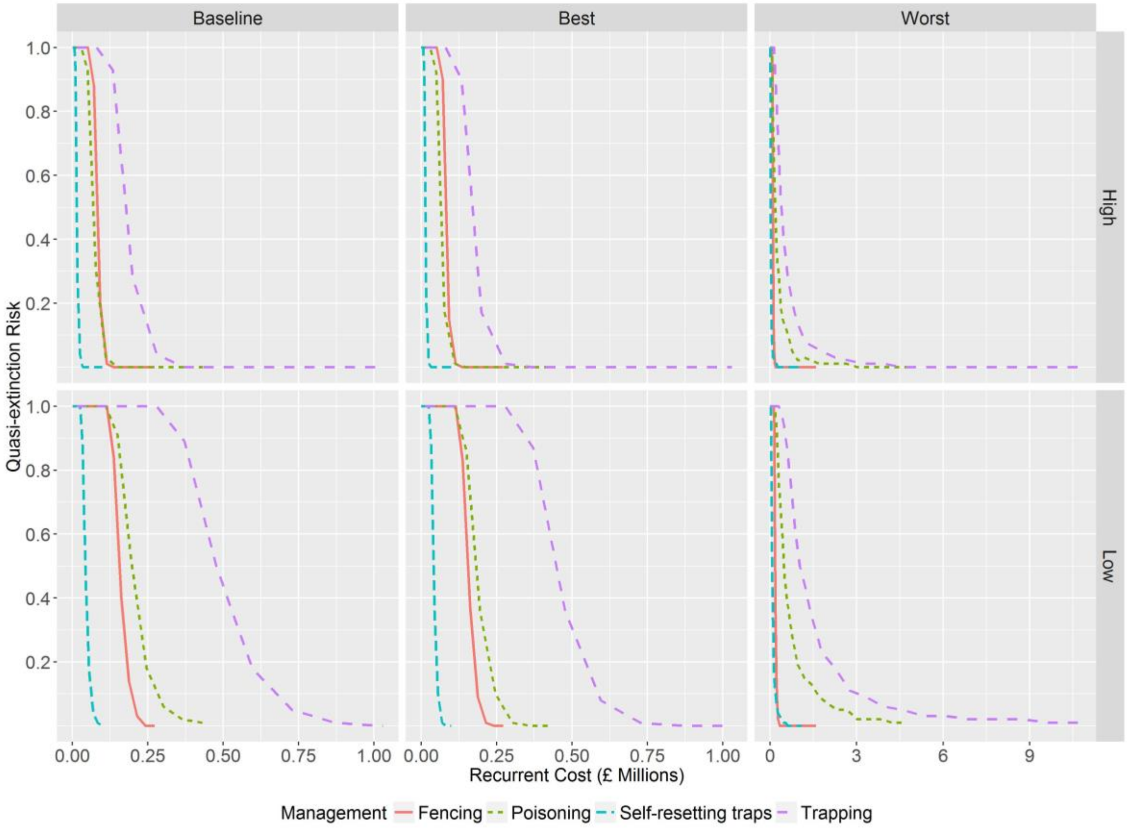

Figure 4.7 The cost-effectiveness of large-scale rat management techniques comparing recurrent costs (regular costs incurred repeatedly; labour) with quasi-extinction risk over 50 years for both a high and low density population of wild Mauritius olive white-eye under a best, baseline and worst-case scenario comparing trapping with DOC150 traps, ground-based poisoning using Diphacinone, Goodnature® A24 self-resetting traps and Xcluder™ predator-proof fencing

4.6 Discussion

Combining population quasi-extinction risk of olive white-eye, generated from the PVA, with management cost in a CEA has successfully illustrated the cost-effectiveness of the four rat management techniques investigated over 50 years comparing total cost, capital expenditure and recurrent costs. This has highlighted the most cost-effective rat management techniques based on a high or low population density, a best, baseline or worst-case scenario and financial resources while incorporating expert knowledge. This eliminates uncertainty caused by limited resources, time and knowledge, to enable a quantitative evaluation of long-term management options and the effective allocation of finite conservation resources to ensure species survival and long-term financial security. Similar studies have been conducted for prioritising management actions for invasive plant species globally, however, this was not in regards to long-term threatened species management (Kerr et al. 2016).

4.6.1 Rat Management Effectiveness

4.6.1.1 Expert Elicitation

Given limited resources and the complexity of conservation decisions associated with threated species management eliciting expert knowledge can play a pivotal role in informing models and decisions through the collection of rigorous empirical data (Martin et al. 2012). The 4-step elicitation process applied here ensures the validity of the expert knowledge while accounting for overconfidence which enables the comparison of numerous management scenarios, a technique successfully applied to other conservation studies comparing management techniques and ranking biodiversity risk factors (Metcalf & Wallace 2013; Canessa et al. 2014; Smith et al. 2015). This comparison has created reliable rat management effectiveness scores which when combined with existing olive white-eye data has produced annual productivity probabilities for management techniques which could have been obtained from field studies but at extreme expense and over an unfeasible time-frame.

Due to these limitations of time and expense some assumptions have been made associating management effectiveness at reaching <10% rat tracking indices with annual olive white-eye productivity as the impact of the management techniques on rat abundance and the subsequent impact on annual olive white-eye productivity cannot be known. However, by incorporating known productivity data under certain rat management techniques and using these to calibrate the remaining techniques alongside expert opinion I am able to at least illustrate the magnitude of difference in effectiveness which can be reflected in the population viability analysis and cost-effectiveness analysis to compare the management techniques and guide decisions.

The expert elicitation in this study involved participants from throughout the world which prevented the inclusion of workshops which can reduce uncertainty and overconfidence further by accounting for linguistic (clearly specified and defined) and epistemic (how much knowledge and validation) uncertainty and allowing experts to alter their responses following group discussions (Metcalf & Wallace 2013; Smith et al. 2015); these additional processes should be conducted where possible when eliciting expert opinion.

4.6.1.2 Reinvasion

A major factor influencing the rat management effectiveness scores and therefore there ranking following the expert elicitation is the reinvasion rate of rats back into the mainland island area and how effectively the management techniques can control this constant reinvasion pressure. There are many factors which can determine the rate of reinvasion to a site with many questions yet to be answered but the control of rats using mainland islands is a developing technique with few absolute answers due to the variability of the sites and species being addressed (Saunders & Norton 2001). Resident rats have been found easier to eradicate from mainland sites as they are less neophobic (the avoidance of an unfamiliar object in a familiar place) and adults are also likely to investigate new food sources first and disperse shorter distances; this doesn’t prevent rat predation but may impact the rate the population can fully re-establish (Hall 2003; Clapperton 2006; King et al. 2011). Predator-proof fences exclude all invasive mammals and have few re-incursions, however, this relies on maintaining fence integrity as rats will continuously patrol fencing and a breach is highly likely to be found within 24 hours although they could only disperse up to 100m into the site within the first few days enabling response management to remove them (Connolly et al. 2009; Innes et al. 2011, 2012). Non-fenced mainland islands are high risk sites for reinvasion and can only become effective if rat populations reach a minimum density over long periods (Carter et al. 2016). The rat management effectiveness scores relay this with predator-proof fencing scoring the highest and the remaining non-fenced techniques all scoring lower and with 0.5 of one another. The reinvasion rate of a mainland island site is something which should be monitored in order to improve and assess management, the tracking tunnel grid will enable this by detecting very low rat densities and identifying incursion ‘hotspots’ to adapt and focus management over time (Martineau 2010; Innes et al. 2011).

4.6.2 Rat Management Impact on Population Viability

Incorporating the annual productivity probabilities, derived from the rat management effectiveness scores, into a population viability analysis has effectively predicted the quasi-extinction risk of an olive white-eye population over 50 years highlighting the minimum area required for a mainland island under the different rat management techniques based on a high or low population density and best, baseline or worst-case scenario.

In past research (Chapter 2; Maggs et al. 2015) predicting the impact of rat management on olive white-eye population growth with a PVA was deemed inappropriate, due to limited data, and instead a two-stage deterministic model was used to predict the annual population multiplication rate. Here PVA was deemed appropriate as although there is limited data the addition of expert elicitation, the use of sensitivity analysis and inclusion of a best, baseline and worst-case scenario greatly reduced uncertainty in the predictions and stochasticity could be incorporated. Also, by presenting the results in a decision-making framework, project managers are able to measure the level of risk they are willing to accept in their decisions and incorporate additional data as it becomes available.

The minimum area required under the baseline scenario is 150-175 hectares assuming a high population density, this rises to 275-300 hectares with a low population density. These areas are very similar to the best-case scenario, however, if a pessimistic view is taken under a worst-case scenario mainland island areas increase greatly in response to rat management effectiveness to 325-950 hectares and 200-600 hectares with a low and high population density respectively (Figure 4.4). This indicates that although the rat management techniques can achieve the same population persistence under the baseline scenario the rat management techniques which can cope with a more pessimistic environment under the worst-case scenario, which accounts for uncertainty in the model, should be favoured to buffer against stochasticity, poor breeding, higher mortality and potential dispersal (McCarthy et al. 2011).

There are numerous meta-analyses and key papers which argue for and against the reliability of PVA but overall they agree that PVA is valid and sufficient to manage endangered species when comparing different consequences of management (Akçakaya & Sjögren-Gulve 2000; Brook et al. 2000; Coulson et al. 2001; Reed et al. 2002; Norris & Mcculloch 2003; Beissinger et al. 2006; Traill et al. 2007), but reliable data must be used, sensitivity analysis should be conducted (McCarthy et al. 1995; Brook et al. 2000) and information should be added to the model as it comes available in an adaptive management approach (Akçakaya & Sjögren-Gulve 2000; Coulson et al. 2001; Beissinger et al. 2006; Armstrong & Ewen 2013). The widespread application of PVA is severely hampered by a chronic lack of data (Norris 2004). Demographic data is not available for a majority of endangered birds world-wide, making it difficult to calculate the area of habitat required, which could account for models not being systematically incorporated into avian research (Norris 2004; Beissinger et al. 2006; Traill et al. 2007). However, even with a lack of data models are useful tools for making predictions and continue to be used in conservation decision-making whether quantitatively, using models, or qualitatively, via conservation managers opinions on how a system operates (Beissinger et al. 2006).

The incorporation of PVA into threatened bird management and its integration into management decisions, despite the lack of data, is not a new concept and has been applied successfully for numerous species throughout the world to understand species demography, population dynamics and guide management e.g. Mauritius Fody (*Foudia rubra*), North Island Robin (*Petroica longipes*), Capricorn silvereye, New Zealand Hihi (*Notiomystis cincta*) and crested coots (*Fulica cristata*) (Safford 1997; Brook & Kikkawa 1998; Armstrong et al. 2006, 2007; Martínez-Abraín et al. 2011). There are also examples of where PVA has been used to investigate potential invasive species management techniques to protect threatened bird species including pulse poisoning techniques for North Island kōkako (*Callaeas wilsoni*), predator-prey dynamics for piping plovers (*Charadrius melodus*), management intensity for the Galapagos mangrove finch (*Camarhynchus heliobates*) and the area of control required for the North Island brown kiwi (*Apteryx mantelli*) (Basse & McLennan 2003; Basse et al. 2003; Fessl et al. 2010; Stringham & Robinson 2015) . However, to the best of my knowledge, PVA has not been used to investigate the population quasi-extinction risk of a critically endangered species to identify the minimum area required to establish species management i.e. a mainland island, comparing four large-scale rat management techniques making this study a unique approach to identifying long-term management options for threatened species.

The sensitivity testing conducted on the PVA highlighted the biological parameters in the Vortex model which were having the greatest impact on the model output, and combining these parameters into a best, baseline and worst-case scenario highlighted variation in population persistence based on uncertainty. Using sensitivity analysis to predict the impact of different management scenarios on the population persistence of critically endangered, data deficient species has been conducted successfully in other studies e.g. North island kōkako and rat management techniques, blue-eyed black lemur (*Eulemur flavi-frons*) and potential habitat destruction and the southern corroboree frog (*Pseudophryne corroboree*) and release techniques (Basse et al. 2003; Canessa et al. 2014; Volampeno et al. 2015). However, again, to the best of my knowledge sensitivity analysis and the creation of best, baseline and worst-case scenarios have not be used to address uncertainty in PVA predictions when calculating the minimum area required to establish species management i.e. a mainland island, comparing four large-scale rat management techniques also making this study a unique approach in addressing uncertainty in long-term invasive species management options.

Combining these two novel approaches, of PVA and sensitivity analysis, to comparing large-scale rat management techniques and predicting mainland island area has identified that there is little variation in the quasi-extinction risk of an olive white-eye population between the various rat management techniques under the baseline or best-case scenarios. This is mainly due to the fact that all the forms of management are capable of effectively reducing rat abundance which improves olive white-eye productivity enough to ensure population persistence over relatively small areas. However, under the worst-case scenario where there is reduced productivity, higher mortality and higher stochasticity rat management effectiveness has a large impact. This indicates that in a turbulent environment the small differences in annual productivity under the different rat management techniques can have a large impact on population persistent and indicates the scale of management which may be required.

4.6.3 Rat Management Cost-Effectiveness

When comparing quasi-extinction risk against mainland island area little variation was seen between the rat management techniques under the best and baseline scenarios, however, when comparing cost against quasi-extinction risk there are clear differences in cost-effectiveness. Breaking down the cost of the rat management techniques and investigating both capital expenditure and recurrent costs separately has also highlighted large differences in cost distribution. Capital expenditure is the largest proportion of the costs and therefore its pattern of cost-effectiveness matches that of the overall costs, however, the cost-effectiveness of recurrent costs illustrates a very different pattern. These differences in cost distribution could greatly influence management decision-making depending of the financial resources available. It could be favourable for a project to invest conservation resources into fixed assets and minimise long-term recurrent costs, on the other hand, for a project where labour is readily available, especially in the form of free volunteer time, investing more in recurrent costs and less in fixed assets could be more appropriate.

Under best and baseline scenarios, trapping (DOC 150) is the most cost-effective rat management technique due to the low cost of equipment and bait and predator-proof fencing the least due to the high cost of fencing and the added eradication phase. Under the worst-case scenarios with higher stochasticity, reduced reproduction and higher mortality the effectiveness score of the management techniques has a greater influence on mainland island area and this is reflected in the cost-effectiveness of the techniques with predator-proof fencing becoming the most cost-effective due to its high rat management effectiveness score. When recurrent costs are considered alone cost-effectiveness changes and under all of the scenarios and population densities self-resetting traps are the most cost-effective technique due to the quick installation, self-resetting mechanism and auto pump lure reducing checking rates to twice per year. Conversely, trapping is by far the least cost-effective due to the high checking rates and trap density required to maintain management effectiveness and high labour involved in making and establishing the management grid.

In turbulent financial times an organisation cannot be confident of financial support 25 or 50 years down the line, this has to be considered in any decision. It could be recommended to choose management based on a worst-case scenario to buffer against more pessimistic years in which case predator-proof fencing would be the most cost-effective rat management technique. Predator-proof fencing has also been found to be the most cost-effective technique over large areas in other studies and have been trialled in numerous countries such as New Zealand, Australia, Hawaii and Mauritius; however, they are only effective if continuously maintained and not compromised by human error and so is the only management technique out of the four which requires continuous financial support (Clapperton & Day 2001; Day & Macgibbon 2007). The other three techniques all have the option of pulsed management whereby if there was a year when funding could not be sourced completely or in part the management could be ‘switched off’ or reduced and reinstated when funding was available again without hindering the long-term effectiveness of the management.

With this financial scenario in mind trapping is the most cost-effective option in terms of overall or capital expenditure costs over smaller areas and is a viable option for a mainland island if set on a 50m x 50m grid which can protect threatened species from rat predation with no secondary environmental impacts and is flexible in location and use (Gillies 2002; Mosher et al. 2010; Reardon et al. 2012). However, under a worst-case scenario the mainland island area increases greatly and the cost-effectiveness reduces and, as other studies have found trapping is very labour intensive and cannot always keep rat abundance below 10% rat tracking indices (Gillies 2002; Franklin 2013; Bogardus 2015; Carter et al. 2016), therefore, an organisation would have to consider whether they have the staffing resources to meet the high labour demands required.

If labour demands are the main financial limitation of an organisation self-resetting traps become the logical choice as the most cost-effective management technique in regards to recurrent costs, which has been found in other studies (Franklin 2013; Carter et al. 2016). They also have the second highest rat management effectiveness score and so could buffer the population against the worst-case scenario while remaining relatively cost-effective. Studies have found that they are able to maintain rat tracking indices below 10% even on a 100m x 100m grid and withstand fluctuations in re-invasion rates; as the more cost-effective option, projects in Hawaii are systematically replacing trapping and poisoning grids with self-resetting traps (Franklin 2013; Bogardus 2014; DOC 2015a, 2015b; Carter et al. 2016). Although self-resetting traps have a high capital expenditure cost they are still more cost-effective compared to predator-proof fencing across small areas and poisoning in any scenario and can reduce the long-term financial pressure on an organisation, ensuring the long-term feasibly of the mainland island.

Poison although effective is controversial, expensive, variable in efficiency and regulated in many countries (Franklin 2013) and does not favour well in the analysis, requiring the largest mainland island area under all management scenarios and as one of the least cost-effective management techniques. This is due to the low rat management effectiveness score assigned from expert elicitation, the high cost of importing a first-generation anticoagulant rodenticide (diphacinone) and the high labour costs in maintaining a poison grid. The second-generation rodenticide brodifacoum has been used effectively for eradication and control for many years, however, there are concerns around its longevity within the environment and secondary poisoning (Booth et al. 2001); especially potential secondary exposure and subsequent poisoning in nestlings of insectivorous passerines (Masuda et al. 2014). Therefore, the use of brodifacoum is controversial and is no longer used for control by DOC and is not legal for control use in the USA, therefore it has not been recommended for use in Mauritius (Gillies 2002; Eason & Ogilvie 2009; Franklin 2013). Diphacinone was chosen based on its reduced secondary impacts on the environment which for large-scale and long-term management is paramount, however, using first-generation rodenticides although effective at removing resident rat populations and controlling rat abundance are less effective at consistently keeping rat abundance at lower levels (Gillies 2002; Gillies et al. 2003; Donlan et al. 2003). In order to maximise poison effectiveness and efficiency management could be pulsed which enables management to be targeted during peak-times of threat i.e. breeding seasons, which avoids continuous management which can cause staff fatigue and can minimise poison aversion or tolerance (Basse et al. 2003; Baxter et al. 2008). Regardless of effectiveness the slow death of rodents from anticoagulants is a significant ethical cost and therefore other more cost-effective methods should be considered (Armstrong et al. 2014).

Costs need to be considered in management decisions as they are based on not only whether the proposed strategy is sufficient to achieve recovery but also whether the likely benefit will justify the expenditure (Brook et al. 2000). Incorporating cost into management decisions has been successfully conducted for invasive species management when comparing potential management scenarios with research comparing the cost of control against eradication (Zabala et al. 2010), conventional control against predator-proof fencing (Clapperton & Day 2001) and self-resetting traps against conventional trapping and poisoning (Franklin 2013; Carter et al. 2016). Cost analysis has also been conducted investigating the benefit of different levels of predator management against the monetary cost of the Puerto Rican parrot (*Amazona vittata*) and the captive breeding of three species of marine turtle (Engeman et al. 2002), the mortality cost to North island robin of aerial poisoning against the benefits to productivity (Powlesland et al. 1999) and comparing the effectiveness of fencing methods against trapping at reducing mammalian predator abundance over 50 years and applying this to the cost-effectiveness of recovering populations of two skink species (*Oligosoma grande* and *O. otagense*) (Hutcheon 2011; Norbury et al. 2014). However, to the best of my knowledge using species quasi-extinction risk as a measure of effectiveness and comparing this with the total, capital and recurrent costs of management separately within a CEA has not been conducted. Therefore, this is a unique approach to CEA which can identify the most cost-effective rat management technique for the establishment of a mainland island in regards to both long-term population persistence and cost distribution.

4.6.4 Adaptive Management

Modelling is an interactive process which involves development, testing, subsequent modification and re-testing (Basse & McLennan 2003). When assessing the impact of management scenarios on population persistence it is important that PVA models are adaptable and not abandoned, adding information over time as it becomes available to refine the parameters, check the realism of the model and guide future fieldwork in an adaptive management approach (Akçakaya & Sjögren-Gulve 2000; Coulson et al. 2001; Beissinger et al. 2006; Armstrong & Ewen 2013). Adaptive management is widely considered to be the best approach for managing biological systems in the presence of uncertainty (Westgate et al. 2013). Some studies argue that there is a trade-off between implementing management and gaining additional information and the benefits of both should be assessed (Maxwell et al. 2015). Here I illustrate how this does not have to be the case. Combining existing data with expert elicitation can enable PVA and relating this with CEA can identify viable, cost-effective management while highlighting knowledge gaps which can be researched and added to improve model accuracy and refine management over time (Volampeno et al. 2015).

An important area of monitoring for the olive white-eye is juvenile dispersal as there is currently no information on how far juveniles disperse from their natal territory and where they establish breeding territories. This is important to establish as dispersal can be very influential in a population (McCarthy et al. 2011). A study investigating the size of a mainland island in relation to North Island brown kiwi recovery found that as dispersal increased the minimum area required for a mainland island also increased and ‘leaking’ sub-adults eventually caused population failure despite the lack of predators within the area (Basse & McLennan 2003). Although dispersal wouldn’t initially jeopardise the recovering olive white-eye population within the mainland island it is vital to establish juvenile dispersal rates in order to identify if a larger mainland island would be required to prevent potential failure due to a source-sink population dynamic (McCarthy et al. 2011); which could add another dimension to the decision-making process based on whether a management technique can be easily expanded. Monitoring rat reinvasion rates would also be important to establish the minimum tracking tunnel indices required to ensure productivity and population persistence, this has been conducted successfully for the North island robin in New Zealand to establish a management target (Armstrong et al. 2006). This would allow conservation managers to monitor rat tracking tunnel indices, identify peak reinvasion periods and adapt management accordingly to enable a better allocation of conservation resources.

