Combining prior predictions with post-release data to guide ongoing management of a reintroduced population

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Abstract

Reintroductions have generally had a low success rate, and lack of monitoring has meant that for most species few data have been available to inform decisions. To help reduce uncertainties in these decisions, adaptive management (AM) provides a framework for improving management based on new information. I used an AM approach for a reintroduced toutouwai (*Petroica longipes*) population in Turitea Reserve. Prior to the reintroduction, monitoring data from 10 previous reintroductions were combined into a Bayesian hierarchical model to make population predictions based on the site's rat density and habitat connectivity to the surrounding landscape. This prior model predicted that population establishment and growth were likely, so the reintroduction was conducted. I monitored the population over its first breeding season to collect site-specific survival and fecundity data. These new data were combined with the prior model to create an updated model to improve predictions. Turitea data showed lower adult survival and fecundity compared to the prior model predictions. The combined model estimated a finite rate of increase (λ) of 0.97, compared to 1.33 from the prior model, suggesting that persistence was less likely than originally predicted. These updated predictions were used to guide the first post-release management decisions following the end of the first breeding season. As rats are known to impact toutouwai fecundity and female survival, I created a set of alternative management options for different rat control options and modelled population predictions for each of these alternatives. Based on these predictions, stakeholders chose the alternative that best achieved the fundamental objectives of the reintroduction – population growth and minimal cost – which was increasing rat control in a core area around the toutouwai territories. This alternative was implemented before the 2022/2023 breeding season to improve survival and breeding success. I continued to monitor the population over the 2022/2023 breeding season so that models could be updated again once the season was over, continuing the AM cycle. Initial analysis of the 2022/2023 nest success suggested that the management change had a positive effect, with the probability of a nest succeeding nearly doubling compared to the previous season. This project highlights the importance of monitoring reintroduced populations to be able to improve reintroduction outcomes through informed management. I recommend using AM to manage reintroduced populations so that better outcomes can be achieved, and the knowledge gained can also inform future reintroduction decisions.

Acknowledgements

I would firstly like to thank Doug Armstrong and Zoe Stone probably more than I am capable of expressing for all their help, friendship and letting me be part of their team. I've really enjoyed working with you guys out in the field especially and hope we get to do it some more. You've both taught me so much about toutouwai, conservation and a heap of other things. And also thank you for being the best last-minute readers ever (so sorry about that!).

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To all the quirky Turitea toutouwai I got to limbo through supplejack and slide down ridges after all summer, obviously couldn't have done this without you. I could sit watching you go about life for hours on end and in some cases I did. I hope we can get your population going strong soon.

Finally, I feel this section wouldn't be complete without mentioning my full-time fieldwork buddy through this thesis and beyond, and constant companion, Ashkii (pictured below). Here's to many more years bush-bashing and birding with you. My rock.

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Chapter One – Introduction

A translocation is the movement of organisms from one area to be released in another area (IUCN, 1987). The three main types of translocation are an introduction, to establish a population, a reintroduction, to re-establish a population, or a restocking, to boost the numbers of a population. A reintroduction is a conservation translocation where a species is being moved from one place where they are present to part of their indigenous range where they no longer exist (Seddon et al., 2007; Armstrong & Seddon, 2008; IUCN, 2013). Depending on outcome goals, a reintroduction, or any conservation translocation, can often be considered successful if it results in a self-sustaining population (Griffith et al., 1989; Parker et al., 2013). While reintroductions have been implemented for over 100 years, they generally have a low success rate (IUCN, 1987; Griffith et al., 1989). In a survey by Griffith et al. (1989) the success rate of translocations of threatened, endangered, or sensitive bird or mammal species was only 46%. Since then, in a review of reintroduction literature between 1979 and 1998, Fischer and Lindenmayer (2000) found that 20/87 (23%) of reintroductions for conservation purposes were reported as successful, 23/87 (26%) were considered failures, with the outcomes of another 44/87 (51%) unknown or uncertain at their time of writing. Low success rates are likely due to poor planning, inappropriate site or habitat conditions, and a lack of prior information on species’ requirements. Inadequate post-release monitoring resulted in a lack of learning from both successful and unsuccessful reintroduction efforts (Seddon et al., 2007; Parker et al., 2013; Seddon & Armstrong, 2016).

Wildlife reintroductions are a complex form of management where multiple decisions need to be made under uncertainty (Panfylova et al., 2019). Reintroduction biology is a relatively new field of science, first formally recognised at a conference in 1993 (Serena & Williams, 1994). It is an applied science that takes a decision science approach, using research and evidence to inform and support conservation translocations in order to achieve better conservation outcomes (Taylor et al., 2017). There is a great deal of uncertainty regarding most aspects of reintroductions both before and after they take place, because they involve moving individuals to an area where they no longer occur (Chauvenet et al., 2015; Panfylova et al., 2019). For example, habitat quality, potential threats, or species’ management requirements can all affect translocation outcomes and they vary between potential sites. Decision science can help guide reintroduction planning through defining goals and management objectives prior to conducting a reintroduction, and developing effective post-release monitoring (Nichols & Armstrong, 2012). Using decision science would increase the research value and knowledge gained from reintroductions, benefitting not only local management of the reintroduced population but also helping inform future reintroductions by reducing uncertainty (Seddon et al., 2007; Armstrong & Seddon, 2008). Without effective monitoring, managers will have little information to guide management and future reintroduction outcomes will not be improved. Monitoring should be done strategically in order to maximise benefit (Ewen & Armstrong, 2007). This means that key objectives need to be defined before the monitoring is planned, and possibly even before the reintroduction is considered in some cases. One of the main aims of monitoring should be to improve knowledge and therefore predictions for subsequent reintroductions (Ewen & Armstrong, 2007). This may be done by means of expert judgement (Martin et al., 2012), but also more formally by estimating parameters from previous reintroductions' data (Ewen & Armstrong, 2007; Parlato & Armstrong, 2012).

Monitoring data that are available before a reintroduction, from monitoring of previous reintroductions, can be used in a Bayesian framework to decrease the amount of uncertainty in population parameters and projections for future reintroductions (McCarthy & Masters, 2005; McCarthy, 2007; Armstrong & Seddon, 2008; Gedir et al., 2013). Dealing with site-to-site variation lends itself to hierarchical variation, variation caused by random effects such as differences among sites (McCarthy & Masters, 2005). After a reintroduction takes place, the process of post-release monitoring enables the inclusion of location-specific data into the Bayesian model, thereby enhancing the accuracy of predictions regarding the reintroduced population's likely trajectory (Gedir et al., 2013; Drummond et al., 2018). This means better decisions can be made regarding a specific reintroduction, and the prior knowledge base for modelling future reintroductions' predictions can be built upon. Particularly where site-specific data are limited such as in early years post-release, Bayesian hierarchical models built including prior data mean that more informed decisions may be made regarding the management of the reintroduced population or for future reintroductions. By updating Bayesian hierarchical models, new data better informs reintroduction management decisions through adaptive management.

Adaptive management is a formal structured approach to making recurring management decisions where there is uncertainty around the decision being made (Holling & Walters, 1978; Walters, 1986; Williams, 2011; Runge, 2013). It is a continuous decision making cycle (Figure 1.1) of defining objectives, modelling predictions under different management alternatives, selecting the best option, monitoring the outcomes, analysing new information gained, and finally reviewing decisions and adapting management (McCarthy et al., 2012). Adaptive management places emphasis on learning about the system that is being managed through monitoring in order to reduce uncertainty. As a result, management practices may adapt or change as knowledge increases, which ideally leads to better outcomes. The Bayesian framework is very suited to adaptive management as it allows for prior data to be combined with newly collected data from monitoring (McCarthy, 2007). Due to the high uncertainty in many components of a reintroduction (Panfylova et al., 2019), adaptive management is a particularly useful tool in reintroduction biology (McCarthy et al., 2012). Management decisions can be reviewed as knowledge increases, and uncertainty of outcomes can be decreased by means of monitoring and methods such as updating Bayesian hierarchical models.

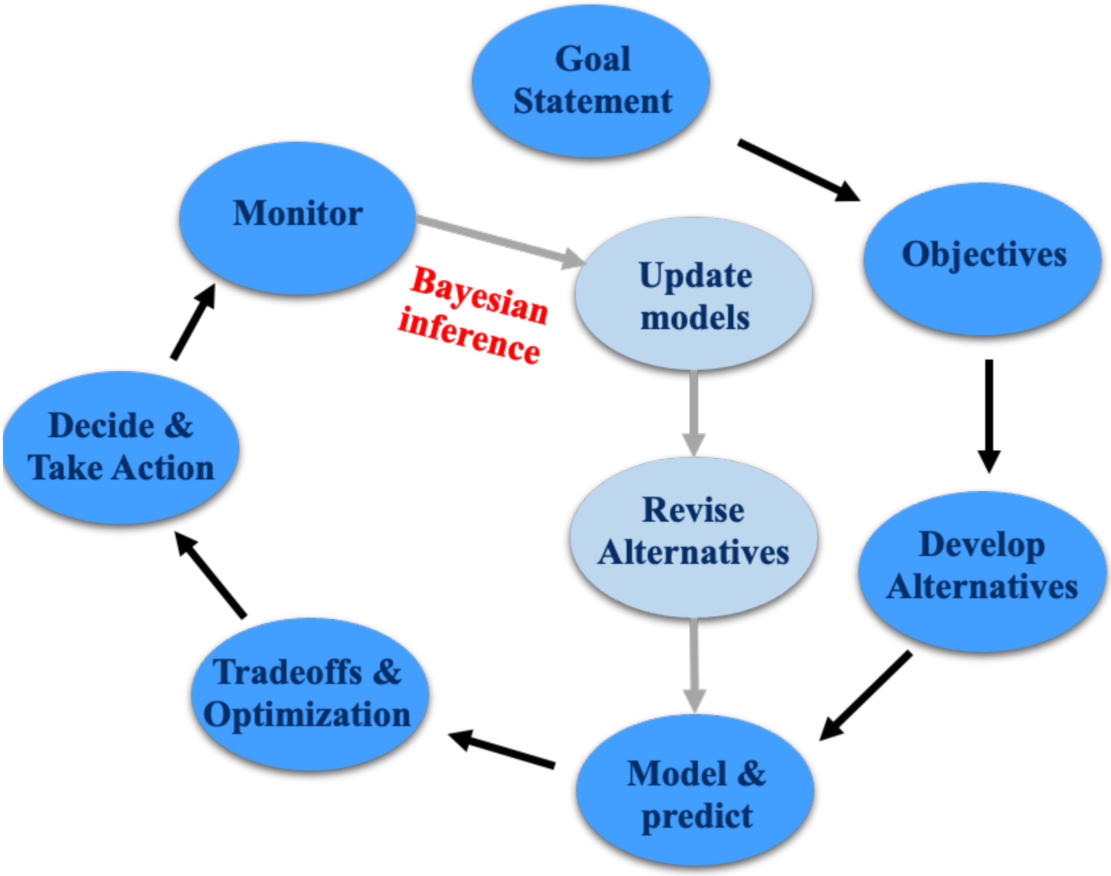

Figure 1.1. The structured, cyclical process of adaptive management, adapted from Canessa et al. (2019).

In Aotearoa New Zealand (NZ), reintroductions and other conservation translocations have a long history, dating back to Richard Henry's efforts to translocate three species of flightless birds to predator-free islands in Fiordland between 1895 and 1907 (Miskelly & Powlesland, 2013). While these first serious translocation efforts failed due to stoat invasions on the islands, they set the stage for future translocations of Aotearoa NZ fauna. Henry's motives for the translocation also are consistent with objectives for most Aotearoa NZ translocations to date – to protect, and so conserve, species and individuals from the impacts of introduced mammalian predators. Aotearoa NZ's fauna have evolved in isolation away from terrestrial mammalian predators with high rates of endemism, reduced predator escape response, and many shared life history traits (e.g., flightlessness, slow reproductive rates) which makes them highly vulnerable to newly introduced predatory species (Holdaway, 1999; Duncan & Blackburn, 2004). Following human settlement, initial human hunting pressures and predation by mammalian predators (kiore, *Rattus exulans*) led to an initial wave of extinctions of many species. Later European arrival meant the introduction of a host of mammalian predators including mustelids (*Mustela spp.*), Norway rats (*Rattus norvegicus*) and ship rats (*Rattus rattus*), and cats (*Felis catus*), which along with increased pressure from human hunting and habitat loss caused further extinctions and population declines (Holdaway, 1989). In current times the largest threat to extinction of many native species is predation by introduced mammals (Holdaway, 1989; Innes et al., 2010; O'Donnell et al., 2015).

Development of predator control and island eradications in Aotearoa NZ has meant translocations have become a critical tool for protecting vulnerable populations and preventing further extinctions (Miskelly & Powlesland, 2013). Many of the remaining species most vulnerable to predation have been translocated to predator-free offshore or mainland islands, leading to many conservation success stories (Armstong & McLean, 1995; Miskelly & Powlesland, 2013; Armstrong, Moro, et al., 2015). With over 1000 documented translocations in Aotearoa NZ by 2015 (Armstrong, Moro, et al., 2015), mostly reintroductions of native species, Aotearoa NZ has been at the forefront of the development of reintroduction biology. A substantial amount of research in the ever-growing field of reintroduction biology has come from Aotearoa NZ (Seddon et al., 2007; Ewen et al., 2012; Armstrong, Hayward, et al., 2015). Much of the recent advances have been focussed on improving reintroduction outcomes though population modelling (e.g., Gedir et al., 2013), making better predictions about reintroduction outcomes (e.g., Parlato & Armstrong,2012, 2013), and using monitoring information to better inform management decisions (e.g., Armstrong et al., 2007).

While not all reintroductions in Aotearoa NZ have had appropriate monitoring, one species with a long history of reintroductions and detailed monitoring data collection is the toutouwai (*Petroica longipes*), or North Island robin (Figure 1.2). The toutouwai is a small, insectivorous passerine weighing approximately 26–32g (Higgins & Peter, 2002). Once present across most of the North Island of Aotearoa NZ, toutouwai have experienced considerable range contractions due to forest clearance following the arrival of humans, particularly after the arrival of Europeans. Introduced mammalian predators, particularly ship rats (*Rattus rattus*), have also contributed to this decline as nests are subject to predation of eggs, chicks, and females during the breeding season (Brown, 1997). These threats, along with the birds' short dispersal range across pasture gaps, have meant that toutouwai are now missing from much of the mainland. They now occur only in small, fragmented remnant populations across a contracted range, and at predator-free or controlled sites where they have been reintroduced (Parlato et al., 2015).

Figure 1.2. One of the released toutouwai (adult male) reintroduced to Turitea Reserve, Palmerston North, October 2021. Photo: K. Macdermid

Toutouwai are socially monogamous and territorial birds with each pair typically remaining in its established territory for its whole life (Armstrong et al., 2000). They breed from September to March, with females capable of having up to three clutches of 1–3 young each. Female are solely responsible for incubating eggs, for a period of around 19 days. Both parents feed chicks for approximately 21 days until chicks fledge, and continue to feed fledglings until they disperse 3–4 weeks after fledgling (Armstrong et al., 2000). Juveniles are sexually mature by the start of the next breeding season (Armstrong et al., 2000). These life history traits make toutouwai nests and adult females highly vulnerable to predation from introduced mammalian predators during the breeding season. However, they are capable of persisting in low-level predator environments, so make an ideal candidate for reintroduction to managed forest reserves. The success of such reintroductions, however, is highly dependent on adequate predator control that maintains rats to a low level (Armstrong et al., 2006a). Toutouwai reintroductions into predator-free sites (offshore islands or predator-proof fenced) sites are often successful whereas those into unfenced mainland areas tend to be unsuccessful (Taylor et al., 2005; Miskelly & Powlesland, 2013).

Any reintroduction may be divided into an establishment phase and a persistence (both short-term and long-term) phase. Failure can occur at any stage. Monitoring during each phase can help identify where and how limiting factors may be impacting the success of a reintroduction (Armstrong & Seddon, 2008; Parker et al., 2013). For instance, post-release dispersal may lead to establishment failure (Le Gouar et al., 2012), while predation may impact the ability for an established population to grow (Armstrong et al., 2006a). Rat abundance is a key limiting factor that impacts both stages of a toutouwai reintroduction (Armstrong et al., 2006a; Parlato & Armstrong, 2012, 2013). One way to measure rat abundance is through rat-tracking rates which provides a relative index of rat abundance as the proportion of baited tunnels that are passed through by a rat in one night (Brown et al., 1996). Parlato and Armstrong (2013) found that this rat-tracking rate was a key predictor for toutouwai reintroduction success, having a negative correlation with population establishment. For long-term persistence, Armstrong et al. (2006a) found an increase in fecundity, adult female survival, and therefore λ (finite rate of increase) in years with lower rat-tracking rates following the reintroduction of toutouwai to Paengaroa Mainland Island. Hence fecundity, adult female survival and λ are key parameters when predicting population growth in toutouwai. Based on toutouwai reintroductions at multiple sites, Parlato and

Armstrong (2012) found that differences in these parameters among sites were partially explained by rat-tracking rates. However, they also found there was variation across sites for the level of rat control required to achieve a growing toutouwai population ($\lambda > 1$). For example, some sites required a rat-tracking rate of < 5% to achieve population growth, whereas others achieved population growth at a much higher tracking rate of 25%. They suggested that high quality habitat may be able to support toutouwai population growth in higher rat densities, particularly if there is low connectivity to surrounding lower quality habitat (Parlato & Armstrong, 2012). Monitoring has shown that toutouwai are capable of persisting at sites where less intensive rat management is needed, which has resulted in them being a commonly reintroduced species across managed habitat in Aotearoa NZ. This study demonstrated that rat-tracking data at potential toutouwai reintroduction sites can therefore be used as a key predictor of model probability of establishment, persistence, and growth of a population reintroduced to that site, so is of key importance in making decisions of whether a site is suitable.

Another factor that has a strong influence on toutouwai reintroductions is connectivity to surrounding unmanaged habitat. Habitat connectivity is the amount of habitat that is accessible to species based on their dispersal capabilities (Taylor et al., 1993). Site connectivity could be represented with two metrics – index or habitat ratio. A connectivity index represents the permeability of surrounding habitat within a 2-km buffer, reflecting the extent to which different vegetation facilitates toutouwai movement (Parlato & Armstrong, 2013). Habitat ratio is the amount of accessible forest within a 2-km buffer around the managed site divided by the area of the managed site itself (Parlato & Armstrong, 2012, 2013). Connectivity is important primarily due to its effect on initial adult dispersal away from release site and apparent juvenile survival, i.e., the probability of a juvenile both surviving to the next breeding season and remaining in the managed area around the reintroduction site (Parlato & Armstrong, 2012). When juveniles disperse from their parents' territories, site connectivity impacts whether they stay inside the reintroduction site. Juveniles dispersing away from the managed reintroduction site leads to lower population growth through reduced recruitment, essentially having a similar effect to low juvenile survival. For this reason the two are generally difficult to disentangle in population models. By tracking juvenile toutouwai, Drummond et al. (2019) found that low mortality contributed more to low juvenile recruitment into the population than dispersal. However, this study was conducted within a fenced peninsular ecosanctuary (Tawharanui, 558-ha) which has fragmented habitat (240-ha of habitat) and low landscape connectivity. There is little information for more connected landscapes about the degree to which dispersal affects population growth, and past toutouwai reintroductions into highly connected sites have largely failed (Parlato & Armstrong, 2013). Being able to distinguish between juvenile mortality and dispersal is therefore still an important factor to consider for predicting future reintroduction outcomes as increased connectivity may result in reintroduction failure (Le Gouar et al., 2012; Richardson et al., 2015). Because of these factors, connectivity metrics in combination with rat-tracking rates from tunnel data are strong predictors for population establishment (Parlato & Armstrong, 2013) and persistence (Parlato & Armstrong, 2012) of toutouwai reintroductions and were used to predict outcomes of a toutouwai reintroduction to Turitea Reserve.

