

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Camera trapping as a novel method for monitoring North Island brown kiwi (*Apteryx mantelli*) and implications in environmental management

A thesis presented

in partial fulfilment of the requirements

for the degree of

Master of Environmental Management

Massey University, New Zealand.



Nathan Fan

2023

Abstract

This thesis focused on the use of camera-trapping as a monitoring method for the North Island brown kiwi (*Apteryx mantelli*). Brown kiwi is a species of conservation concern and there is a need for methods that allow the monitoring of population numbers and trajectories to inform conservation practices. Traditional monitoring tools for brown kiwi are either invasive or labour-intensive, and camera-trapping offers a cost-effective and less invasive alternative. This thesis utilizes camera trap data collected between 2014 and 2017 for a feral cat study (Strang, 2018) on South Ponui, a beef and sheep farm in the Auckland area. The objectives of this study were to assess the possibility of camera-trapping for monitoring brown kiwi by investigating camera trap placement strategies to optimize capture rates, exploring the camera trap rates in fragmented habitats compared to the continuous forest, and determining the effect of the number of cameras on capture rate. Little is known about how brown kiwi use agricultural land. However, this knowledge is important because agricultural lands cover approximately 40% of New Zealand and an expected spinoff of Predator Free New Zealand 2050, a project aiming at eradicating introduced predators by the year 2050, is that native species could expand their range into agricultural lands. Therefore, I examined the nocturnal habitat utilization of brown kiwi and provided management strategies for their future conservation on agricultural lands.

Strang deployed from six to 28 camera traps to 28 fixed locations in a 36 ha sampling grid (Strang, 2018). I analyzed the video data using generalized linear mixed models (GLMMs) and heat maps. The findings indicated that camera-trapping was effective in monitoring brown kiwi, including in assessing their nocturnal habitat utilization. The study revealed that brown kiwi predominantly utilize forest habitats during their nocturnal activities, followed by scrub and pasture edge habitats. Three camera trap placement strategies were identified to maximize capture rates, including positioning traps in forests or edge habitats on gentle or steep slopes, with autumn and winter identified as optimal seasons for monitoring. The study also revealed that camera traps placed in fragmented habitats maintained their GLMMs predictive ability compared to the cameras placed in continuous habitats. Additionally, by reducing the number of cameras, it is determined that if the grid cell size does not exceed 37 ha per camera, the GLMM prediction ability remains consistent. These findings have management implications, emphasizing the importance of intensive predator control in forests and edge habitats bordering pastures, preserving, and increasing native forest patches on farms, and controlling livestock access to forests. The attraction of brown kiwi to fragmented habitats underscores the need to safeguard remnants of native forests on agricultural lands, facilitating their dispersal across the landscape. Moreover, the study suggests that

incorporating camera-trapping into the brown kiwi monitoring toolbox offers benefits such as scaling up management efforts, increasing community engagement, and reducing long-term costs. Ultimately, these findings contribute to the understanding and conservation of the North Island brown kiwi.

Acknowledgements

I would like to express my sincere gratitude to my three supervisors, Professor Isabel Castro, Professor Diane Pearson, and Associate Professor Phil Battley, for their invaluable guidance and support throughout this journey. Your expertise and encouragement helped me to complete this research and write this thesis. Isabel, thank you for providing me with an alternative project in a short period of time when my original project did not work out. Thank you for introducing me to the kiwi world and taking me to Ponui Island to let me get the actual experience of being a wildlife ecologist and a kiwi researcher. I absolutely love it! Diane, thank you for encouraging me and replying to my endless questions patiently during the whole process. The writing skills and expertise on environmental management you provided really helped me to integrate my favourite topic (kiwi) into this research. Phil, thank you for all the data analysis ideas and the one-on-one data analysis lessons. Your input helped me to build the base of this study. Your encouragement supported me when I was stuck in different models.

I would also like to give my thanks to Kathryn Strang for giving me permission to use her video data. Also, the Chamberlin family, thank you for having me on your farm for my fieldwork. To my family, your support has always been my greatest motivation. Every time when I could not make progress, you were there to listen to me and try your best to help me to untangle my thoughts. Thank you and love you all!