4.6.5 Ecosystem Restoration

When managing invasive species it is important to understand their interactions and how managing one species may impact predator-prey dynamics which could have a secondary impact on species vulnerable to these predators. In New Zealand a decrease in rat densities through management caused an increase in bird predations by stoats potentially due to a decrease in alternative diet or an influx into the area following rat removal (Murphy et al. 1998; Basse et al. 2003). Managing all known predators is therefore important until the impact of them individually is known (Alterio et al. 1999). Due to this ‘surprise factor’ and secondary unexpected and undesired results of invasive species management mainland islands are starting to take a ‘multi-species/multi-threat’ approach focusing less of species restoration and more on ecosystem conservation which has shown to be more effective (Saunders & Norton 2001; Carter et al. 2016). Controlling a suite of invasive species can create high quality habitats suitable for many species and has led to island-type responses in native plants and animals (Jones & Merton 2012). PVA due to their single species focus are limited where the goal is the management and conservation of multiple species or an ecosystem, however, species can act as an indicator to guide and inform overall management as their performance is easier to measure than broader ecological goals (Akçakaya & Sjögren-Gulve 2000; Saunders & Norton 2001).

It is highly recommended that any mainland island established in Mauritius to ensure olive white-eye species survival takes a multi-species/multi-threat approach, to avoid any surprise factors. Both small Indian mongoose and feral cats should be targeted alongside rats to prevent any secondary impacts on other threatened species within the region e.g. the endangered Mauritius pink pigeon (*Nesoenas mayeri*) which is very vulnerable to predation from mongoose and feral cats and could become a target if rat abundance depleted. Management methods which could be used to target multiple invasive mammals have been outlined in Appendix 4.2 for all four management scenarios investigated in this study; however, these approaches would require further research to identify the most cost-effective technique.

4.7 Conclusion

For small declining populations, which are at the greatest risk of extinction, decisive and innovative management actions are required to prevent population decline and ultimately avert extinction but with high levels of uncertainty and the fear of negative outcomes deciding on the best action is challenging (Meek et al. 2015). The focus on value for money is also an increasingly important aspect of conservation management, given that resources for conservation are far exceeded by the potential needs that could be funded (Innes et al. 2012). Identifying the most viable and cost-effective management technique and making these challenging decisions are a logistical and financial risk. Here I have illustrated how to break down these challenging decisions with clear quantitative decision-making tools which enable an organisation to evaluate and assess each management possibility on a site and species specific basis and in regards to both the scale of management and the capital expenditure and recurrent costs minimising uncertainty and the fear of failure.

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Appendix 4.1

Literature Review: Invasive Species Management

The four rat management scenarios selected for consideration within Mauritius were selected based on the techniques applied across New Zealand, the leaders in mainland island management. There are around 111 mainland island areas across New Zealand of which 72% target invasive rat species, of these 37.5% use trapping, 22.5% use predator-proof fencing, 20% use trapping plus poisoning, 17.5% use poisoning alone and 2.5% use self-resetting traps (Butler et al. 2014). The method of trapping plus poisoning was not included in the literature review as none of the other methods were combined and so all remained independent.

During a literature review the widest possible range of sources should be accessed to capture information, with both published and unpublished data being included, and therefore a number of general sources where used: electronic databases both general and scientific (Google © and Google scholar ©), bibliographies (data sources cited in literature obtained from databases) and subject experts (obtained through direct personal contact/knowledge exchange) (Pullin e tal. 2006). The main question for the search was, what methods are implemented for mainland rat control areas in regards to trapping, ground-based poisoning, self-resetting traps (Goodnature© A24) and predator-proof fencing. All the literature found was filtered based on relevance of title, then relevant abstract content and finally availability of required information from the methods section (location, management technique, equipment used, spacing's of rat control, total area of rat control, frequency of checks, additional invasive species targeted, rat abundance monitoring). A meta-analysis was not being conducted on the effectiveness of the selected rat management techniques, instead, a qualitative synthesis was conducted allowing an informal evaluation of the results found to identify appropriate conservation management methods (Pullin et al. 2006).

Rat Management Summary

Rat Trapping

In both tropical and temperate regions 56% of sites used ≤50m spacing's and 44% >50m spacing's (n=17). Best practice guidelines for trapping suggest one trap in every rat home range (DOC 2005), in Mauritius ship rat home ranges vary between 0.3-0.4ha (55m-63m^2) (Hall 2003) and therefore a 50m x 50m grid was chosen for the trapping management scenario. In tropical regions 43% of sites conducted fortnightly checks and the remaining rates of weekly, 10 day, monthly and 6 weekly accounted for just 14.2% each therefore fortnightly checks were selected (n=7).

Rat Poisoning

In tropical and temperate regions 48% of sites used ≤50m spacing's and 52% >50m spacing's (n=21). Best practice guidelines for trapping were applied to poisoning suggesting one trap in every rat home range (DOC 2005), in Mauritius ship rat home ranges vary between 0.3-0.4ha (55m-63m^2) (Hall 2003) and therefore a 50m x 50m grid was chosen for the poisoning management scenario. For sites which conduct continuous poisoning management 36% of sites conduct fortnightly checks, which are all in the tropical regions, and the remaining rates of 3-5 days, 2 months and 1-3 months accounted for 12.5% and monthly for 25% (n=8), therefore, fortnightly checks were chosen based on the higher proportion of sites and the tropical region.

Self-resetting Traps

In tropical and temperate regions 100% of sites used a 50m x 100m grid and so these grid spacing's were chosen for the self-resetting management scenario (n=7). In tropical regions 66% of sites conducted 4-6 week checks and the remaining rates of 2 weeks and monthly checks accounted for 7% and 27% respectively (n=15), however, following the introduction of the auto pump lure checks have been reduced to 6 monthly and so this has been chosen based on guidelines (Goodnature 2015).

Predator-proof Fencing

The criterion for a predator-proof fence is an amalgamation on the features recorded during the knowledge exchange in New Zealand for the fencing and inner fence precautionary predator control and a predator-proof fence trial conducted in Mauritius (Day 2004; Tatayah et al. 2005)

Table A4.1 Large-scale rat management 'mainland island' review. Outlining site details, the management technique implemented, the target invasive mammal and additional comments. Mustelids and ferrets are groups under mongoose as these target species require the same technique and therefore can be used as a reference. The information provided by each reference varies and therefore the data obtained differs between sites, however, as much information was gathered from the references as possible

Site, Area (ha), Location, Reference	Management Technique	Rats	Mongoose (Mustelids and ferrets)	Cats	Comments
Trounson, New Zealand (Saunders & Norton 2001)	Trapping		Perimeter trapping at 100m spacing's with Fenn traps	Perimeter trapping at 200m spacing's with leg hold, live traps and Steve Allan Conibear® traps	Review paper
Trounson, New Zealand (Saunders & Norton 2001; Gillies 2002)	Poisoning	100m x 100m grid reduced to 100 x 50m. Checked every 2 months, Philproof© stations	Perimeter trapping at 100m spacing's with Fenn traps	Perimeter trapping at 200m spacing's with leg hold, live traps and Steve Allan Conibear® traps	Review paper Four rounds of none toxic poison followed by a knock out phase with 1080 then brodifacoum. Snap-trapping was conducted within the mainland island a and control sites monthly for 3

					consecutive nights before and after poisoning
Trounson, New Zealand (Saunders & Norton 2001; Gillies 2002)	Tracking Tunnnels	Tracking tunnels set for one night			
Mapara, 1400 ha, New Zealand (Innes et al. 1999; Basse et al. 2003)	Poisoning	50m x 50m grid over 12ha covering Kōkako territories			Kōkako (*Callaeas wilsoni)* recovery
Mapara, 1400 ha, New Zealand (Innes et al. 1999; Basse et al. 2003)	Trapping	50 x 50m grid over 12ha covering Kōkako territories			Kōkako (*Callaeas wilsoni)* recovery
Rotoiti Nature Reserve, 825 ha, New Zealand Waipapa Ecological Area, 1100ha, New Zealand	Poisoning	100 x 50m grid using 1080, brodifacoum or Pindone; recommended grid			Kaka (*Nestor meridionalis)* recovery

Eglington Valley, 13000 ha, New Zealand (Moorhouse et al. 2003)		size			
Pikiariki, New Zealand (Innes et al. 1995)	Poisoning	30m spacing's checked every 3-5 days			
Mapara, New Zealand (Innes et al. 1995)	Poisoning	50m spacing's using drainage tubes, checked weekly then monthly after 5 weeks		200m spacing's using Fenn traps	
Wenderholm Regional Park, New Zealand (James & Clout 1996)	Poisoning	50m x 100m grid in 50cm "Novacoil" drainage tube stations			Kereru (*Hemiphaga novaeseelandiae)* management. Low reinvasion as on a peninsula
Central North Island, New Zealand (Armstrong et al. 2014)	Poisoning	50m x 50m grid, poison changed monthly			North Island Robin (*Petroica longipes)* management

Central North Island, New Zealand (Armstrong et al. 2014)	Trapping & Poisoning	50m x 50m grid. A knock out phase with 10 days of trapping then poisoning with bromodailone			North Island Robin (*Petroica longipes)* management
Maruia, New Zealand (Alterio et al. 1999)	Trapping	150m spacing’s in a circular line	150m spacing’s in a circular line		Investigating the trappability and densities of stoats and rats
Cook Islands, 150 ha (Robertson et al. 1994)	Poisoning	50m x 50m grid using “Novacoil” drainage pipe bait stations and brodifacoum poison. Outer stations 100m spacing’s then decreased to 25m after a year			Kakerori (*Pomarea dimidiate*) recovery
Isabella Island, Galapagos (Fessl et al. 2010)	Poisoning	50m x 50m grid using plastic tubes and brodifacoum			Galapagos Mangrove Finch (*Camarhynchus heliobates*) management
Hawaii	Poisoning	4 Protecta® bait stations per territory			Oahu elepaio

(Vanderwerf et al. 2011)		using diphacinone			(*Chasiempis ibidis*)
Hawaii (Vanderwerf & Smith 2002)	Poisoning	1.06 plastic poison boxes per hectare (1 every 100m) using diphacinone			Oahu elepaio (*Chasiempis ibidis*) management
Hawaii (Vanderwerf & Smith 2002)	Trapping	1.14 traps per territory (1 every 100m) using snap-traps			Oahu elepaio (*Chasiempis ibidis*) management
Hawaii, 15ha (Vanderwerf 2001)	Poisoning	1.2 poison bait stations per hectare (1 every 100m) using diphacinone			Oahu elepaio (*Chasiempis ibidis*) management (*Chasiempis ibidis*)
Hawaii, 15ha (Vanderwerf 2001)	Trapping	1.53 snap-traps per hectare (1 every 100m)			Oahu elepaio
Hawaii (Malcolm et al. 2008)	Poisoning	100m x 50m grid using diphacinone			Po'ouli (*Melamprosops phaeosoma*)
Hawaii	Trapping	100 x 50m grid using			Po'ouli (*Melamprosops*

(Malcolm et al. 2008)		snap-traps			*phaeosoma*)
Tahiti (Blanvillain et al. 2003)	Poisoning	30-50m spacing along line through valley using plastic piping and bromadiolone			Tahiti Flycatcher (*Pomarea nigra*)
San Jorge, Mexico (Donlan et al. 2003)	Poisoning	25m x 25m grid but for eradication			Eradication poison trial
Seychelles (Rocamora & Baquero 2007)	Poisoning	50m x 50m grid using plastic tubes checked every 2 week			Seychelles white-eye (*Zosterops modestus*)
Seychelles (Rocamora & Jean-louis 2008)	Poisoning	50m x 50m grid using plastic tubes checked every 1-3 months but too infrequent to control rats			Seychelles white-eye (*Zosterops modestus*)
Hawaii (Franklin 2013)	Self-resetting traps	100m x 50m with 50m spacing around the edge			A24 vs snap-trap cost-benefit

Hawaii (Franklin 2013)	Self-resetting traps	100 x 50m with 50m spacing around the edge			A24 vs snap-trap cost-benefit analysis
Macraes Flats, 2100ha, New Zealand (Norbury et al. 2014)	Trapping		100m x 100m grid Used variety of traps including DOC 150 and 250, Fenn, Timms, Conibear® and leg-holds	100m x 100m grid Used variety of traps including DOC 150 and 250, Fenn, Timms, Conibear® and leg-holds	Predator-proof fencing vs trapping Buffer of 1500m
Rotokare Scenic Nature Reserve, 230 ha, New Zealand Knowledge exchange (Rorkare Scenic Reserve 2013)	Predator-proof Fencing	2m high, 25 x 6mm stainless steel mesh, curved hood, under-ground skirt, hot wire, solar powered vehicle access gate and culverts	Have trapping around the inner fence perimeter, buildings and roads; DOC 200, 250, rat and mouse traps. Checked every two weeks (weekly in high risk period e.g. summer and tourists), rebaited monthly		Xcluder® On the ridge so clear of forest but problem with eroding soil
Rotokare Scenic Nature Reserve, 230 ha, New	Tracking tunnels	50m x 50m grid conducted twice and			

Zealand Knowledge exchange		year and if the fence is breached			
Boundary Stream Mainland Island, 800ha, New Zealand Knowledge exchange	Trapping		100m x 150m DOC200 double set traps	200m around edge DOC250	
Boundary Stream Mainland Island, 800ha, New Zealand Knowledge exchange	Poisoning	75m x 150m grid using 1080 cereal poison in Philproof© bait stations, checked every 4-12 weeks			
Boundary Stream Mainland Island, 800ha, New Zealand Knowledge exchange	Self-resetting Traps	50m x 100m grid, 1,500 traps in total	Trapping around the edge as a buffer from mustelids conducted by the council		
Te Urewera, New Zealand (Gillies et al. 2014)	Self-resetting Traps	100m x 50m grid across140ha with 25m spacing's around the	100-200m spacing's along ridges with A24 traps across 4037ha		

		perimeter			
Boundary Stream Mainland Island, 800ha, New Zealand Knowledge exchange	Tracking Tunnels	12 lines of 10 tunnels at 50m spacing's checked monthly			
Bushy Park, 98ha, New Zealand Knowledge exchange	Predator-proof Fencing	Checked weekly, keeps out everything except mice, curved hood, uUnder-ground skirt, no hot wire, vehicle access gate	Traps around the outside edge which are checked weekly		Xcluder® fence
Maungatautari, 3367ha, New Zealand Knowledge exchange	Predator-proof Fence	Check fence monthly, curved hood, under-ground skirt, hot wire, solar powered, water gate and entry gate alarms, vehicle access gate, pedestrian access gate, swinging water gates (major streams), culverts with	No buffer zone. Rat traps and poison around the edge of the inner-fence every 25m zig-zagged next to and away from fence. Stoat traps every 100m along inner fence. checked monthly		Xcluder® 'Kiwi' fence

		fixed screen (minor outlets), culverts with self-cleaning streams (for all inlets from agricultural land)			
Maungatautari, 3367ha, New Zealand Knowledge exchange	Tracking Tunnels	50m x 50 grid, checked monthly approx. 4,500 tunnels			
Rotoiti Nature Recovery Project, 847ha, New Zealand Knowledge exchange	Poisoning	100m x 100m grid Philproof© stations. Pulsed rat poisoning one before breeding season then another if bait take is high 3 weeks later (aerial drops during beech masting years) No official buffer Prior to this checked			Tracks are maintained and clear markers used to reduce time

		every 6 weeks			
Rotoiti Nature Recovery Project, 825ha, New Zealand (Gillies 2002)	Trapping	100m x 100m grid (100m x 150m on upper slopes), Victor snap-traps			Could not reduce rat indices to below 5% but did decrease robin mortality
Rotoiti Nature Recovery Project, 5000ha, New Zealand Knowledge exchange			Stoat and possum trapping, DOC200 and 250, checked every 2-4 weeks depending on trapping rates No official buffer Services annually	Both live and Timms traps. No official buffer	
Rotoiti Nature Recovery Project, New Zealand Knowledge exchange (Gillies et al. 2014)	Self-resetting Traps		A24 traps every 100m along ridges in boxes to protect non-target species		
Rotoiti Nature Recovery	Tracking	4 times a year – not in			

Project, New Zealand Knowledge exchange	Tunnels	the rain			
Shakespear Open Sanctuary, 500ha, New Zealand Tawharanui Open Sanctuary, 550ha, New Zealand Knowledge exchange	Predator-proof Fencing	No hotwire, 50ha buffer (very important as this is an open sanctuary on a peninsula), checked weekly, vehicle gates checked annually, pedestrian gates manual not electrical (people got stuck in electric ones), fences checked after major weather events	500 traps serviced monthly (I think this is the buffer on the outside)		Vegetation cover from inside the fence to prevent soil cracking Gravel around the base of fence; better drainage and moisture retention
Zealandia, 225ha, New Zealand Knowledge exchange	Predator-proof Fence	First fence, designed by themselves, no hot wire, woven mesh, curved hood, under-ground skirt, water gates, pedestrian manual gates,			

		biosecurity bag checks, fence checked every 2 weeks, soil erosion issues, zinc blast hood welts, mouse poisoning within the site, no inner trapping			
Zealandia, 225ha, New Zealand Knowledge exchange	Tracking Tunnels	Two lines 200m spacing’s checked annually and after a breach			
Tawharanui, 550ha and Shakespear, 500ha,New Zealand Knowledge exchange	Tracking Tunnels	Monthly (remain in place for 3 weeks then collected to monitor presence/absence)			
Kaiaraar, Barrier Island, 100ha, New Zealand (Gillies 2002)	Trapping	25m x 50-75m grid, Victor snap-traps			Successfully maintained rat indices below 5%

Northerm Te Urewera, 1400ha, New Zealand (Gillies 2002)	Trapping	25m x 50-75m grid, Victor traps			Successfully maintained rat indices below 5%
Hurunui, 6000ha, New Zealand (Gillies 2002)	Trapping	100m spacing along lines using Fenn traps			
Ark in the Park, 2450 ha, New Zealand (Martineau 2010)	Poisoning	50m x 100m grid Philproof© stations (4247 stations), brodifacoum bait is renewed 3 times a season prior to bird breeding and finished mid austral winter			800ha buffer zone but not around the area, a site at the top of the mainland island for poison and trapping
Ark in the Park, 2450ha, New Zealand (Martineau 2010)	Trapping		Fenn and DOC 200 traps at 200m spacing's around the perimeter and along tracks across the site, checked and re-baited fortnightly and the	Cat traps are set along the mustelid lines every 500m and checked at the same frequency	800ha buffer zone but not around the area, a site at the top of the mainland island for poison and trapping

			peripheral weekly		
Ark in the Park, 2450ha, New Zealand (Poorter 2010)	Tracking Tunnels	Lines with 10 tunnels 50m apart, conducted 4 times a year with tracking tunnels inside and outside the mainland island			
Waikato Region, 2.2-9.9ha, New Zealand (King et al. 2011)	Trapping	25m x 50m, Victor snap-traps in tunnels, baited with peanut butter			Part of reinvasion study so trapped to localised extinction and then allowed to recolonise
Waikato Region, 2.4 – 9.9ha, New Zealand (King et al. 2011)	Tracking Tunnels	50m x 50m grid using Black Trakka™ tracking cards in tunnels			
Maui, 20 – 40ha, Hawaii (Malcolm et al. 2008)	Poisoning	50m x 100m grid using diphacinone			
Maui, 20 – 40ha, Hawaii	Trapping	50m x 100m grid using victor snap-traps			

(Malcolm et al. 2008)		checked when bait was changed			
Oahu Army Natural Resources Program, Hawaii (Mosher et al. 2010)	Poisoning	25m x 50m grid, diphacinone poison fixed in station, checked weekly for first 6 weeks then fortnightly			Small scale management. This management is seasonal for Oahu Elepaio (*Chasiempis ibidis*) breeding success
Oahu Army Natural Resources Program, Hawaii (Mosher et al. 2010)	Trapping	25m x 50m grid, victor snap-traps not covered, checked weekly for first 6 weeks then fortnightly			Small scale management. This management is seasonal for Oahu Elepaio (*Chasiempis ibidis*) breeding success
Oahu Army Natural Resources Program, 26ha, Hawaii (Mosher et al. 2010)	Trapping	25m x 25m grid, Victor traps in tunnels, peanut butter bait, 12.5m spacing for perimeter traps. Checked daily for 1.5 weeks then fortnightly			Large-scale year-round management

Kahanahaiki, 26ha, Hawaii (Bogardus 2015)	Trapping	50m x 100m grid of Victor snap-traps			Prior to Goodnature® A24 installation
Kahanahaiki, 26ha, Hawaii (Bogardus 2015)	Self-resetting Traps	50m x 100m grid of Goodnature® A24 traps (25m x 100m in some places based on past rat snap catch data) Checked monthly			
Kahanahaiki, 26ha, Hawaii (Bogardus 2015)	Tracking Tunnels	38 tunnels across the site monitored one prior and monthly after management with a control site			Rat activity is higher with Goodnature® A24 than when victor traps were used
Ekahanui, 72ha, Hawaii (Bogardus 2015)	Trapping	25m x 25m grid with Victor traps, checked fortnightly			This was a trial comparing traps on the ground and up trees and covered and uncovered
Palikea, 9ha, Hawaii	Trapping	25m x 25m grid with			This was a trial comparing

(Bogardus 2015)		12.5m spacing around the edge. Used Victor snap-traps and Ka Mate Ltd traps, checked fortnightly			Victor and Ka Mate Ltd traps
East Makaleha, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Victor snap-traps (40) and Goodnature® A24 (20), checked 4-6 weeks			Two small grids
Ekahanui, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (620), checked every 2 weeks			Large-scale grid active from Dec-June
Ekahanui, Hawaii, (Bogardus 2015)	Trapping & Self-resetting Traps	Victor traps (47) and Goodnature® A24 (30) checked 4-6 weeks			Many small grids all year-round
Kahanahaiki, Hawaii (Bogardus 2015)	Predator-proof Fencing				Constructed 1998
Kahanahaiki, Hawaii	Self-resetting Traps	Goodnature® A24 traps (170), checked			Large-scale grid

(Bogardus 2015)		monthly			
Kamaohanai, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Ka Mate Ltd traps (47) and Goodnature® A24 (10), checked every 6 weeks			Small grid
Kapuna, Hawaii (Bogardus 2015)	Self-resetting Traps	Goodnature® A24 traps (4 and 5), checked every 6 weeks			Two small grids active seasonally
Koiahi, Hawaii (Bogardus 2015)	Self-resetting Traps	Goodnature® A24 traps (8), checked every 6 weeks			One small grid
Makaha Unit, Hawaii (Bogardus 2015)	Self-resetting Traps	Goodnature® A24 traps (110), checked monthly			Large-scale grid
Makaha Unit, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Victor snap-traps (24) and Goodnature® A24 (13), checked every 6 weeks			Two small grids, active seasonally for bird breeding