Turitea Reserve is part of a 4,000-ha managed area at the northern edge of the Tararua Ranges (Figure 1.3) that includes the Turitea stream water catchment area. The reserve is managed by Palmerston North City Council (PNCC). The altitudinal range is from 83–620m above sea level, with tawa (*Beilschmiedia tawa*) forest at lower altitudes merging into hardwood forest at mid altitudes, and with horopito (*Pseudowintera colorata*) forest dominant at higher altitudes. The reserve has high habitat connectivity, connected to Tararua Forest Park, a continuous stretch of broadleaf and subalpine forest down to the southern end of the North Island, at its southern boundary. There are smaller areas of restored native corridors and fragments, as well as pine forest around its north-western side, particularly along the Turitea Valley leading towards Palmerston North (Figure 1.4). This connectivity may impact establishment and recruitment, as birds are able to disperse out of the reserve's predator control network.

The managed area has an intensive predator control network, consisting primarily of DOC200 traps and brodifacoum bait stations, which have been effective at maintaining rats at low levels. A 1,860-ha core management area (within Turitea Reserve boundaries in Figure 1.4) is covered by both traps and bait stations, while the remaining 2,000-ha of connected forest is managed with bait stations. Within the reserve, trap density is an average of 0.48 traps/ha and bait stations are at an average density of 1.16 stations/ha. Predator control was initially implemented in 2003 to eradicate possums (*Trichosurus vulpecula*) from the reserve but continued control has helped maintain low numbers of rats and mustelids (PNCC, 2022). Due to the intensive predator management within the reserve, rat-tracking rates have been maintained consistently around 20% since 2014 (Figure 1.5) and a toutouwai reintroduction was proposed by PNCC and the mana whenua Rangitāne in 2018.

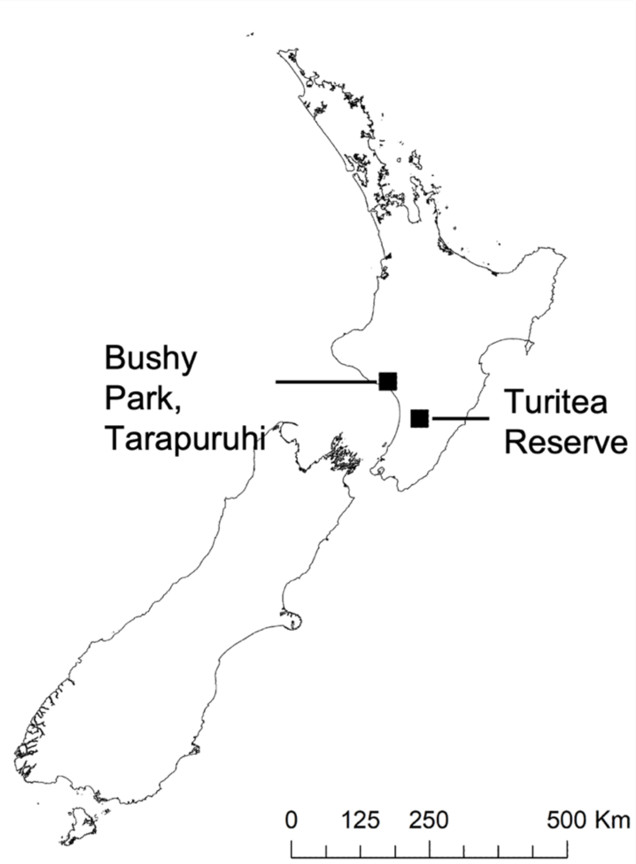

Figure 1.3. Location of the reintroduction site, Turitea Reserve, and the source site, Bushy Park-Tarapuruhi, within Aotearoa NZ.

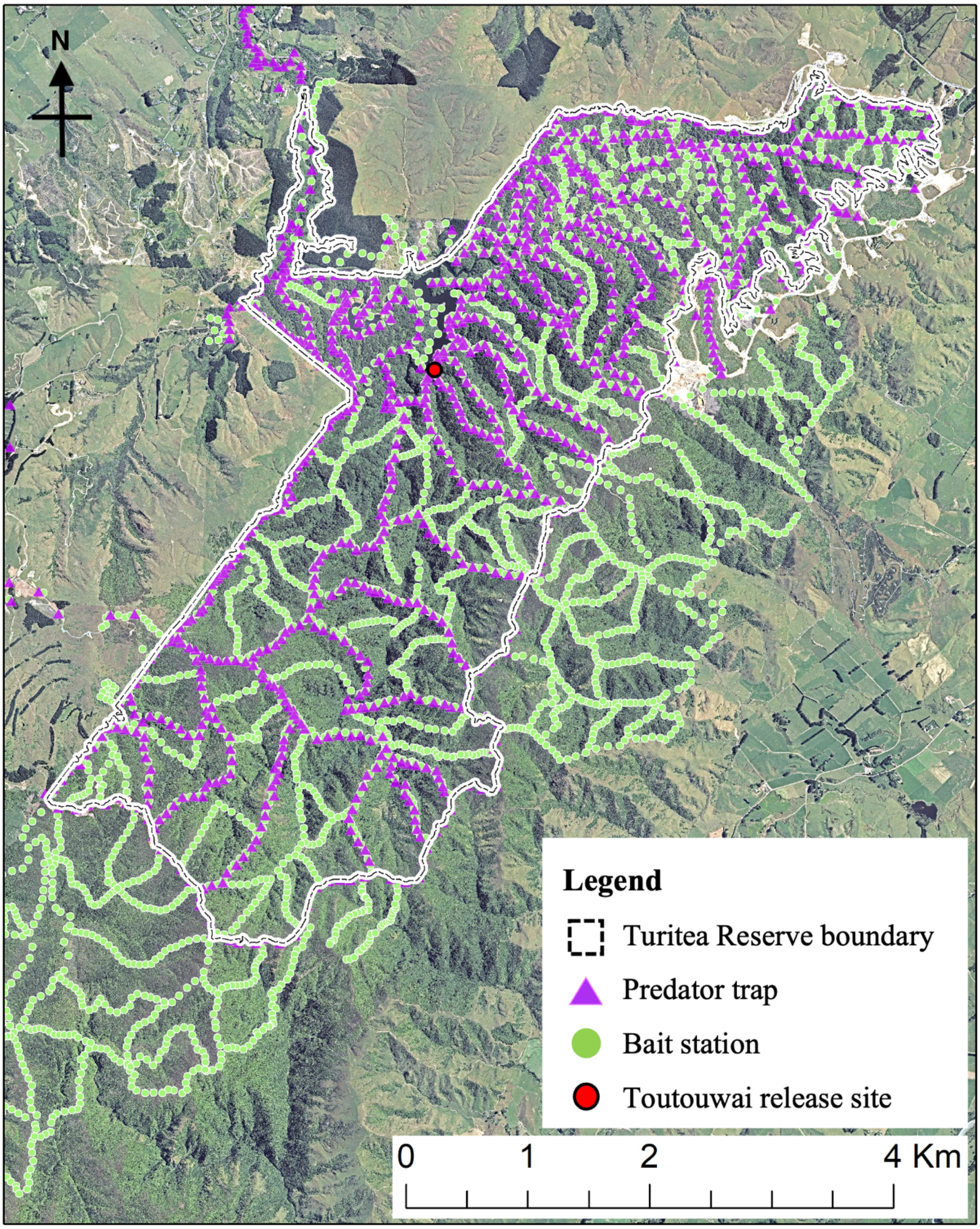

Figure 1.4 Pest control in and around the Turitea Reserve prior to the toutouwai reintroduction in April 2021 and during the first post-release breeding season over the 2021/2022 summer. Aerial imagery sourced from the LINZ Data Service and licensed by Manawatū-Whanganui LASS Ltd for reuse under CC BY 4.0.

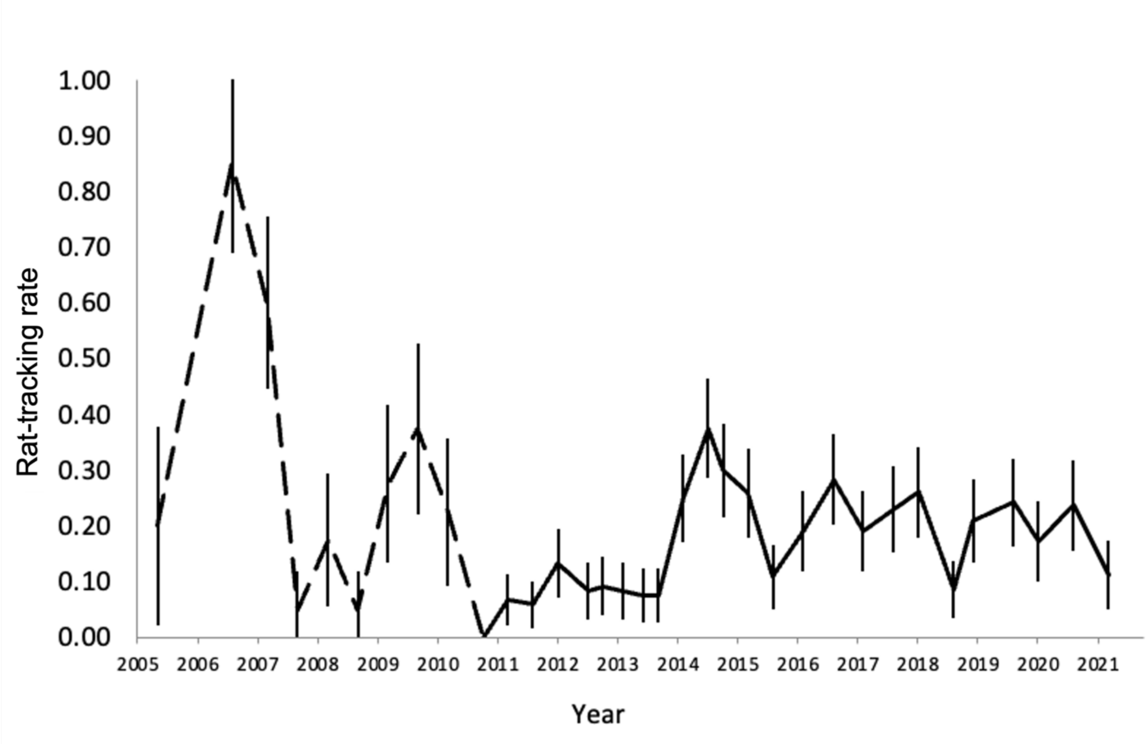

Figure 1.5. Rat-tracking rate within the Turitea reserve since 2005, with 95% confidence intervals. Before 2011 tunnels were left out for two nights, shown by the dashed line. From 2011 onwards, the more standard technique of setting tunnels out for one night was adopted. Figure from unpublished data (PNCC , 2022).

Modelling of data from previous reintroductions (Parlato & Armstrong, 2012, 2013) demonstrated that site connectivity and rat-tracking rates could be reliably used to make prior predictions for any future reintroduction. Bayesian hierarchical modelling for toutouwai involves analysing vital rates at previous reintroduction sites in relation to rat tracking rates and habitat connectivity (Parlato & Armstrong, 2012). A recent rat-tracking rate from rodent monitoring in the Turitea, along with Turitea connectivity scores were used in Bayesian hierarchical models to make predictions about likely outcomes of a reintroduction to the reserve (Figure 1.6). A connectivity index was calculated based on the level permeability in landcover (grass/pasture, water, urban, regenerating scrub, exotic plantation and native forest) for toutouwai movement within the surrounding landscape, where 0 = no permeability (grass/pasture, water and urban landcovers) and 100 was highly permeable (native forest). This connectivity index was then used to predict the number of released birds present at the start of the first breeding season based on potential dispersal (Parlato & Armstrong, 2013), and the “habitat ratio” (amount of accessible habitat within 2 km divided by the area of reserve) was used to predict apparent juvenile survival (Parlato & Armstrong, 2012). These predictions suggested that the population would have reasonable chance of persisting in the reserve under its current management regime. However, given the large variation in predator control requirements for toutouwai, it was possible that higher intensity control could be implemented by managers to further decrease rat-tracking rates if required. This offered alternative strategies for ongoing management of the Turitea population should post-release monitoring suggest it was needed in order to increase the likelihood of population persistence, that is, there was an opportunity for adaptive management.

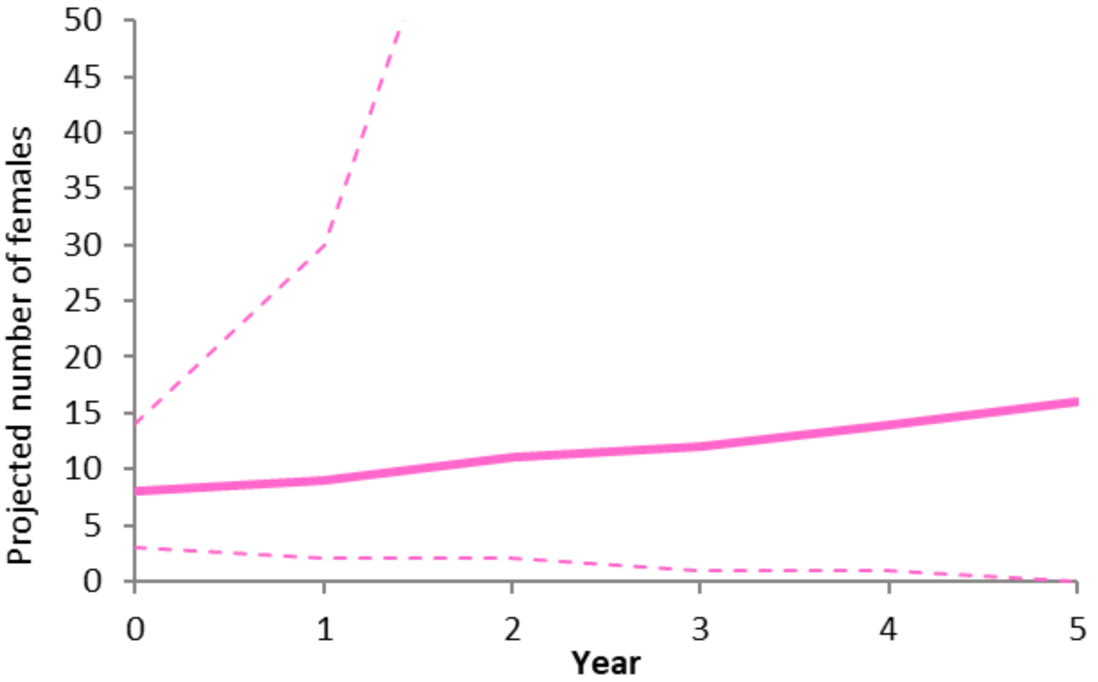

Figure 1.6. Population projection with 95% credible intervals (CRI) for a reintroduction into the Turitea Reserve, using Parlato and Armstrong's (2012, 2013) models based on data from other toutouwai reintroduction sites. This projection was made in 2018 using the rat-tracking rate at the time (0.19), habitat ratio, and random effects. It was included in the translocation proposal submitted to the New Zealand Department of Conservation (DOC) that year (PNCC, 2018).

In April 2021, 40 toutouwai were translocated from Bushy Park-Tarapuruhi to the Turitea Reserve in Palmerston North, Aotearoa NZ (Figure 1.3). In this thesis I use post-release data to reduce the uncertainty of prior population models and projections for the newly reintroduced Turitea toutouwai population. This information is then used to inform the management decisions for the reintroduced population as part of an adaptive management process for this site. Adaptive management is a repeating cycle (Figure 1.1) and this thesis takes us through one cycle of decision making following a reintroduction.

In Chapter 2, I describe the collection of population data used to update the Bayesian hierarchical model that made prior predictions for the population performance. I report the results from this monitoring over the first breeding season and combine these new data with data from other toutouwai reintroduction sites using Bayesian updating to decrease uncertainty in these predictions.

In Chapter 3, I explain how the updated models were used to guide management of the Turitea population using structured decision-making methods. Predictions were made for multiple management alternatives for the ongoing management of the population over the next year, and the best management alternative in relation to the fundamental objectives of the reintroduction, was selected in consultation with stakeholders.

This thesis is part of an ongoing conservation and management scenario. Information learned will guide future management, including for this reintroduced population. This is a key aspect of adaptive management. Chapter 4 gives an overview of what has been learned, touches upon provisional outcomes of the decisions made in Chapters Two and Three, and discusses the benefits of this research in the broader fields of conservation and reintroduction biology.

Chapter Two – Using toutouwai post-release monitoring data from the Turitea Reserve to update prior predictions

Introduction

Reintroductions are a type of conservation translocation where a species is translocated back to part of their indigenous range that they no longer inhabit (IUCN, 2013). While having been carried out for conservation purposes for over 100 years now, reintroductions have a low rate of success (Griffith et al., 1989; Seddon et al., 2014). In order to improve reintroduction success rates and management, it is essential to implement post-release monitoring (Seddon et al., 2007). Monitoring of a reintroduced population can give valuable insights as to causes of outcomes and therefore improve knowledge and outcomes of future reintroductions (Ewen & Armstrong, 2007). Such monitoring can be used to formally update prior models to improve their precision and accuracy, in order to better inform management decisions (Figure 2.1). In many cases it can be useful to monitor over multiple years in order to improve the accuracy of estimates for survival and fecundity rates which are the parameters critical for population growth.

Where there has been monitoring carried out for multiple reintroductions of the same species, data may be combined using Bayesian hierarchical modelling to increase the precision of population parameter estimates and population projections (Parlato & Armstrong, 2012). Bayesian inferences have been shown to be an effective way to decrease uncertainty in many aspects of ecological research (McCarthy & Masters, 2005). It is a relatively new method of analysis for population ecology (King et al., 2009) with many benefits in its abilities to allow complex data to be modelled while accounting for uncertainty and random variation (Parlato & Armstrong, 2012). Compared to other modelling approaches, Bayesian hierarchical models lend themselves to reintroductions because they provide a means to combine prior knowledge from previous reintroductions with post-release data in order to produce posterior knowledge. To help determine potential outcomes of a reintroduction and therefore not waste valued resources and lives, some form of prior knowledge is required before a reintroduction (IUCN, 2013). This can then be added to by post-release data after monitoring to improve knowledge and aid in adaptive management (Drummond et al., 2018).

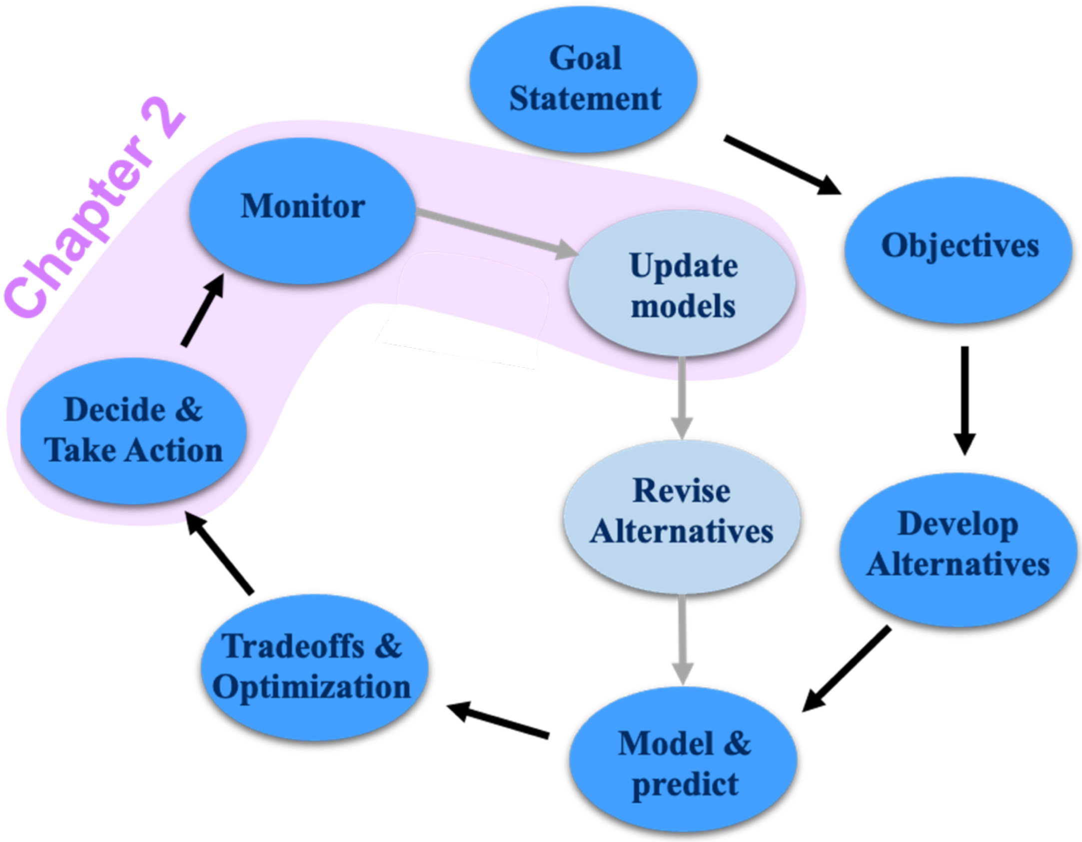

Figure 2.1. The cycle of adaptive management, highlighting the role of monitoring and updating models (covered in this chapter) in the cycle. Adapted from Canessa et al. (2019)

Prior information can be analysed in a Bayesian framework to predict appropriate sites for species to be translocated to, that is sites where there is high probability of population establishment (Parlato & Armstrong, 2013) and persistence (Parlato & Armstrong, 2012). Prior models will ideally account for factors that may influence the success of the reintroduction, such as habitat connectivity and habitat quality including presence of other species such as predators or competitors, as well as modelling random effects. By combining data collected from multiple sites the accuracy of the model is increased. In some cases there is no prior data for a species or reintroduction situation, so expert knowledge may be used as prior information (Martin et al., 2012), but also prior data from other comparable species may be used effectively where available (Armstrong & Davidson, 2006; Parlato & Armstrong, 2018). In order to predict future tīeke, North Island saddleback (*Philesturnus rufusater*) reintroduction success to sites where predators were present, Armstrong and Davidson (2006) and Parlato and Armstrong (2018) each combined data from a previous tīeke reintroductions to predator-free sites with data from a toutouwai, North Island robin (*Petroica longipes*), reintroduction. Tīeke had never been studied in the presence of mainland predators before and thus toutouwai data could be used to model relationships between tīeke population parameters and rat density to provide information on site suitability and management. Tīeke were reintroduced to Boundary Stream Mainland Island in 2004 where mammalian predators were present, based on the models by Armstrong and Davidson (2006). While a population did establish, it failed to persist long-term. One reason for this may have been because the model predictions rely on guessing the relative vulnerability of toutouwai and tieke to rat predation (Armstrong & Davidson, 2006). However, using data from toutouwai importantly allowed a formal decision making process to be carried out for whether to proceed with the reintroduction, and would also decrease uncertainty and allow for formal decision making to occur for ongoing management of a reintroduction until site and species specific data was available (Armstrong & Davidson, 2006; Parlato & Armstrong, 2018).