Table of Contents

Chapter 1: Introduction	12
Background	12
Habitat utilisation of North Island brown kiwi on agricultural landscapes	12
New monitoring tool for North Island brown kiwi	15
Aims and objectives	16
Thesis outline	17
Chapter 2: Literature review	18
Study species.....	18
Kiwi taxonomy.....	18
North Island brown Kiwi behaviour and ecology	19
North Island brown kiwi breeding ecology and activity patterns	20
North Island brown kiwi habitat utilisation	20
Brown kiwi status and agents for the decline	23
Brown kiwi conservation and management programmes	24
Brown kiwi monitoring	25
Camera-trapping Method	27
Concept and development	27
How do camera traps work?.....	29
Major applications of camera traps in monitoring mammals	30
Extended applications on avifauna	31
Number of captures and capture rates.....	31
Sampling effort	34
Summary	35
Chapter 3: Methodology	37
Study site.....	37
Data collection	38
Data set used in this study	38
Data processing for this study	40
Classification of Macrohabitats	40
Classification of geographical features, time intervals and seasons	41
Assigning independent events.....	43
Seasonal variation in capture rates.....	43
Classification of fragmented and continuous habitats	43
Data processing for random reducing cameras	44
Data analysis	45
Generalised Linear Mixed Model	45
Capture rate	48

Heat maps in QGIS	48
Chapter 4: Results	49
Overview of the dataset.....	49
Overall model using 28 camera trap grids: Effects of macrohabitat type, season, and slope level on camera trap capture rates.....	49
Activity hot spots	52
Effects of time interval for defining independent events on capture rates.....	54
Results of camera traps located in continuous (n=13) and fragmented (n=15) habitats.....	59
Activity hot spots in fragmented habitats	63
Results of randomly reducing camera traps	65
Summary	69
Chapter 5: Discussion	70
Camera trapping can be used for monitoring the North Island brown kiwi	70
Brown kiwi nocturnal habitat use from camera trapping method.....	71
What factors influence the capture rate of camera trap on brown kiwi	73
Habitat	73
Season	74
Slope level and aspect	75
Swamp/Water features	76
Track	76
Sampling effort when using camera traps	77
Camera traps in fragmented habitats.....	77
Reduced number of camera traps and time interval for sampling independence	77
Implications of using camera trapping method in kiwi management	78
Increase the scale of future kiwi management	78
Increase community engagement in kiwi conservation	79
Lower costs in the long term and less observer bias.....	80
Implications of brown kiwi habitat utilisation in future management	80
Summary	85
Chapter 6: Conclusion.....	87
Objective 1. Findings of brown kiwi habitat utilisation on agricultural landscapes using camera traps and management implications for future brown kiwi conservation.....	88
Objective 2. Camera traps placement and capture rates	89
Objective 3. Camera trap deployment strategies and sampling effort in future brown kiwi management	90
Limitations	91
Future research.....	92
Overall summary.....	92
Reference list.....	94

Appendix A 107
Appendix B 113

List of figures

Chapter 3

Figure 3.1. Location of the study site, Ponui Island. A. The red dot shows the location in the inner Hauraki Gulf, about 30km east of Auckland. B. The study site, in the southern part of Ponui Island (Southern Ponui Farm).	36
Figure 3.2. The 28 camera traps were placed in a 500m x 500m grid throughout southern Ponui Island.	37
Figure 3.3. Camera trap locations near swamp areas and streams	40
Figure 3.4. Camera trap locations on various sizes of major roads and animal trails.	40
Figure 3.5. The continuous habitat located in the central of Ponui Island consisted of the Kauri forest and other broadleaf forests	42