Makaha Unit, Hawaii (Bogardus 2015)	Self-resetting Traps	Goodnature® A24 traps (80), checked every 6 weeks			Large-scale grid
Manuwai, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Victor snap-traps (14), Ka Mate Ltd (11 and Goodnature® A24 (8), checked every 6 weeks			One small grid active seasonally for bird breeding
Moanalua, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (300), checked every 2 weeks			Many small grids, active seasonally for bird breeding
Ohikilolo, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Victor snaptraps (47) and Goodnature® A24 (53), checked every 6 weeks			Many small grids
Palihua, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (200), checked every 2 weeks			Many small grids, active seasonally for bird breeding
Palikea, Hawaii	Predator-proof				Constructed 2012

(Bogardus 2015)	Fencing				
Palikea-Mauna Kapu, Hawaii (Bogardus 2015)	Trapping	Victor snap- traps (15), checked every 6 weeks			
Palikea, Hawaii (Bogardus 2015)	Trapping	Ka Mate Ltd (250), checked every 2 weeks			Large-scale grid
SBW Haleauau, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (28), checked every 6 weeks			One small grid
SBW Haleauau, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Victor snap-traps (3) and Goodnature® A24 (3), checked every 6 weeks			One small grid, active seasonally for bird breeding
SBW Haleauau, Hawaii (Bogardus 2015)	Trapping & Self-resetting Traps	Victor snap-traps (450) checked fortnightly and Goodnature® A24 (50) checked monthly			Many small grids, active seasonally for bird breeding

W. Makaleha, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (28), checked every 6 weeks			One small grid
Waianae Kai, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (20), checked every 6 weeks			One small grid, active seasonally for bird breeding
Waieli-Hapapa, Hawaii (Bogardus 2015)	Trapping	Victor snap-traps (35), checked every 6 weeks			One small grid
Waieli-Hapapa, Hawaii (Bogardus 2015)	Predator-proof Fencing				Constructed 2011
Harts Hill, 200 ha, New Zealand, (DOC 2015a)	Self-resetting Traps	Goodnature® A24 traps, 100m x 50m grid. Checked monthly and lure and canisters changed every 6 months			
Harts Hill, 600ha, New Zealand	Self-resetting Traps	Goodnature® A24 traps 100m x 100m			

(DOC 2015b)		grid. Checked monthly and lure and canisters changed every 6 months			
Isles of Scilly, United Kingdom (Pender 2014)	Poisoning	Eradication using “Novacoil” drainage tubes with brodifacoum, bromadiolone and difenacoum			
Native Island, 62ha, New Zealand (Carter et al. 2016)	Self-resetting Traps	Goodnature® A24 100m x 50 grid, checked monthly. Canisters and lures replaced every 6 months. Peanut butter lure			
Native Island, 62ha, New Zealand (Carter et al. 2016)	Tracking Tunnels	5 lines of tracking tunnels 50m intervals either 5-10 tunnels long			Black Trakka™ cards

Sanctuary Mountain Maungatautari, New Zealand (Innes et al. 2011)	Tracking Tunnels	50m x 50m grid using Black Trakka™ tunnels and cards conducted monthly			A reinvasion experiment showed the tracking tunnels detected all of the rats introduced

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Appendix 4.2

Rat Management Techniques

4.2.1 Rat trapping

Equipment options

Little nipper rat trap – These traps are single kill traps which are baited with a peanut butter and oat mix placed on the plate, secured by a spike. The trap is triggered when a rat places weight onto the plate at which point the spring bar is released and the rat is killed with a lethal blow to the head or neck. The traps are either placed in a box for covered to prevent trapping non-target species and preventing the traps from being damaged or weathered. The traps are temperamental to set and in wet environments and can take a long time to set properly (it is easy to set them badly but will then fail to catch anything); this could have a large impact on labour costs on a large scale. There are also no safety mechanisms to prevent injury other than 'being careful'. These traps are cheap to purchase and have been used on the olive white-eye project for many years to provide some degree of rat protection to nests. However, due to the power of the blow the bar can become warped and gaps created; this can enable rats to become injured or escape. To avoid this traps require close maintenance and if used continuously regular replacement. These traps are not available in Mauritius and would need to be imported e.g. UK. A different brand of snap-trap design, Victor® traps, have been approved for use and deemed humane by the National Animal Welfare Advisory Committee (NAWAC) in New Zealand.

Figure A4.2.1 Little nipper rat trap

www.pest-stop.co.uk

DOC150 – These traps have been specially designed by the Department of Conservation (DOC) in New Zealand to replace older spring traps and meet humaneness standards based on emerging international standards. They trap small prey including rats, mice and hedgehogs. They work in a similar way to the little nipper traps with weight on the plate triggering the release of a spring bar which kills the rat

Figure A4.2.2 DOC 150 trap

www.cmisprings.com

by crushing its upper body. The trap bait isn't placed on the plate itself but positioned beyond the trap causing the rat to walk over the plate and springing the mechanism (the trap is within a box which prevents access to the bait any other way). The DOC traps (150, 200 and 250) have been approved for use in England to catch grey squirrels, rats, stoats and weasels (see Spring Trap Approval (Variation) (England) Order, 2007) and meet the guidelines as humane traps for stoats, rats and hedgehogs by the NAWAC in New Zealand. These standards prove the humaneness of the trap which should be a priority when planning large-scale rat management. The traps are made from stainless steel which ensures longevity and due to the reinforced spring and frame do not warp with use, requiring far less maintenance and much higher reliability. The traps are very strong, however, there is a setting tool available to enable the operator to set the trap without having direct contact and they have an easy to set mechanism which makes the process very quick and efficient.

DOC250 – These traps are exactly the same as the above description but are larger and designed for catching bigger prey such as the weasels and ferrets. If a multi-species approach is taken within the mainland island small Indian mongoose (*Herpestes javanicus*) would also require trapping, these traps would be better equipped for targeting this prey. Mongooses are a similar size and weight to ferrets and so it can be assumed that these traps would be effective at trapping them.

Figure A4.2.3 DOC 250 trap
www.cmisprings.com

Timms trap – These traps target feral cats and possums and meet the guidelines set by the NAWAC in New Zealand under the Animal Welfare Act 1999. These traps are baited with meat skewered on a spike within the trap. Moving this spike triggers a spring and like the traps above the spring mechanism will kill the cat with a lethal blow to the head or neck. The access hole for these traps is large to enable access for cats so they would be raised above the ground and a cover potentially added to prevent non-target species entering. It is easy to set and doesn't

Figure A4.2.4 Timms trap
www.landcareresearch.co.nz

require any contact with the trap; it is set by pulling a cord on the back.

Figure A4.2.5 Treadle Live Trap

www.livetrap.com

Treadle live trap – These traps cause no injury to the cat and enable its removal for humane euthanasia. This method can be the preferred management option if there are domestic cats in the area or there is pubic objection to kill trapping. The traps can be placed on the ground and are triggered by a treadle mechanism which shuts the door when the cat puts presser on the plate. There is a handle of the top which enables easy transport. Stainless steel traps could be used to increase longevity and they would be covered to protect the cat and trap from weather conditions.

Proposed rat management method

Scale - Results from six major mainland sites in New Zealand found that traps need to be set at 25-50m x 75-100m grids over the operational area to achieve results similar to brodifacoum and the DOC current best practice guidelines advice spacing traps no greater than 100 x 50m apart with perimeter traps as 25m spacing's (Gillies 2002; DOC 2005). Within the literature the scale of trapping grids varies between both temperate and tropical climates and small and large-scale management (Appendix 4.1). Although 25m x 25-50m grids have been used in Hawaii these have been over relatively small management areas of 2.4 – 100ha. On a large-scale this high density of traps may be unnecessary. Most examples of rat trapping use either a 50m x 50m or 100m x 100m grid over 1400ha and 6000ha respectively; although these examples are in New Zealand these illustrate the labour feasibility. The DOC best practice guidelines state that there should be at least one trap in each rat home range, in Mauritius rat home range length is 55m, in New Zealand ship rat home range length is between 100-200m (Hall 2003; DOC 2005). This illustrates that the density of rats within Mauritius is potentially higher than temperate regions and therefore smaller trap intervals are required, this has also been suggested by experts (Grant Harper, BRS Biodiversity Restoration Specialist, *pers comm*).

Based on the literature and rat densities within Mauritius a 50m x 50m grid will be established with perimeter traps at 25m spacing's. The traps will be checked daily for the first two weeks after which, ensuring rat trapping rates have decreased, they will be checked fortnightly; this method is based on the examples in Hawaii (Appendix 4.1).

Figure A4.2.6 DOC trap in box

www.landcareresearch.co.nz

Equipment - Although many projects use Victor ® traps to manage rats we shall use the DOC150 stainless steel traps as they are the most humane, durable and safe equipment available for large-scale rat trapping. Under the guidelines and to ensure that non-target species are not targeted DOC traps have to be placed within specially built boxes. These would be built within Mauritius to the specification available from DOC using local materials (Figure A4.2.6). The entrance holes will be kept small to ensure mongoose and non-target species can't access. The traps will be baited with a peanut butter and oat mix during the initial 'knock out' phase after which alternative, longer lasting, baits shall be used e.g. hen eggs.

Proposed multi-species management method

The DOC150 traps would still be implemented across the mainland island on a the same scale, however, DOC250 traps would also be placed across the grid at a much lower density to target small Indian mongoose (all within boxes). Mongoose home-ranges in Mauritius are much larger than rats at 0.25-1.1km^2 and so fewer traps would need to be distributed, however, they are not territorial and so can achieve densities of 50 animals/km^2 (Roy et al. 2002). The mongoose have a home-range length of 500m and so DOC250 traps will be placed on the grid replacing the DOC150 traps on a 200m x 200m grid. This will ensure a high trap density to target the potentially high mongoose density. The DOC250 traps will have larger entrance holes to allow mongoose access; rats can still be caught in DOC250 traps and so this would not impact trap density for rats. DOC250 traps will be baited with hen eggs or rat carcases trapped within the grid.

Feral cats are also a threat to endemic Mauritian species, however, cats within the Combo region are extremely rare and so targeted trapping would be used. Treadle live cat traps will be used and placed around the border of the mainland island at 200m spacing's set for one night every fortnight baited with meat (Rabbit or chicken skin) or fish (salted) depending on availability. Traps would be covered to protect both the trap and the cat from rain and sun, blocking the back to prevent pawing. All cats caught will be transported in the traps for humane euthanasia. Timms traps would not be used as the risk of trapping non-target species could be high due to the open entrance and installing it above the ground where birds may perch and investigate. Cats can also be caught in DOC250 traps, providing additional protection across the whole management area. Both mongoose and cat trap densities are based on trapping grids used in New Zealand for stoats and feral cats but also mongoose behaviour within Mauritius (Roy et al. 2002; Appendix 4.1).

4.2.2 Ground-based rat poisoning

Equipment options

Philproof © - Many large-scale rat management projects use Philproof © stations. They are made completely from recycled plastic and are therefore extremely durable and light weight. The bait tray (not in place in the photo) can be easily removed and the bait changed. There are two types of tray available, one which can hold loose granular bait and one with spikes which can secure poison blocks within the station; preventing rats removing and hoarding bait. They are secured to trees or posts and keep the bait dry. They are manufactured in New Zealand and would have to be imported to Mauritius.

Figure A.4.2.7 Philproof © poison station

Bait Box – These bait boxes are commercially manufactured and available in most countries. The poison is placed within the waterproof box and can be either granular or fixed blocks. The boxes are secured at ground level to trees or posts and attract rats due to the dark, dry environment. The bait boxes are used at some mainland island sites but where poisoning is at a low density and in place as a precautionary tool i.e. within a predator-proof fence.

Figure A4.2.8 Rat bait box

Drainage tubes – This method is a widely used across large-scale rat management areas due to its durability,

Figure A4.2.9 ‘Novacoil’ drainage tube light weight and low cost. The ‘novacoil’ drainage tube is widely available and merely requires slight modification for use as a station. The tube is secured into place nailed on a raised wooden/compressed plastic block, approximately 20cm above the ground. This nail is then used to place the poison blocks onto within the tube. This is accessed by cutting a hole above the nail and covering it with a slightly larger piece of tube to create an access door; this is secured into place with wire. These stations provide a dark, dry environment which attract rats and prevent poison hoarding my fixing the blocks in place.

Hockey stick – The post or tree-mounted ‘hockey stick’ design is made using plastic gutter piping available commercially. The design fixes the poison within the entrance hole positioned approximately 20cm above the ground. Numerous blocks can be placed within the pipe, accessed from the top, which means bait is continuously available and rats cannot hoard it. This design keeps the poison dry and research in Mauritius has found this design to be more efficient than ground piping with loose poison; raising it above the ground also deterred snails (Tatayah et al. 2007).

Figure A4.2.10 Hockey stick bait station Tatayah et al. (2007)

Proposed rat management method

Scale - Based on rat management using poison grids from throughout the world, in both tropic and temperate regions, a 50m x 50m grid would be used. This scale has been used to protect passerine species in Seychelles, Galapagos, the Cook Islands and New Zealand (Appendix 4.1). The stations will be checked fortnightly however this frequency could be adapted depending on bait consumption (Appendix 4.1).

Equipment - Ground based drainage tubes will be used as bait stations as they are one of the most commonly used, effective and low cost techniques. The drainage piping, along with addition equipment to modify the piping, will be available within Mauritius avoiding importation time and costs; this means any replacements can be made quickly and easily. Although research in Mauritius identified the hockey stick design as the most efficient method the equipment for this design is expensive. It is suggested to follow the results and fix the poison within the drainage tubes which should prevent poison hoarding by rats and a similar efficiency (Tatayah et al. 2007; Mosher et al.

2010). Diphacinone poison shall be used due to its low secondary-impacts and bioaccumulation (Eason & Ogilvie 2009).

Proposed multi-species management method

The poison gird will still be established across the mainland island at the same scale; however, additional DOC250 and live cat traps will also be established at the same scale described for the proposed multi-species trapping management method to also target small Indian mongoose and feral cats. These will also be checked fortnightly along with the bait stations.

4.2.3 Self-resetting traps

Equipment options

Goodnature® A24 – The self-resetting trap has been designed to humanely kill rodents without any secondary impacts and reducing labour costs. They meet the New Zealand NAWAC guideline and are supported by the Department of Conservation (Jansen 2011; Ross 2015). The trap is powered by a CO^2 canister which activates a piston killing the rat instantly when it brushes against a trigger when attracted to a lure within the trap. The striker returns on a spring and resets itself and the auto lure pump keeps the lure fresh to attract multiple rats with minimal maintenance. They have the potential of reducing labour costs as the self-resetting mechanism and auto lure pump reduce trap checks to every 6 months depending on rat densities. The gas canisters can kill up to 24 rats before the canister runs out. These traps are being used in more than 15 countries including New Zealand, Hawaii, the Caribbean and the UK (Goodnature 2014).

Figure A4.2.11 Goodnature® A24 self-resetting trap www.goodnature.co.nz

Proposed rat management method

Scale and equipment - A 100m x 50m grid will be established with the Goodnature® A24 traps. This scale is based on projects which have already implemented the technique over a small and large-scale and in temperate and tropical regions and have found it effective at reducing and maintaining rat tracking indices (using present/absent tracking tunnels) to undetectable levels (0%) within 3-5 months (Goodnature 2014; DOC 2015). The A24 traps have also proven effective at reducing rat indices to undetectable levels over a 100m x 100m grid in New Zealand, however, we will use a higher trap density based on projects in tropical regions and DOC best practice for trapping (DOC 2005; Franklin 2013). The A24 traps will be mounted to trees 20cm above the ground and baited with the new auto pump lure. These lures have been developed to attract rats for up to 6 months and remain stable in tropical and temperate conditions (Goodnature 2015). The traps will be checked on a monthly basis to refresh the lure and check the CO_2 canisters initially and reduced to 6 monthly checks when rat densities decrease. The canisters and lures will be replaced every 6 months, if the canisters aren't changed before this, following Goodnature guidelines.

Proposed multi-species management method

Goodnature® A24 traps have been used effectively to control rats and protect various species and taxa including birds, lizards, turtles and plants. They have also been used to target and control other invasive species besides rats, these include stoats in New Zealand, mongoose in Hawaii, mink in Finland and grey squirrels in the UK (Goodnature 2014). Based on this the A24 traps will also be used to target mongoose across the grid. The traps would remain in place but a different lure will be used. The 'black magic' lure available for stoats contains dehydrated animal extracts suspended in protein paste which could also work for mongoose based on their carnivorous diet. These lures will be placed within the traps on a 200m x 200m grid. To target feral cats live traps will be established as with the proposed multi-species trapping management with 200m spacing's around the border of the mainland island, however, traps would be set and checked for one night monthly to match the A24 trapping frequency.

4.2.4 Predator-proof fencing

Equipment options

Xcluder® - Predator-proof fences have been successfully developed in New Zealand to create predator-free areas and protect threatened species. All fences have the same basic design with mesh fencing, an underground skirt (to prevent burrowing) and a curved hood (to prevent climbing). Xcluder® are the main company who build the fences and have done so throughout the world, having conducted a trial in Mauritius in 2005 (Tatayah et al. 2005). Fences are extremely effective when maintained and require less labour once built, however, they are vulnerable to reinvasions and therefore surveillance and maintenance is paramount and continuous.

Figure A4.2.12 Maungatautari Mountain Sanctuary Xcluder™ predator-proof fence

Proposed rat management method

Scale - The predator-proof fence would be erected around the border of the mainland island area. The fence would involve major construction work conducted by Xcluder® and local contractors. Once the fence was complete the initial eradication of rats would be conducted following the proposed rat management using a 50m x 50m grid checked weekly. A predator-proof fence is a multi-species technique and therefore mongoose and feral cats would also be targeted and would hopefully be eradicated through secondary poisoning from consuming poisoned rats (Alterio et al. 1997; Gillies & Pierce 1999; Murphy et al. 1999). If any remain then additional trapping would be conducted with mongoose trapping on a 200 x 200m grid and cat trapping at 200m spacing's around the perimeter, checked weekly, until all were removed; this would be decided through tracking tunnel indices. The fence would be checked weekly for any breaches in any of the material e.g. holes in the mesh, rust holes on the hood etc. Within the fence permanent trapping and poisoning would be in place along the inner fence line with 50m spacing's for rat poisoning, 100m spacing's for mongoose trapping and 200m spacing's for cat traps, these would be checked (cat traps set the day before) monthly. The 50m x 50m poison grid and 200 x 200m trapping grid established across the area, for the initial eradication, would remain in place encase the fence was compromised in which case the grid can be activated to remove any invaders.

Equipment –

Fence - The fence would be built by Xcluder® with Mauritian contactors hired and trained where available. The fence would incorporate the following features –

- All wood would be treated; sourced in Mauritius
- Stainless steel woven mesh (also being installed at Zealandia as it is flexible in hot and cold temperatures and doesn't degrade as easily compared to galvanised fence mesh); imported
- Underground skirting to prevent mammals burrowing into the mainland island
- Rolled hood with aluminium rivets; sourced in Mauritius
- All welding welts on the hood will be zinc blasted to prevent corrosion; a technique used by electrical companies so sourced in Mauritius
- Hot wire along the top of the fence powered by solar panels to detect any breaches as the fence wouldn't be walked daily; imported but some parts may be available within Mauritius
- Manual pedestrian gates
- Electric vehicle gates
- Gate alarms encase they remain open
- Culverts for small water outlets
- Self-cleaning culverts for small water inlets
- Water gates for large outlets with alarms fitted encase jammed open

Initial eradication - The initial eradication would use drainage tubes, as described in the proposed rat poison management, with brodifacoum poison; brodifacoum poison would be acceptable due to the short-term, singular use. If mongoose and feral cats remained present DOC250 would be placed across the site at 200m x 200m grid live cat traps at and 200m spacing's along the inner fence line.

Monitoring - Drainage tube poison bait stations would be placed around the inner perimeter of the fence containing brodifacoum (there will be no rats within the fence to consume the poison and therefore secondary poisoning would not be a problem), DOC250 traps will be used for mongoose trapping and live cat traps.

Proposed multi-species management method

The establishment of a fence would exclude all mammalian predators and therefore the methods are the same as above.

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Appendix 4.3

Expert Online Questionnaire

Created in SurveyMonkey ® and approved by the Zoological Society of London Ethics Committee on the 03/05/2016

Mainland Islands - *The effectiveness of rat management*

WELCOME

I would like to invite you to participate in this online questionnaire as part of my PhD research at the Institute of Zoology, Zoological Society of London and University College London.

This questionnaire is part of a wider study within my PhD which aims to create a decision-making framework for identifying the area required to establish a mainland island in Mauritius and the most cost-effective management technique to implement in regards to population extinction risk; specifically the extinction risk of the critically endangered Mauritius olive white-eye (Zosterops chloronothos).

You have been selected to complete this questionnaire based on your expert experience and knowledge into the management of invasive rat species, in particular, large-scale management in the form of mainland islands. You are one of 20 experts who have been requested to participate in this questionnaire from numerous international organisations.

The aim of this questionnaire is to gain expert opinion into the effectiveness of five large-scale rat management techniques which are being considered for a mainland island in Mauritius -

1) Rat trapping

2) Ground-based rat poisoning

3) Ground-based rat poisoning plus rat trapping

4) Self-resetting traps

5) Predator-proof fencing

My previous research has identified the impact of no rat management, snap trapping alone and snap trapping plus ground-based poisoning on olive white-eye productivity; however, due to time and financial limitations I cannot conduct field trials for poisoning alone, self-resetting traps and predator proof fencing. Instead, using expert opinion, I hope to generate an effectiveness score for each rat management technique based on their effectiveness to achieve <10% rat tracking tunnel indices throughout the year; due to the variation in the breeding season start and finish dates management will be implemented throughout the year, rather than during sensitive periods, to ensure continuous protection. This effectiveness score can then be combined with the existing olive white-eye productivity data to predict annual productivity under poisoning alone, self-resetting traps and predator proof fencing.

The predicted olive white-eye annual productivity values under all five rat management techniques will then be used, within a population viability analysis, to explore the extinction risk of the olive white-eye population under a range of rat management scenarios over various mainland island areas. Separate analyses shall be conducted for the different rat management techniques modifying the olive white-eye productivity accordingly. Combining the results of these analyses with the cost of management I can create a decision-making framework which can allow the project managers to identifying the optimal mainland island area and the most cost-effective rat management technique.

Your participation in this questionnaire is completely voluntary and anonymous, unless you choose to be acknowledged, and you can discontinue participation at any point. This questionnaire has been approved by the Zoological Society of London Ethics Committee and all data will be collected and stored in accordance with the Data Protection Act 1998. Data will be retained for the duration of the research on a secured drive and accessed by myself only as the principal researcher.