In their studies both Armstrong and Davidson (2006) and Parlato and Armstrong (2018) also mention that the prior information should be updated with site and species-specific post-release data using Bayesian updating, which would improve the accuracy of the model for the population in question. The ability of Bayesian methods for updating prior predictions with post-release data to improve their precision for making population predictions is a big asset for reintroduction biology, yet few studies have addressed this methodology for improving precision of models in a reintroduction situation (Drummond et al., 2018). The use of Bayesian hierarchical models for decision making for reintroductions has been noted by some as an area for growth and development (Armstrong & Reynolds, 2012; McCarthy et al., 2012; Converse & Armstrong, 2016). The updating of prior models with post-release data to guide ongoing management decisions is one such area that could vastly improve reintroduction outcomes (Armstrong & Seddon, 2008; Taylor et al., 2017). Many reintroduction programmes focus on initial establishment, with minimal following up of long-term outcomes. Post-release monitoring and addition of data into models focuses on improving long-term outcomes and ensuring fundamental objectives that focus on persistence are carried out. The knowledge gained has significant value, as it can inform adaptive management strategies to enhance the chances of population persistence.

The translocation proposal for toutouwai into the Turitea Reserve (PNCC, 2018) used a prior model to predict establishment and subsequent dynamics of the population after reintroduction (Figure 1.4), similar to the process used by Parlato and Armstrong (2012, 2013). By combining data collected from multiple prior reintroductions and considering recent connectivity and rat-tracking rates at Turitea, it was predicted that a toutouwai reintroduction to the Turitea reserve would have a reasonable chance of successful establishment and persistence (Figure 1.6). The Turitea Reserve is a 1,860-ha water catchment area within a 4,000-ha managed area near Palmerston North, Aotearoa NZ, managed by Palmerston North City Council (PNCC). It has had an extensive pest control programme in place since 2003, with possums almost completely eradicated, and rat numbers decreased from when control initially began in 2003 (Figure 1.5). Recent rat-tracking rates, the probability of a rat going through a baited tunnel, averaged 0.19 prior to the toutouwai reintroduction proposal. Past reintroductions at some sites were predicted to persist with a rat tracking rate of 0.25, while some other sites require a tracking rate of < 0.05 (Parlato & Armstrong, 2012). Based on site parameters, it was predicted that the current rat-tracking rate at Turitea would be low enough for the reintroduction to have a reasonable chance of succeeding. However, due to remaining uncertainties, prior models should be updated with post-release monitoring data in order to increase the accuracy of this prediction and guide adaptive management to improve chance of persistence if needed.

In this chapter, I report estimates of survival and fecundity produced from data collected from the reintroduced Turitea toutouwai population over its first breeding season. I then combine the modelling of these data with the prior model to improve the precision of survival and fecundity estimates for the Turitea population produced from prior data. These estimates were used to update the population predictions, which were then used to inform the next management decisions made for the population at the end of the breeding season (Chapter 3). I also estimate nest success in Turitea over the first breeding season. While there was no prior estimate for nest success, nest success is a sensitive indicator of predator impacts (Armstrong, Raeburn, et al., 2002), so is useful for assessing the effectiveness of management changes.

Methods

Toutouwai monitoring

In April 2021, 40 toutouwai were translocated from Bushy Park-Tarapuruhi to Turitea Reserve. From release in April to July 2021, toutouwai were monitored using radio telemetry. From August and through September, the start of the 2021/2022 breeding season, I searched the reserve in order to find as many pairs and individual toutouwai as possible that had survived. As batteries in the transmitters worn by the birds for initial post-release monitoring had run down (and most transmitters had fallen off the birds too), I did these initial searches mostly by walking bait station lines (Figure 2.2) and playing recordings of territorial calls every 50 – 100 m to detect responsive birds that responded to the vocalisations.

More effort was directed in areas where birds were last known to have settled or be located by radio telemetry. Additional surveys were undertaken across the reserve to ensure any remaining birds were detected. Based on a 100 m buffer around all survey routes (the detection range of call playback) I searched approximately 690-ha during the initial searches (Figure 2.2). Pest control teams working in the reserve were also listening and looking for toutouwai casually during this time but not playing recordings at regular intervals. Any detections by pest control teams were also used to locate individuals and identify territories.

Once I knew the location of territories, I checked these territories at least weekly until the end of March 2022 to generate data on survival and fecundity of the birds found. Sexes are easy to distinguish in toutouwai by behaviour over and just prior to breeding season as males sing territorially and will also courtship feed females. Toutouwai typically respond to and therefore can be located by hand claps, voice calls, or other noises, so playback calls were used rarely at this stage as they are unnecessary and often make observing males difficult as they go to the top of the canopy and sing.

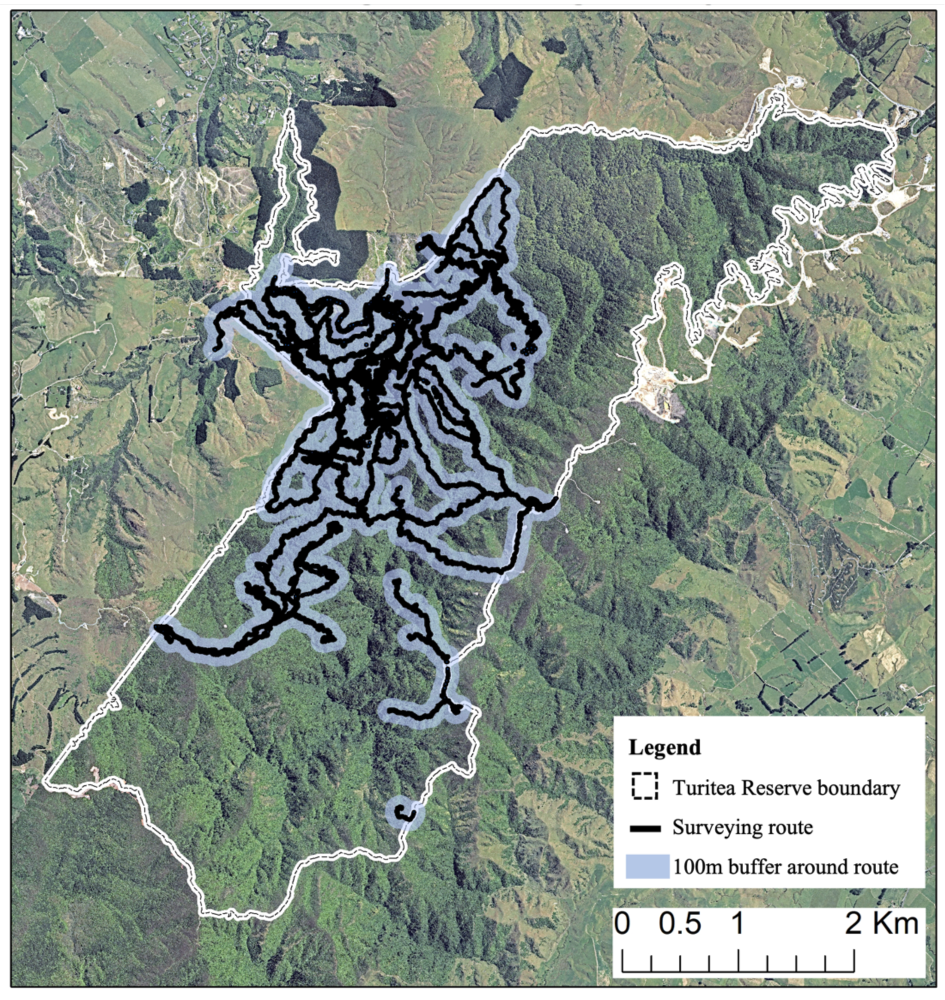

Figure 2.2. Pre-breeding season toutouwai survey effort in 2021 to locate territories. Calls were played approximately every 50–100 m and a 100 m buffer is shown around routes representing the range we assume birds would be detected in.

Breeding monitoring in Turitea was carried out from September 2021 until the last young fledged in mid-February 2022. Pairs were observed for behaviours that suggested that they were at certain stages of breeding or were raising young. Upon being found birds were fed mealworms (*Tenebrio molitor*) and I observed individuals for at least 20 minutes to ensure I could detect any changes in behaviour, and that any potentially nesting females (which can remain on their nests for prolonged periods when incubating) could be detected. The different stages I recorded were:

1. Pre-breeding feeding/pair bonding
2. Male courtship feeding female (sometimes accompanied by courtship dancing or copulation attempts)

3. Nest building
4. Incubating female
5. Chick feeding
6. Fledgling feeding
7. Failed nest attempt

During the early breeding season and other times before egg laying, males will feed mealworms to females. As males are generally more responsive due to their territorial defence behaviours, females are often located by following a male with a mealworm. Following egg-laying, once females are incubating, the male will call the female off the nest to feed her mealworms. Females will typically return to the nest before 20 minutes and so can be followed to locate the nest to record nest stage and survival. If the chicks have hatched both parents feed so can be observed taking mealworms to the nest. Once chicks have fledged parents will continue to feed the fledglings for 3–4 weeks before fledglings disperse. Observation of parents' feeding behaviour can accurately provide the number of chicks fledged, even when fledglings are not seen. Sometimes fledglings are hard to find, particularly in the first weeks after leaving the nest when they tend to stay high in the canopy. Therefore, if parents are consistently taking mealworms in opposite directions or to different locations from each other, it can be assumed they have more than one fledgling. Lack of expected incubation and feeding behaviours (stages 4–6) or reversion to stages expected at earlier stages (1–3) usually mean a nest has failed.

Using this behavioural observation method I was able to determine whether nests succeeded or failed, how many offspring were produced, and also monitor the survival of the adults over the breeding season. These methods are standard in collecting survival and fecundity data for toutouwai populations (Armstrong et al., 2006b; Parlato & Armstrong, 2012; Drummond et al., 2018).

Rodent Monitoring

Prior information tells us that rat density is a key parameter in survival and reintroduction of toutouwai (Armstrong et al., 2006b; Parlato & Armstrong, 2012). Therefore it is useful to have a comparable index of rodent density at sites where toutouwai monitoring is occurring.

This is done in the form of tracking tunnels. Tracking tunnel data have been collected regularly since 2003 in the Turitea Reserve and in nearby control sites where there is less predator control. In recent years monitoring has taken place biannually, over summer in the months of January and February, and over winter in the months of July and August. I carried out monitoring in these months in 2021 and 2022. A total of 109 tunnels were set on the predefined lines (Figure 2.2) in the reserve on each occasion.

A pre-inked card (Gotcha Traps NZ) was placed in each tunnel for one night. Tunnels were baited with peanut butter in a way that an animal must walk through the central third of the card, where there is wet ink, to reach the lure, therefore leaving identifiable prints on the non-inked outer thirds of the card as they pass through the tunnel (Brown et al., 1996). There were 12 pre-established lines in Turitea of 10 tunnels each with a 50-m spacing between tunnels. Four of these lines were established on existing trap lines, while eight were established on random compass bearings.

The summer 2022 rat index based on this tracking data is used as a parameter in the model to help predict survival, fecundity and therefore population persistence under certain rat tracking rates.

Habitat Ratio

The habitat ratio is the connectivity index used to predict apparent juvenile survival, and is calculated as the amount of accessible forest within a 2-km buffer around the managed site divided by the area of the managed site itself. Habitat ratio was calculated using maps of the land cover within the 2-km buffer using methods from (Parlato & Armstrong, 2012). The area of inhabitable forest within the 2-km buffer was summed. This included mature native and exotic forest and developing scrub > 3 m high. Areas that could only be reached by crossing > 110 m of non-habitat (e.g., pasture, water, and urban) were excluded, as this is the estimated distance that dispersing juvenile toutouwai do not cross (Richard & Armstrong, 2010).

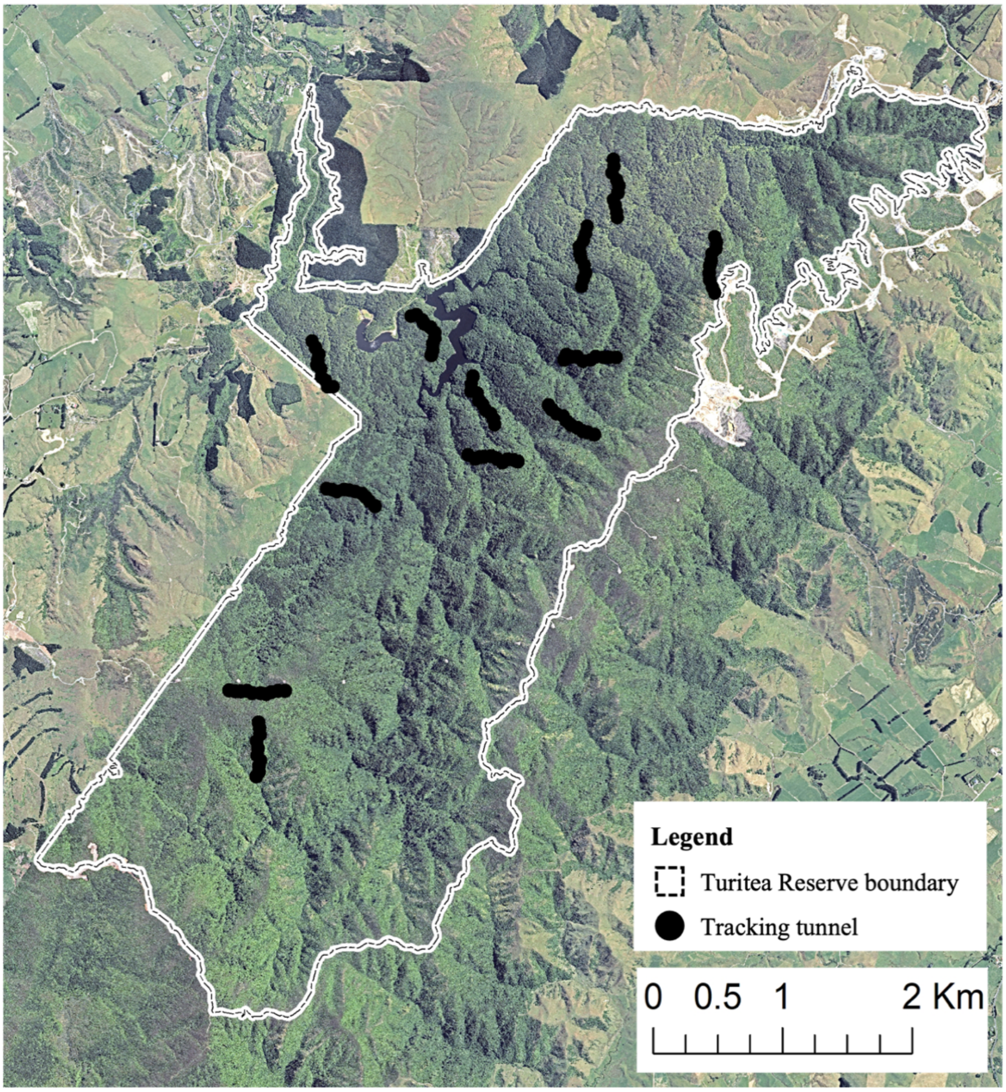

Figure 2.3. Location of tracking tunnel lines in Turitea Reserve used for monitoring rodent abundance. Each line consisted of 10 tunnels. The most eastern line was not monitored in 2021 or summer 2022 due to access issues because of windfarm construction.

Modelling

Data were modelled using OpenBUGS version 3.2.3, which uses Markov Chain Monte Carlo (MCMC) techniques to fit Bayesian hierarchical models including multiple random effects (Spiegelhalter et al., 2014). All models were run for 11500 iterations with an initial burn in of 500 iterations, which I checked was sufficient by visually inspecting the chains.

Informative priors for population parameters were generated using a model built by Parlato and Armstrong (2012) (Appendix 1). This model integrated data from 10 previous toutouwai reintroduction sites. The effects of a site being a peninsula or not on juvenile survival were removed from the model as Drummond et al. (2019) found no support for this. Data on survival, fecundity, habitat ratio and rat-tracking from the 10 previous reintroduction sites were fitted to the model in order to produce the parameter estimates for the new site based on its habitat ratio and pre-release rat tracking rates.

Adult survival probabilities are given as:

$$\log(\emptyset A_{i,j,sex}) = \alpha sA + \beta s1 * \log(1 - rt_{i,j}) * (1 - sex) * bs_{i,j} + \gamma sA_i$$

where αsA is the intercept, $\beta s1$ is the effect of rats and indicates whether the individual is female (0) or male (1), $rt_{i,j}$ is the rat tracking rate, $bs_{i,j}$ indicates whether the interval is over the breeding season (1) or not (0), and γsA_i is the random site effect. Rat-tracking rate is only calculated to affect adult female survival in breeding season. As females are most affected by rats in breeding season, when they are vulnerable to predation on the nest (Brown, 1997), their survival outside of breeding season is calculated as being the same as males.

Fecundity, measured as number of fledglings per female, is given as:

$$\log(\mu_{i,j}) = \alpha f + \beta f1 * \log(1 - rt_{i,j}) + \gamma f_i$$

where αf is the intercept, $\beta f1$ is the effect of rats, $rt_{i,j}$ is the rat tracking rate, and γf_i is the random site effect

Juvenile recruitment, the probability of surviving from fledgling to the start of the next breeding season and staying in the managed area, is given as:

$$\log(\emptyset J_i) = \alpha sJ + \beta s3 * hr_i + \gamma sJ_i$$

where αsJ is the intercept, $\beta s3$ is the effect of connectivity, hr_i is the site's habitat ratio, and γsJ_i is the random site effect.

Lambda (λ), the finite rate of increase of the population, is calculated from adult female survival, female juvenile recruitment, and fecundity. It is given as:

$$\lambda_i = \emptyset F_i + \frac{1}{2} * \emptyset J_i * \mu_i$$

where $\emptyset F_i$ is the annual adult female survival probability, $* \emptyset J_i$ is the probability of a juvenile surviving from fledging to the next breeding season (and remaining in the managed area), and μ_i is the fecundity. The sex ratio of recruits was assumed to be 50:50.