Chapter 4

Figure 4.1. Capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the southern part of Ponui Island. A. effect of habitat on capture rate; B. effect of season on capture rate; C. effect of slope on capture rate. Stars denote significant difference.	49
Figure 4.2. Heat map showing brown kiwi activity in the southern part of Ponui Island. A. activity from the 28 cameras placed in the 500m x 500m grid. The larger the point, the higher the capture rate of brown kiwi from the camera trap site; B. activity from the three major habitats: forest, scrub and scrub and pasture edge; C. activity from the three levels of slopes: gentle (0 – 8.5 degrees), moderate (8.5 – 16.5 degrees) and steep (>16.5 degrees).	51
Figure 4.3. Difference between the capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the southern part of Ponui Island when independent detection events were classified based on different time intervals: 15min, 30min, 45min and 60min. A. effect of habitat on capture rate; B. effect of season on capture rate; C. effect of slope on capture rate.	54
Figure 4.4 Capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the southern part of Ponui Island when independent detection events were classified based on different time intervals: 15 min, 30 min, 45 min and 60 min.	55
Figure 4.5. Capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the fragmented habitats section of the Southern Ponui Island. A. effect of habitat on capture rate; B. effect of season on capture rate; C. effect of slope on capture rate. Stars denote significant differences.	59
Figure 4.6. Heat map showing brown kiwi activity from the camera traps set up in the fragmented habitats section of Southern Ponui Island. A. activity from cameras placed in the 500m x 500m grid in the fragmented habitats. The larger the point, the higher the capture rate of brown kiwi from the camera trap site;	

B. brown kiwi activity from three major habitats: forest, scrub and scrub and pasture edge; C. brown kiwi activity from the three levels of slopes: gentle (0 – 8.5 degrees), moderate (8.5 – 16.5 degrees) and steep (>16.5 degrees).....61

Figure 4.7. Capture rates \pm SD of brown kiwi from camera traps set up in the three main habitats in the southern part of Ponui Island after randomly reducing cameras and repeating for 10 times. A. effect on capture rate after randomly reducing 1 camera from each habitat every month; B. effect on capture rate after randomly reducing 2 cameras from each habitat every month; C. effect on capture rate after randomly reducing 3 cameras from each habitat every month.....64

Figure 4.8. Capture rate \pm SD of brown kiwi from camera traps set up in different seasons in the southern part of Ponui Island after randomly reducing cameras and repeating for 10 times. A. effect on capture rate after randomly reducing 1 camera from each habitat every month; B. effect on capture rate after randomly reducing 2 cameras from each habitat every month; C. effect on capture rate after randomly reducing 3 cameras from each habitat every month.....65

Figure 4.9. Capture rate \pm SD of brown kiwi from camera traps set up in different slope levels in the southern part of Ponui Island after randomly reducing cameras and repeating for 10 times. A. effect on capture rate after randomly reducing 1 camera from each habitat every month; B. effect on capture rate after randomly reducing 2 cameras from each habitat every month; C. effect on capture rate after randomly reducing 3 cameras from each habitat every month.....66

List of Tables

Chapter 3

Table 3.1. Macrohabitats, geographical features and seasons related to the 28 trap sites used in this study that evaluated as predictors for the number of kiwi videos. These are the fixed effects. Camera location ID is the only random effect identified in this study.....43

Chapter 4

Table 4.1. Generalised linear mixed model with Poisson distribution results for the overall model on factors influencing the number of brown kiwi videos captured at camera trap sites. Independent detection events were classified based on 30-minute intervals. The table below contains the three major factors that were identified in the best model (habitat, season and slope), followed by the factors that were eliminated in each phase of a stepwise backwards elimination. The factors are listed in the order in which they were eliminated, and the AIC values of the model are shown for each elimination. df = degrees of freedom.....47

Table 4.2. Results of the best Generalised linear mixed model including estimate, standard error (Std. Error), z value and P-value to indicate significance levels for each category as a predictor of the number of brown kiwi videos captured at different camera sites. Independent detection events were classified based on 30 minutes intervals. The intercept includes the missing category for the reference factor: Habitat – Forest, Season – Autumn, Slope – Gentle.....48

Table 4.3. Generalised linear mixed model with Poisson distribution results for the overall model on factors influencing the number of brown kiwi videos captured at camera trap sites, by sampling interval. The table contains the three major factors that were identified in the best model, habitat, season and slope, followed by the factors that were eliminated in each phase of a stepwise backwards elimination. The factors are listed in the order in which they were eliminated, and the AIC values of the model are shown for each elimination. df = degrees of freedom.....52

Table 4.4. Results of the best Generalised linear mixed model include estimate, standard error (Std. Error), z value and P-value to indicate significance levels for each category as a predictor of the number of brown kiwi videos captured at different camera site, by sampling interval. The intercept includes the missing category for the factor; Habitat – Forest, Season – Autumn, Slope – Gentle.....53