The questionnaire will take approximately 20 minutes to complete.

Thank you for considering participating in this questionnaire the results of which will contribute to my research, invasive species management and ultimately the protection of the Mauritius olive white-eye.

If you have any questions arising from the information above please contact me before you to decide whether to participate by emailing Gwen.Maggs@ioz.ac.uk

* Having read the information provided above, do you agree to participate in the questionnaire?

○ Yes

○ No

* Would you like to be acknowledged for your participation in this questionnaire?

○ Yes

○ No

If you choose to be acknowledged please provide your name and organisation

Name:

Organisation:

Research collaborators –

Mainland Islands - *The effectiveness of rat management*

Background Information

Invasive species are a major threat to island biodiversity, causing species decline and extinction globally. The Indian Ocean island of Mauritius is no exception with invasive rats contributing to the extinction of 50% of the endemic species and still posing a threat to the endemic passerines, including the critically endangered Mauritius olive white-eye (Figure A4.3.1)

The Mauritius olive white-eye has experienced a continuous population decline and habitat restriction to an estimated 80 pairs across a 25km2 area in the Black River Gorges National Park. Threats to the species are thought to include habitat destruction and degradation and competition with introduced bird species but primarily nest predation by invasive rats.

My research has identified rats as a major threat to olive white-eye productivity, however, territory based rat management can mitigate this threat and prevent further population decline by increasing annual productivity (Maggs, et.al., 2015). These findings highlight rat control as a viable management option for the olive white-eye and provide evidence for perusing large-scale, long-term management in the form of a mainland island. However, the challenge now is to identify the optimal rat management solution.

My current research, working with in-situ partners, aims to identify the most cost-effective long-term solution for controlling rats across the white-eyes range on mainland Mauritius. This will be achieved by combining your expert opinion with stakeholder workshops and scientific research into population viability and cost-effectiveness analysis. This approach will create a decision-making framework which can enable the effective allocation of finite conservation resources, build the capacity of the in-situ NGO and ensure the long-term survival of the olive white-eye.

Study Site - The chosen study site is the Combo region in the Black River Gorges National Park where the highest density of olive white-eye breeding pairs remain at 25 – 30 pairs (Figure A4.3.2). Combo has a degraded, riparian habitat with an average canopy height of 10m with small open grassland fragments (Figure A4.3.3). This peninsula of the National Park is surrounded by agricultural land producing sugar cane and private lands for deer hunting; which contain large grasslands and forest (Figure A4.3.2). There is clear seasonality within the area with a cool/dry season between March and August and a warm/wet season between September and February.

Study Species – The Mauritius olive white-eye is the rarest of the nine remaining land bird species of Mauritius and are in the top 10% of the EDGE bird species list. They are part of an ancient white-eye lineage having evolved from Asia prior to the African species. They are a monogamous, multi-brooded species breeding in austral summer between August and March defending territories of approximately 0.5 ha in size. The male and female participate equally in all of the nesting stages, building small open cup nests within the upper canopy on small outer branches; females lay 1-3 eggs. Nestling predation by invasive rats is a major threat to the species, however, rats do not predate on adult birds.

Figure A4.3.1 Mauritius olive white-eye pair mutually preening

Rat Behaviour - Both ship and brown rats (*Rattus rattus* and *Rattus norvegicus*) are present in Mauritius and will both be targeted by mainland island rat management. A long-term study of rats in Mauritius found that rat management through poisoning can remove resident rat populations but the areas are subsequently re-colonised from the surrounding rat home-ranges. In Mauritius rat home-ranges vary between 0.3 – 0.4 ha (55 - 63m home-range length), there is no significant difference between males and females, and their size is not found to change in response to poisoning. There are annual fluctuations in rat densities with high levels of rat abundance between September and December. This may be due to natural annual fluctuations in response to rat breeding cycles or environmental factors. Additionally rat densities could increase due to agricultural activities with rats dispersing into the National Park when the surrounding sugar cane fields are harvested between June and December.

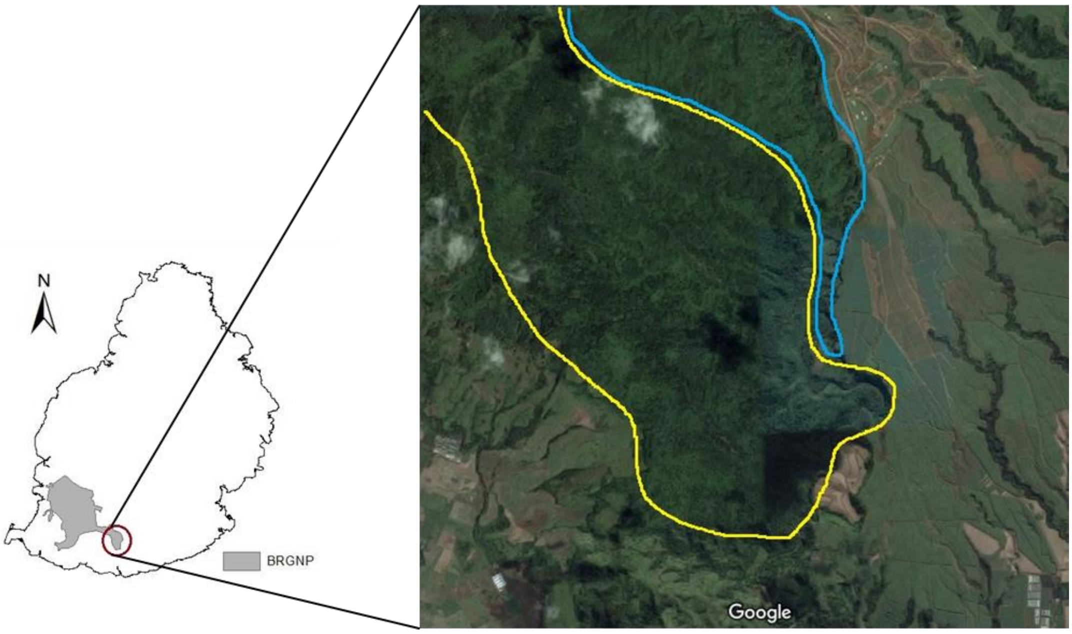

Figure A4.3.2 The Combo region of the Black River Gorges National Park (BRGNP; yellow area), private lands for deer hunting (blue area) and surrounding area of agricultural land (sugar cane)

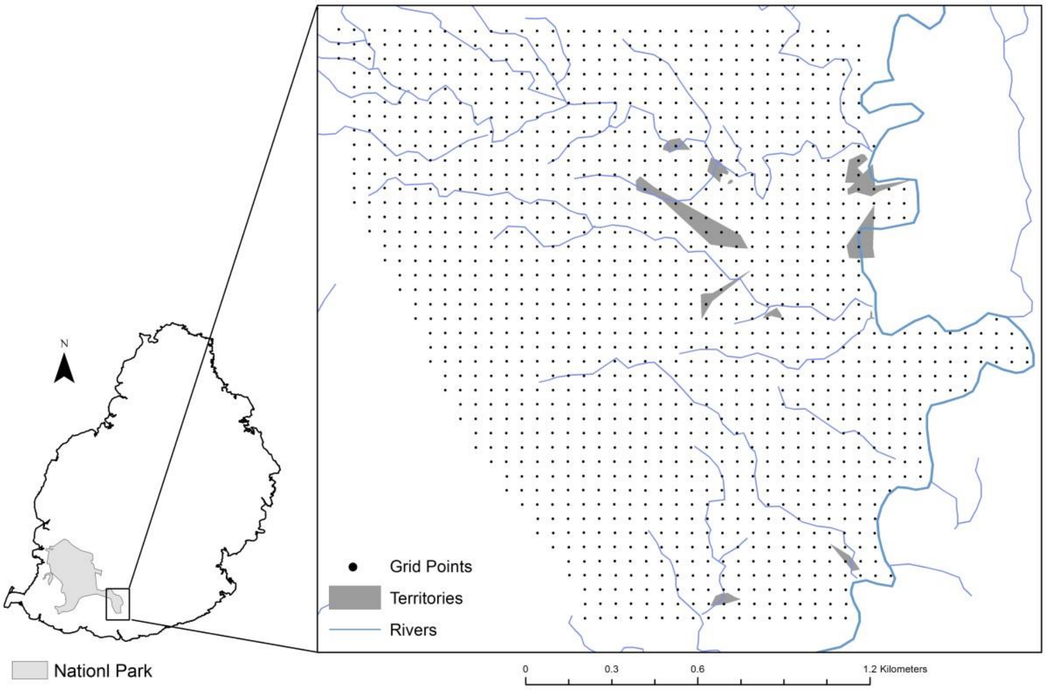

Figure A4.3.3 Schematic representation of a 50m x 50m grid mainland island over the Combo region of the Black River Gorges Nation Park in relation to olive white-eye breeding territories and river systems

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Example Question

The questions here are designed using the 4-step interval elicitation procedure. This involves asking four main questions -

1. Rate the **highest likelihood** that the management will achieve the target of <10% rat tracking indices

2. Rate the **lowest likelihood** that the management will achieve the target of <10% rat tracking indices

3. Rate the **best guess** of the likelihood that this method will achieve the target of <10% rat tracking indices

4. Rate **how confident** you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

5. Provide any feedback on the proposed management technique

These questions enable you to rate your best guess, that the management will achieve <10% rat tracking indices, with confidence intervals and a confidence rating in your prediction (Figure A4.3.4)

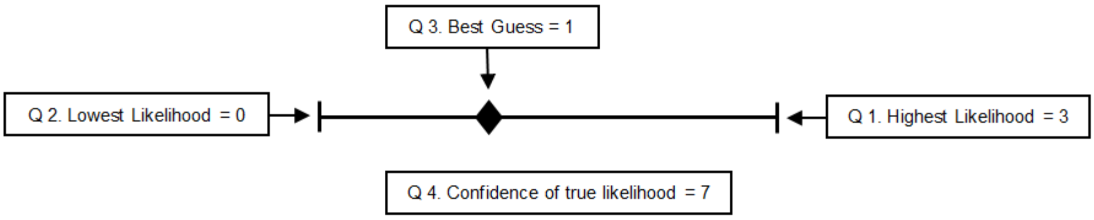
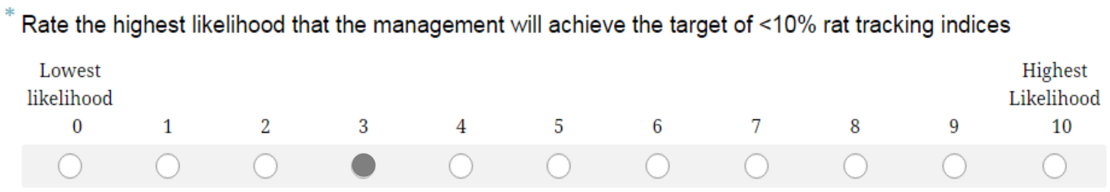


Figure A4.3.4 Speirs-Bridge et.al. (2010) *Risk Analysis* - Values correspond to the example answers below

Example Management -

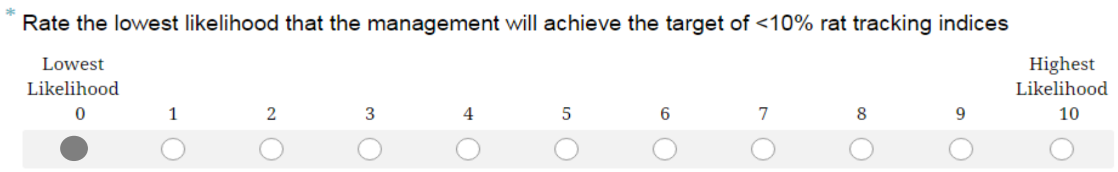
The example management will be using rat trapping over a 25m x 25m grid using Victor snap-traps baited with a peanut butter and oat mix and checked and re-set for 3 consecutive nights once a month



* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

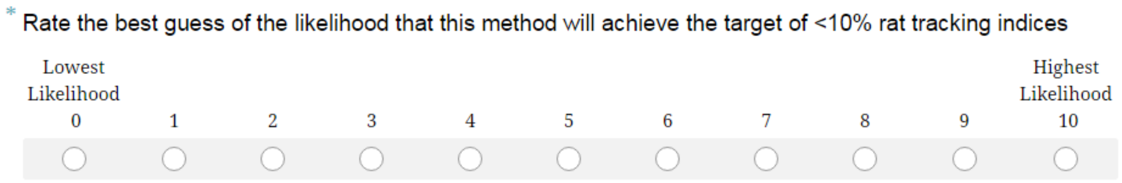
Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○

"I have rated the highest likelihood as 3, this means that I think that there is a 30% maximum chance that the management will achieve a <10% rat tracking index"


* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

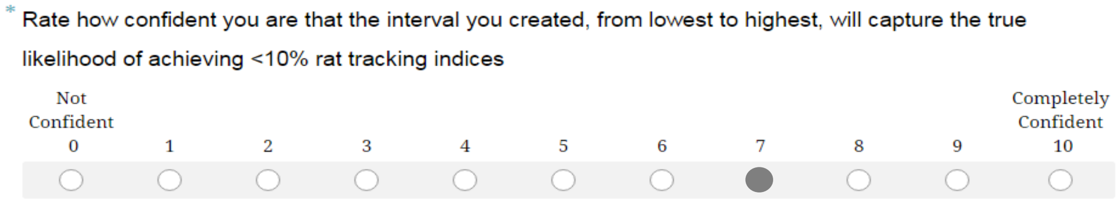
Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
●	○	○	○	○	○	○	○	○	○	○

"I have rated the lowest likelihood as 0, this means that I think that there is a 0% minimum chance that the management will achieve a <10% rat tracking index"


* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	○	○	○	○	○	○	○	○

"I have rated my best guess as 1. This means that I think that there is, most likely, a 10% chance that the management will achieve a <10% rat tracking index"


* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident 0	1	2	3	4	5	6	7	8	9	Completely Confident 10
○	○	○	○	○	○	○	●	○	○	○

“I have rated my confidence that the interval I have created, from lowest to highest, will capture the true value, as 7. This means I think there is a 70% chance that the true likelihood of the management achieving a <10% rat tracking index will sit between these values; in my case between 0 and 30%"

Please provide any comments on the management technique described above

(optional) –

"This final question allows participants to voice their opinion on the management technique proposed and whether there are any alterations or improvements which could be made based on their knowledge and experience"

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Mainland Islands - *The effectiveness of rat management*

Rat Management Techniques

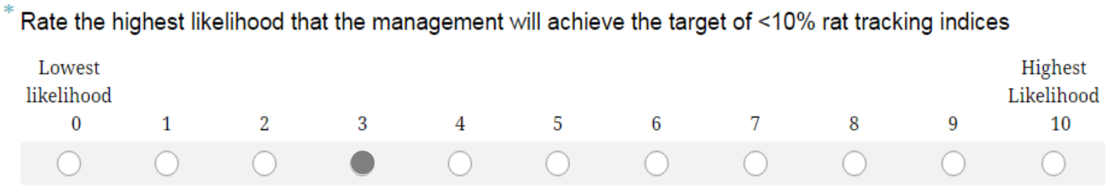
1. Rat Trapping

Scale: 50m x 50m grid with perimeter traps at 25m spacing's

Equipment: DOC 150 Traps

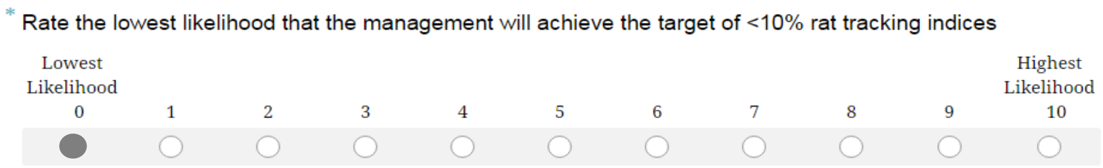
DOC 150 traps will be used based on their humane and durable design, they will be placed in boxes built to the specifications of the Department of Conservation to protect non-target species and prevent mis-sprung traps. The traps will be checked daily and baited with peanut butter and oat mix for the first two weeks after which, ensuring rat catch per unit effort has decreased, they will be checked fortnightly and baited with longer lasting baits e.g. chocolate or hen eggs.

Figure A4.3.5 Doc series trapping systems Doc 150



* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○



* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
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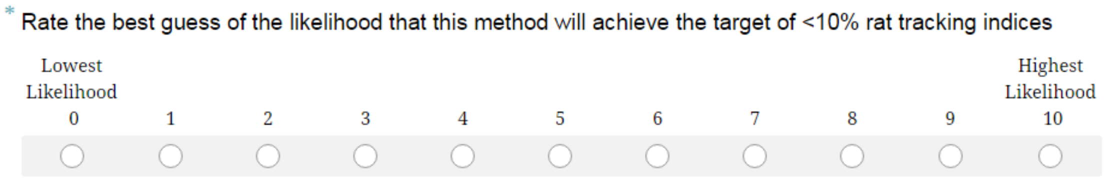
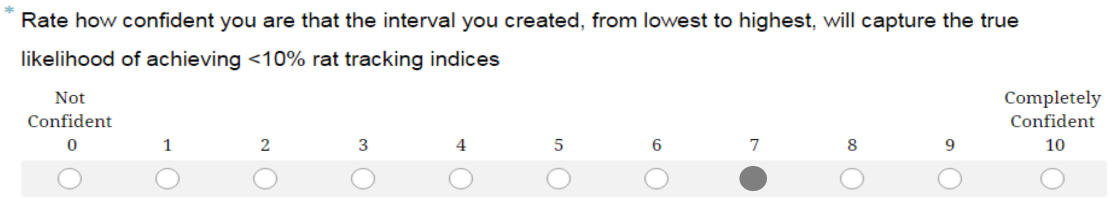


* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	○	○	○	○	○	○	○	○



* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident 0	1	2	3	4	5	6	7	8	9	Completely Confident 10
○	○	○	○	○	○	○	●	○	○	○

Please provide any comments on the management technique described above

(optional) –

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Mainland Islands - *The effectiveness of rat management*

Rat management techniques

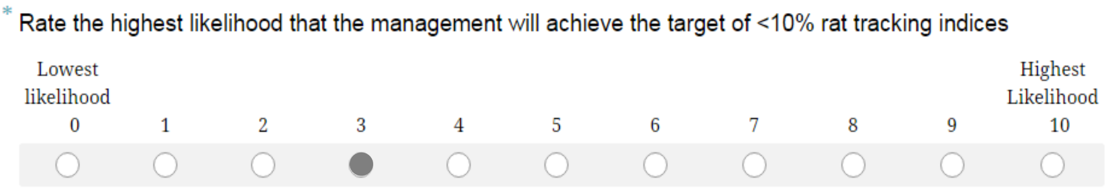
2. Rat Trapping continued

Scale: 50m x 50m grid

Equipment: Little Nipper snap-traps

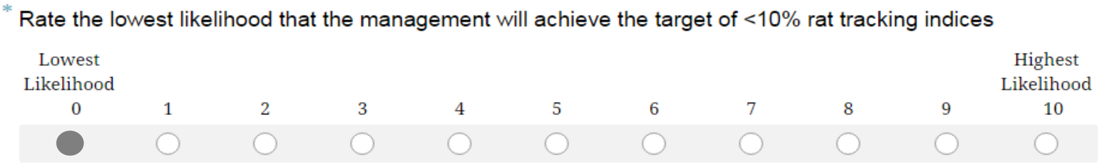
As an alternative rat trapping method Little Nipper rat snap-traps could be used. All traps will be placed in specially built wooden boxes to protect non-target species and prevent mis-sprung traps. The traps will set and checked for 3 consecutive nights every 2 months baited with peanut butter and oat mix.

Figure A4.3.6 Rat snap-trap in specially built box at Rotoiti Nature Recovery Project (left) and a Little Nipper rat snap-trap (right; www.pest-stop.co.uk)



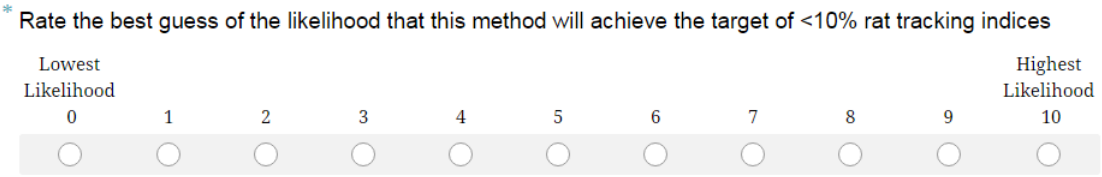
* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○



* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
●	○	○	○	○	○	○	○	○	○	○



* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
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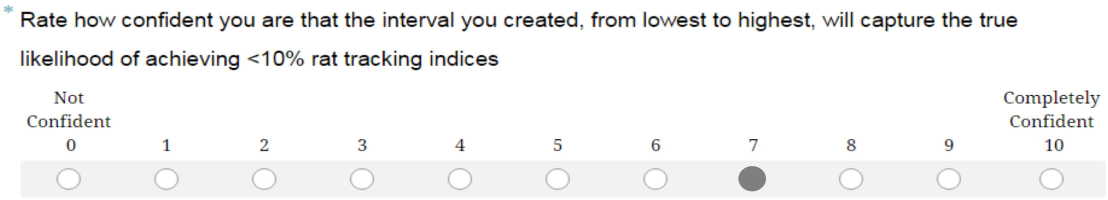

* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident 0	1	2	3	4	5	6	7	8	9	Completely Confident 10
○	○	○	○	○	○	○	●	○	○	○

Please provide any comments on the management technique described above

(optional) –

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Rat Management Techniques

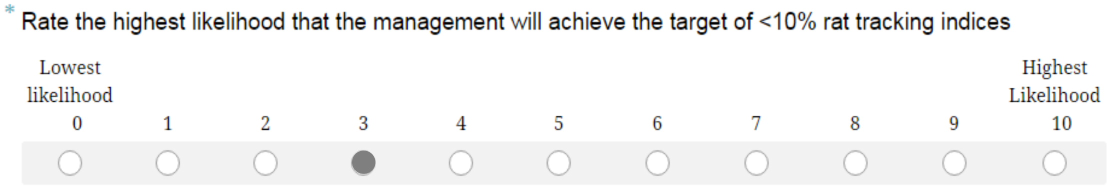
3. Ground-based Poisoning

Scale: 50m x 50m grid

Equipment: Ground-based plastic drainage tubes

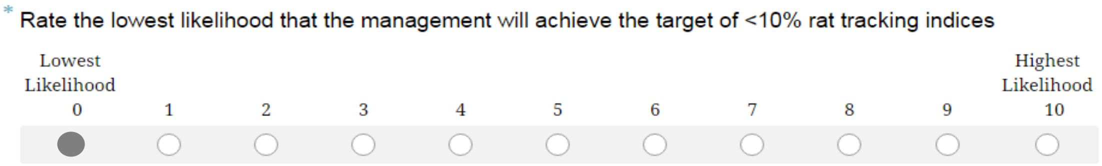
Plastic drainage tubes will be used as bait stations, based on their durability and low cost, with poison fixed within the stations to prevent hoarding by rats. The stations will be checked fortnightly however this frequency could be adapted depending on bait consumption. The type of poison used will vary every 1-2 years to avoid rats becoming immune to the bait and first-generation anticoagulants shall be used to avoid secondary poisoning e.g. Pindone and Diphacinone.