The rat tracking rate for the original model was 0.19, as this was the rate from when the reintroduction was proposed. I re-ran the prior model using the rat-tracking rate for the 2021/2022 breeding season (0.24), as this allowed direct comparison with the model updated based on the new data. I used this model to generate population projections from the start of the breeding season using the number of males and females found as the starting population.

I first modelled the Turitea data independently of prior data (Appendix 1). Only adult survival and fecundity Turitea data were modelled. As this is the first breeding season of the population, there was no juvenile survival data at this stage. Uninformative priors were used for all parameters in this model.

Turitea data were integrated into the prior model using Bayesian updating methods. The two sets of code were combined so that parameter estimates from the previous sites became informative priors that were updated using Turitea data. The rat-tracking rate from during the 2021/2022 breeding season was used in the model. Habitat ratio remained the same.

Adult survival at Turitea was modelled using a state-space formulation of a live-recapture model (Schofield et al., 2009) from encounter histories of the toutouwai from early September to the end of March. Individuals, recognised by their unique colour band combination, are either seen (1) or not seen (0) each time their territories were checked. It was not possible to check all territories on the same days, so missing values (NA) were entered for unchecked territories on days that other territories were checked. Only birds that were encountered from the first of September onwards were included in the model, excluding all toutouwai that were not known to survive from release until the breeding season, thereby excluding post-release effects on survival. Some individuals were not recorded at the start of monitoring and only showed up later in the breeding season. For these individuals, they were only marked as present in the encounter history from their first encounter.

Fitting the live-recaptures model to these data allowed the probability of resighting any individual surviving a time interval such as one year. The adult survival function was the same as for the prior model with distinction between sexes. Female survival during the breeding season was modelled as a function of breeding season rat-tracking rate. Females are generally the limiting sex in a toutouwai population and they are vulnerable to rat predation on the nest, so survival rates are graphed here only for adult females, and population projections use adult female survival data.

Fecundity was modelled using Poisson regression, with the log of the mean number of fledglings considered to be a function of the rat-tracking rate, similar to the prior model. This gave a distribution for the number of fledglings per female. No age distinction was made between females, as female toutouwai are capable of breeding in their first season, and specific ages of released birds were undetermined.

I modelled the nest records (Appendix 1) to estimate nest success, i.e., the probability of a nest surviving for the 40 days necessary to fledge chicks (typically 19 days incubation and 21 days brooding (Powlesland, 1997)). Nest success can be calculated by estimating the daily survival rate (DSR) and raising this to the power of 40. To facilitate estimating the DSR, I constructed a matrix consisting of a row for each nest and a column for each day of the breeding season. Survival status was entered as a one when active, a zero when failed and an NA (missing value) for days nests were not checked (Schmidt et al., 2010). DSR in the model was assumed constant as with such a small sample size it was inappropriate to consider more complex models. One nest was monitored with a trail camera (Browning Spec Ops Edge) from the end of incubation until the nest failed approximately a week later, and so the survival status inferred from these camera data was included in the matrix.

Results

A total of 18 birds, 10 females and 8 males, were found in the pre-breeding surveying and subsequently monitored over the 2021/2022 breeding season. Nineteen nests were monitored between September and March, only six of which were successful. Eleven chicks fledged from the six successful nests, with eight known to have survived to independence. These eight were banded to help with ID in the future. Over the course of the breeding season three males and five females disappeared, none of which have been seen again. The number of rodent monitoring tunnels tacked by rats in winter 2021 was 16/109, giving a rat tracking rate of 0.15. In summer 2021/2022 28/119 tunnels were tracked by rats so the rat tracking rate was 0.24. The habitat ratio was 1.45.

Survival

The prior model predicted an adult female annual survival probability of 0.76 (0.62–0.87 95% credible intervals (CRI)) (Figure 2.4). From the 6 months of Turitea data only, annual adult female survival probability was estimated to be 0.34 (0.14–0.61 95%CRI) (Figure 2.4). When combined, the mean of the posterior distribution for adult female annual survival was calculated at 0.67 (0.50–0.80 95%CRI) (Figure 2.4).

The adult male survival estimate of 0.37 (0.15–0.66 95% CRI) from Turitea data was also much lower than estimated from the prior model (0.77, 0.63–0.89 95% CRI). The combined model has a mean adult male survival estimate of 0.69 (0.51–0.82 95% CRI).

Juvenile survival was estimated at 0.39 (0.18–0.62 95% CRI) from the prior model. As juvenile survival was unable to be updated with Turitea data following the first breeding season, the combined model has the same distribution, which is used to calculate lambda (λ) in the combined model.

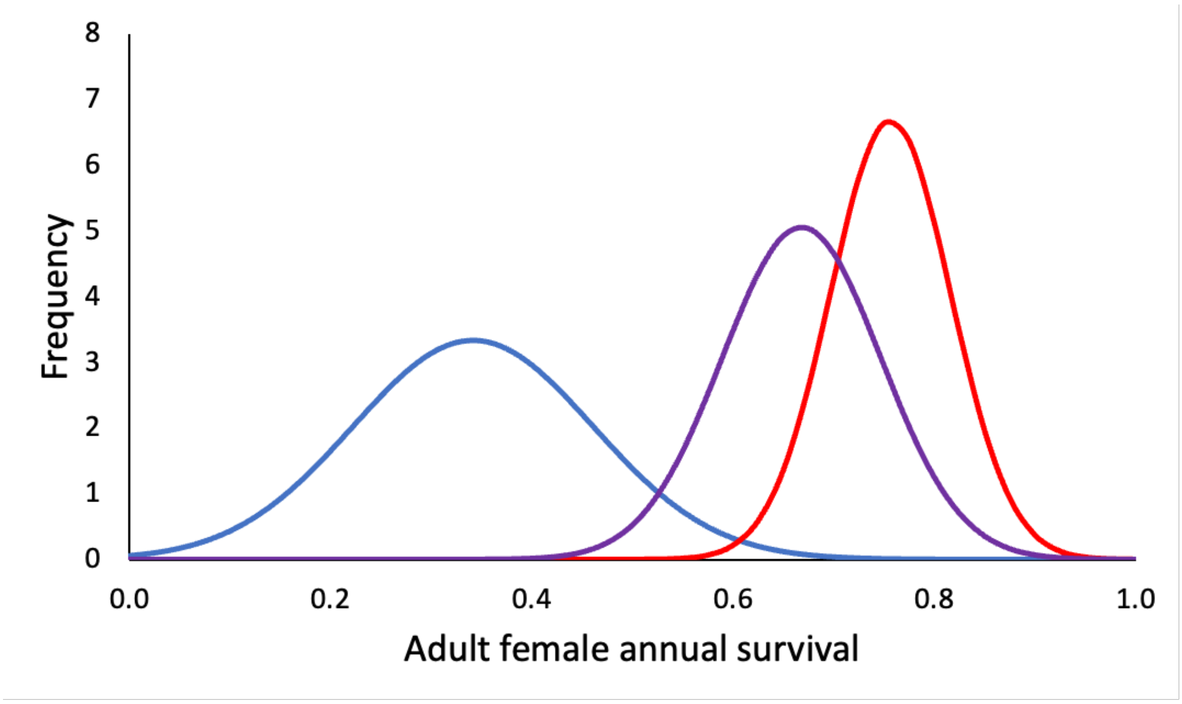

Figure 2.4. Probability distribution for annual adult female survival probability for toutouwai from prior data (red), Turitea 2021/2022 breeding season data (blue), and both data sets combined (purple).

Fecundity

The prior model predicted a mean fecundity of 2.94 fledglings per female (Figure 2.5), with 95% CRIs ranging from 1.40 to 4.78. The mean fecundity from the 10 females monitored at Turitea in the first breeding season was only 1.09 fledglings per female (0.57–1.76 95% CRI). The combined model predicted 1.53 fledglings per female.

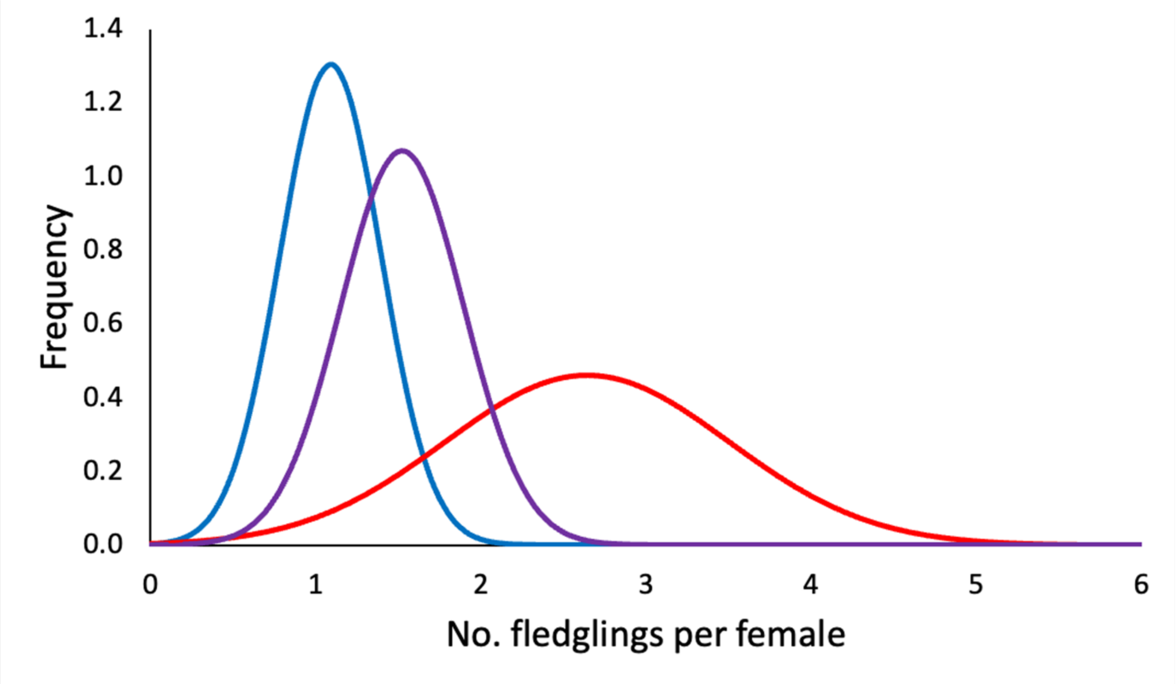

Figure 2.5. Probability distributions for fecundity (number of fledglings per female) for toutouwai at the Turitea Reserve from prior data (red), Turitea 2021/2022 breeding season data (blue), and both data sets combined (purple).

Population Predictions

Using the parameters of survival and fecundity we can make predictions about the population trajectory in future years. The prior model predicted that the finite rate of increase (λ) would be fairly confidently > 1 (mean λ= 1.33; 0.93–1.89 95% CRI) (Figure 2.6), meaning under this model population growth was possible (Figure 2.6). The updated model predicts of a lambda slightly under 1 (mean λ = 0.97; 0.72–1.26 95% CRI) (Figure 2.6). This means that growth is now much more uncertain, and the population may be declining under current site conditions and management.

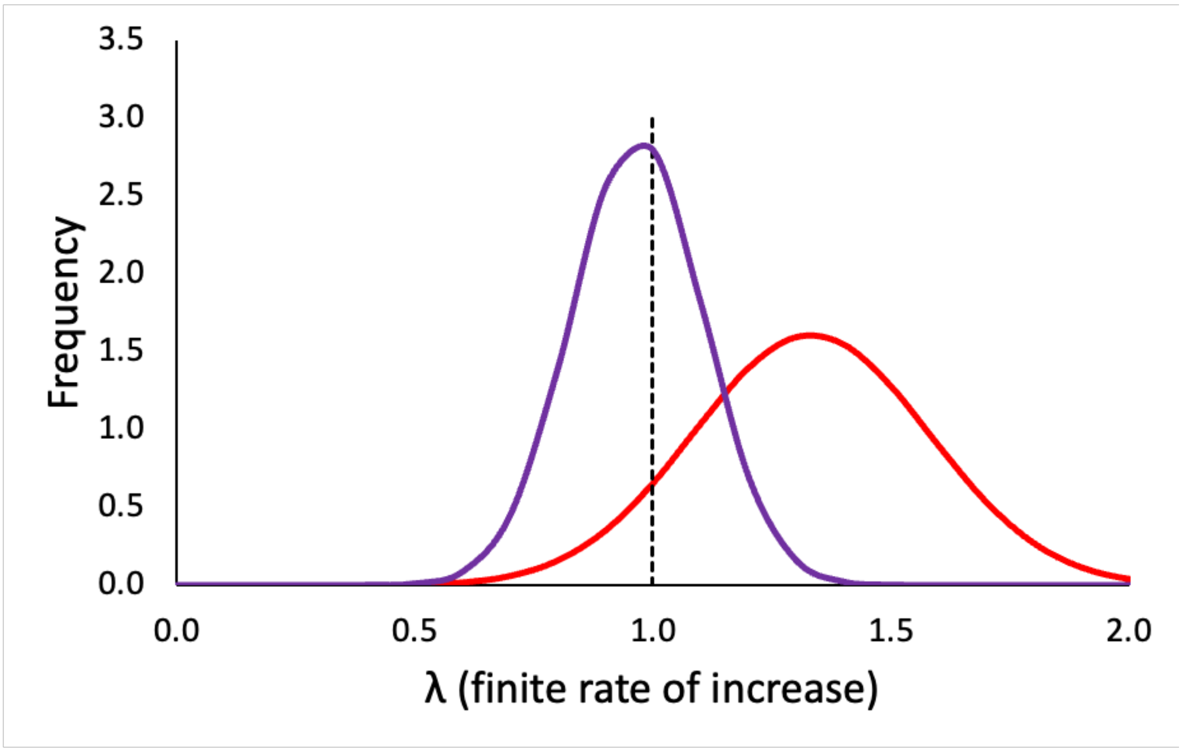

Figure 2.6. Distribution of the finite rate of increase from the prior model (red) and the posterior model (purple).

This is reflected in the updated population projections that include Turitea data (Figure 2.7). The prior projection, based on parameters from previous reintroduction sites, indicated reasonable confidence that the population would persist under current site conditions, with a median of 36 adult females predicted to be in the population by 2026. Projections from the model updated with Turitea data predicted a slow decline in the median number of females over the five years following release to 2026 when the median prediction was 8 females remaining in the population. Using the updated model, population extinction is possible by 2026, with the 2.5% prediction limit of the number of females reaching 0. Growth is still possible under this model but is much less likely.

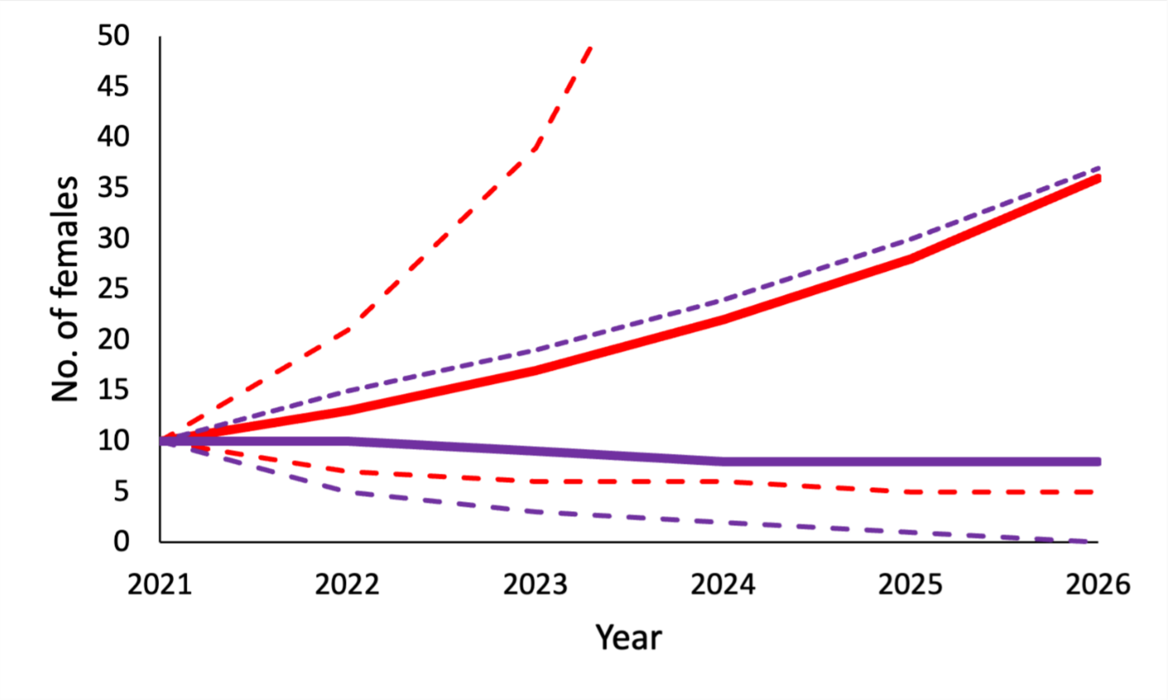

Figure 2.7. Population projection from the prior model (red) and the updated population projection from the combined model (purple) for the Turitea toutouwai population with 95% predictions intervals (dashed lines). Both of these projections started with the number of females known to be present at the start of the first breeding season after reintroduction and used the rat tracking rate from the breeding season at Turitea Reserve.

Nest success

Six out of nineteen nests monitored succeeded, giving an apparent nest success of 0.32. Modelling of nest records gave a daily survival rate of 0.97 (0.95-0.98, 95% CRI). Based on this DSR, the probability of a nest surviving 40 days, that is from eggs being laid to chicks fledging, was also 0.32 (0.15-0.52, 95% CRI) (Figure 2.8).

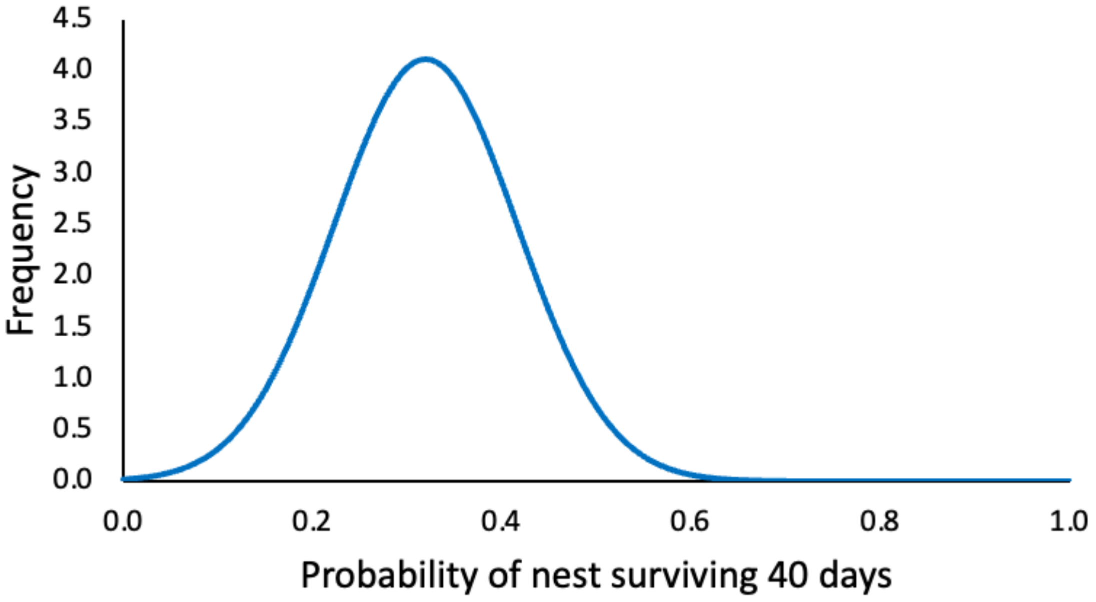

Figure 2.8. Distribution of nest success probability modelled using data from the Turitea 2021/2022 breeding season.