Table 4.5. Generalised linear mixed model with Poisson distribution results for the overall model on factors influencing the number of brown kiwi videos captured at camera trap sites located in the continuous and fragmented habitats in the southern part of Ponui Island. The table below contains the major factors that were identified in the best model, followed by the factors that were eliminated in each phase of a stepwise backwards elimination. The factors are listed in the order in which they were eliminated, and the AIC values of the model are shown for each elimination. df = degrees of freedom.....56

Table 4.6. Results of the best Generalised linear mixed model include estimate, standard error (Std. Error), z value and P-value to indicate significance levels for each category as a predictor of the number of brown kiwi videos captured at camera sites located in continuous and fragmented habitats in the southern part of Ponui Island. The intercept includes the missing category for the factor of continuous habitat: Habitat – Forest, Season – Autumn. The intercept includes the missing category for the factor of fragmented habitat; Habitat – Forest, Season – Autumn, Slope – Gentle.....57

Table 4.7. Results of random reducing the number of camera traps for 10 times until the original model collapse.....62

Chapter 1: Introduction

Background

Habitat utilisation of North Island brown kiwi on agricultural landscapes

Biodiversity, which is short for biological diversity, is defined as the diversity of living organisms from land to sea, including variability within species, known as genetic diversity, between species, and within and across ecosystems (United Nations, 1992). Biodiversity loss is considered one of the most critical environmental issues in the world (Brockerhoff *et al.*, 2006). Humans have drastically affected three-quarters of the earth's land surface and about 70% of its oceans. The size and health of the global ecosystems have decreased by an average of 47% relative to their natural baseline, with some ecosystems deteriorating more than others. The terrestrial biodiversity hotspots, which are the regions with high levels of endemism and species richness that are under threat, are experiencing more reductions in condition and extent as well as more rapid declines than other regions. For example, between 2010 and 2015, the most biologically diverse terrestrial ecosystems, tropical forests, were decreased by 32 million ha (Tyukavina *et al.*, 2016).

According to data from World Wide Fund for Nature (WWF) in 2016, there was an average of 58% decrease in the population size of vertebrate species between 1970 and 2012. About 600 seed plants have become extinct over the past 250 years, primarily from tropical islands and biodiversity hotspots, a pattern that also reflects the loss of animal species (Humphreys *et al.*, 2019).

New Zealand is internationally recognised as a biodiversity hotspot, contributing significantly to world biodiversity with about 80,000 endemic species found nowhere else on the planet (Myers *et al.*, 2000). The high endemism in New Zealand was created by the evolution of the species and ecosystems in geographical isolation for 80 million years (Croxall *et al.*, 2012). Indigenous biodiversity is also important to the Māori (the original inhabitants of New Zealand) because nature and people are connected through whakapapa (genealogy), tikanga (customary practices), taha wairua (spiritual wellbeing), te reo Māori (the Māori language), kai (food), rongoā (medicines) and toi (the arts). The relationship between nature and people in the Māori culture is reciprocal as they are kaitiaki (guardians) to each other (Waitangi Tribunal, 2011). Hence, biodiversity loss in New Zealand and the growing gap between the remaining biodiversity and people are eroding these connections, practices, and responsibilities (Waitangi Tribunal, 2011). For international branding purposes, a significant part of the national economy, the tourism industry, heavily relies on the country's indigenous biodiversity (Norton *et al.*, 2020). With the arrival of humans, the landscape was dramatically altered, and many mammalian predators and herbivores were introduced (Clout,

2002). These issues have caused 289 plant species become threatened and a further 749 plant species to be at risk, which represents roughly 40% of the indigenous plant species in New Zealand. Furthermore, around 40% of the remaining 417 bird species in New Zealand (56 species are extinct) are currently threatened or endangered (Brown, 2015). Almost 85% of indigenous reptile species are threatened or endangered, being at a significant risk of extinction (Brown, 2015). In conjunction with the dramatic loss in the size and health of indigenous ecosystems, these figures on endangered species reveal the crisis status of the remaining New Zealand indigenous biodiversity.