Figure A4.3.7 Preparing plastic drainage tube bait stations, Department of Conservation (left; www.teara.govt.nz), and checking rat poison within a drainage tube bait station, Isles of Scilly seabird recovery project (right; www.ios-seabirds.org.uk)



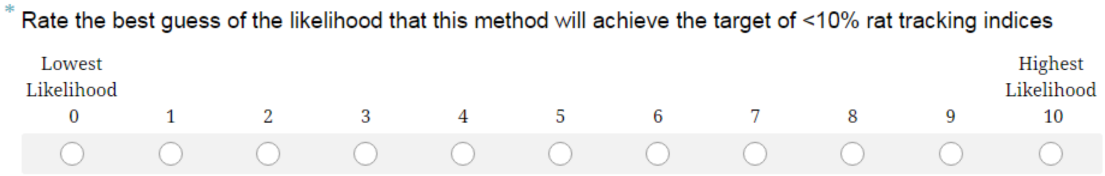
* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○



* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
●	○	○	○	○	○	○	○	○	○	○



* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
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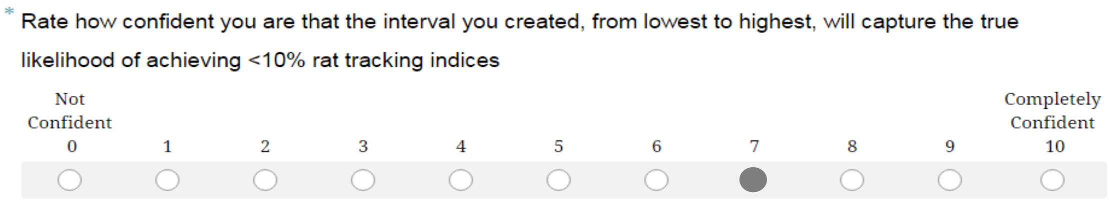


* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident 0	1	2	3	4	5	6	7	8	9	Completely Confident 10
○	○	○	○	○	○	○	●	○	○	○

Please provide any comments on the management technique described above

(optional) –

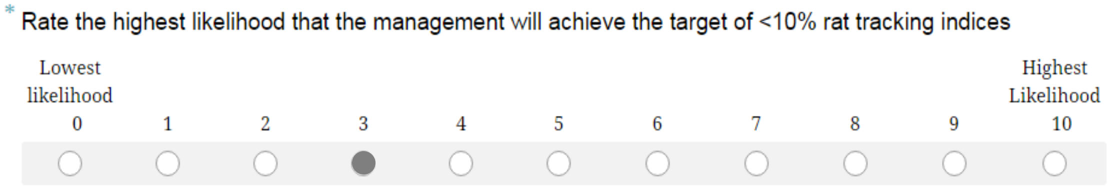
Rat Management Techniques

4. Ground-based Poisoning & Rat Trapping

Scale: 25m x 25m grid

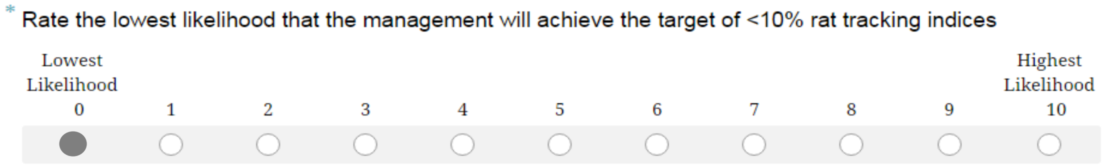
Equipment: Plastic drainage tubes will be used as poison bait stations, based on their durability and low cost, with poison fixed within the stations to prevent hoarding by rats. Rat snap-trapping will also be conducted using Little Nipper rat snap-traps placed within specially built boxes to protect non-target species and prevent mis-sprung traps. Bait stations and snap-traps will be placed at alternative points on the 25m x 25m grid resulting in poison tubes and snap-traps at 50m intervals. The type of poison used will vary to avoid rats becoming immune to the bait and first-generation anticoagulants shall be used to avoid secondary poisoning e.g. Pindone and Diphacinone. Bait stations will be checked fortnightly however this frequency could be adapted depending on bait consumption. Snap traps will be set for three nights very two months baited with a peanut butter and oat mix.

Figure A4.3.8 Checking rat poison within drainage tube bait station, Isles of Scilly seabird recovery project (left; www.ios-seabirds.org.uk), rat snap-trap in specially built box, Rotoiti Nature Recovery Project (middle) and Little Nipper rat snap-trap (right; www.pest-stop.co.uk)



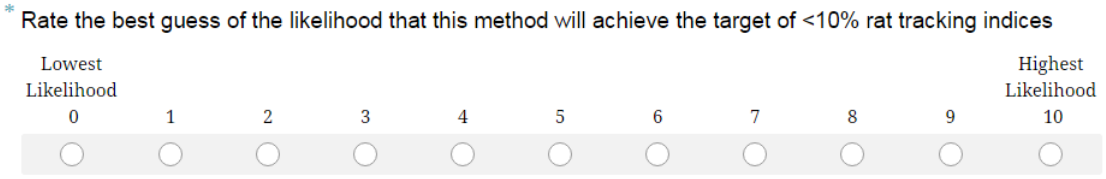
* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○



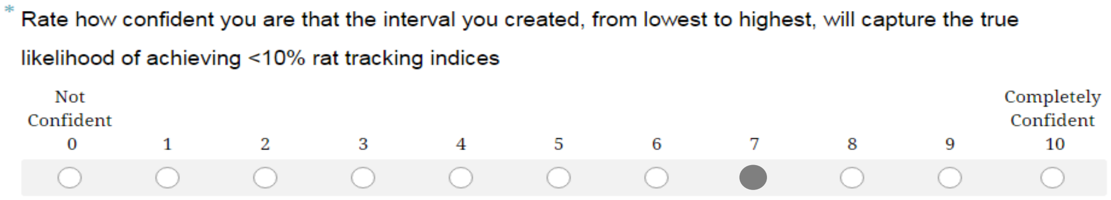
* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
●	○	○	○	○	○	○	○	○	○	○



* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	○	○	○	○	○	○	○	○



* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident 0	1	2	3	4	5	6	7	8	9	Completely Confident 10
○	○	○	○	○	○	○	●	○	○	○

Please provide any comments on the management technique described above

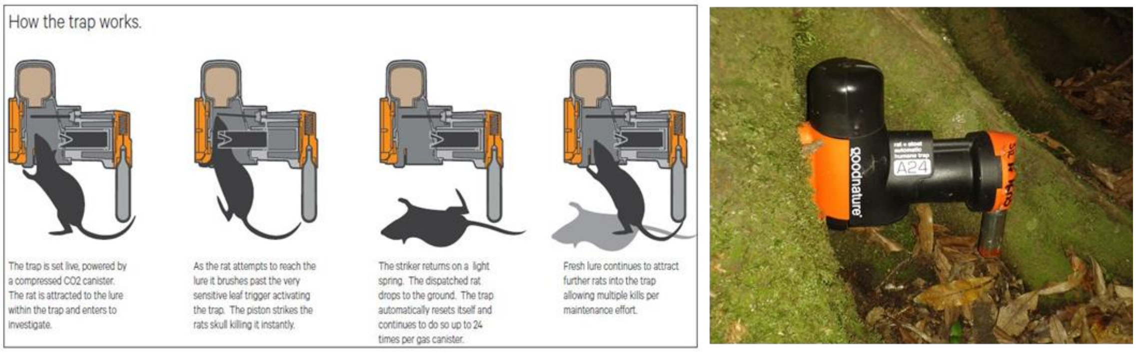
(optional) –

Rat Management Techniques

5. Self-resetting Traps

Scale: 50m x 100m grid

Equipment: Goodnature® A24 traps will be used, as the leading design in rat self-resetting traps. The traps will be installed in accordance with the manufacturer's specifications, mounted to trees 20cm above the ground, and baited with the chocolate long-life lure. These lures have been developed to attract rats continuously over 6 months and remain stable in tropical conditions. The traps will be checked on a monthly basis to refresh the lure and check the CO^2 canisters; however this frequency could be adapted depending on kill frequencies. The canisters and lures will be replaced every 6 months, if they haven't been changed before this time, following Goodnature ® guidelines.


How the trap works.

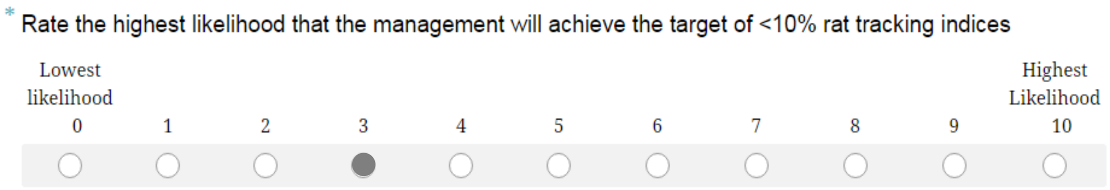
The trap is set live, powered by a compressed CO2 canister. The rat is attracted to the lure within the trap and enters to investigate.

As the rat attempts to reach the lure it brushes past the very sensitive leaf trigger activating the trap. The piston strikes the rats skull killing it instantly.

The striker returns on a light spring. The dispatched rat drops to the ground. The trap automatically resets itself and continues to do so up to 24 times per gas canister.

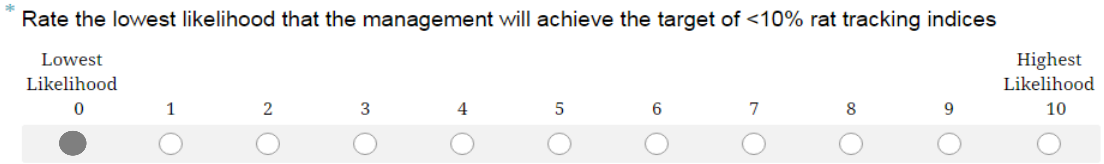
Fresh lure continues to attract further rats into the trap allowing multiple kills per maintenance effort.

Figure A4.3.9 Goodnature ® A24 self-resetting trap "how the trap works" (left; www.goodnature.co.nz) and an A24 trap in Boundary Stream Mainland Island, Department of Conservation (right)



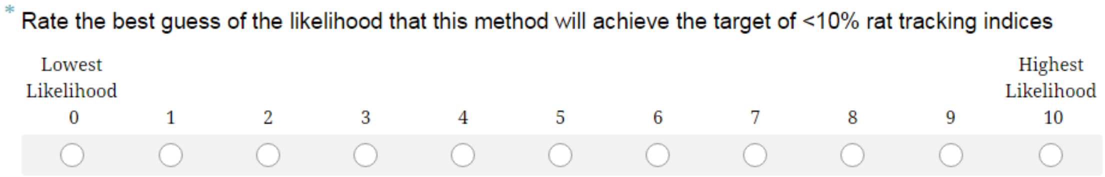
* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○



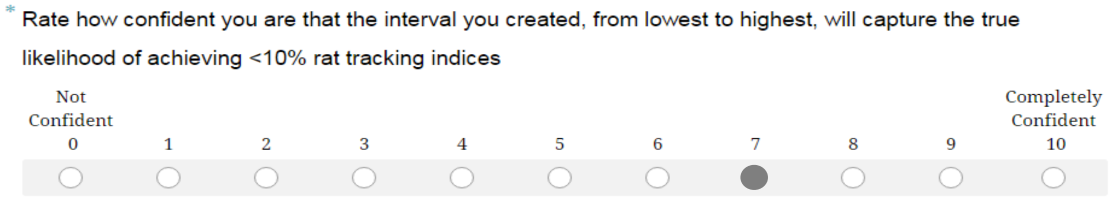
* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
●	○	○	○	○	○	○	○	○	○	○



* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	○	○	○	○	○	○	○	○



* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident 0	1	2	3	4	5	6	7	8	9	Completely Confident 10
○	○	○	○	○	○	○	●	○	○	○

Please provide any comments on the management technique described above

(optional) –

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Rat Management Techniques

6. Predator-proof Fencing

Scale and initial eradication: The predator-proof fence will be erected around the border of the mainland island area. Once the fence is complete the initial eradication of rats will be conducted following the ground-based rat poisoning technique in section 2. Plastic drainage tube bait stations will be placed on a 50m x 50m grid and checked weekly. Second-generation anticoagulant, Brodifacoum, will be used for the eradication and although this poison can have secondary impacts it is highly effective and will only be used for this singular, short-term operation. A predator-proof fence is a multi-species technique and therefore small Indian mongoose and feral cats will also be targeted, these species will hopefully be eradicated through secondary poisoning from consuming Brodifacoum poisoned rats. If any remain additional trapping will be conducted with mongoose trapping on a 200m x 200m grid, based on a home-range length in Mauritius of 500m, and cat trapping at 200m spacing's around the inner fence perimeter, based on very low densities of cats on the Combo region. DOC 250 traps will be used to target mongoose baited the hen eggs and live cat traps, baited with meat or fish. These traps will be checked weekly (cat traps set the day before) along with the poison bait stations until all target species are removed; this will be decided through tracking tunnel indices.

Fence Equipment: The fence will be built by Xcluder ®, a leading company in predator-proof fencing and experienced with predator-proof fence trials in Mauritius. The fence will incorporate the following features –

- Stainless steel woven mesh which can expand and contract in the high temperatures
- An underground skirting to prevent mammals burrowing into the mainland island
- A rolled hood to prevent mammals climbing over the fence
- A hot wire along the top of the fence, powered by a solar panel system, to detect any fence breaches
- Manual pedestrian gates to allow public access into the National Park
- Electric vehicle gates to allow access by project and National Park staff
- Gate alarms encase they remain open
- Culverts for small water outlets

- Self-cleaning culverts for small water inlets

- Water gates for large outlets with alarms fitted encase jammed open

Long-term Maintenance: The fence will be checked weekly for breaches in any of the materials i.e. holes in the mesh, rust holes on the hood or over-grown vegetation. Within the fence permanent trapping and poisoning will be in place along the inner fence perimeter with 50m spacing's for rat poison bait stations, 100m spacing's for mongoose DOC 250 traps and 200m spacing's for cat live traps, these will be checked (cat traps set the day before) monthly. The 50m x 50m rat poison grid and 200m x 200m mongoose trapping grid established across the area for the initial eradication will remain in place in the event of re-invasion in which case the grid can be activated.

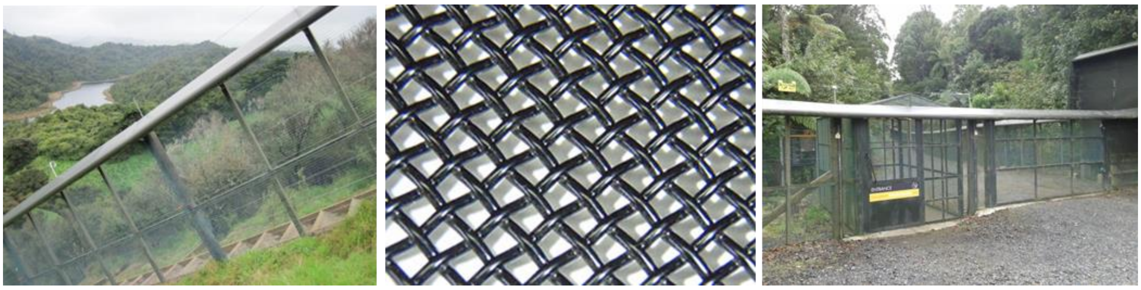
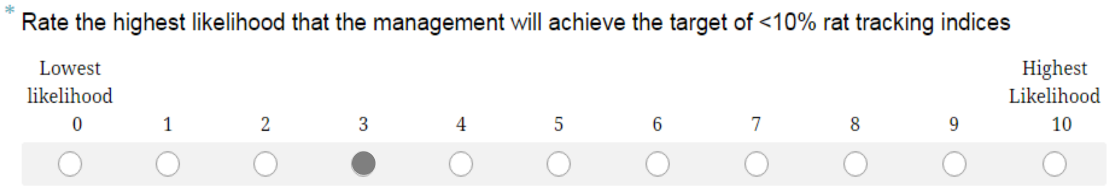
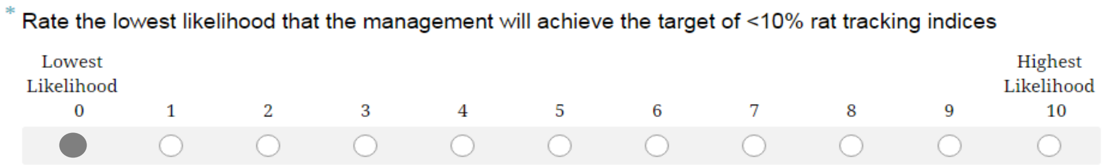


Figure A4.3.10 Xcluder™ fence at Rotokare Scenic Reserve Trust (left; www.rotokare.org.nz), stainless steel woven mesh (middle; www.xcluder.co.nz), and Xcluder™ fence at Maungatautari Ecological Island Trust illustrating the hot wire system and manual pedestrian gate (right)



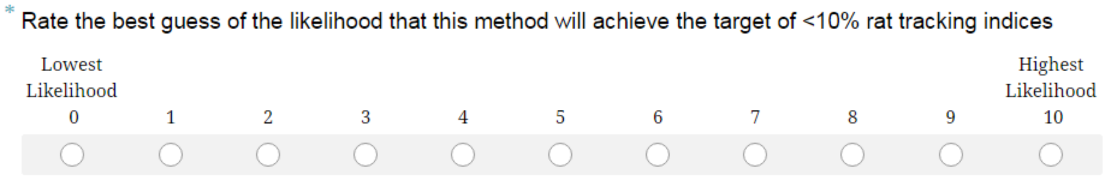
* Rate the highest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
○	○	○	●	○	○	○	○	○	○	○



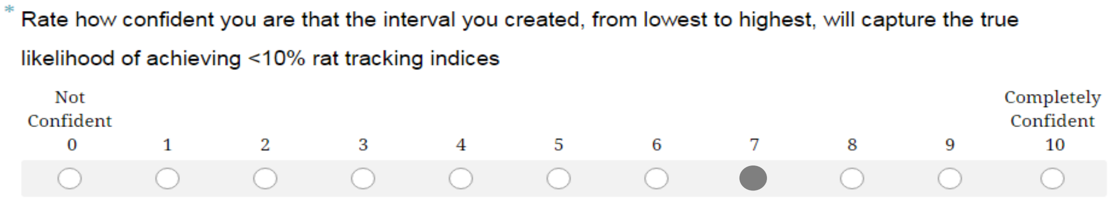
* Rate the lowest likelihood that the management will achieve the target of <10% rat tracking indices

Lowest Likelihood 0	1	2	3	4	5	6	7	8	9	Highest Likelihood 10
●	○	○	○	○	○	○	○	○	○	○



* Rate the best guess of the likelihood that this method will achieve the target of <10% rat tracking indices

Lowest Likelihood										Highest Likelihood
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	○	○	○	○



* Rate how confident you are that the interval you created, from lowest to highest, will capture the true likelihood of achieving <10% rat tracking indices

Not Confident										Completely Confident
0	1	2	3	4	5	6	7	8	9	10
○	○	○	○	○	○	○	●	○	○	○

Please provide any comments on the management technique described above

(optional

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THANK YOU

Thank you for participating in this questionnaire.

The input of your expert opinion is vital for my research in order to conduct a robust analysis of population viability and management cost-effectiveness. This research will enable the development of a decision-making framework allowing the Mauritius Wildlife Foundation, our partner in-situ NGO, to identify the optimal management solution for the Mauritius olive white-eye.

This research will be published as a chapter in my PhD Thesis and also submitted for publication in a relevant scientific journal. A copy of both my PhD Thesis chapter and any subsequent publications will be sent to you as a record of you participation and contribution. If you have chosen to not remain anonymous you shall be acknowledged in both the PhD Thesis chapter and any publications deriving from the information gathered through this questionnaire.