Discussion

Overall, monitoring showed high mortality and low nesting success of toutouwai in Turitea Reserve during the first breeding season following their reintroduction. The prior model predicted survival and fecundity rates high enough to allow population persistence and growth at Turitea, based on the rat-tracking rate and habitat ratio at the site, but there was considerable uncertainty. Survival and fecundity were both considerably lower in modelled Turitea data than prior models predicted though, meaning these rates were lower than expected based on other sites. Mean survival probability of adult females was only 0.34 compared to a prior prediction of 0.76, while Turitea data predicted mean fledglings per female of 1.09 on compared to mean fecundity of 2.94 predicted by the prior model. There was no overlap in the 95% credible intervals of the prior model survival with the Turitea survival indicating survival probability was significantly lower than expected based on other sites. For survival, there is much higher uncertainty in the mean (a wider distribution) in the Turitea model, whereas the prior model is quite precise. When combined, the posterior model predicts a survival rate closer to that predicted by the prior model (mean survival = 0.68). Fecundity predicted by the prior model had a wide distribution, compared to a narrow distribution of the Turitea data possibly due to a lot of unexplained variation among sites for the prior model. Therefore, the fecundity predicted by the posterior model leans more towards the fecundity predicted by the Turitea data – 1.53 fledglings per female – than we see in survival.

The finite rate of population increase (λ), needs to be over one for population growth. This is the most fundamental requirement for reintroduction success (Parlato & Armstrong, 2012). A λ of one is the absolute minimum for growth as populations with λ close to one are prone to stochastic extinction (Armstrong & Reynolds, 2012). The prior model predicted a growing population (λ>1). The lambda 2.5% credible limit was 0.93, giving a very low chance that lambda would be less than one. Updated with the Turitea data mean lambda was 0.97 for the posterior model, meaning there is now approximately only ca. 50% chance of population growth. It is unlikely that a reintroduction would have been approved under these odds without a change in management to improve the population parameter estimates and therefore lambda (IUCN, 2013).

Based on the posterior model, the mean number of adult females is predicted to remain approximately the same over the five years following release, although the 2.5% prediction limit reaches zero by 2026. If λ is close to 1, due to the small number of birds remaining in the population, it may be vulnerable to extinction by demographic and environmental stochasticity, and allee effects such as being unable to find a mate. While Taylor et al. (2005) found that reintroduced populations both of toutouwai and tīeke were able to grow and persist from very small founder numbers, much of their research was based on predator-free island populations where the birds had high survival and reproduction rates. This may not be the case for a large mainland site such as Turitea, where predators are managed but not completely eradicated and dispersal may impact recruitment. Additionally, lack of genetic diversity and inbreeding depression may cause decreased fitness in the population if it continues to remain at low numbers (Taylor et al., 2005; Jamieson et al., 2007). More rapid population growth in future would limit the effects of inbreeding depression on the Turitea population.

The parameter estimates for Turitea are currently from a very small population size, being from just 18 adult individuals monitored over one breeding season. Because of this, parameter estimates are generally not reliable enough to accurately inform management decisions (Gedir et al., 2013; Drummond et al., 2018). Bayesian methods account for uncertainty in their models and inform the uncertainty around parameter estimates. One of the advantages of being able to combine prior information with site data is the increase in confidence of estimates. Where there is uncertainty about whether a population will grow or persist from site data, combining with prior data may reduce uncertainty earlier than if only site data were modelled (McCarthy et al., 2012; Gedir et al., 2013). This means that management decisions may be made earlier and with more certainty, which may positively impact the population in ways such as ensuring growth and persistence. The updated model showed that there was less certainty that growth would occur, but this was because survival and fecundity at Turitea was less than expected. If Turitea parameter estimates for survival and fecundity remain low in subsequent breeding seasons, a further decline in λ would be expected from updated models as more data reduces remaining uncertainty. Intervening management would be needed to increase survival and fecundity estimates for Turitea to ensure population persistence and growth.

Low estimates for survival and fecundity may be due to rats in the reserve having a greater impact than expected based on the tracking rate. It is known that ship rats prey on toutouwai nests, causing nest failure, egg or chick loss, and sometime adult female loss (Brown, 1997; Powlesland et al., 1999). Because many of the early nests of the season failed, motion capture cameras were deployed at some nests where the location allowed. The one nest with a camera on it that failed was preyed on by a rat, confirming that rats were negatively impacting nest success and fecundity. At least three females disappeared at the same time as nest failures over the season and were not encountered again which also indicates that rats may have preyed upon these nests and killed adult females. Two other females disappeared shortly after their previous nest attempts so it is possible they died due to predation on nests we did not detect before failing. If so, as many as half of our known females at the start of the breeding season may have died as a result of rat predation. The effect of rat-tracking rate is included in the models as it has been shown to have a significant effect on probability of individual establishment (Parlato & Armstrong, 2013) and probability population growth (Parlato & Armstrong, 2012) due to its impacts on adult female survival and fecundity. However, the rat-tracking requirement for persistence varies between sites (Parlato & Armstrong, 2012). It was predicted that a rat-tracking rate of ca. 0.20 would be sufficient to allow a population to grow in Turitea. However, results suggest that Turitea may be similar to some of the sites in the prior model that require a much lower rat-tracking rate (so increased predator control) to ensure population persistence and growth.

The low fecundity at Turitea was attributable to low nest success – a 0.32 probability estimate of a nest surviving the 40 days necessary for young to fledge. The 97.5% credible limit was 0.52, indicating that it is unlikely there is a more than 50% chance that a nest will fledge chicks. There was no prior distribution for nest success, so no combined model could be built that may improve accuracy. Because fecundity was lower than predicted by the prior model it is expected this would be the case with nest success as these are closely related. However, fecundity does not necessarily reflect nest success rates accurately due to the sometimes very small amount of time to re-nesting after a failure (Armstrong, Raeburn, et al., 2002). Female survival can also be impacted by nest failures as they sometimes die due to nest predation (Brown, 1997).

The 0.32 rate of nest success, while low, is not incomparable to data on nest success from similar (mainland/unfenced/not predator-free) sites published by(Armstrong, Raeburn, et al., (2002). At Boundary Creek, which had similar predator control to Turitea (intensive bait station and trapping network), nest success was 0.47 (95%CL 0.23-0.73). In Pureora Forest Park and Paengaroa Scenic Reserve when there was little or no control of mammalian predators, nest success was ca. 0.25. Rat tracking rates at Pureora were between 0.4 and 0.6 during this period (Powlesland et al., 1999), so considerably higher than in Turitea. An intensive predator control programme in Pureora where rat-tracking rate was reduced to > 7% of tunnels tracked across the following breeding season (Powlesland et al., 1999), increased nest success to 0.6 (0.44-0.74, 95%CI). Lewis et al. (2009) also found sites they analysed had varying nest success, from 80% within a predator-proof fenced site to < 15% at other sites where predators were present. However, the low nest success at Tiritiri Matangi Island (33%) where mammalian predators are completely absent showed that other aspects such as habitat quality or avian predation are also at play (Armstrong, Raeburn, et al., 2002). There may also be a predation impact from other mammalian predators such as mustelids or cats at sites where these are present. While these sites have different environmental conditions that may contribute to varying nest success, there is a clear relationship between mammalian predator presence (primarily rats) and nest success. Therefore, nest success can be a useful indicator of the impacts of management changes (Armstrong, Raeburn, et al., 2002) and so will be useful for assessing future breeding seasons at Turitea as pest management is adapted. If predator numbers are decreased by changes in management we would expect to see an increase in nest success, as was observed in the Pureora Forest toutouwai population (Powlesland et al., 1999).

Nest success, calculated from DSR, was the same as the observed proportion of nests that succeeded over the season at Turitea – 0.32. The observed proportion, or apparent success, tends to overestimate nest success as nests that fail soon after laying are not always detected (Mayfield, 1961; Armstrong, Raeburn, et al., 2002; Dinsmore et al., 2002; Jehle et al., 2004; Rotella, 2009). The more intense the monitoring regime, the closer the apparent success will be to the calculated estimate, as nests are less likely to be missed from the data. For example at Pureora forest, where there was an intensive monitoring programme, with checks every three days (Powlesland et al., 1999), apparent nest success was only 2% higher than nest success estimated from DSR, while at other sites compared by Armstrong, Raeburn, et al. (2002) with less intensive monitoring, apparent nest success was considerably higher than estimated true success. The results from Turitea suggest that the intensive monitoring was enough to pick up the majority of nest attempts and thus the majority of failures. It should be noted that although assumed constant in the model due to sample size restraints, actual daily survival probability is not necessarily constant across the season for different nesting attempts and that it is also not constant throughout a nest attempt (Klett & Johnson, 1982; Armstrong, Raeburn, et al., 2002; Dinsmore et al., 2002). Further investigation into particularly the variation of DSR over the season in Turitea could potentially inform timings of management strategies to attempt improve the DSR earlier in the season for example, if that is where DSR is lower for the Turitea population.

While all parameter were lower than expected based off previous sites, perhaps the most notable difference was in adult survival. Both male and female survival in Turitea were considerably lower than the prior information predicted. Rat-tracking rate is known to have an effect on female survival during the breeding season (Armstrong et al., 2006b; Parlato & Armstrong, 2012). However, neither Armstrong et al. (2006b) nor Parlato and Armstrong (2012) found that rat-tracking rate explained variation in male survival, suggesting it is not affected by rat density. This may indicate that rat density was not solely responsible for low adult survival over the breeding season. Toutouwai have been found to experience food shortages, which can affect nest survival (Boulton et al., 2008). However, no research has been done on the effect of food shortages on adult survival in toutouwai. A study on another small passerine, silvereyes (*Zosterops lateralis*), found that climatic fluctuation and population density were key factors affecting survival (Sandvig et al., 2017). Although this study did not determine whether this was related to food abundance, they suggested that food availability may become a constraint on survival at lower rainfall and where there is competition for food. Intra-specific density-related food shortages are unlikely to be present in Turitea due to the small founding population size, however habitat degradation from red deer (*Cervus elaphus*) present in the reserve may contribute to poor resource availability. Deer are environmental pests in New Zealand, and can significantly impact vegetation structure and leaf litter composition in native forests through browsing and grazing (Tanentzap et al., 2009). In addition, high abundances of other insectivorous species (e.g., pōpokotea (*Mohoua albicilla*), miromiro (*Petroica macrocephala*)) may increase resource competition (Innes et al., 2010; Miskelly et al., 2021). These factors may impact toutouwai foraging , but more research would be needed to determine the extent of this, and the role it has on adult survival and breeding success.

Adult survival may also have been impacted by predators other than rats. Cats (*Felis catus*) are known to prey on toutouwai (Fitzgerald & Veitch, 1985). As toutouwai often feed on the ground, they would be at risk of cat predation during this time (Innes et al., 2010). Both males and females would be exposed to predation while feeding. This could be one reason why male survival was particularly low at Turitea, as monitoring and trapping have detected high densities of cats, particularly along the reserve boundary. Additionally, cats could prey on low nests. Several of the nests monitored over the breeding season were < 5 m above ground and so may have been vulnerable to cats. Both male and females will defend the nest if threatened so also could have been vulnerable. Native avian predators could also be responsible for on and off nest predation. Ruru (*Ninox novaeseelandiae*) are known to predate toutouwai nests (Brown, 1997). Additionally, karearea (New Zealand falcon, *Falco novaeseelandiae*), accomplished aerial hunters, have been observed preying toutouwai at a low rate at other sites (Seaton et al., 2008), so could affect adult survival rates. On at least two occasions in Turitea, ruru have come to toutouwai playback calls (pers. obs.), and on one occasion a karearea has (pers. comm. Zoe Stone), which could suggest they recognise the calls through experience as potential food. It is important that monitoring continue to assess whether low adult survival is typical for this site, and what potential causes may be. For example, if under new management targeting rodents, implemented before the 2022/2023 breeding season, survival remains low then it may suggest that other factors may be contributing to low adult survival. This could be highly useful information for site selections for future reintroductions.

Our findings show that vital rates for the reintroduced population were considerably lower than expected based off previous sites. When used to update the prior model, these data decreased the uncertainty of predictions for the Turitea population. Unfortunately, this showed that the population now has a lower chance of persistence than predicted by the prior model. In order to improve its chance of persistence and growth it is recommended for management the be reviewed. By monitoring and updating models we were able to determine that a change in management would likely be needed for the reintroduction to be successful. This shows the importance of strategic monitoring and updating knowledge. It would be extremely useful, with much learning benefit, to continue monitoring this population and updating models to see if results here are typical and also to see how the population fare under adapted management. Additionally, these results and future monitoring will help aid in decision making for future reintroductions.

Chapter Three – Adapting management of the Turitea toutouwai population

Introduction

Adaptive management is a structured approach to recurrent management decisions that involves learning through management and updating management decisions as knowledge is gained (Williams, 2011; Allen & Garmestani, 2015). It uses a structured decision making (SDM) framework to allow conservation management decisions and actions to be made despite some uncertainty of outcomes. Adaptive management began to develop as a conservation strategy in the late 1970s and 1980s (Holling & Walters, 1978; Walters, 1986) and has since become more popular for management in many areas, although it is frequently misapplied and misunderstood (Allen & Garmestani, 2015). Adaptive management involves the defining of objectives, identification of alternative management options, predictions of outcomes of alternative strategies, recognition of uncertainties, making the optimal decision based on objectives, and monitoring after the decision is made (Williams, 2011). The knowledge gained from monitoring allows prior predictions to be updated, eliminating some uncertainty. From here, alternatives management options may be revised, and so the cycle continues as outlined in Figure 3.1.

Adaptive management lends itself well to reintroductions as there is much uncertainty in predicted outcomes (Armstrong & Seddon, 2008). By learning through adaptive management we are able to decrease uncertainty so make more informed management decisions and improve predictions for future reintroductions (Runge, 2013). A Bayesian framework is an ideal way to incorporate results of monitoring with prior knowledge (McCarthy, 2007) in order to review management decisions (McCarthy et al., 2012; Ewen et al., 2023). In a Bayesian framework, complex data can be modelled while also accounting for uncertainties and random variation (Parlato & Armstrong, 2012). Bayesian hierarchical models can be updated with new data as it is collected and thus they provide a means to combine post-release data from a reintroduction with prior data. This can decrease the amount of uncertainty around key parameters of a population (survival and fecundity, for example), allowing decisions to be made earlier and with more certainty (Gedir et al., 2013; Drummond et al., 2018).

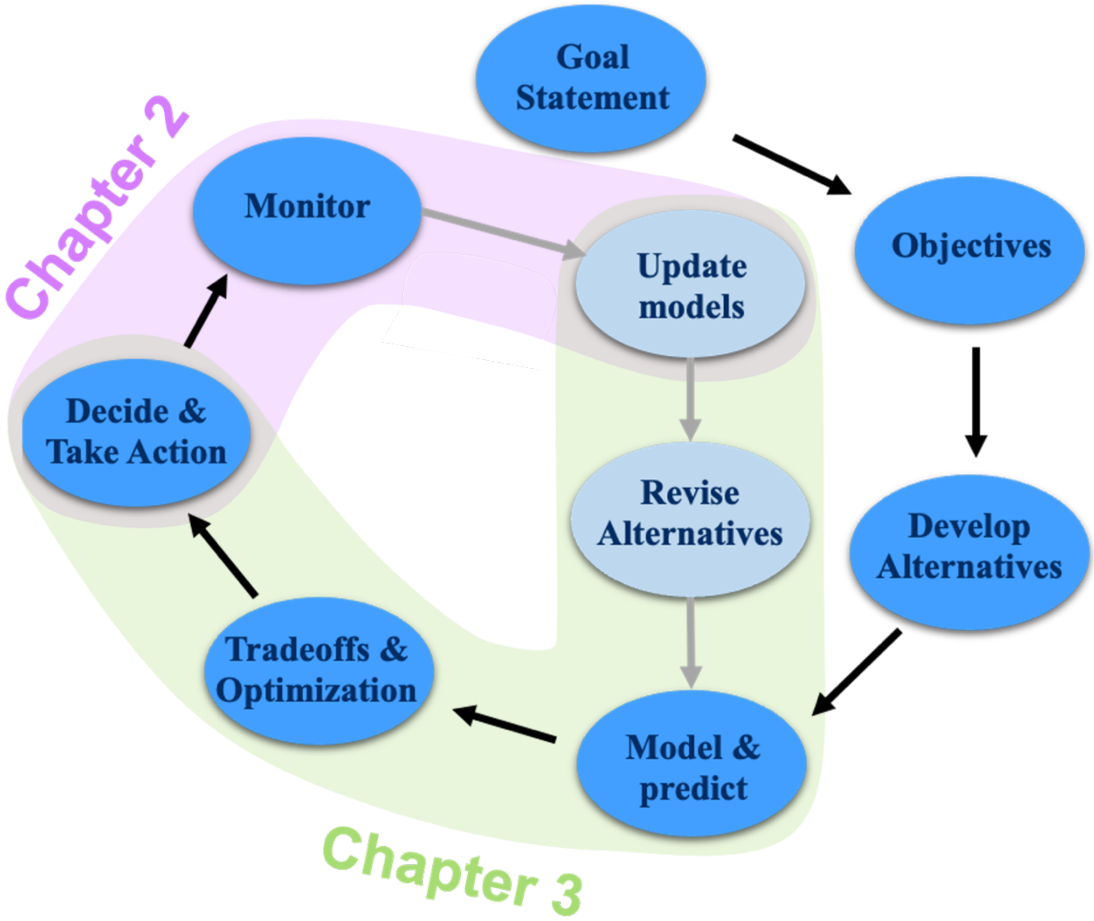

Figure 3.1. The structured cycle of adaptive management in relation to the structure of this thesis, adapted from Canessa et al. (2019). Chapter 2 covers the monitoring and updating of models following the initial reintroduction and associated management decisions made prior to the reintroduction. This chapter follows on from Chapter 2 as a study of the how the updated models have been used to make more inform ongoing management of the population.

Adaptive management may be passive or active. Although there is often much ambiguity between the two, the main distinction is the degree to which the fundamental objectives of the decision being made emphasise the reduction of uncertainty (Moore & McCarthy, 2010; Williams, 2011) – that is, how much the decision is being made for the sake of learning.

Active adaptive management actively anticipates the value of learning (Williams, 2011; McCarthy et al., 2012). Alternatives may be selected for the sake of improving knowledge, even if it is not the best alternative for resource management in the short term (McCarthy & Possingham, 2007). The aim of active adaptive management is to improve knowledge for future management (McCarthy et al., 2012; Runge, 2013), which distinguishes it from an experiment where there is no aims of management benefit. Active adaptive management has been used effectively in New Zealand to determine the food requirements for reintroduced populations of hihi (*Notiomystis cincta*) (Armstrong et al., 2007). Passive adaptive management is not guided by the objective of learning (Williams, 2011). An apparent best alternative is implemented for the system or resource being managed and monitoring of outcomes improves knowledge (McCarthy et al., 2012). This learning means that the best known alternative may change in the future. Again, this differs from a 'reactive' managing approach, as the former uses monitoring to decrease uncertainty in order to assist management decisions in the future, in contrast to changing management without formally considering the use of monitoring data to improve knowledge for future decisions. Passive adaptive management is generally simpler and so often much more practical for managing reintroduced populations, as there is less risk that a sub-optimal management alternative will be implemented (i.e., for the sake of learning in active adaptive management) and result in an unsuccessful reintroduction (Canessa et al., 2016). Additionally, it may be more easily understood by stakeholders not familiar with the process of adaptive management.

The decision to proceed with the toutouwai reintroduction into the Turitea Reserve was made based on an integrated Bayesian hierarchical model made by Parlato and Armstrong (2012) combining data from 10 other toutouwai reintroduction sites. The main decision faced in the proposal was whether to attempt to reintroduce toutouwai into Turitea reserve. Ship rats (*Rattus rattus*), which are present in the reserve, negatively impact reintroduced toutouwai populations by decreasing adult female survival and fecundity (Armstrong et al., 2006a). Because of these concerns, alternatives considered prior to the reintroduction were: A) not reintroduce toutouwai, B) proceed with the reintroduction with current management, or C) to increase predator control before proceeding with the reintroduction. Modelling prior to the reintroduction predicted that population establishment, persistence and growth was likely at Turitea under the management already in place in the reserve (Figure 1.6). Therefore option B was selected as based on information available at the time of decision, it was believed to give the best trade-off between maximising the probability of achieving a successful reintroduction and minimising cost. To facilitate a passive adaptive management approach, monitoring was to take place after the reintroduction so that prior models could be updated with site specific data to reduce uncertainty, and future management decisions could therefore be more informed. Monitoring of the population over its first breeding season showed that survival and fecundity were significantly lower than expected based on data from other sites (Chapter 2). Updated models from the monitoring data suggested that the population would have less than a 50% probability of persisting under the current management.