To solve the biodiversity crisis in New Zealand, it is crucial to understand and know how to measure biodiversity. An important aspect to focus on is ecosystem integrity (De Leo and Levin, 1997). High-integrity ecosystems preserve the whole spectrum of fauna and flora and their essential environmental components, such as water and soil, and fill their maximum environmental potential (Roche and Campagne, 2017). These components need to function sustainably (Lee *et al.*, 2005). Ecosystem health can be used to describe the condition of an ecosystem regarding its capability to provide ecosystem services. Ecosystem health can be determined by the presence or absence of specific native species, the proportion of different types of species, sizes, and ages of organisms (Lu *et al.*, 2015).

Robertson and Colbourne (2017) suggested that kiwi birds (*Apteryx spp.*) should be considered as an indicator of the health of the ecosystem. They proposed that if possible, their “iconic” species status should be used so that their management can benefit other endemic species inhabiting the same ecosystems. Besides being a national icon, kiwi are also regarded as special birds in the Māori culture. Traditionally, they were an essential food source, and their feathers were used to make cloaks (kahu kiwi) which were taonga (treasures) often designated for Māori chiefs (Keane, 2010a). Due to their significant cultural value to Māori and the customary knowledge about kiwi birds, mana whenua are crucial participants in kiwi management. This relationship between kiwi and mana whenua has been formally acknowledged by many hapu and iwi as part of their Treaty of Waitangi settlement claims, which include explicit reference to recovery activities for these species (Waitangi Tribunal, 2011). Since kiwi birds have great value in New Zealand’s biodiversity and Māori culture, it is necessary to put more effort into their management and measurement of management outcomes.

The name of kiwi birds was given by the Māori people, hence both the singular and plural forms are the same. When Māori people arrived in New Zealand around 800 years ago, kiwi populations started declining, and their distribution has drastically shrunk, primarily because of the introduction of Polynesian dogs (*Canis familiaris*) and the destruction of forests by man-made fires (McGlone,

1989). The pace of kiwi population decline increased after European settlement because more vicious mammalian predators, such as mustelids (*Mustela spp*) and more dogs, were introduced into the country. More importantly, since the European settlement started, most lowland scrub and forests were replaced by pasture, which caused a massive loss of suitable kiwi habitats (Robertson and Colbourne, 2017). The habitat loss has slowed down but not stopped. It was estimated that between 1996 and 2018, approximately 40 800 ha of native forest and scrub habitats transformed into non-native land cover, specifically agricultural land. Also, during this time, native grasslands totalling around 44 800 ha and other native land cover totalling 5500 ha were changed to non-native land cover types (Dymond *et al.*, 2017).

In New Zealand, the primary land use is pastoral farming, covering at least half of the total land area, and comprising about 40% of sheep and beef farms and about 10% of dairy farms (Norton and Pannell, 2018). This sector is vital to New Zealand's economy, accounting for 36% and 39% of export revenues in 2017 and 2018 respectively (Norton *et al.*, 2020). Most pastoral farms are located at lower elevations lands, where there is the greatest loss of original habitat (Perry *et al.*, 2014) and the minimum public conservation land, even though substantial remnants of indigenous vegetation still exist (Norton and Pannell. 2018). The areas dominated by pastoral agroecosystems have a distinct composition and spatial arrangement of indigenous biodiversity than areas with large public conservation lands (Norton *et al.*, 2020). Native habitats on pastoral farms are typically small and isolated and usually have undergone different degrees of modifications to their structure and composition because of human activities such as grazing and edge effects (Ruffell and Didham. 2017). Most of these native habitats are not protected in any way, whereas a selected few are under the protection of covenants, such as the Queen Elizabeth II covenant (Norton and Pannell, 2018). The composition of these habitats usually includes native forest remnants and regenerating scrub and forests in formerly farmed areas. The native habitats may consist of a continuous native forest or only a few scattered trees (Norton *et al.*, 2020).

Despite native habitats on agricultural landscapes being isolated and fragmented, many regionally and nationally rare animal species persist across these landscapes in rural areas of the country (Pawson *et al.*, 2010). Although species that need vast intact habitats are usually absent, such as kākā (*Nestor meridionalis*) and kōkako (*Callaeas cinerea*), other rare species, such as North Island brown kiwi and pōpokatea/whitehead (*Mohoua albicilla*), can be frequently found in these habitats (Norton *et al.*, 2020). Although predation from mammalian predators and habitat fragmentation are still causing the continued decline of native animal species in these habitats, the native biodiversity that still exists in agricultural landscapes is essential throughout broad areas of lowland New Zealand since these remnants are often all that survives of the original ecosystems before human

arrival (Norton and Pannell, 2018). Therefore, it is crucial to find an approach for future agroecosystem design that can optimise pastoral farming and biodiversity management at the same time. There are still knowledge gaps of native biodiversity on agricultural landscapes, such as the dispersal pattern of indigenous species and the interactions between indigenous species with varying behavioural traits and the fragmented habitats on agricultural landscapes (Norton *et al.*, 2020).