If you have any questions or feedback in regards to this questionnaire, the rat management techniques discussed or my research as a whole please do not hesitate to contact me at Gwen.Maggs@ioz.ac.uk

Figure A4.3.11 Mauritius olive white-eye

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Appendix 4.4

Methods for Vortex Model Parameters

The methods for generating the Vortex 10 model parameters used to simulate a mainland olive white-eye population under different large-scale rat management techniques. All parameters remained the same for all rat management models but annual productivity varied to illustrate the impact management techniques have on reproductive rates and therefore the population extinction risk over a 50 year period. Data used in the calculation of these parameters was sourced from the Mauritius olive white-eye recovery project 2007 to 2015 (Cole et al. 2008; Maggs et al. 2009, 2010, 2011; Hotopp et al. 2012; Ferrière et al. 2013, 2014, 2015)

Number of Years

Due to the short-term dataset the population was modelled over a short period to avoid unrealistic predictions; 50 years (Beissinger & Westphal 1998)

Extinction Definition

Extinction definition is set at <60 individuals, with an equal sex ration. This equates to 30 pairs based on the current maximum population estimate for the Combo region (Nichols et al. 2004). This model is simulating the Combo population not the whole olive white-eye population therefore the population should not drop below the current size and if it does it should be assumed extinct

Environmental Variation (EV) correlation between reproduction/survival

This value is set at zero which makes EV in reproduction independent of EV in mortality. I have set this at zero as EV can cause nest failure for the olive white-eye but it doesn't simultaneously cause mortality. During extreme weather and small cyclones on Ile aux Aigrettes no olive white-eye within the reintroduced population have ever gone missing but nests have failed

Age of First Offspring

All males and females are known to breed in their first year if they are paired based on data collected in the reintroduced Ile aux Aigrettes population

Maximum Age of Reproduction

The maximum age of a breeding olive white-eye is 10 years based on re-sightings and breeding data of individually ringed olive white-eye collected in the reintroduced Ile aux Aigrettes population

Maximum Lifespan

The maximum age of an olive white-eye is 10 years based on daily re-sightings data of individually ringed olive white-eye collected in the reintroduced, supplementary fed, Ile aux Aigrettes population. This maximum age has been applied to the mainland Combo population assuming food availability is not a limiting factor

Maximum Number of Broods per Year

The maximum number of broods is classed as one so that annual productivity data can be inputted as individual nest productivity is unknown in the mainland Combo population

Maximum Number of Progeny per Brood

The maximum number of progeny per brood is 3 and the maximum number of broods per year is 3 therefore 9 is the maximum annual productivity. These values are based on both detailed breeding data collected in the reintroduced population on Ile aux Aigrettes and also nests harvested from the wild Combo population for captive rearing and release onto Ile aux Aigrettes

Sex ratio at birth – in percentage of males

We assume an equal sex ration in annual productivity which is supported by both Ile aux Aigrettes and Combo (hand-reared broods) data

Percentage of Females Breeding

This exact value is unknown for the mainland Combo population; however, olive white-eye will breed if paired. This represents the percentage of females paired to account for unpaired and therefore non-breeding females

Standard Deviation in Percentage of Breeding Females due to EV

The amount of variation in the percentage of females breeding due to EV is unknown but it hasn’t been seen to effect male and female pairings on Ile aux Aigrettes so it has been set at a low value. If there are enough males for females they will have breeding attempts regardless of the environmental conditions

Distribution of Broods per Year

In this section 100% of pairs are assumed to have 1 brood attempt, none breeding birds are accounted for in the percentage of females/males breeding

Distribution of Number of Offspring per Female per Brood

The mean annual productivity value was drawn from a Poisson distribution with a specified mean value and does not require standard deviation.

Mortality - from age 0 to 1 years (%)

Daily survival rates for both juveniles and adults were calculated through separate hazard models run with the “survreg” function in the survival package in R version 3.2.5 (R Core Team 2016) using daily re-sighting data from ringed individuals on Ile aux Aigrettes, 2008-2015. The parameter estimates from these models were then back-transformed to generate the daily survival rates which were calculated to the power of 365 to generate annual survival for both juveniles and adults. These survival rates were then subtracted from 1 to generate the annual mortality rates

Standard Deviation in 0 to 1 mortality due to EV (%)

The seven years of data used to calculate annual mortality rates is insufficient to adequately capture environmental variability in survival rates. Such a short run of data almost certainly underestimates variability because it is unlikely that infrequent extreme events would appear in the data. Also, the Ile aux Aigrettes population is possibly buffered against environmental variation by supplementary feeding. Based on this an estimate of 10% and 5% standard deviation was applied for juveniles and adults respectively; juveniles generally experience higher mortality rates than adults. Sensitivity testing of this parameter showed little variation when altered ±20%, therefore indicating that it does not have a major influence of the model output

Percentage of Males in the Breeding Pool

This exact value is unknown for the mainland Combo population. We assume most male olive white-eye will breed unless there are not paired and so has been set at the same percentage of breeding females

Initial Population Size

The initial population size has been calculated based on the mainland island area which is being assessed for quasi-extinction risk. There is a low and high population density for each management type as the maximum density of olive white-eye pairs in the Combo region is currently unknown. This is calculated from detailed data on defended territories assuming two birds per territory

Carrying Capacity

The carrying capacity is set the same as the initial population size in order to simulation the quasi-extinction risk of a stable ‘recovered’ population at different mainland island areas over 50 years

Standard Deviation in Carrying Capacity due to EV

The impact of environmental variation on the olive white-eye population is currently unknown and so its impact has been set low assuming little variation. Sensitivity testing of this parameter showed little variation when altered ±20%, therefore indicating that it does not have a major influence of the model output

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Appendix 4.5

Mainland Island Costs

Grid Establishment

Costs for the grid establishment are based on Mauritius pricings in 2015 (plus an annual inflation of 1.6% for costing in 2016) and current costs in the UK. Quantities are based on estimates made by an experienced predator control field worker from the Department of Conservation (DOC) in New Zealand based on a theoretical mainland island grid of 1271 points over the Combo region and a team of five people containing two staff members and three volunteers. All items sourced in the UK or New Zealand have been converted from GBP or NZD to MUR based on the exchange rate on the 21/06/16 and 03/07/16 respectively.

Table A4.5.1 The equipment, materials and labour required to establish a 50m x 50m grid based on cost per grid point (GP) and also one-off costs (1 off)

Grid establishment	Equipment	Details	Units	Cost MUR	Cost GBP	
Grid Lines	1. GPS			34606.85	667.83	1 off
	2. Chain Saw			19304.00	372.52	1 off
	3. Chainsaw service			3556.00	68.62	1 off
	4. Chainsaw safety equipment			7620.00	147.05	1 off
	5. Ear guard			508.00	9.80	1 off
	6. Thick/safety gloves			203.20	3.92	1 off
Grid Markers	7. Marker Pens			93.47	1.80	1 off

	8. Soldering Iron			152.40	2.94	1 off
	9. Wire cutters			132.08	2.55	1 off
	10. Machetes			304.80	5.88	1 off
Grid Lines	11. Replacement chains			3.20	0.06	GP
	12. Chain bar lube			5.60	0.11	GP
	13. Petrol - Chainsaw		per 4 L	1.61	0.03	GP
Grid Markers	14. Grid point markers	plastic tags	per tag	50.00	0.96	GP
	15. Flagging tape	1 roll per 500m	per 50m	16.39	0.32	GP
	16. Metal wire		per meter	15.24	0.29	GP
	17. Staff labour	2 staff	per day	12.70	0.25	GP
	Volunteer labour	3 volunteers	per day			
			One-off costs	66480.80	1282.92	
			Costs per GP	104.74	2.02	

1. GPS – Four GPS would be purchased for the grid establishment, deploying the rat management equipment and conducting monitoring and management. These would be purchased from the UK with a 15% import tax and converted to MUR

2. Chainsaw – This would be used to cut the grid lines for establishing the mainland island grid. This would be purchased in Mauritius

3. Chainsaw service – This has been costed in encase the chainsaw needs to be serviced during the grid establishment

4. Chainsaw safety equipment – This would be sourced in Mauritius and would include all safety equipment needed e.g. helmet and trousers
5. Ear guards – These would be sourced in Mauritius and would be used by staff clearing the forest debris behind the chainsaw handler
6. Thick/safety gloves- These would be sourced in Mauritius and would be used by the staff clearing the debris behind the chainsaw handler
7. Marker Pens – Sourced in Mauritius and used to label the grid point reference numbers on the markers more clearly
8. Soldering Iron – This would be sourced in Mauritius and used to mark the plastic grid point markers so the reference number is permanent
9. Wire cutter – These would be used by the team to attach the plastic grid markers to the trees
10. Machetes – These would be sourced in Mauritius and would be used by the team to maintain the grid lines and tidy the lines following the initial cutting with the chainsaw
11. Replacement chains – These would be sourced in Mauritius. The DOC field worker estimated it would take 14 days to establish a grid using two chainsaw chains. To calculate the cost of chainsaw chains per grid point I divided the number of grid points (1271) by two to get the number of grid points her chain (635.5), I then divided the cost of a chain by this number of grid points to get the cost per grid point
12. Chain bar lube – This would be sourced in Mauritius. It was estimated by the DOC field worker that establishing the grid would require one tube of chain bar lube per day. I first calculated the number of grid points which could be established per day by dividing the number of grid points in the theoretical grid (1271) by 14 (the number of days taken to establish it) which equated to 90.78 grid points per day. I then divided the cost of a tube of lube by the number of grid points per day to get the cost of lube per grid point

13. Chainsaw petrol – The DOC field worker estimated 4L of petrol per day for the chainsaw which can be sourced in Mauritius. The cost of 4L of petrol was divided by the number of grid points established per day (90.78) to get the cost of fuel per grid point

14. Grid point markers – It was decided to use plastic grid point markers as they would last longer in the environment, these are available in Mauritius. These were costed as one per grid point

15. Flagging Tape – This would be sourced from the UK with an import tax of 15% added and converted from GBP to MUR. This tape would be used by field workers to mark the grid prior to the cutting on the lines to make this process quicker and to mark the grid lines to assist the monitoring and management afterwards. The cost of flagging tape was estimated at one roll per 500m, to generate the cost per grid point this was divided by 10 to get the cost per 50m (the distance between each grid points)

16. Metal wire – This can be sourced in Mauritius and was costed at 1m per grid point used to attach the grid marker to the tree

17. Staff and volunteer labour – This was based on the daily cost of staff and volunteers costing for two staff members and three volunteers. The cost for the team of five per day was calculated and divided by the number of grid points established per day (90.78) to calculate labour cost per grid point

Trapping

All the items sourced from the UK or New Zealand have been converted from GBP or NZD to MUR based on the exchange rate on the 21/06/16 and 03/07/16 respectively.

Table A4.5.2 The equipment, materials and labour required to implement trapping management across a mainland island based on the cost per grid point (GP) and also one-off costs (1 off)

Grid point establishment	Equipment	Details	Units	Cost MUR	Cost GBP	
Trapping equipment	18. Setting Tool	NZD-MUR		11322.67	218.50	1 off
	19. DOC 150 traps	NZD-MUR		2324.13	44.85	GP
Trap boxes	20. Treated planks			44.45	0.86	GP
	21. Galvanised mesh			12.20	0.24	GP
	22. Stainless steel nails			19.81	0.38	GP
Making trap boxes	23. Staff labour	2 staff	per day	192.19	3.71	GP
	Volunteer labour	3 volunteers	per day			
Distributing traps	24. Staff labour	2 staff	per day	15.38	0.30	GP
	Volunteer labour	3 volunteers	per day			
Initial knock out	25. Staff labour	2 staff	per day	80.72	1.56	GP
	Volunteer labour	3 volunteers	per day			
			One-off costs	11322.67	218.50	
			Cost per GP	2688.88	51.89	

18. Setting tool – These are sourced from New Zealand and a 15% import tax has been added. They are made specifically for the DOC trap range and enable the trap setting without handling making resetting traps a lot quicker and safer

19. DOC150 Traps – These are sourced from New Zealand and an impart tax of 15% has been added. The stainless steel design were costed for as the have an increased longevity in the field

20. Treated planks – These would be sourced in Mauritius. They would be used to make a box ensuring the trap is not miss-sprung and protecting non-target species. The wood comes in sheets and the cost per grid point was calculated by dividing the sheet by the number of boxes which could be made from it based on the DOC guideline dimensions (DOC 2014)

21. Galvanised mesh – This would be sourced in Mauritius. It is used within the trap box to block the ends and ensure rats are directed to the trap to ensure a successful kill. The mesh is sold per meter and the cost per grid point was calculated by dividing the one meter sheet by the number of boxes which could be made from it based on the DOC guideline dimensions (DOC 2014)

22. Stainless steel nails – These would be sourced in Mauritius. These are used to make the trap box and the number required per grid point was calculated from the DOC guidelines (DOC 2014)

23. Making trap boxes; labour – It was estimated by the olive white-eye project manager that six boxes could be made per day by a team of five people. The cost of labour was calculated based on the daily cost of staff and volunteers costing for two staff members and three volunteers. The daily cost for the team of five per day was combined and divided by the number of traps boxes made per day to calculate labour cost per grid point

24. Distributing traps; labour – Based on past grid establishment in Mauritius and work conducted in New Zealand is has been estimated that 15 traps could be distributed per person per day. This is based on approximately 10 minutes to place a trap and 10 minutes between points (50m), over an estimated 6 hour day, this equates to 18 traps per person but this was reduced to account for delays. This would be conducted with the help of a vehicle to get to distant locations. In total 75 traps could be distributed per day, the cost per grid point was calculated by dividing the cost of two staff and three volunteers per day by the number of grid points distributed

25. Initial ‘knock out’ labour – It was assumed that checking DOC150 traps would take around the same time as Goodnature® A24 traps which is estimated at 40 traps per day per person from Boundary Stream Mainland Island. Between five people this is 200 traps per day, the cost of labour per day was then divided by 200 to get the cost of per grid point check; this was then multiplied by 14 for the initial knock out of 14 days

Table A4.5.3 The running costs of a trapping grid for materials, equipment and labour over a 50 year period, the time scale used to predict the population extinction risk, incorporating an annual inflation rate of 2% based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016)

Grid Running	Equipment	Details	Units	Cost MUR	Cost GBP	
	26. Replacement costs	Traps and boxes		13431.48	259.19	GP
	Bait	27. Peanut butter and oats	Knock out	76.02	1.47	GP
		Eggs	per year	42.00	0.81	GP
		28. Eggs	50 years	3665.38	70.73	GP
	Staff labour	2 staff	per check	5.77	0.11	GP
	Volunteer labour	3 volunteers	per check			
	Staff labour	5 staff	per year	138.38	2.67	GP
					0.00	
	29. Staff labour	5 staff	50 years	12076.49		GP

26. Replacement costs – The total cost of a DOC150 trap and the trap box was calculated and using an annual 2% inflation rate, based on the predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the annual cost

of the trap and box was calculated over 50 years. The equipment won't need replacing annually but it was predicted that all the traps and boxes would need replacing over a 15 year period. Therefore, the cost of a trap and box was taken at 15, 30 and 45 years to generate the replacement costs per grid point incorporating inflation

27. Bait; peanut butter and oats – This bait would be used for the two week 'knock out' phase at the start of management. The bait would be sourced in Mauritius and the price is based on the amount of bait used for rat trapping with snap traps conducted in the Combo region during 2010/11 (Chapter 2; Maggs *et al.* 2015). To calculate the cost of bait per grid point I divided the number of traps by the cost of bait per check, this was then multiple by 14 to calculate the cost of bait over the initial two week knock out phase

28. Bait; eggs – For long term management eggs would be used for bait as these would last longer between the fortnightly checks. The cost of an individual egg would be multiplied by 24 to get the cost of bait per year per grid point. To calculate the cost of rebaiting over 50 years, the time over which the population extinction risk was calculated, a 2% inflation rate was added to the annual cost and the total cost of the 50 years was used an a running cost per grid point

29. Staff labour – The daily costs of two staff and three volunteers was divided by 200, the number of traps which could be checked per person per day (see point 25), to calculate the labour cost per grid point this was then multiplied by 24 to calculate the annual cost per grid point based on fortnightly checks. The cost of management over 50 years was then calculated incorporating a 2% annual inflation rate (see point 28)

- Number of grid points - The number of grid points for a 50m x 50m grid was calculated by dividing the area, in hectares, by 50 which was then multiplied by ten to get the number of rows in the grid. An extra row was then added to this value to account for the additional row at the end of the area. This final value was then squared to get the number of grid points within a square area; the shape of the area impacts the number of grid points and so all the areas were assumed square to make them comparable and standard =((ha/50)*10+1)^2

- Extra 25m perimeter points – In the trapping grid traps are set at 25m spacing's around the edge of the mainland island area. To account for these extra points the area of the mainland island was divided by 50 to calculate the number of grid points per row, this value was then multiplied by 4 to get the number of additional traps around the perimeter of the square area in addition to those at the 50m points =((ha/50)*10)*4

- Tracking tunnel points – These are based on 100m x 100m grid at alternative points to the management grid points to monitor the reinvasion rates and patterns of rats into the mainland island area. The number of points was calculated by dividing the area, in hectares, by 10 and squaring this value assuming a square mainland island area =(ha/10)^2

Poisoning

All the items sourced from the UK or New Zealand have been converted from GBP or NZD to MUR based on the exchange rate on the 21/06/16 and 03/07/16 respectively.

Table A4.5.4 The equipment, materials and labour required to implement poisoning management across a mainland island based on the cost per grid point (GP) and also one-off costs (1 off)

Grid Point Establishment	Equipment	Details	Units	Cost MUR	Cost GBP	
Bait stations	30. Drainage tubes	0.5m		22.86	0.44	GP
	31. Wire	per meter		15.24	0.29	GP
	32. Compressed plastic	0.5m		320.04	6.18	GP
	33. Nails	3		6.09	0.12	GP
34. Making bait stations	Staff labour	2 staff	per day	9.23	0.18	GP
	Volunteer labour	3 volunteers	per day			

35. Distributing bait stations	Staff labour	2 staff	per day	4.50	0.09	GP
	Volunteer labour	3 volunteers	per day			
			Cost per GP	271.28	5.24	GP

30. Drainage tubes – This would be sourced in Mauritius. The cost per meter was divided by two for the cost per grid point based on 0.5m of drainage tube per bait station

31. Wire – This would be sourced in Mauritius and 1m used per grid point to secure the lid on to the bait station and secure poison blocks within the station

32. Compressed plastic – This would be sourced in Mauritius and the cost per meter was divided by two estimating 0.5m would be used per grid point as a stake to secure the bait station 4 inches above the ground

33. Nails – These stainless steel nails would be sourced in Mauritius and three would be used per bait station

34. Making bait stations; labour – The labour involved in making a grid point is based on values obtained when bait stations were made in Mauritius for small scale rat management. A team of eight people made 400 poison tubes in two days, 400 was divided by two to get the number of stations per day and then divided by eight to get the number of stations which could be made per person per day. I then multiplied this by five to calculate the number of bait stations which could be made per day by a team of five people. The combined labour cost of two staff and three volunteers was then divided by the number of stations made per day to generate the labour cost per grid point

35. Distributing bait stations; labour – The distribution of tubes was calculated using values obtained when bait stations were distributed in Mauritius for small scale rat management. A team of 25 distributed 400 bait stations in one day. I divided 400 bait stations by 25 to calculate the number of stations distributed per person per day, this was then multiplied by five to calculate the number of bait stations which could be distributed per day by a team of five. I then divided the cost of labour per day for a team of five by the number of stations distributed to get the cost of labour per grid point

Table A4.5.5 The running costs of a poison grid for materials, equipment and labour over a 50 year period, the time scale used to predict the population extinction risk, incorporating an annual inflation rate of 2% based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016)

Grid Running	Equipment	Details	Units	Cost MUR	Cost GBP	
	36. Replacement costs	Bait stations		2029.34	39.16	GP
	37. Poison	NZD	per year	1017.21	19.63	GP
			50 years	88773.18	1713.11	GP
	Staff labour	2 staff	per check	2.31	0.04	GP
	Volunteer labour	3 volunteers	per check			
	Staff labour	5 staff	per year	55.35	1.07	GP
	38. Staff labour	5 staff	50 years	4830.60	93.22	GP
			Cost per GP	95633.11	1845.49	

36. Replacement costs - The total cost of a bait station was calculated and using an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the annual cost of a bait station was calculated over 50 years. The equipment will not need replacing annually but it was predicted that all stations would need replacing over 15 years. Therefore, the cost of a bait station was calculated at 15, 30 and 45 years to generate the replacement costs per grid point incorporating inflation

37. Poison – The poison would be sourced from New Zealand as it is a first generation rodenticide which cannot currently be purchased in Mauritius. A 15% import tax was added to the unit price for a 10kg box of block diphacinone bait and then converted from NZD to MUR. Each poison block weighs 28g and so the number of blocks per 10kg box was calculated. To calculate the amount of bait consumed per year per bait station bait consumption data was used from small scale rat management conducted in the Combo region in 2010/11 calculating the average consumption per bait station over 6 months (Chapter 2; Maggs *et al.* 2015). This was then multiplied by two to estimate the annual consumption of poison blocks per bait station per year. The 10kg poison blocks was then divided by the annual consumption of poison blocks per station per year to estimate the number of grid points which could be supplied over one year by a 10kg box, the cost of the 10kg box was then divided by the number of poison stations supplied to get the cost of poison per grid point over one year. A 2% inflation rate was then applied to the annual cost to calculate the cost of poison over 50 years, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the sum of these years was then used as the cost per grid point over 50 years

38. Staff labour – The number of bait stations which could be checked per day was calculated using values obtained from bait station checks in Mauritius for small scale rat management. A team of eight could check 400 bait stations in half a day; this was multiplied by two to get the daily number of stations checked per day which was divided by eight to get the number of stations checked per day per person. This value was then multiplied by five to calculate the number of bait stations which could be checked per day by a team of five. I then divided the cost of labour per day, for two staff and three volunteers, by the number of stations checked to get the cost of labour per grid point. The cost per grid point was then multiplied by 24 to calculate the annual cost per grid point based on fortnightly checks. The cost of management over 50 years was then

calculated incorporating a 2% annual inflation rate based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016)

- Number of grid points - The number of grid points for a 50m x 50m grid was calculated by dividing the area, in hectares, by 50 this was then multiplied by ten to get the number of rows in the grid. An extra row was then added to this value to account for the additional row at the end of the area. This final value was then squared to get the number of grid points within a square area, the shape of the area impacts the number of grid points and so all the areas were assumed square to make them comparable and standard =((ha/50)*10+1)^2

- Tracking tunnel points – These are based on 100m x 100m grid at alternative points to the management grid points to monitor the reinvasion rates and patterns of rats into the mainland island area. The number of points was calculated by dividing the area, in hectares, by ten and squaring this value assuming a square mainland island area =(ha/10)^2

Self-resetting Traps

All the items sourced from the UK or New Zealand have been converted from GBP or NZD to MUR based on the exchange rate on the 21/06/16 and 03/07/16 respectively.