In this chapter I review the structured decision process that led to the initial reintroduction then work through the steps of passive adaptive management using the breeding season monitoring and updating of Bayesian models (Chapter 2) to revise the management of the Turitea toutouwai population (Figure 3.1) after their first breeding season. The primary management problem discussed was the control of rats in the reserve. Predictions based on updated modelling under each alternative were presented to stakeholders, who then selected the management alternative they believed best achieved the fundamental objectives based on the updated information. The alternative selected was then implemented by the Turitea managers, and I repeated the monitoring of the Turitea toutouwai population over the 2022/2023 breeding season to assess the effectiveness of the amended management. Management alternatives will again be revised with more information and less uncertainty after the current 2022/2023 toutouwai breeding season, based on the same structured process.

Adapting Turitea Reserve management

Stakeholders

In adaptive management, objectives of the decision being made must be clearly defined before the problem is considered. This is done by the stakeholders, i.e., people that have vested interest in the project. This translocation was a collaboration of multiple organisations. The primary stakeholders were Palmerston North City Council (PNCC) who submitted the proposal in partnership with local mana whenua, Rangitāne. Regarding the translocation process, PNCC sought advice from expert in translocations, Professor Doug Armstrong from Massey University, who provided the modelling that predicted that there was a reasonable probability of a toutouwai population establishing and persisting in Turitea Reserve. Parker Conservation undertook the translocation, alongside Massey University staff and students who were also involved in the catching and releasing of the birds and led post-release monitoring. The local mana whenua, Rangitāne, were actively involved in all stages of the proposal, advising on kaitiakitanga (conservation or environmental guardianship and protection from a Māori perspective), and were involved in catching and releasing of ngā manu (birds) from Bushy Park-Tarapuruhi to Turitea Reserve. Horizons Regional Council provide funding for the pest control in the Turitea catchment area so was also a stakeholder, as was the New Zealand Department of Conservation, who issued the permit to proceed with the reintroduction. From the source site, Bushy Park-Tarapuruhi, both the Bushy Park Trust and the mana whenua, Ngā Rauru, were consulted with and expressed their support for the project. For the purpose of the adaptive management framework for Turitea, the stakeholders involved in ongoing management decisions were PNCC and Rangitāne, with advice from Massey University staff and Parker Conservation. Other stakeholders (e.g., Bushy Park-Tarapuruhi and Ngā Rauru) would need to be involved if a second translocation (reinforcement) was considered through the adaptive management process.

Fundamental objectives

There are two fundamental objectives for the ongoing management of the Turitea toutouwai population (Table 3.1) consistent with objectives defined prior to the reintroduction. A third objective, minimising impacts on the source toutouwai population, was included in the initial reintroduction decision and will be included again if a reinforcement is considered.

Alternative Management Options

Alternative management options were devised based on expert knowledge of the site, species, threats, and options available. Rats are known to have a large impact of toutouwai populations and an increase in rat density can decrease the chance of a successful toutouwai reintroduction (Armstrong et al., 2006a; Parlato & Armstrong, 2012). As this is the main management issue for toutouwai persistence alternative strategies were developed for rat control (Table 3.2).

Table 3.1. Fundamental objectives for the ongoing management of the Turitea Reserve reintroduced toutouwai population, and how these objectives may be measured.

Objective		Measurable attributes/uncertainty
1.	Maximise the size of reintroduced toutouwai population in Turitea	Number of female toutouwai in 10 years; 95% prediction intervals
2.	Minimise costs	Amount of money spent on translocation and for changes in predator control related to this reintroduction

Table 3.2. Management alternatives considered for the ongoing adaptive management of the reintroduced toutouwai population in Turitea Reserve. The predicted outcomes of management alternatives are reported in terms of the fundamental objectives, with 95% prediction intervals for population sizes shown in parentheses. Cost increase is given as the known increase for alternative 3. For alternative 2 a cost increase was calculated by multiplying the costs of alternative 3 to fill the whole 1,860-ha reserve.

	Management Alternative (rat control)	**Rat tracking rate**	**Predicted number of adult females (2026)**	**Annual predator control cost increase ($)**
1	Status quo	0.24	8 (0–37)	0
2	Reserve wide – general control	0.05	10 (1–56)	616,425
3	Protecting territories only – core area control	0.05 in lower reserve area	10 (1–56)	127,585

The rat tracking rate in January to early March 2022 was recorded as 0.24, on the higher side of what has been recorded within the reserve over the last ten years but not significantly higher (Figure 1.5). The first management alternative was do nothing, so to keep management as is, which would incur no extra cost (Table 3.2). However, monitoring results showed that the Turitea toutouwai had poor survival (Figure 2.4) and fecundity (Figure 2.5) under the current tracking rate, so is unlikely to grow (objective 1) under this alternative (Figures 2.6, 2.7)

In order to improve the probability of persistence and growth in the population, increased predator control is needed (Chapter 2). Ideally under increased control the rat tracking rate would be brought down to < 0.05, which is a common target in intensive rat control programmes. One strategy to achieve this was to increase rat control across the whole reserve (alternative 2) to attempt to reduce the reserve-wide tracking rate to < 0.05. However, the observed distribution of known toutouwai pairs across the reserve, based on monitoring, gave us an alternative option to this strategy. The territories of the known 13 pairs in the reserve were clustered in a 223-ha area (territory locations + 200 m buffer) around the two reservoirs (Figure 3.2). This meant that there was the potential to increase control in just that area – what is known as core area strategy (Moorcroft et al., 2010; Brown et al., 2015). This means that predator control is only intensified within the core toutouwai habitat (alternative 3) in the reserve with the aim of decreasing rat numbers in the territories to improve survival and fecundity.

One other alternative could have been potentially included in Table 3.2, to remove all management in the reserve. However, this was never going to be considered as the management is in place for the protection of multiple other species such as populations of tītipounamu (riflemen, *Acanthisitta chloris*) and pōpokotea (Whiteheads, *Mohoua albicilla*), as well as the forest, ecosystem and catchment integrity and health (PNCC, 2006), as well as for the benefit of the toutouwai population.

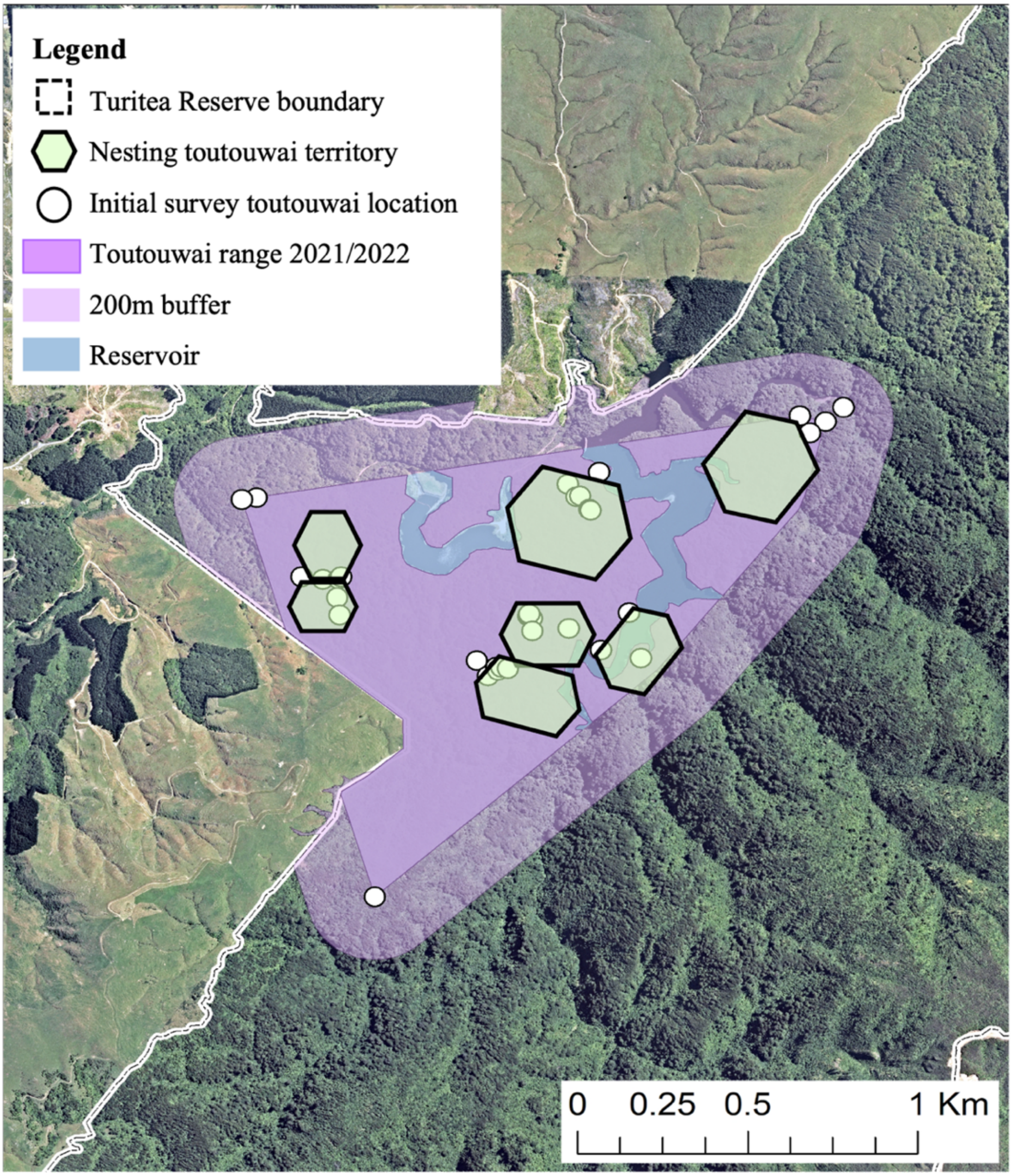

Figure 3.2. Known territory locations of toutouwai in Turitea Reserve from the 2021/2022 breeding season, with the core occupied area based on a minimum convex polygon (MCP) of toutouwai observations, buffered by 200 m.

Modelling

I used the model that was updated following the first breeding season at Turitea (Chapter 2, Appendix 1) to make population predictions under the two rat tracking rates expected under the different management alternatives, i.e., 0.24 and 0.05. I made population predictions over five years under the two different tracking rates, starting with 10 females (the number found at the start of the 2021/2022 breeding season). I assumed that the breeding territories would remain within the core area over this period, hence projections under management alternatives 2 and 3 are the same (Table 3.2).

As reported in Chapter 2, the model updated following the 2021/2022 breeding season predicted that there was a > 50% chance that the population would not grow under current management practices (Figure 3.3; Figure 3.4). The finite rate of increase (λ) needs to be > 1 for population growth to be expected, and populations with a λ close to one are at high risk of stochastic extinction. Under a 0.24 rat tracking rate (alternative 1) λ is estimated to be 0.97 (0.72–1.26 95% CRI) (Figure 3.2). Model projections had a median of 8 adult females in the population by 2026 (0–37, 95% prediction intervals), a decrease from the start of the 2021 breeding season (Figure 3.3). Under a 0.05 rat-tracking rate (alternative 2–3), λ is estimated to be slightly higher at 1.04 (0.77–1.40 95% CRI) (Figure 3.2). This is still very close to one so very vulnerable to stochastic extinction. At this lower tracking rate, a median of 10 adult females (1–56, 95% prediction intervals) was predicted after five years from an initial 10 females (Figure 3.3).

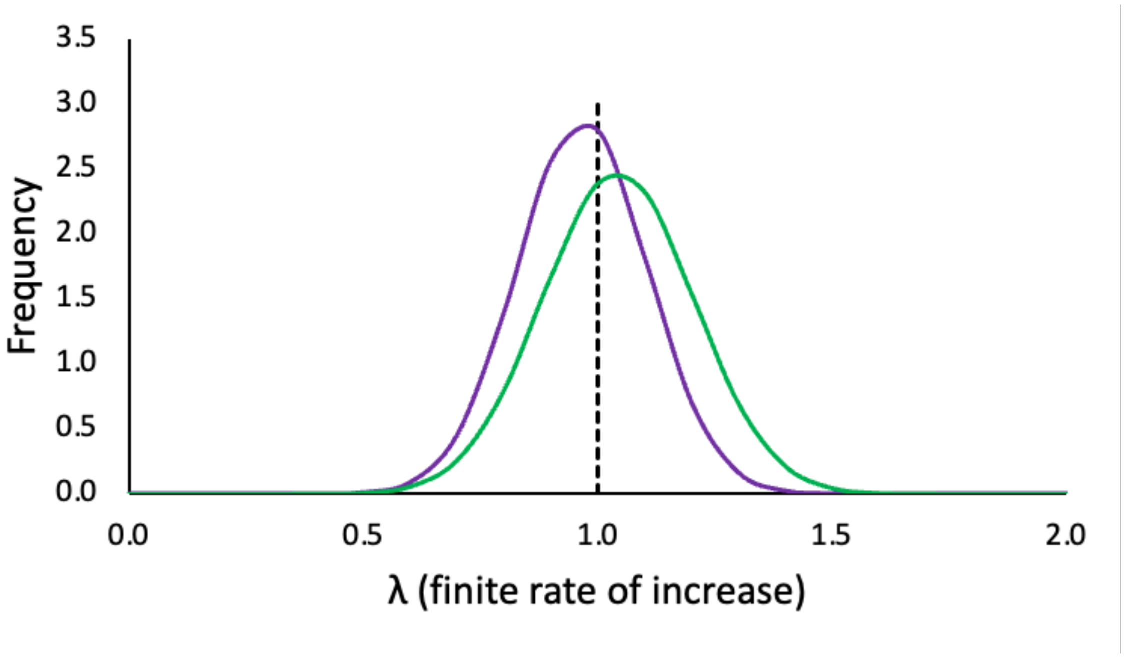

Figure 3.3 Distribution of lambda from the posterior model under the 0.24 rat-tracking rate (purple) from the 2021/2022 breeding season (management alternative 1, and a 0.05 rat-tracking rate (green) for management alternatives 2 and 3.

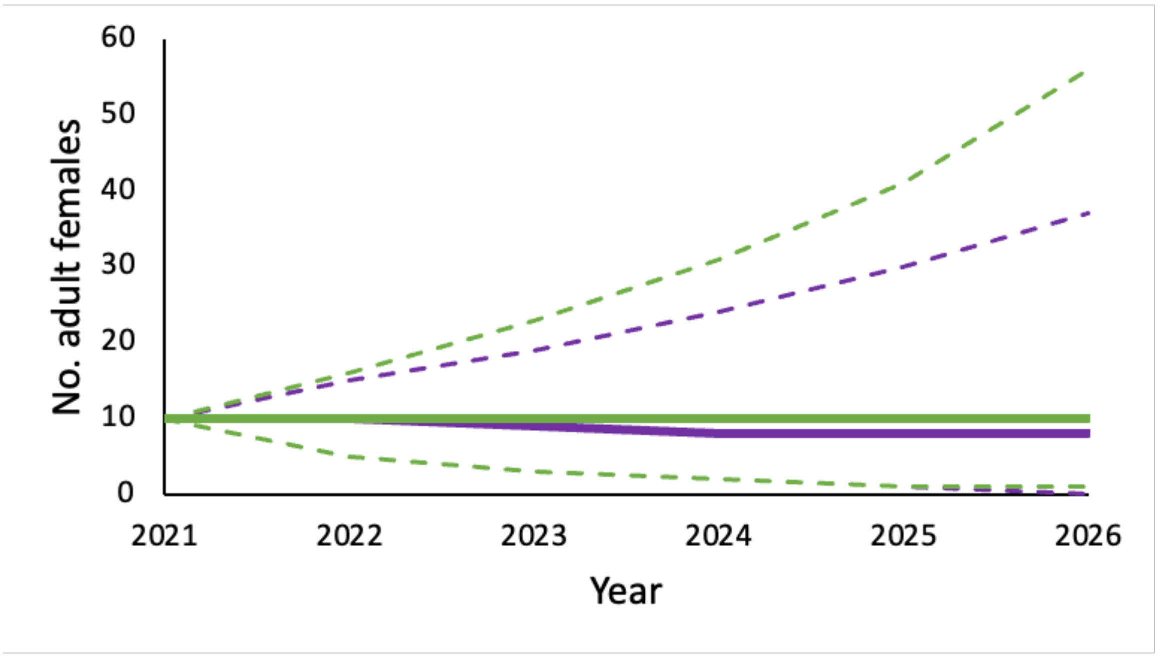

Figure 3.4. Population projections from the updated model showing the median number of adult females predicted under a 0.24 rat-tracking rate (purple; management alternative 1) and a 0.05 rat-tracking rate (green; management alternatives 2 and 3) with dashed lines showing 95% prediction intervals.

Trade-off and optimisation

Trade-offs between alternative strategies were made by the decision-makers' judgement. Management alternatives 2 (reserve-wide control) and 3 (core area control) were predicted to slightly improve the chances of the toutouwai population growing (Table 3.2). Both of these alternatives increase the cost from a standard year's predator control, while maintaining the same management in place has no extra cost but this strategy is also not predicted to improve the population's chances of persisting and growing.

Achieving a < 0.05 tracking rate across the whole reserve would be a considerable increase in control from current predator control practices due to steep and difficult terrain with some large spaces between current trap lines in areas of the reserve due to this (Figure 1.4). As well as the high cost of labour, there would be a high cost of the increase in traps and poison baits needed to lower the rat tracking rate to < 0.05 reserve-wide (Table 3.2). This cost was estimated in Table 3.2 by multiplying the known costs of increasing control in a core are (alternative 3) by the amount required to cover the 1,860-ha reserve with the same level of pest control implemented in the core area. This alternative would, however, produce benefits for other species and across the reserve as a whole as a by-product of increasing control for toutouwai, if the 0.05 tracking rate could be achieved. This does not directly relate to the fundamental objectives of the toutouwai reintroduction, but may be a consideration to stakeholders who have wider goals for the reserve. It was believed that the increase control alternatives (2 and 3) were not likely to have a negative effect on other native species. This would be something to monitor using the yearly five-minute bird counts (Dawson & Bull, 1975), however, once the new management regime is in place.

It was clear that alternative 3 would incur a much lower cost than alternative 2. Because it was anticipated that the breeding toutouwai territories would remain within the core area over the next five years, it was anticipated that alternative 3 would have the same benefit to the toutouwai population as alternative 2 in the short-term. It was possible that some dispersing juveniles would in fact establish outside the core area in that time frame, meaning alternative 3 would have less benefit to the population than alternative 2, but this is a complex scenario to model.

Decision

The decision between the management alternatives was made in April 2022 following a presentation of results to the stakeholders. Because alternatives 2 and 3 both aimed to get the rat tracking rate to < 0.05 in the area of the reserve toutouwai are known to inhabit, they give the same λ and same population projections. Alternative 3 (control in core area) was the cheaper option. Therefore alternative 3 was chosen by the stakeholders, meaning they believed it achieved the best trade-off among the fundamental objectives.

There were several methods discussed for reducing rat density in the core area. Over the first breeding season, rodent control in the core area consisted of 368 bait stations (1.29/ha) containing brodifacoum and 225 DOC200 traps (0.79/ha) along management lines (Figure 1.4). Some lines, generally in harder to access areas, only have bait stations, or also have traps but fewer at larger spacings. Most lines are within the recommended 100m spacing with only a few larger spaces between lines that could be filled by new lines. Adding these new lines would probably not have provided the increase in control necessary to achieve the desired rat density (rat tracking rate < 0.05).

It was thought a combination of traps and poison novel to the reserve would be an effective way to decrease the rat density in the core area. RatAbate striker baits were deployed over a ca. 285-ha area around the toutouwai territory locations (Figure 3.5) in July 2022, and again in August, to knock back the rat population prior to the 2022/2023 breeding season. The active ingredient of striker baits is diphacinone, a first-generation anticoagulant, which is mixed with a feed lure and contained in a biodegradable mould on weatherproof card (Connovation, NZ). Each deployment consisted of ca. 10,000 baits which are stapled to trees. While not as toxic in a single dose to rodents as brodifacoum, diphacinone has the advantages of being less toxic to birds and less persistent in carcasses (decreasing risk of secondary poisoning) (Donlan et al., 2003; Eisemann & Swift, 2006). This means it is safer to deploy in high density where there are non-target bird species present. In addition to the striker baits, recently developed auto-resetting AT220 traps were deployed over an area of ca. 800-ha, including the toutouwai core area (Figure 3.3). These traps are able to catch multiple rats between services making them more efficient than the DOC200 traps also used in the reserve (NZ AutoTraps, NZ). Both the striker baits and the AT220 traps were deployed on existing pest control lines and throughout the forest between lines.