Table A4.5.6 The equipment, materials and labour required to implement self-resetting trap management across a mainland island based on the cost per grid point (GP) and also one off costs (1 off)

Grid Point Establishment	Equipment	Details	Units	Cost MUR	Cost GBP	
39. Goodnature A24	>500 traps	NZD		4356.58	84.07	GP
	500 + traps			3788.33	73.11	GP

40. Distributing traps	Staff labour	2 staff	per day	3.29	0.06	GP
	Volunteer labour	3 volunteers	per day			
			One-off costs			
			Cost per GP >500	4359.87	84.13	
			Cost per GP 500 +	3791.62	73.17	

39. Goodnature® A24 – The traps would be sourced from New Zealand. The different costs of the traps depending on the quantity purchased was obtained from the supplier, Goodnature®, which provided a cost per A24 trap (including a lure and CO^2 canister) for purchases up to 500 and 500+. A 15% import tax was applied to the unit cost and then converted to MUR for cost per grid point

40. Distributing traps – Goodnature®, the supplier of A24 self-resetting traps, estimated that 70 traps could be installed per person per day, this was then multiplied by five to calculate the number of A24 traps which could be distributed per day by a team of five people. The labour costs for a team of five, two adults and three volunteers, were then combined and divided by the total number of traps distribution per day to calculate the labour costs per grid point

Table A4.5.7 The running costs of a self-resetting trap grid for materials, equipment and labour over a 50 year period, the time scale used to predict the population extinction risk, incorporating an annual inflation rate of 2% based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016)

Grid Running	Equipment	Details	Units	Cost MUR	Cost GBP
	41. Replacement costs	Goodnature A24	>500	24375.43	470.39
			500+	21196.03	409.03

42. Lures - NZD	>1000	per year	553.68	10.68
		50 years	48320.11	932.46
	1000+	per year	533.28	10.29
		50 years	46539.90	898.11
43. CO^2 canisters - NZD	>100	per year	320.55	6.19
		50 years	27974.80	539.85
	>1000	per year	308.89	5.96
		50 years	26957.54	520.21
	1000+	per year	272.18	5.25
		50 years	23753.15	458.38
Staff labour	2 staff	per check	2.31	0.04
Volunteer labour	3 volunteers	per check		
Staff labour	5 staff	per year	4.61	0.09
44. Staff labour	5 staff	50 years	402.55	7.77
		Cost per point >100	101072.90	1950.46
		Cost per point 100-500	100055.63	1930.83
		Cost per point 500-1000	96876.23	1869.48
		Cost per point 1000+	91891.63	1773.28

41. Replacement costs – These would be sourced from New Zealand with an import tax of 15% and converted to MUR. The cost of a Goodnature® A24 self-resetting trap was calculated based on the quantity price (>500 or 500+) and using an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the annual cost of an A24 trap was calculated over 50 years. The equipment will not need replacing annually but it was predicted that all stations would need replacing over 15 years. Therefore, the cost of a bait station was calculated at 15, 30 and 45 years to generate the replacement costs per grid point incorporating inflation

42. Lures - These would be sourced from New Zealand so an import tax of 15% was added and the price converted to MUR. The cost of a Goodnature® auto lure pump was calculated based on the quantity price (>1000 or 1000+) and using an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the annual cost of two auto lure pumps were calculated over 50 years. These annual values were then combined to get the total cost of lures over 50 years per A24 trap based on the auto lure pump lasting 6 months

43. CO^2 Canisters - These would be sourced from New Zealand so an import tax of 15% was added and the price converted to MUR. The cost of a Goodnature® CO^2 canister was calculated based on the quantity price (<100, 100 - 1000 or 1000+) and using an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the annual cost of two auto CO2 canisters were calculated over 50 years. These annual values were then combined to get the total cost of lures over 50 years per A24 trap. This number of canisters Is based on the Goodnature® guidelines to change the canister every six months (a canister comes with the A24 unit which would be used for the initial knock out of rats)

44. Staff labour – The number of A24 traps which could be checked per day was calculated based values obtained from bait station checks in Mauritius for small scale rat management, assuming the checks of the equipment would take the same amount of time. A team of eight could check 400 bait stations in half a day; this was multiplied by two to get the daily number of stations checked per day which was divided by eight to

get the number of stations checked per day per person. This value was then multiplied by five to calculate the number of bait stations which could be checked per day by a team of five. I then divided the cost of labour per day, for two staff and three volunteers, by the number of stations checked to get the cost of labour per grid point. The cost per grid point was then multiplied by two to calculate the annual cost per grid point based on six monthly checks, the length of time the auto lure pump will last. The cost of management over 50 years was then calculated incorporating a 2% annual inflation rate

- Number of grid points - The number of grid points for a 50m x 100m grid was calculated in two stages, firstly, by dividing the area, in hectares, by 50 which was then multiplied by ten get the number of rows in the grid; an extra row was then added to this value to account for the additional row at the end of the area. To calculate the number of columns in the grid the area, in hectares, was divided by ten an extra row was then added to this value to account for the additional row at the end of the area. These two values were then multiplied together to get the number of grid points within a square area, the shape of the area impacts the number of grid points and so all the areas were assumed square to make them comparable and standard =((ha/50)*10+1)*((ha/10)+1)

- Tracking tunnel points – These are based on 100m x 100m grid at alternative points to the management grid points to monitor the reinvasion rates and patterns of rats into the mainland island area. The number of points was calculated by dividing the area, in hectares, by ten and squaring this value assuming a square mainland island area =(ha/10)^2

Predator-proof Fencing

All the items sourced from the UK or New Zealand have been converted from GBP or NZD to MUR based on the exchange rate on the 21/06/16 and 03/07/16 respectively.

Table A4.5.8 The equipment, materials and labour required to conduct the eradication of rats, mongoose and cats from a predator-proof fence mainland island based on the cost per grid point (GP), per kilometre (km) and also one-off costs (1 off)

Grid and Fence Establishment	Equipment	Details	Units	Cost MUR	Cost GBP	
45. Poison stations - rats	Drainage tubes	0.5m		22.86	0.44	GP
	Wire	per meter		15.24	0.29	GP
	Compressed plastic	0.33m		213.36	4.12	GP
	Nails	3		6.09	0.12	GP
Making bait stations	Staff labour	2 staff	per day	9.23	0.18	GP
	Volunteer labour	3 volunteers	per day			
Distributing bait stations	Staff labour	2 staff	per day	4.50	0.09	GP
	Volunteer labour	3 volunteers	per day			
46. Trapping equipment - Mongoose	Setting Tool	NZD		11322.67	218.50	1 off
	DOC 250 traps	NZD		2562.50	49.45	GP
Trap boxes	Treated planks			44.45	0.86	GP
	Galvanised mesh			12.20	0.24	GP
	Stainless steel nails			19.81	0.38	GP
Making trap boxes	Staff labour	2 staff	per day	192.19	3.71	GP
	Volunteer labour	3 volunteers	per day			
Distributing traps	Staff labour	2 staff	per day	15.38	0.30	GP
	Volunteer labour	3 volunteers	per day			

47. Live Traps - cats	Made in Mauritius by MWF			950.00	18.33	GP
48. Distributing traps	Staff labour	2 staff	per day	15.38	0.30	GP
	Volunteer labour	3 volunteers	per day			
49. Fence	Per km	NZD		7975263.56	153903.19	KM
				11322.67	218.50	GP
				271.28	5.24	GP
				2846.53	54.93	GP
				965.38	18.63	GP
				8980712.94	150700.80	KM
				77803.47	1501.42	1-off
Eradication costs	50. Poison	Brodifacoum		390.14	7.53	GP
	51. Trap bait - mongoose	eggs		21.00	0.41	GP
	52. Trap bait - cat	salted fish		82.50	1.59	GP
	53. Staff labour	2 staff	per check	27.68	0.53	GP
	Volunteer labour	3 volunteers	per check			
		Eradication costs	Rat and labour	417.82		GP

Mongoose	21.00	GP
Cat	27.68	GP

45. See points 30-35

46. See points 18-24, however, for mongoose DOC250 traps would be purchased to target the larger mammal

47. Live traps would be used to target cats, the materials for these are sourced in Mauritius and made by the Mauritian Wildlife Foundation (MWF)

48. See point 24

49. The price of a fence, per km, was calculated using the costing estimates in Scofield, Cullen & Wang (2011). Visiting mainland islands across New Zealand through the knowledge exchange it was apparent that the maximum level of protection would be needed for a fence in Mauritius including features such as a hot wire along the top of the fence, culverts for water entrances and exits, high quality mesh, manual pedestrian gates and electric vehicle gates. Therefore, I did not take an average cost of all the mainland islands discussed by Scofield et.al (2011) but instead took the average cost per km for the fences which have these features; Mountain Sanctuary Maungatautari and Rotokare Scenic Nature Reserve. These costs in New Zealand include the total cost of the fence including equipment, materials and labour, an inflation rate of 2.1% was added to the cost of the fencing to account for inflation since they were built around 2006. An import tax of 15% was then added to the cost to account for materials which would be imported and converted to MUR

50. Poison –For eradication a second generation poison brodifacoum would be used based on the single, short-term application and its high level of effectiveness. This poison can be sourced in Mauritius and the cost per kg was divided by the amount used per poison tube (80g) to get the cost of poison per grid point. This cost was then multiplied by 12 based on weekly checks over three months; the estimated time taken to eradicate the rats from inside the fence, to get the cost per grid point

51. Trap bait; mongoose – Eggs would be used as bait for mongoose, these are available in Mauritius. The cost of an egg was multiplied by 12 based on weekly checks over three months; the estimated time taken to eradicate the mongoose from inside the fence, to get the cost per grid point

52. Trap bait; cat – Salted fish would be used in the traps and can be sourced in Mauritius. The cost per kg was divided by the amount used per trap (25g) to get the cost per grid point. The cost of the salted fish was then multiplied by 12 based on weekly checks over three months; the estimated time taken to eradicate the mongoose from inside the fence, to get the cost per grid point

53. Staff labour - The daily cost of two staff and three volunteers was added together and then divided by 500 based on the number of poison grid points which can be checked per day (point 38), this was then multiplied by 12 based on weekly checks over three months to get the cost per grid point. This labour cost was combined with the rat poison management cost bring based on a 50m x 50m grid which the mongoose and cat management is incorporated in to

Table A4.5.9 The running costs of a predator-proof fence for materials, equipment and labour over a 50 year period, the time scale used to predict the population extinction risk, incorporating an annual inflation rate of 2% based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016)

Grid Running	Equipment	Details	Units	Cost MUR	Cost GBP
54. Fence checking	Staff labour	2 staff	per km check	131.04	2.53
	Volunteer labour	3 volunteers	per km check		
	Staff labour	5 staff	per year	6814.13	131.50
	Staff labour	5 staff	50 years	594675.63	11475.79

55. Fence Maintenance	Staff labour	2 staff	per 3 month check	131.04	2.53	
	Volunteer labour	3 volunteers	per 3month check			
	Staff labour	5 staff	per year	524.16	10.12	
	Staff labour	5 staff	50 years	45744.28	882.75	
Predator control	Replacement costs	56. Fence		13084265.20	252494.50	KM
		57. Bait stations		2029.34	39.16	GP
		58. Traps and Boxes		14765.19	284.93	GP
		59. Live traps		5315.33	102.57	GP
	60. Poison	Brodifacoum	per year	390.14	90.35	GP
			50 years	34048.25	7884.58	GP
	61. Eggs		per year	21.00	0.41	GP
			50 years	1832.69	35.37	GP
	62. Salted Fish		per year	82.56	1.59	GP
			50 years	7205.09	139.04	GP
	Staff labour	2 staff	per check	2.31	0.04	GP
	Volunteer labour	3 volunteers	per check			

Staff labour	5 staff	per year	27.68	0.53	GP
63. Staff labour	5 staff	50 years	2415.30	46.61	GP
		One-off costs - mongoose	13724685.11	264853.05	KM
		Cost per point - rat	412068.46	7951.92	GP
		cost per point - mongoose	16597.88	320.30	GP
		Cost per point - cat	12520.42	241.61	GP

54. Fence checking – The length of time is takes to check the predator-proof was based on expert opinion gathered while conducting a knowledge exchange in New Zealand with mainland island managers. I calculated, from the number of hours it takes to check each mainland island fence, the average distance (km) which can be checked per day by a team of five people -

Mainland Island	Time to check fence (hours)	Time to check fence (minutes)	Distance of fence (km)	Mins/km	Km/day (8 hours=480 mins)
Rotokare Scenic Nature Reserve	40	2400	8.2	2400/8.2= 293	480/293= 1.6
Tawhananui Open Sanctuary	2	120	2.7	120/2.7= 44.4	480/44.4= 10.8
Zealandia	5	300	8.2	300/8.2= 36.6	480/36.6= 13.1
				Average km/day	8.5
				Team of 5 km/day	42.5

The cost of two staff and three volunteers was then divided by the number of km which can be checked per day (42.5) to get the labour cost per km of fence. This was then multiplied by 52 to get the annual costs of checks per year based on weekly checks. The cost of management over 50 years was then calculated incorporating a 2% annual inflation rate

55. Fence maintenance - The labour cost per km of fence for a team of five, calculated in point 54, was used and multiplied by four to get the annual costs of fence maintenance based on checks every three months. The cost of management over 50 years was then calculated incorporating a 2% annual inflation rate

56. Replacement cost; Fence – The cost per km of fencing (point 49) was taken and an annual inflation rate of 2% was incorporated over 50 years and the cost per km of fence at 25 years was taken and used as a replacement cost assuming all of the fence will need replacing over this period

57. Replacement cost; Bait station - See point 36

58. Replacement cost; Traps and boxes - See point 26 but the cost of DOC250 traps was used instead of DOC150

59. Replacement costs; Live traps - The cost of live traps was taken and using an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), the annual cost of live traps was calculated over 50 years. The equipment will not need replacing annually but it was predicted that all the traps would need replacing over 15 years. Therefore, the cost of the live traps was calculated at 15, 30 and 45 years to generate the replacement costs per grid point incorporating inflation

60. Poison – The cost of poison per grid point (point 50) was taken and multiplied by 12 based on monthly checks and an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was then added to the annual cost of poison over 50 years. The total of this cost was calculated as the cost to maintain a poison tube over 50 years per fence perimeter point

61. Eggs - The cost of eggs per grid point (point 51) was taken and multiplied by 12 based on monthly checks and an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was then added to the annual cost of eggs over 50 years. The total of this cost was calculated as the cost to maintain a poison tube over 50 years per fence perimeter point

62. Salted Fish - The cost of salted fish per grid point (point 52) was taken and multiplied by 12 based on monthly checks and an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was then added to the annual cost of salted fish over 50 years. The total of this cost was calculated as the cost to maintain a poison tube over 50 years per fence perimeter point

63. Labour costs – The labour cost per grid point (point 53) was multiplied by 12 to get the annual cost of labour per grid point based on monthly checks and an annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was then added to the annual cost of labour over 50 years. The total of this cost was calculated as the cost to maintain a the perimeter management over 50 years per grid point, based on rat poisoning which has the highest density of points

- Length of the fence – The area of the mainland island, in hectares, was multiplied by 10 to calculate the length of each side of the mainland island in meters, this was then multiplied by 4 to calculate to perimeter of the mainland island in meters and divided by 1000 to get the distance in km =((ha*10)*4)/1000

- Number of rat grid points - The number of grid points for a 50m x 50m grid was calculated by dividing the area, in hectares, by 50 this was then multiplied by 10 get the number of rows in the grid. An extra row was then added to this value to account for the additional row at the end of the area. This final value was then squared to get the number of grid points within a square area, the shape of the area impacts the number of grid points and so all the areas were assumed square to make them comparable and standard =((ha/50)*10+1)^2

- Rat perimeter points – The number of perimeter rat points every 50m were calculated by multiplying the area, in hectares, by 10 to calculate the distance of one side of the mainland island in meters, this was then multiplied by 4 to get the total distance and finally divided by 50 to calculate how many points would fit along the perimeter =((A145*10)*4)/50

- Mongoose grid points – The number of grid points for a 200m x 200m grid was calculated by dividing the area, in hectares, by 10 this was then divided again by 2 to get the number of rows in the grid. An extra row was then added to this value to account for the additional row at the end of the area. This final value was then squared to get the number of grid points within a square area, the shape of the area impacts the number of grid points and so all the areas were assumed square to make them comparable and standard =(((ha/10)/2)+1)^2

- Mongoose perimeter points – This was calculated the same as for rats but the distance in meters divided by 100 to calculate how many mongoose traps would fit along the perimeter based on 100m spacing's =((A145*10)*4)/100

- Cat perimeter points - This was calculated the same as for rats but the distance in meters divided by 200 to calculate how many cat traps would fit along the perimeter based on 200m spacing's =(((A145*10)*4)/200)

- Tracking tunnel points – These are based on 100m x 100m grid at alternative points to the management grid points to monitor the reinvasion rates and patterns of rats into the mainland island area. The number of points was calculated by dividing the area, in hectares, by 10 and squaring this value assuming a square mainland island area =(ha/10)^2

Tracking Tunnels

Table A4.5.10 The costs per grid point (GP) for establishing and running a tracking tunnel serviced monthly over 50 years , incorporating an annual inflation rate of 2% based on a predicted trend in 2020 using inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016)

	Equipment	Details	Units	Cost MUR	Cost GBP	
Tracking Tunnels	64. Black Trakka™ Tunnel	NZD		293.16	5.66	GP
	65. Replacement Cost	NZD		1640.25	31.65	
	66. Black Trakka™ cards	NZD	per card	50.27	0.97	GP
			per year	603.22	11.64	GP
			50 years	52643.49	1015.89	
	Staff labour	2 staff	per check	4.61	0.09	GP
	Volunteer labour	3 volunteers	per check			
	Staff labour	5 staff	per year	55.35	1.07	GP
	67. Staff labour	5 staff	50 years	4830.60	93.22	GP
			Cost per GP	59407.49	1146.42	GP

64. Black Trakka™ tunnels – The cost of a Trakka™ tunnel was taken and a 15% import tax applied and then converted from NZD to MUR

65. Replacement cost – An annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was added to the cost of a tracking tunnel and calculated over 50 years. The equipment will not need replacing annually but it was predicted that all tunnels would need replacing over 15 years. Therefore, the cost of a tunnel was calculated at 15, 30 and 45 years to generate the replacement costs per grid point incorporating inflation

66. Black Trakka™ cards – The cost of a pack of 50 cards was taken and an import cost of 15% added, this was then converted from NZD to MUR and divided by 50 to calculate the cost per card. The cost per grid point was then multiplied by 12 based on monthly checks. An annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was added to the cost of a tracking tunnel card and the annual cost of a traps and boxes was calculated over 50 years. These values were combined to calculate the running cost of a tracking tunnel over 50 years.

67. Labour costs – The cost of a team of five, two staff and three volunteers, was calculated and the sum divided by 500, this is based on the number of poison stations which can be checked per day (point 38). The daily labour cost per tracking tunnel was then multiplied by two as the cards have to be distributed one day and collected the following. This value was then multiplied by 12, based on monthly check, to calculate the annual cost of labour per grid point. An annual 2% inflation rate, based on a predicted trend in 2020 based on inflation rates reported by the Central Statistics Office, Mauritius (Trading Economics 2016), was added to the cost of a tracking tunnel labour and calculated over 50 years. These values were combined to calculate the labour cost of a tracking tunnel over 50 years

Chapter 5

Discussion

5.1. Thesis Overview

This thesis has illustrated how the combination of conservation tools can increase our understanding of both the ecology and conservation of highly threatened species focusing on both wild and reintroduced populations of the Mauritius olive white-eye. Here I identify the role of management and created decision-making tools to enable the timely application of robust and viable long-term management for a highly threatened species while accounting for financial, logistical and epistemic uncertainty.

The Mauritius olive white-eye, prior to 2001, was a data deficient species with very little understanding around their biology, ecology and above all their limiting factors. Knowing your species is a vital step in conserving a threatened population (Carl G. Jones *pers.comm*) and although reports on the status of the olive white-eye have been published (Cheke 1987; Safford 1991) it was not until 2001 when the first species specific research was conducted by Nichols et al. (2004, 2005a, 2005b). This research highlighted the continued decline of the population and their low productivity and described the species breeding biology in detail; paving the way for the Mauritius olive white-eye recovery project which continued detailed monitoring and commenced intensive management to create a sub-population on a mammalian predator free island (Cristinacce et al. 2006; Cole et al. 2007, 2008; Maggs et al. 2009, 2010, 2011; Hotopp et al. 2012; Ferrière et al. 2013, 2014, 2015). Through this research and management knowledge of olive white-eye breeding biology and general behaviour was vastly increased, however, the ecology of the species and how it interacts with introduced and native fauna and flora is still little understood, hindering the development of long-term management.

The focus of Chapter two was to increase our knowledge of the wild olive white-eye population, investigating the ecological impact of rat management and whether it can ensure population persistence on the mainland; as although rat species are highly suspected as a threat to the olive white-eye their impact has never been quantified. Identifying limiting factors is another vital step in conserving threatened populations (Carl G. Jones *pers.comm*) but while habitat destruction is an obvious cause of species loss the impact of invasive animals is often difficult to evaluate (Cheke & Hume 2008) especially for small, declining populations as this requires replicate populations which these species lack. Here I developed a method for overcoming this problem by combining a small-scale field experiment with demographic models to investigate the impact of management of vital rates and population growth. These analyses showed that the presence of rat management could produce a 5-6 fold increase in olive white-eye annual productivity which in turn could stabilise population growth. In the absence of rat management, the analysis suggests the olive white-eye population will decline by about 14% per annum. This rate of decline is high and would have caused species extinction if this rate had been constant since the introduction of rats in the 1600s. However, olive white-eye were most likely a widely distributed and densely populated species and so as the population declined the pressure of rat predation will have compounded and the rate of decline increased to this current, alarming value. These findings have increased our understanding of the wild population of olive white-eye in a short timeframe, which is paramount for declining species, identifying rats as a major liming factor and confirming rat control as a viable option for future management.

The reintroduction of olive white-eye to the island nature reserve Ile aux Aigrettes has successfully established a breeding population supported by supplementary feed (SF). However, the role SF plays and how this impacts olive white-eye ecology has not been quantified and so the *ad libitum* management is expanding exponentially with population growth and becoming costly in terms of conservation resources. The focus of chapter three was to investigate what drives the demand for SF within the population and whether identifying these drivers can enable management refinement. Here I created a novel dataset combining daily consumption rates of SF with environmental seasonality, breeding behaviour, natural plant resource availability and management techniques, illustrating a decision-making framework for identifying the mismatch between supply and demand to enable the refinement of current *ad libitum* management and devise a potential long-term exit strategy. This approach showed that the demand for SF peaks during energetically expensive phases of the breeding cycle, when natural plant resource availability is low, and in the morning. From these findings the supply of SF in the short-term can be refined through a responsive management approach providing SF at feeding stations in response to time of day and breeding behaviour. The long-term supply of SF can also be reduced by increasing natural plant resource availability through the planting of key species in order to improve natural food continuity and reduce demand over time. These findings have greatly increased our understanding of the feeding behaviour and ecology of olive white-eye highlighting the role of management and how it is utilised in relation to native fauna on Ile aux Aigrettes. These decision-making tools, for assessing supply and demand, provides scientific evidence for the refinement and potential removal of management over time through a responsive approach and integrated ecosystem management; enabling the effective allocation of finite conservation resources without jeopardising species recovery.