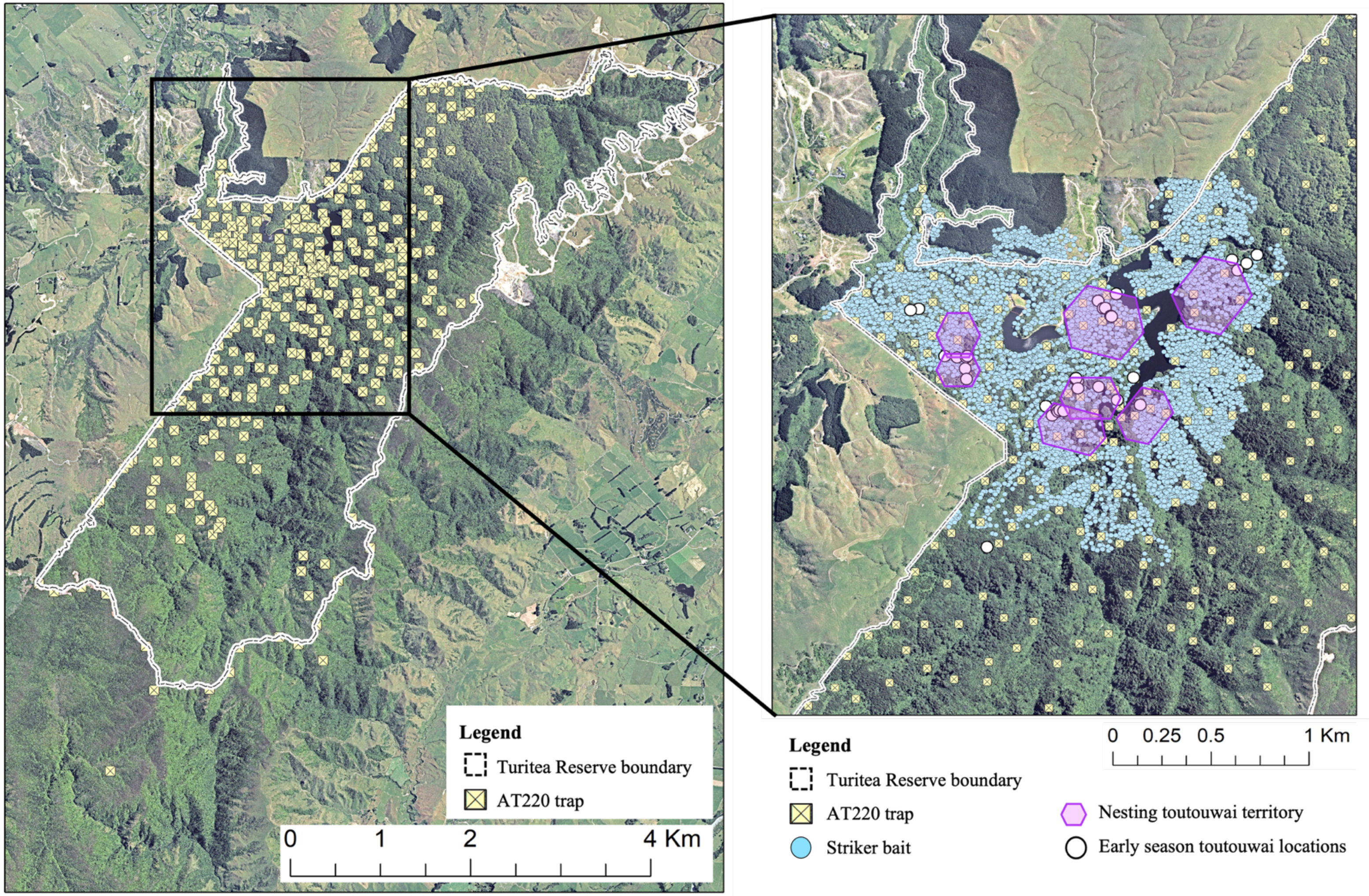

Figure 3.5. New management implemented under the core area management alternative to increase rat control around monitored toutouwai territories. AT220 traps are permanently in place while temporary Striker baits were deployed twice over winter 2022. Core area for management decisions was defined by toutouwai territories that were identified during the 2021/2022 breeding monitoring (Chapter 2).

Monitoring

The decisions were made with the knowledge that population monitoring would be continued post-decision and models updated so that more informed management decisions may be made in due course. Monitoring of the 2022/2023 breeding season is currently near completion at the time of writing (February 2023) and models will be updated again at its completion (late March 2023) to give updated population parameters and projections.

Rodent monitoring for summer 2023 has also been partially carried out at time of writing. From the two lines that have been completed, rodent lines within the core control area (Figure 3.5) had a rat tracking rate of 0 (0/20), while the one tracking line that is within the AT220 control area but outside of the striker baited area had a rat tracking rate of 0.2 (2/10). Where no additional control has occurred there was a 0.40 rat tracking rate (8/20) for the two lines that have been completed so far. This rat-tracking rate is a standard result for those lines, which suggests the decline in tracking rates inside the core control area is likely to be the result of the increase management.

With just one known nest left to fledge chicks, I modelled nest success so far this season in OpenBUGs version 3.2.3. Nest success is a sensitive indicator of whether changes in management have had an effect (Armstrong, Raeburn, et al., 2002). Nest success was calculated using the method described in Chapter 2 and Appendix 1. The model was run for 11500 iterations with an initial burn in of 500 iterations. Results were compared to nest success of the 2021/2022 breeding season (Figure 3.6).

In the 2021/2022 breeding season mean nest success probability was estimated to be 0.32 (0.15–0.52 95% CRI). Under the more intensive rodent control in the 2022/2023 breeding season nest success is estimated to be 0.59 (0.29–0.85 95%CRI). This suggests that the new management has been very effective at increasing nest success, with nest success almost doubling. There has been a corresponding increase in fecundity, with 11-12 young fledged from 5 females, as compared to 11 young fledged by 10 females in 2021/2022. As fecundity is closely linked to nest success we expect to see an increase in fecundity in updated models at the end of the season. As adult females are known to sometimes be preyed on by rats while nesting (Brown, 1997), adult female survival will also possibly increase. One of 5 females has disappeared over the 2022/2023 season at time of writing, and her disappearance was not obviously associated with nest predation. In 2021/2022 4 of 10 disappeared over breeding season, with at least three disappearances coinciding with nest predation events.

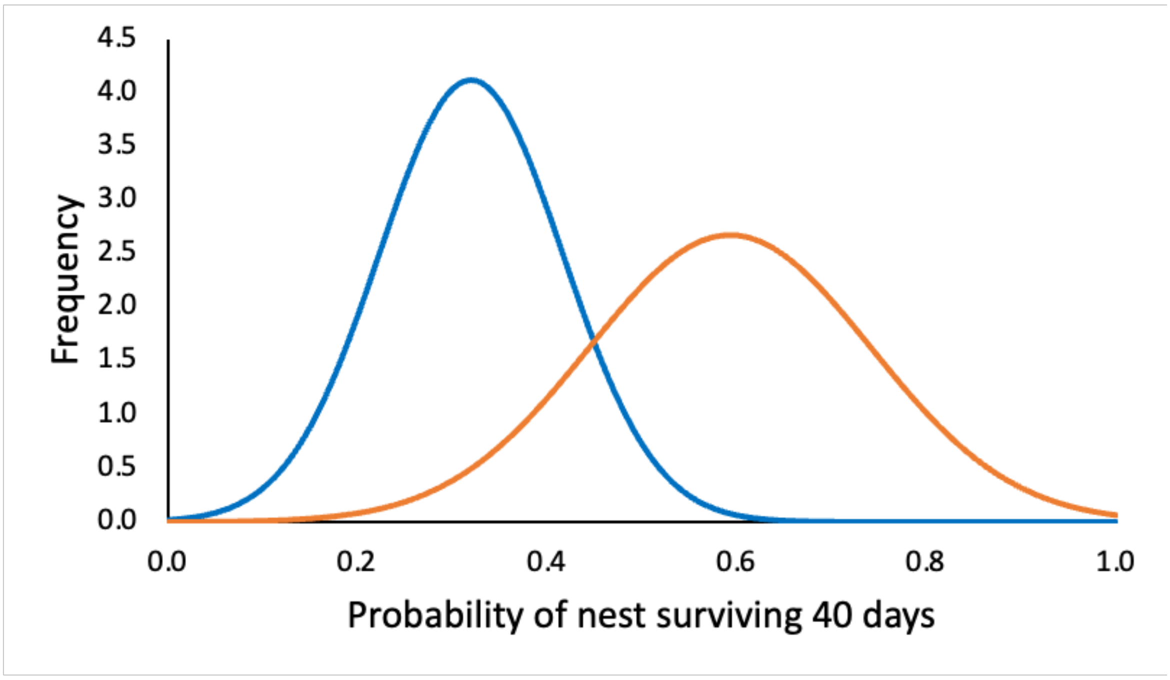

Figure 3.6 Nest success comparison between 2021/2022 breeding season (blue), under the previous rodent control regime (alternative 1), and 2022/2023 breeding season as of February 2023 (orange), under the new rodent control regime (alternative 3).

Discussion

Results from the updated Bayesian hierarchical model suggested that under previous rodent management (alternative 1) the Turitea toutouwai population had a < 50% chance of persisting. Adult survival and fecundity were considerably lower at Turitea than expected based on data from previous toutouwai reintroductions. Population persistence and growth were identified as key objectives by decision makers. In order to make it more likely that the population would persist and grow a change in pest control management would be required. Using the structured process of adaptive management, three management alternatives were devised (Table 3.2). The two alternatives that increased pest control improved population projections from a median of eight adults females remaining in the population by 2026 to a median of 10. The 95% prediction intervals for the number of females in 2026 did not reach zero under increased control alternatives but did under alternative 1. The alternative that stakeholders thought best achieved the fundamental objectives (Table 3.1) involved increasing control in a core area around the toutouwai territories. By increasing control primarily within a 285-ha area around the toutouwai territories, the aim was to achieve the recommended rat-tracking rate of < 0.05 within this core area. As we made the assumption in our modelling that the population would remain within the core area for the next five years, this management alternative resulted in the same population projections as increasing control reserve-wide, but at a much lower cost (Table 3.2).

Similar core area strategies have been implemented previously for management of other species to best achieve management goals. For example in the northern Te Urewera Mainland Island most pest species were controlled to the maximum extent possible in core areas selected for kokako (*Callaeas wilsoni*) protection (Parkes & Murphy, 2003; Moorcroft et al., 2010). Outside of these areas in the much larger area of habitat, control was still present but less intensive. The idea behind this strategy in Te Urewera was that the benefits from the increased protection in the core area may be enough to maintain population numbers outside of the core area even if it was only by means of dispersal. Maintaining a less intensive pest control program outside the core area, as is the case in Turitea with existing control, can enhance the benefits of the core area protection, for example by reducing migration of pests back to the highly protected core area (Parkes et al., 2017). Work done on Mt. Taranaki in Aotearoa NZ following a 1080 poison drop showed that a 1000-ha self-resetting ground trapping network (comprised of Goodnature A24 traps; Goodnature, NZ) was able to maintain an area of 0.56km^2 (56-ha) at the centre of the bock at a rat-tracking rate of <0.05 (±0.019, 95%CI) (Ross et al., 2020). Traps closer to the outside of the trapping block encountered rats more frequently and so the gas cannisters in the self-resetting traps ran out more quickly. In Turitea, the wider distribution of the AT220 traps than the striker zone (Figure 3.4) should provide a buffer to the more intensively controlled core area than the previously existing control network would by itself. This may decrease the rate of rodent immigration back into the core area which should help maintain a lower tracking rate in the core area for a longer period.

Because all but one of the nests monitored in the 2022/2023 breeding season have already fledged or failed, we were able to use nest success as an indicator of how effective the change in management has been for the toutouwai population. Nest success is a sensitive indicator of the effects of management (Armstrong, Raeburn, et al., 2002). Because toutouwai can repeatedly re-nest after nest failures and many failures may be offset by one successful nest with a large brood size, the increases in fecundity (young fledged per female) may not be as pronounced as increases in nest success (Armstrong, Raeburn, et al., 2002). The nest success estimate at Turitea improved considerably from the 2021/22 season to the 2022/23 season from 0.32 to 0.59. This marked increase suggests that the implemented management strategy has had a positive effect on the Turitea toutouwai population.

Powlesland et al. (1999) measured toutouwai nest success at a treatment site and a non-treatment site for their study on the effects of a 1080 (sodium fluoroacetate) poison drop in Pureora Forest Park in Aotearoa NZ. While Powlesland et al. (1999) reported apparent nest success rather than obtaining nest success estimates that take into account nests that may have been missed or failed before detection, Armstrong, Raeburn, et al. (2002) analysed their raw data to obtain estimates using similar methods as for Turitea data. The site without predator control the nest success estimate was 0.25. After the increase in predator control (the 1080 operation) at the treatment site nest success was estimated to be 0.60. These results are comparable to Turitea results from before and after increasing control in the core area. Interestingly, Powlesland et al. (1999) reported similar rat tracking rates in their treatment areas to the rates at Turitea recorded so far in the core area after increasing control. However, their non-treatment site, which only had an estimated nest success of 0.25, so lower than at Turitea in 2021/2022, had a much higher rat tracking rate (0.67–0.80) than seen at Turitea that breeding season (0.24). While this lower tacking rate in Turitea is likely a result of the long-term pest control in the reserve, the similarities between nest success before pest control increased at Turitea and with control at Pureora again suggests rats have a greater impact in Turitea than expected from other sites (see Chapter 2). This could mean that for the population to be able to persist in Turitea, the increased pest control implemented for the 2022/2023 breeding season may need to be continued in order to maintain a low rat density and high enough nest success and other population parameters.

The initial translocation proposal included the possibility for a reinforcement translocation of toutouwai to the reserve. As survival and fecundity were much lower than expected in Turitea based on data from other sites, the decision of whether to proceed with a reinforcement translocation was not considered after the 2021/2022 breeding season. The addition of more individuals to a population with a λ close to or under one, so at risk of population extinction could be considered a waste of these animals' lives and may be considered ethically inappropriate (Harrington et al., 2023). However, it may also reduce demographic stochasticity, and other negative effects of small population size (Armstrong & Ewen, 2001), improving the population's chance of persisting. Proceeding with a reinforcement reintroduction may be contemplated in the future using structured decision making, alongside other management decisions.

Monitoring of the reintroduced Turitea toutouwai population showed that survival and fecundity were lower than predicted from previous reintroductions, meaning that it was uncertain whether the population would persist. A decline to zero adult females was possible by 2026 without alternative management. This shows the importance of post-release monitoring in reintroduction programmes. Much time and effort goes into reintroduction programmes but without reliable post-release monitoring, there is no way to increase the chance of achieving outcomes or improving knowledge for the future (Runge et al., 2011; Nichols & Armstrong, 2012; Parker et al., 2013). Essentially, monitoring of the Turitea toutouwai population has continued after management has changed. This means that we can observe the effectiveness of management and learn how this type of system responds to such changes in management, and revise decisions accordingly – i.e., adaptive management. Preliminary results suggest that the management has had a positive effect on the population, such as observed with nest success. However, results from this season will be used to update the Bayesian hierarchal model and population predictions, and management alternatives will be reconsidered formally. Ideally, it would be useful to continue monitoring until uncertainty about the population's fate is minimal, but there is a trade-off between the cost of monitoring and the value of information it provides. As well as providing more informed management decisions for the Turitea population, these results further benefit future reintroduction decisions for other sites. My results will help reduce uncertainty around decisions in future reintroductions, particularly those that have similar environmental and management conditions to Turitea. In other reintroduced toutouwai, tīeke and hihi populations Armstrong, Davidson, et al. (2002) found that five years of monitoring was sufficient to be confident the population had a high chance of persistence. If λ is close to 1 longer is usually needed

(Drummond et al., 2018). Benefits can be increased by monitoring over an even longer term (Armstrong et al., 2023). However, benefits may not outweigh the cost and resources required, or the opportunity cost. These decisions would have to be considered by stakeholders, and a value-of-information analyses (Canessa et al., 2015) can aid these decisions.

In structured decision making and adaptive management there is sometimes formal weighting of objectives, i.e., precisely how valuable achieving each objective is to stakeholders (Linkov et al., 2006). This may then be used to weigh up how well each alternative strategy fulfils each objective, to give an overall best option. This was not done in the making decisions for the Turitea toutouwai management. It was left to decision makers to judge how valuable particular outcomes were to them compared to the costs, which is a commonly taken approach. Cost and conservation benefits are often conflicting objectives for trade-offs (Hemming et al., 2022), but are weighted differently (either formally or objectively) for each decision. For example, in some cases cost can be a minor concern to the importance of the conservation, such as with highly endangered species (Runge et al., 2011). However, this trade-off did not exist when deciding whether to increase rat control over the core area (alternative 3) or whole reserve (alternative 2) for 2022/2023. Because we believed these two alternatives would both result in a 0.05 rat-tracking rate around the toutouwai territories in the immediate future, the lower cost alternative gave the same predicted improvement in population growth.

The structured framework used for adaptive management of Turitea Reserve gave us a rational basis for changing management in response to monitoring, yet still remain in line with the fundamental objectives of the reintroduction. This differs from simply responding to the findings by altering management in a “trial and error” approach which tend to not recognise uncertainties, nor plan for learning such as to decrease these uncertainties (Duncan & Wintle, 2008; McCarthy et al., 2012). The process of adaptive management made the decision-making process clear, and means that there is a clear path forward to future management decisions. Decisions were made with specific, defined objectives in mind with multiple strategies considered. Multiple strategies were considered and predictions in regard to objectives made for each. The strategy that best achieved the fundamental objectives was implemented. Finally, post-decision monitoring means that alongside likely short-term population benefits, we will also learn from the decision and so future management decisions regarding the toutouwai population will be made with more certainty.

Despite the fact that examples like the Turitea toutouwai management presented in this chapter demonstrate the usefulness of adaptive management for reintroductions, there are very few examples of its application in making reintroduction decisions (Taylor et al., 2017). Here predictive modelling and monitoring was used to adapt management and improve the probability of persistence in a newly reintroduced population vulnerable to local extinction within the next few years. Data already collected suggests that the new management is having a positive effect. By modelling these data alongside prior data at the end of the season, it will serve to inform ongoing management of the Turitea toutouwai population by decreasing uncertainty of predictions, meaning more informed management decisions can be made. Species such as toutouwai, which have gathered substantial reliable post-release data multiple reintroduction efforts, demonstrate how these data can be used to perform successful adaptive management in reintroduction programmes. As there is emphasis on learning in adaptive management, benefits extend beyond population management. Data collected through adaptive management can inform decision-making for future reintroductions and ongoing management.

Chapter Four – General Discussion

In 2021 a population of toutouwai was reintroduced into Turitea Reserve, a managed reserve near Palmerston North, Aotearoa NZ (Figure 1.3). As part of the reintroduction proposal, predictions were made about the potential outcomes of reintroducing a toutouwai population to the reserve (Figure 1.6). This was done using survival, fecundity, and site data from previous toutouwai reintroductions combined in a Bayesian hierarchical model (Parlato & Armstrong, 2012, 2013), and the recent rat-tracking rate and connectivity scores for Turitea, as these are parameters known to influence reintroduction success (Armstrong et al., 2006a; Parlato & Armstrong, 2012, 2013). Results from this (known as prior) suggested that a successful reintroduction into Turitea Reserve was possible. However there was uncertainty around these predictions and so an adaptive management strategy (Figure 1.1) was used for the management of the reintroduced population. To decrease uncertainty of predictions I monitored the reintroduced population over their first breeding season to collect survival and fecundity data from the population that could be combined with the prior model. Updated predictions could then be used to make more informed management decisions after the first breeding season.