Chapter two highlighted the important role of rat management in olive white-eye conservation but long-term, large-scale management comes with many uncertainties in regards to financial, logistical and knowledge requirements. Chapter four focused on addressing these uncertainties to create decision-making tools for identifying the most cost-effective, long-term management plan for creating low-predation 'mainland islands' for olive white-eye. Here, by combining knowledge exchange, expert elicitation, population viability analysis and cost-effectiveness analysis I developed novel decision-making tools comparing four large-scale rat management techniques; trapping, poisoning, self-resetting traps and predator-proof fencing. This approach identified what rat management options are available, how effective they are at controlling rat populations, what impact this has on olive white-eye population viability and what option is likely to be most cost-effective. The results of this chapter have provided the olive white-eye recovery project with viable management options which they can use to identify the most appropriate long-term solution for their logistical and financial situation alongside key stakeholders. The aim of this analysis was not to provide an overall answer but tools to guide collaborative and decisive evidence-based conservation which accounts for uncertainty and minimises risk for threatened species management which has been achieved.

This research has produced valuable scientific evidence into olive white-eye ecology and conservation which can guide management decisions and future research and above all enable population persistence and long-term survival; bridging the gap between science and management which is rarely achieved in conservation biology. It is hoped that this research will act as a model study system for other threatened species facing similar limiting factors and long-term uncertainty both in Mauritius and globally.

5.2. Conservation in Mauritius; Ecosystem Restoration

In Mauritius species have been saved from the brink of extinction, however, the conservation work has been criticized for being too species specific and there is a growing need for a more all-encompassing and economically more sustainable ecosystem approach (Florens 2013). Endemic threatened plant species and invertebrates also face increasing pressures from habitat destruction, fragmentation and invasive species and although invasive mammal eradication and habitat restoration on island nature reserves, such as Round Island or Ile aux Aigrettes, have been successful more work is still required for mainland Mauritius (Florens 2013). Controlling a suite of invasive species can create high quality habitats suitable for many species leading to island-type responses in native plants and animals (Jones & Merton 2012) and the need for large-scale management has been recognised for Mauritius (NBSAP 2006) but is still proving difficult (Florens 2013).

Conservation management areas (CMAs) have been established on mainland Mauritius to protect native vegetation communities by minimising the impact of invasive species, which cause degradation, by removing exotic plants and excluding deer and pigs (Cheke & Hume 2008). The CMAs are relatively small areas averaging at 4.7ha (±6.1) and accounting for <1% of the remaining mainland native habitats and while the first CMA was established in 1937 no new management sites have been implemented in the last 20 years (Cheke & Hume 2008; Florens 2013). Although small areas, the CMAs were found to attract native fauna and so the CMA concept was expanded from vegetation plots to ecosystem management in 1996 across the largest CMA (24ha; Cheke and Hume, 2008). Echo parakeet (*Psittacula eques*) and pink pigeon (*Nesoenas mayeri*) were reintroduced and passerine numbers were seen to increase but the management of native forest needs to be developed further, across larger areas and using research to identify the most effective management techniques (Cheke & Hume 2008).

My research provides the tools required to develop CMAs in Mauritius and establish a mainland island, using the olive white-eye as an indicator species, adopting a more robust, evidence-based approach to conservation and restoration. The establishment of a mainland island in Mauritius has been identified as a viable long-term management plan for the olive white-eye by recovery project stakeholders during a species management workshop where the impact of invasive rat species and potential management options were discussed (Chapter 2 and 4) with project managers, directors, funders and researchers (Maggs et al. 2015a). During this workshop it was recognised that any management should take an ecosystem approach to protect other highly threatened fauna and flora targeting a suite of invasive species. Taking a 'multi-species/multi-threat' approach is vital until the impact of species individually is known in order to avoid the 'surprise factor' of secondary unexpected and undesired results (Alterio et al. 1999; Saunders & Norton 2001; Caut et al. 2009; Carter et al. 2016). Examples of surprise factors include bird predations by stoats following a reduction in rat densities (Murphy et al. 1998), the increase in mice following rat eradiation (Innes et al. 1995) and the increase in shrews on Ile aux Aigrettes also following rat eradication which, in Mauritius, could have a large impact on skink and invertebrate populations (Cheke & Hume 2008; Brown et al. 2014).

The question now for olive white-eye conservation is not whether a mainland island is viable, how large an area is required, or which management technique is most cost-effective but what is the optimal location for a mainland island which can enable an ecosystem approach while protecting the olive white-eye. Recent research has highlighted that in cases where species face extreme endangerment it is better to embrace a more flexible recovery approach which could deviate from historical baselines (Jachowski et al. 2015). One novel strategy is the enhancement of mainland habitat using exotic plants which can facilitate species recovery e.g. higher nesting success for the Mauritius Fody in the exotic *Cryptomeria japonica* due to reduced rat and crab-eating macaque predation (Safford 1997). In addition to this it is felt that single species management can drive habitat protection and ecosystem restoration (Jones & Merton 2012). Based on these theories the Combo region could be an appropriate location for a mainland island, as although degraded habitat, it supports the largest remnant population of olive white-eye and provides ample resources in the form of the exotic *Syzygium jambos* (Safford & Hawkins 2013) which could ensure population persistence of the species while forming a basis for the rehabilitation of native vegetation and bird species as a long-term conservation strategy. However, site selection is beyond the scope of this thesis as it does not provide criteria for site assessment for the olive white-eye or other threatened species and the Combo region is among numerous options which should be considered, therefore, a separate project is needed to identify potentially suitable areas for a mainland island on Mauritius.

Ecosystem restoration in Mauritius cannot be based solely on the recovery of one species, although it can drive the implementation of evidence-based management, therefore all threatened fauna and flora should be incorporated in any decision-making in regards to a multi-species/multi-threat mainland island (Saunders & Norton 2001; Jones & Merton 2012). It is recommended that a collaborative approach be taken using structured decision-making methods (Gregory et al. 2012) to incorporate the opinions and views of all related stakeholders including government, NGO’s, researchers, project managers, directors and funders to create transparency and enable the optimal solution to be achieved; a method which has been incorporated successfully in other conservation management programmes (Failing et al. 2013; Ewen et al. 2015).

5.3. Implications for Threatened Species Management; Addressing the Fear of Failure

The conservation of highly threatened and extremely small populations faces many challenges which are compounded by their high risk of extinction, vulnerability to environmental and demographic stochasticity and insufficient funds to conserve the world’s biodiversity (Mccarthy 2014; Meek et al. 2015). Decisive and innovative management actions may be crucial to reverse the declining trajectories of these threatened populations but there is a high level of uncertainty associated with conservation efficiency and a fear of failure and so practitioners may be deterred from necessary management actions and decision-making (Mccarthy 2014; Meek et al.

2015). Research has highlighted the need for mechanisms to review available information and make recommendations to practitioners as currently relevant information remains in undocumented experiences of individual staff members, and even when data are gathered and documented they often remain in field offices in relatively inaccessible form, therefore, most decisions are based on experience rather than evidence (Sutherland et al. 2004; Pullin & Knight 2005; Kapos et al. 2008). A lot of funds go into to conservation and habitat restoration and ideally decisions on these funds should be made based on effectiveness of actions in achieving the objectives as demonstrated by scientific experiment (Sutherland et al. 2004; Pullin et al. 2004). However, research suggests that the majority of conservation actions remain experience-based and rely heavily on traditional land management practices as many management interventions remain unevaluated (Pullin et al. 2004); not knowing management effectiveness or if it works weakens the case for investment (Sutherland et al. 2004).

There is a need to systematically evaluate the effectiveness of conservation interventions to provide an efficient framework through which scientific evidence can be used to support decision-making in policy and practice (Pullin & Knight 2005). A framework developed by Meek et al. (2015) compiles the barriers identified by thirty-eight conservation experts and addresses these to enable the effective management of threatened populations providing useful ways to approach existing challenges which helps decrease uncertainty and delays caused by the apprehension of outcomes. Here I demonstrate how the methods used in my research and the tools I have developed (Chapter 2 and 4) for the conservation of the Mauritius olive white-eye address these roadblocks through knowledge exchange, literature reviews, expert elicitation, stakeholder workshops, population modelling and cost-effectiveness analysis. My findings act as a case study illustrating how the solutions proposed by Meek et al. (2015) can be effectively applied to threatened population management to achieve swift, effective, evidence-based conservation tackling uncertainty and the fear of failure.

The roadblocks highlighted by Meek et al. (2015) include (1) the lack of information sharing and interpretation, (2) ineffective methods to make decisions in a data poor environment, (3) multiple stakeholders and conflicting interests and (4) outcome-based performance metrics.

The lack of information sharing and interpretation stems from two areas, firstly the peer-review process delaying the availability of information and focusing on successful management making managers unaware of the science available, and secondly the lack of information sharing between academic researchers and conservation managers resulting in poor engagement and communication and secondary resources being used instead of scientific evidence (Pullin et al. 2004; Knight et al. 2008; Cvitanovic et al. 2015; Meek et al. 2015). To tackle these two areas Meek et al. (2015) suggest creating digital repositories compiling literature from journals, 'grey literature' and expert opinion and support collaboration to share skills and to promote bridging the research-implementation gap (Knight et al. 2008). Through my research I have tackled these issues firstly by compiling a literature review (creating a digital repository for small recovery projects is not easily achieved or practical) of current published research and 'grey literature' reports and conducting a knowledge exchange with experts in the field. Using a 'boundary organisation' approach (Cook et al. 2013; Cvitanovic et al. 2015) I facilitated knowledge exchange between management experts and threatened species project managers obtaining grey literature and expert knowledge to add to the literature review, identifying potential management techniques and the demands and practicalities involved enabling an accurate assessment of their cost-effectiveness (Appendix 4.1 and 4.2). Secondly I addressed the research-implementation gap (Knight et al. 2008) through a 'co-production' approach (Cvitanovic et al. 2015; van Kerkhoff & Lebel 2015) with full cooperation between myself, the academic researcher, and the threatened species project managers. This was achieved by pool resources from the onset collaborating on design, implementation and analysis allowing my findings to be fed directly back to the project managers and enabling evidence-based conservation decisions bridging the science-management divide (Roux et al. 2006)

Having ineffective methods to make decisions in a data poor environment results from the lack of data on population trends, demographic rates, ecological interactions and threats for small populations which can hinder accurate predictions of population response to conservation actions (Meek et al. 2015). Acquiring this information is costly and timely which is problematic when pressing conservation actions are required, therefore, better strategies need to be developed to incorporate uncertainty into decision-making processes, as the fear of uncertainty can lead to the avoidance of decision-making (Meek et al. 2015). Meek et al. (2015) suggest improving the ability to forecast conservation outcomes while accommodating uncertainty and using a decision-making process which includes the evaluation of uncertainty. Through my research I improved the ability to forecast conservation outcomes by creating a novel approach to predicting the impact of conservation management conducting a small-scale field experiment and up-scaling the results using demographic models to predict the impact on vital rates and population growth. This eliminated uncertainty by identifying a major limiting factor and providing scientific evidence for the application of management to mitigate the threat (Chapter 2; Maggs et al., 2015b). With numerous management techniques available to tackle threats additional uncertainty developed regarding the effectiveness of the techniques, this was addressed through additional analysis using population viability analysis in combination with expert elicitation. Here expert opinion was elicited to score the effectiveness of management techniques available (identified through the knowledge exchange; Appendix 4.2) as running field trials for each technique would be financially and logistically unfeasible. Based on their effectiveness I developed a frame-work comparing the management techniques under a best, baseline and worst-case scenario to evaluate their impact on population persistence while accounting for uncertainty in the model parameters caused by limited data (Sections 4.3.4 and 4.3.5). In addition to effectiveness the cost of management creates even more uncertainty due to inadequate conservation budgets and the likelihood of an investment being successful (Bottrill et al. 2008). Using the results of the population viability analysis I conducted cost-effectiveness analysis to create a decision-making framework for identifying the most cost-effective management technique based on the quasi-extinction risk threshold desired. This accounts for total, capital expenditure and recurrent costs under a best, baseline and worst-case scenario eliminating financial uncertainty and accounting for uncertainty in the predictions. These frame-works provide a tool for assessing and evaluating management options to enable timely decision-making while accounting for logistical, financial and epistemic uncertainty.

Upsetting important others is another component of fear which can occur when there are multiple stakeholders with conflicting interests (Conroy et al. 2002). Improving knowledge exchange between decision–makers and scientists is fundamental to support sustainable management. An approach termed ‘interdependency’ recognises that all participants in knowledge exchange can contribute and it emphasises the need for a two-way exchange between scientists and decision-makers (Contandriopoulos et al. 2010; Cvitanovic et al. 2015). Meek et al. (2015) mirror this approach and suggest by increasing communication between stakeholders you can increase understanding by ensuring access to the best scientific information and enabling science-based decision-making; making decisions more defensible when outcomes are negative. To tackle this issue a stakeholder workshop was held between project managers, directors, funders and academic researchers where the scientific evidence was discussed (Chapter 2; Maggs et al., 2015b) and expert opinion was shared (Maggs et al. 2015a). This approach highlighted project priorities and enabled all relevant stakeholders to come to a unified decision on future management goals, guiding science-based conservation while ensuring transparency among stakeholders.

Outcome-based performance metrics refer to programmes and managers which are commonly evaluated based on the outcomes of the conservation/management actions (Meek et al. 2015). Conservation actions can be expensive yet funds are limited and short funding cycles and expectations of return on investment generate pressure for programmes to claim success and “bury failure” (James et al. 1999; Bottrill et al. 2011; Meek et al. 2015). The challenge is to minimise delay as ideas flow from intent through scientific capability, and finally to implementation to achieve desired outcomes, however, even with the most competent managers and conservation teams decisions can be made which are unsuccessful (Fazey et al. 2012; Meek et al. 2015). Meek et al. (2015) suggest that this can be tackled by combining the solutions previously outlined through information sharing, better handling of uncertainty, collaboration and also clarifying expectations and re-thinking measures of success. My research has tackled this by collaborating between field teams and academics, sharing monitoring data and scientific knowledge so science-based conservation can be implemented, collaborating with experts to reduce levels of uncertainty around new management techniques and to gain information from grey literature and collaborating with stakeholders to share information and create transparency; enabling expectations to be clarified taking uncertainty into account and not making individuals responsible for potential negative outcomes.

These barriers to the conservation and management of species on the brink of extinction have highlighted clearly the challenges faced by highly threatened species and the problems encountered by conservation managers and academic researchers. The framework outlined and the solutions proposed address ways to approach existing challenges which helps decrease uncertainty and delays caused by the apprehension of outcomes and enable evidence-based decision-making. The methods adopted through my research have illustrated how these solutions can be applied to the conservation of a highly threatened species highlighting how tackling these apprehensions and barriers can enable swift, effective, evidence-based conservation tackling uncertainty and the fear of failure. The approaches taken are, however, case specific but the framework presented my Meek et al. (2015) provide various tools for researchers and managers to adopt and apply to different scenarios depending on the barriers being faced.

5.4. Future Research

5.4.1. Supplementary Feeding and Adaptive Management

Adaptive management is widely considered to be the best available approach for managing biological systems in the face of uncertainty, however <5% of articles assessed claimed to use adaptive management (Westgate et al. 2013). It is a systematic approach to improving management through learning and when actively applied it can combine both short-term management objectives with learning so that long-term management outcomes can be achieved (McDonald-Madden et al. 2010). A majority of conservation decisions are not evidence-based but remain experienced-based relying heavily on traditional practices, adaptive management aims to bridge the gap between conservation research and conservation practice to enable good decisions despite uncertainty in the ecology of a system or the impact of management (Pullin et al. 2004; Armstrong et al. 2007; McDonald-Madden et al. 2010). However, it requires risky strategies in the short-term and experimentation is only considered acceptable if it is expected to be repaid in the long-term through an improved understanding of a system (Rout et al. 2007). For highly threatened and extremely small populations there is a high risk of extinction compounded by their vulnerability to environmental and demographic stochasticity (Meek et al. 2015), therefore, applying risky short-term strategies through adapting management could be detrimental.

On Ile aux Aigrettes the reintroduced olive white-eye population is one of these extremely small, vulnerable populations, and although the provision of *ad libitum* supplementary feed is enabling a breeding population to establish it is becoming costly in terms of conservation resources. Chapter three, by implementing decision-making tools, addressing the mismatch between supply and demand, has successfully identified the areas of management which can be refined through adaptive management without jeopardising population persistence. These findings provide a key first step which can be shared directly with the recovery project managers highlighting areas for future research and adaptive management, engaging individuals across the knowledge-action boundary and enabling evidence-based decisions while eliminating uncertainty (Cook et al. 2013).

Using an adaptive management approach it is suggested that future research on Ile aux Aigrettes focuses on reducing the provision of supplementary fed responding to olive white-eye feeding times and breeding activity. Supply should be reduced in response to time of day, removing the afternoon feed based on significantly higher demand during the morning period; providing enough feed in the morning to meet demand throughout the day. In regards to breeding activity, the supply of all three food types should be reduced in response to dominant pair breeding stage and whether a dominant pair is present at the feeding station. Monitoring survival and productivity closely throughout and re-evaluating the management and its effects will ensure any unforeseen negative impacts are identified and prevent population decline.

Responsive management using an adaptive management approach can only reduce the demand for supplementary feed so far, in order to eliminate the overall demand for supplementary feed project managers need to increase natural plant resource availability. Key plant species have been identified in Chapter three, however, certain plant species could be more nutritious than others, identifying these could further focus ecological restoration on Ile aux Aigrettes in regards to olive white-eye management. To identify if certain key plant species are more nutritionally important than others research should be conducted to identify the nutritional content of the nectar and fruit and investigate how nectar and fruit availability may fluctuate throughout the day and year in response to environmental factors. This could assist in understanding the relationship between the environment and plant phenology and enable project managers to identify periods of natural food shortages or the impacts of long-term threats such as climate change and investigate how supplementary feed could buffer any long-term negative impacts (Correia et al. 2015).

5.4.2. Knowledge Gaps within the Mainland Population

Population viability analysis (PVA) is valid and sufficient to manage endangered species when comparing different consequences of management but information should be added to the model as it comes available in an adaptive management approach (Akçakaya & Sjögren-Gulve 2000; Coulson et al. 2001; Beissinger et al. 2006; Armstrong & Ewen 2013). Due to the rarity of the olive white-eye some of the data used in the PVA in Chapter four were based on the reintroduced olive white-eye population on Ile aux Aigrettes rather than the mainland population. Although using alternative populations or even species to fill knowledge gaps has been conducted in other threatened species PVA (Fessl et al. 2010) and sensitivity analysis reduces uncertainty in these parameters filling these knowledge gaps will further increase the accuracy of the model predictions and reduce uncertainty.

I suggest that monitoring of the mainland olive white-eye population should focus on filling these knowledge gaps. In 2010 the ringing of adult and juvenile (ringed post fledging before leaving the natal territory) olive white-eye in the Combo region began to enable individual olive white-eye to be identified (Maggs et al. 2011) and through detailed monitoring and re-sighting start investigating both adult and juvenile survival. This has continued but should be built upon to increase our understanding of the mainland population demographic rates and the influence of environmental stochasticity. In addition to survival this data would help identify the maximum breeding age for males and females and the percentage of breeding birds within the mainland population; data which is currently sourced from the reintroduced population.

As highlighted in Chapter four there is currently no understanding of juvenile dispersal in the mainland olive white-eye population, however, dispersal can be very influential (McCarthy et al. 2011). Prior to 2010 juvenile dispersal could not be researched as mainland olive white-eye were not individually ringed, however, following the efforts of the recovery project to ring both juveniles and adults dispersal can start to be investigated. This should be a priority for the recovery project as dispersal out of a mainland island site can cause population failure despite the lack of predators within the area (Basse & McLennan 2003). Although dispersal wouldn't initially jeopardise the recovering olive white-eye population within a mainland island it is vital to establish juvenile dispersal rates in order to identify if a larger mainland island would be required to prevent potential failure due to a source-sink population dynamic (McCarthy et al. 2011).

5.4.3. Mainland Island Establishment through Structured Decision Making

Conservation management action should be evidence-based and there is a call for evidence-based invasive species management (Doherty & Ritchie 2016). This thesis has taken an evidence-based approach to invasive species management illustrating the tools required to quantitatively assess long-term management for the Mauritius olive white-eye; identifying invasive rats as a population limiting factor, assessing the viability of large-scale management, estimating the area required and highlighting the cost-effectiveness of management techniques. These methods have identified a mainland island as a viable long-term management option; however, the question now is what is the optimal location for a mainland island which can enable an ecosystem approach while protecting the olive white-eye. Site selection is beyond the scope of this thesis therefore additional research is required to identify potentially suitable areas for a mainland island adopting a multi-species/multi-threat approach (Saunders & Norton 2001); as it should always be considered that the control of one species can impact another (Doherty & Ritchie 2016). I recommend that a collaborative approach to decision-making be taken to incorporate the opinions and expertise of all related stakeholders and enable the optimal solution to be achieved considering all native Mauritian fauna and flora.

Improving knowledge exchange between decision–makers and scientists is fundamental to support sustainable management, an approach termed ‘interdependency’ recognises that all participants in knowledge exchange can contribute and it emphasises the need for a two-way exchange between scientists and decision-makers (Contandriopoulos et al. 2010; Cvitanovic et al. 2015). There should be an emphasis on ensuring that all voices and concerns are heard and meaningfully incorporated, working collaboratively with a diversity of people and organisations who care about the outcome of restoration decisions (Failing et al. 2013). This can be achieved through structured decision-making, a method for helping individuals and groups think through tough multidimensional choices characterised by uncertain science, diverse stakeholders, and difficult trade-offs (Gregory et al. 2012). This enables decisions to be made in a way that is rigorous, inclusive, defensible and transparent preventing ad-hoc decisions which lack solid foundations, key information and result in inferior alternatives (Gregory et al. 2012). The method of structured decision-making has been applied successfully in other conservation management programmes for the New Zealand Hihi (*Notiomystis cincta*) and river restoration in western Canada (Failing et al. 2013; Ewen et al. 2015).

Applying structured decision-making in Mauritius for the establishment of a mainland island would enable the collaboration of government, NGO’s, scientific researchers, project managers, directors and funders, bridging the gap between researchers and management; something successfully achieved for threatened species management in the Seychelles (Kaiser-Bunbury et al. 2014). Also, by adopting a ‘co-production’ type approach to knowledge exchange and decision-making (Cvitanovic et al. 2015; van Kerkhoff & Lebel 2015), within structured decision-making, the research-implementation gap could be addressed minimising the delay between scientific planning and the implementation of management (Knight et al. 2008); which for threatened species management is paramount.

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