In Chapter Two, I used monitoring data from the Turitea population to update prior models (Figure 2.1). Survival and fecundity were both lower than expected in Turitea based on data from previous reintroductions. Mean survival of adult females from Turitea data was estimated to be 0.34 compared to the 0.76 estimated from the prior model (Figure 2.4). Male survival was also particularly low from Turitea data (mean = 0.37) compared to predicted (mean = 0.77). This was unusual as rat presence is not known to explain male survival (Parlato & Armstrong, 2012). Mean fecundity, in number of fledglings per female, was 1.09 from Turitea data compared to the prior estimated fecundity rate of 2.94 fledglings per female (Figure 2.5). The combined model, which was used to make updated population projections and inform decisions, gave an estimated adult female survival of 0.67 and a mean fecundity of 1.53. Lower adult female survival and fecundity meant that λ, the finite rate of population increase, was lower (mean $\lambda = 0.97$) (Figure 2.6). A λ of > 1 is the minimum requirement for population growth. This meant that the probability of the population persisting and growing was now less likely than predicted prior to the reintroduction. The median projection from the updated model showed a decline in number of females by 2026, with population extinction within the prediction intervals by 2026 (Figure 2.7).

In Chapter Three, I continued the cycle of adaptive management by using updated models to inform management for the population (Figure 3.1). Modelling results suggested that in order for the reintroduction to have long-term success, i.e., have a persistent, self-sustainable population, changes in reserve management would be needed. I used adaptive management to review management alternatives for the toutouwai population to advise stakeholders on how to adapt their management for improving its chances of persistence and growth. Their main decision was whether (and if so, how) to change the predator control in the reserve. The alternatives considered were to not changing management, increase control reserve-wide, or increase control in a core area around the known toutouwai territories (Table 3.2). I used the updated population model to make predictions for the toutouwai population over the next five years under each alternative. After being informed of predicted outcomes for each alternative, the stakeholders believed the core area alternative best achieved the fundamental objectives (Table 3.1) for the reintroduction. This strategy was subsequently implemented (Figure 3.5) for the 2022/2023 breeding season and monitoring has been underway to learn the outcomes of this decision so that uncertainties can be decreased for future management decisions.

Using a Bayesian hierarchical model to combine post-release data from the reintroduced population with prior data allowed us to decreased the uncertainty about population predictions. The model that was submitted as part of the translocation proposal predicted that a population would be able to establish and grow at the site but there was high uncertainty as to outcomes. With the reduction of uncertainty by adding site monitoring data to the model, we learned that there was > 50% chance of the population persisting. As only one year of Turitea data was added, uncertainty is still high. With each year of monitoring data collected we would expect uncertainty of outcomes to decrease (Drummond et al., 2018). For a reintroduced toutouwai population in Tawharanui Regional Park Drummond et al. (2018) found that seven years of post-release data was needed before they could be certain of population persistence i.e., λ 95% CRI completely > 1. In Tawharanui, mean λ was > 1 after all breeding seasons. In Turitea, the addition of one year of site data to the prior model has meant $\lambda < 1$. In a similar situation to Turitea, after at least seven years of monitoring a managed reintroduced hihi population on Mokoia Island there was still much uncertainty whether it would persist (Armstrong, Davidson, et al., 2002). This will likely mean that more years of monitoring will be required than at Tawharanui to be certain if the population will persist or not. Updating the Bayesian hierarchical model after the 2022/2023 breeding season will provide further insight into this and how the population's survival and fecundity, and therefore λ, have responded to the more intense management control. We will also be able to incorporate juvenile survival data from Turitea into the 2022/2023 model, which could not be included in the 2021/2022 model due to data not yet being available.. Bayesian methods lend themselves to reintroductions as they illustrate the uncertainty around outcomes. This also means they are a useful tool in adaptive management (McCarthy et al., 2012), which involves the making of decisions under uncertainty.

Taking an adaptive management approach for the Turitea toutouwai may have been essential for the persistence of the population and will continue to be so as long as there is considerable uncertainty in population projections. Without changing management, the population would have likely declined further over upcoming breeding seasons if survival and fecundity from 2021/2022 are typical for the site, resulting in a failed reintroduction attempt. Even with the improved population projections from implementing the core area management alternative (Chapter 3), there is a chance that the population will decline (Figure 3.4). The low adult male survival estimate from Turitea may suggest that nest predation by ship rats is not the only reason for low vital rates at the site. This means that while increasing rat control should improve nest success (Figure 3.6) and fecundity, low adult survival due to other factors, such as food limitation (Boulton et al., 2008) or cat predation, may yet result in population decline to local extinction. Rat presence may impact food availability to toutouwai through competition, or by impacting overall forest health (Innes et al., 2010). Therefore decreasing their numbers may improve this factor. However, adult male survival has not been low at other sites where rats have been present at similar tracking rates (Armstrong et al., 2006; Parlato & Armstrong, 2012, 2013) so it is likely rats are not the only cause of low survival at Turitea. Results from models updated after the 2022/2023 breeding season, when rat-tracking rate is expected to be lower, should provide more information on whether this is likely, and whether additional management is necessary. Continued monitoring will allow us to make more informed management decisions in the future by improving our knowledge of the population and how it responds to changes in management. Should survival remain low it may be beneficial to use different types of monitoring such as radio telemetry to track individuals in order to gain a better understanding of factors influencing the population. This would be useful information for potential reintroduction sites in the future.

Although an increase was observed, λ remained close to one under a rat-tracking rate of 0.05 – the target rate for intensive predator control - which means that in order to be more certain of population persistence long-term monitoring will be required (Drummond et al., 2018; Armstrong et al., 2023). While monitoring the Turitea toutouwai until persistence or failure can be confidently predicted would be ideal, it will be left to stakeholders to determine whether this is a valued use of their resources. From an adaptive management perspective, it would be beneficial to continue monitoring as long as possible, as this maximises the amount that can be learned from the population, as well as ensuring that the best management practices are in place. For example, long term monitoring of a griffon vulture (*Gyps fulvus*) reintroduction as part of an adaptive management framework showed that the best decision for which age birds to release in later years of monitoring was quite different to the optimal decision in early years (Runge, 2013). Continued monitoring may depend on results from updated models after the 2022/2023 breeding season is complete. Nests success at the time of writing (February 2023) was nearly double that of the 2021/2022 breeding season, suggesting the new management is having a positive effect. Apparent fecundity was also increased and apparent adult survival over the breeding season was also higher than the 2021/2022 survival estimate. It may be necessary to continue to implement increased control, such as striker bait operations for future years in order for vital parameters to remain high enough to support a viable population. Again, as there are increased costs associated with this, this is something stakeholders will need to assess the value of as part of making a decision in adaptive management. With improved survival and fecundity in the population, however, a reinforcement translocation could still be considered for future management decisions, which could improve the population's chance of persisting by reducing effects of demographic stochasticity (Armstrong & Ewen, 2001). The possibility of this occurring may act as a greater incentive for stakeholders to continue increased levels of pest control for more years.

In 2007, Seddon et al. noted that reintroductions are often carried out as a one-off management exercise (that generally generate a lot of publicity) with little or no post-release monitoring or follow-up management (which is less attractive to media). Even with continued development of the science of reintroduction biology this is still the case for many conservation translocations. Adaptive management is an underused, and commonly misused, tool in reintroductions (Taylor et al., 2017). In fact, literature that fully enacts adaptive management as I have done in this thesis, is rare across conservation biology (Westgate et al., 2013). Many examples given by Westgate et al. (2013) demonstrate active adaptive management. Examples of passive adaptive management are even less reported. Yet as a method for combining learning and management, they are perhaps more useful for bridging the gaps between stakeholder commitment, managers, and science, particularly where risk is high or a resource is considered too valuable for stakeholders to be willing to trial potentially less successful alternatives (Canessa et al., 2016). By using modelling methods such as Bayesian updating which lend themselves to reintroductions (Parlato & Armstrong, 2012, 2013) and passive adaptive management (McCarthy et al., 2012) we are able to both learn for the sake of the population being managed and to decrease uncertainty for the management of future reintroductions. In conservation biology, management decisions are frequently required to be made when outcomes are uncertain (Runge et al., 2011). An adaptive management approach is an effective way to manage while decreasing uncertainties through learning. By fully implementing an adaptive management approach for the management of the reintroduced Turitea toutouwai population, we had the opportunity to improve the probability of achieving long-term success of the reintroduction through changes in management, an opportunity we may otherwise have missed.

Conclusions

Translocations have long been recognised as a useful tool for achieving a variety of conservation outcomes (Griffith et al., 1989; IUCN, 2013; Parker, 2013). However, if they are not followed up with post-release monitoring and analyses, little is learned, regardless of whether they succeed or fail. While monitoring can be a costly and time consuming process it can provide necessary information required to achieve current and future reintroduction objectives. Investing in post-release monitoring informed us that survival and fecundity were lower for the Turitea population than predicted by an initial model using Bayesian statistics. We were able to use a Bayesian hierarchical model to combine our site data with prior information. Bayesian updating is a useful tool for adaptive management as it allows data to be progressively added to models to decrease uncertainty and better inform decisions. Using an adaptive management approach can aid in collecting and using data effectively for making-decisions. It also provides a structured framework in which learning can occur and uncertainty can be decreased for future decisions.

In this thesis I reported every step of the adaptive management process being used to manage a reintroduced population. This can be used as an example for guiding adaptive management of future reintroductions in similar situations. Our results, process, decisions, and outcomes all highlight the usefulness of adaptive management and its importance as a decision-making process for reintroductions and other conservation translocations. Particularly for reintroductions where there is high uncertainty of success, such as reintroducing native species to non-predator-free mainland sites in Aotearoa New Zealand, I recommend pursuing an adaptive management programme, as we have done here, to improve chances of achieving reintroduction objectives.

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Appendix One - OpenBUGS code

Modelling the toutouwai population reintroduced to Turitea Reserve

The model generates informative priors for vital rates through hierarchical modelling on data from 10 previous reintroductions, then updates those distributions based on survival and fecundity data collected over the first breeding season at Turitea. Estimates based on the previous data alone can be generated by deleting Section D, whereas estimates based on the Turitea data alone can be generated by deleting sections B and E. It is necessary to specify initial values such as those shown below.

Inits

```
list(a.f=1, b.f.1=0, sd.f.site=0.1, a.s.A=-0.25, a.s.J=-2.0, b.s.1=0, b.s.3=0, sd.s.site.A=0.1,
sd.s.site.J=0.1)
```

```
Model {

# A. UNINFORMATIVE PRIORS (note that constraints applied to keep in plausible ranges)

        # intercepts for the three vital rates
        a.f ~ dnorm (0, 1) I(,1.79)       # intercept for log(mean fecundity)
        a.s.A ~ dnorm (0, 1) I(,-0.1)     # intercept for log(adult survival)
        a.s.J ~ dnorm (0, 1) I(,-0.1)     # intercept for log(apparent juvenile survival)

        # effects on the vital rates
        b.f.1 ~ dnorm (0, 1) I(0,)        # effect of rat tracking on fecundity
        b.s.1 ~ dnorm (0, 1) I(0,)        # effect of rat tracking on female survival
        # peninsula effect originally included ("b.s.2" was removed)
        b.s.3 ~ dnorm (0, 1)              # effect of habitat ratio on juvenile survival

        # site-to-site variation in the three intercepts
        sd.f.site ~ dunif(0,0.7)
        tau.f.site <- pow(sd.f.site,-2)
        sd.s.site.A ~ dunif(0,0.2)
        tau.s.site.A <- pow(sd.s.site.A,-2)
        sd.s.site.J ~ dunif(0,0.4)
        tau.s.site.J <- pow(sd.s.site.J,-2)
```

```
# B. MODEL DATA FOR 10 PREVIOUS SITES TO OBTAIN INFORMATIVE PRIORS

    # Assign random effects
    for(i in 1:10) {
        re.f.site[i] ~ dnorm(0,tau.f.site)          # assign random fecundity site effect
        re.s.site.A[i] ~ dnorm(0,tau.s.site.A)  # assign random adult survival site effect

        re.s.site.J[i] ~ dnorm(0,tau.s.site.J)      # assign juvenile survival site effect
    }

    # Model rat tracking data
    for(i in 1:39) {            # for each site-year...
        p.bs[i] ~ dunif(0,1)                        # prior tracking probabilities
        x.bs[i] ~ dbin(p.bs[i], n.bs[i])            # update with data where available
    }

    # Model fecundity data
    for (i in 1:211) {                  # for each female-year except at Zealandia...
        f[i] ~ dpois (mu[i])        # sample number young fledged by the female that year
        log(mu[i]) <- a.f+b.f.1*log(1-p.bs[site_yr.f[i]])+re.f.site[site[site_yr.f[i]]]
        # model fecundity as function of b-season tracking rate & random site effects
    }
    for(i in 1:2) {             # for two site-years at Zealandia (site-years 13-14, site 5)
        fmean.est[i] ~ dlnorm(log.fmean[i],tau.log.fmean[i])
        tau.log.fmean[i] <- pow(SE.fmean[i]/fmean.est[i],-2)
        # sample estimate from distribution defined by unknown mean and SE
        log.fmean[i] <- a.f+b.f.1*log(1-p.bs[12+i])+re.f.site[5]
        # model fecundity as function of rat tracking prob. and random site effect
    }

    # Meta-analysis of survival data from estimates and SEs for each site-year
    for(i in 1:39) {            # for each site-year...
        s.F.bs.est[i] ~ dlnorm(log.s.F.bs[i],tau.log.s.F.bs[i])
        # sample estimated adult female breeding-season survival
        tau.log.s.F.bs[i] <- 1/pow(SE.s.F.bs[i]/s.F.bs.est[i],2)
        # calculate precision of log(tau(s-hat)
        log.s.F.bs[i] <- a.s.A+b.s.1*log(1-p.bs[i])+re.s.site.A[site[i]]
        # model ad. fem. b-season surv. as fn. of rat tracking & random site effects

        s.M.bs.est[i] ~ dlnorm(log.s.M.bs[i],tau.log.s.M.bs[i]) # as above but for males
        tau.log.s.M.bs[i] <- 1/pow(SE.s.M.bs[i]/s.M.bs.est[i],2)
        log.s.M.bs[i] <- a.s.A+re.s.site.A[site[i]]
        # model adult male breeding-season survival with random site effects

        s.F.nb.est[i] ~ dlnorm(log.s.F.nb[i],tau.log.s.F.nb[i])# as above but nb-season
        tau.log.s.F.nb[i] <- 1/pow(SE.s.F.nb[i]/s.F.nb.est[i],2)
        log.s.F.nb[i] <- a.s.A+re.s.site.A[site[i]]
        # model adult female non-breeding-season survival with site random effects

        s.M.nb.est[i] ~ dlnorm(log.s.M.nb[i],tau.log.s.M.nb[i])        # as above but nb
```

```
        tau.log.s.M.nb[i] <- 1/pow(SE.s.M.nb[i]/s.M.nb.est[i],2)
        log.s.M.nb[i] <- a.s.A+re.s.site.A[site[i]]
        # model adult male non-breeding-season survival with site random effects

        s.J.est[i] ~ dlnorm(log.s.J[i],tau.log.s.J[i])     # as above but for juveniles
        tau.log.s.J[i] <- 1/pow(SE.s.J[i]/s.J.est[i],2)
        log.s.J[i] <- a.s.J+b.s.3*hr[site[i]]+re.s.site.J[site[i]]
        # model apparent juv. jurv. as fn. of habitat ratio with site random effects
}


# C. DERIVE PRIORS VITAL RATES AT NEW SITE (TURITEA RESERVE)

# Calculate intercepts for each vital rate at new site, incorporating random effects
a.f.new ~ dnorm(a.f,tau.f.site) I(,1.79)
a.s.A.new ~ dnorm(a.s.A,tau.s.site.A) I(,-0.1)
a.s.J.new ~ dnorm(a.s.J,tau.s.site.J) I(,-0.1)

log(mu.new) <- a.f.new+b.f.1*log(1-p.bs.new)
# model fecundity as function of breeding-season rat-tracking rate
log(s.M.new) <- a.s.A.new    # adult male survival probability = intercept
log(s.F.new) <- a.s.A.new+0.33*b.s.1*log(1-p.bs.new)
# model adult female suvival as function of breeding-season rat-tracking rate
log(s.J.new) <- a.s.J.new+b.s.3*hr.new
# model apparent juvenile survival as function of habitat ratio
lambda.new <- s.F.new+0.5*mu.new*s.J.new
# calculate lambda for new site under current rat-tracking rate


# D. MODEL DATA FOR NEW SITE OVER FIRST BREEDING SEASON

# Model fecundity data
for (i in 1:n.ind.f) {             # for each female...
        fl[i] ~ dpois(mu.new) # sample number of young fledged by female
}

# Assign uninformative re-sighting priors
a.p ~ dnorm(0, 0.01)            # mean logit(p), where p=resighting probability
b.sex.p ~dnorm(0,0.01)          # effect of sex on logit (p))
s.t.p ~ dunif(0,2)              # sd among surveys in logit(p)
tau.t.p <- pow(s.t.p, -2)       # convert sd to tau, i.e., sd to precision

# Assign random effects to resighting probabilities
for (j in 2:n.surveys) {
        re.t.p[j] ~ dnorm(0, tau.t.p)
}

# Model survival from encounter histories
for (i in 1:n.ind) {            # for each individual...
        alive[i,first[i]] <- 1               # is known alive when first encountered
```

```
            for (j in first[i]+1:n.surveys) {        # for each subsequent survey

                #survival
                log(phi[i,j]) <- a.s.A.new+b.s.1*log(1-p.bs.new)*(1-sex[i])
                # model survival probability as function of sex and rat-tracking
                phi.int[i,j] <- pow(phi[i,j],int[j])
                # calculate probability of surviving over interval
                palive[i,j] <- phi.int[i,j]*alive[i, j-1]
                # pr. alive = surv. prob. for interval x whether it was alive last survey
                alive[i,j] ~ dbern(palive[i,j])   # whether individual alive is sampled

                #resighting
                logit(p[i,j]) <- a.p + b.sex.p*sex[i] + re.t.p[j]
                # model re-sighting prob. as functino of sex & random time effect
                pseen[i,j] <-alive[i,j]*p[i,j]
                # prob. of individual being seen = re-sighting prob. x whether alive
                seen[i,j] ~ dbern(pseen[i,j])
                # whether individual seen is sampled from Bernoulli distribution
            }
        }


        # E. POPULATION MODEL
        F[1] <- N.F.start       # number of adult females at start of first breeding season
        M[1] <- N.M.start       # number of adult males at start of first breeding season

        for (t in 1:5)    {     # for first 5 years...
            J.mu[t] <- mu.new*F[t]          # calculate expected no. juvenilves produced
            J[t] ~ dpois(J.mu[t])           # sample actual no. of juveniles
            N1[t+1] ~ dbin(s.J.new,J[t])    # sample no. recruits
            F1[t+1] ~ dbin(0.5,N1[t+1])     # sample no. of those recruits that are female
            M1[t+1] <- N1[t+1]-F1[t+1]      # calculate no. of those recruits that are male
            F2[t+1] ~ dbin(s.F.new, F[t]) # sample no. of surviving adult females
            M2[t+1] ~ dbin(s.M.new, M[t]) # sample no. surviving adult males
            F[t+1] <- F1[t+1]+F2[t+1]       # add up total adult females next season
            M[t+1] <- M1[t+1]+M2[t+1] # add up total adult males next breeding season
            N[t+1] <- M[t+1]+F[t+1]         # add up total adults next breeding season
        }

    }
```

Modelling nest success of the toutouwai population reintroduced to Turitea Reserve

This model uses estimates daily survival rate (DSR) to calculate the probability of a nest surviving 40 days (NS). The data includes each day of the breeding season, with an NA on days where nests were not checked, a 1 where the nest was active, and a 0 when a nest fails or before it was active. DSR was assumed constant.

```
Model {

#       DSR ~ dunif(0,1)        # daily survival probability
#       NS <- pow(DSR,40)   # derive probability of nest surviving 40 days
        NS ~ dunif(0,1)         # probability of nest surviving 40 days
        DSR <- pow(NS,(1/40))           # derive probability of nest surviving 40 days, daily survival probability

        for (i in 1:n.nests) {
                for (j in first[i]+1:last[i]) {
                        alive[i,j] ~ dbern(p.alive[i,j])
                        p.alive[i,j] <- alive[i,j-1]*DSR            # done for each day, i.e., models the missing values too
                }
        }


}
```