Zhang *et al.* (2021) indicated that within the same landscape, native birds with varying habitat preferences and mobility capacities would exhibit distinct space-use patterns. Such information is crucial for the proactive management of native species in agricultural landscapes since it reveals where future efforts should be concentrated, such as planting to enhance the quality of fragmented habitats to improve the dispersal of the focal species. As mentioned above, the North Island brown kiwi is quite commonly found in fragmented habitats on production landscapes (areas where agriculture, livestock grazing, or forestry take place) and plantations (Pawson *et al.*, 2010), and they are also an important biodiversity indicator and a significant cultural symbol. Hence, this thesis aims to learn and understand the activities of the North Island brown kiwi in fragmented habitats and how they utilise habitats on agricultural landscapes.

New monitoring tool for North Island brown kiwi

Our understanding of the present state of indigenous biodiversity is hindered by large knowledge gaps. To properly address the biodiversity issues in New Zealand, it is important to invent new tools and develop new techniques to improve the management of species and ecosystems further (Sullivan and Molles, 2016). One of the prioritised innovation areas is environmental monitoring and reporting, which is important for measuring the effectiveness of management initiatives and indicating where future investment needs to be allocated (Peters *et al.*, 2016). To achieve innovation in this area, there is a need to develop real-time and remote data collection approaches complemented by automated analysis technologies. Furthermore, these new tools or approaches need to be specific and effective to monitor cryptic species and integrate citizen science into monitoring (Peters *et al.*, 2016). For example, kiwi birds are an important part of New Zealand's biodiversity and have cryptic nocturnal characteristics. Moreover, they are already popular among New Zealanders.

Currently, a limited number of methods can be used for monitoring brown kiwi effectively, including call count surveys, kiwi conservation dog surveys and radio telemetry (Robertson and Colbourne, 2017). However, these methods have various disadvantages, including observer bias (e.g., call count surveys), being labour-intensive (e.g., kiwi dog surveys and radio telemetry) and

invasive to target species (e.g., radio telemetry, kiwi-dog surveys) (Craig *et al.*, 2011). Passive acoustic monitoring (PAM) is one of the growing technologies for monitoring avian species, particularly for monitoring elusive species, such as kiwi birds. The acoustic recorder can be left at study sites for a period, which allows for longer survey time and less disturbance to target birds than the traditional call count surveys and radio telemetry monitoring (Jahn *et al.*, 2022). Since a single person can set up several recorders in one day and sound data can be replayed, it is less labour-intensive in the field and more accurate than the monitoring methods conducted by human surveyors (Jahn *et al.*, 2022). These advantages of the PAM approach are also shared by the camera-trapping method (Link *et al.*, 2022). However, there is no research that has been conducted on using the camera-trapping method for studying kiwi. Therefore, this thesis will explore whether the camera-trapping method can be a novel approach for monitoring brown kiwi, and what influential factors may affect the ability to use the camera-trapping method for monitoring brown kiwi.

Aims and objectives

The central aims of this thesis are to investigate whether camera-trapping can detect brown kiwi in a way that can be used to monitor their habitat utilisation in an agricultural landscape, to identify the factors that can influence the capture rate of camera traps on brown kiwi in a high-density population, and to inform management strategies for future brown kiwi management. This study was conducted at the southern end of Ponui Island, at South Ponui Farm, located in the Hauraki Gulf. The data used in this thesis are camera trap bycatch data collected by Kathryn Strang from 2014 to 2017 for her PhD research. The original research focused on studying the behaviour and ecology of feral cats (*Felis catus*) on this island using camera traps (Strang, 2018). The central aims of this thesis can be divided into three objectives:

- **Objective 1:** Investigate the habitat utilisation of brown kiwi in a high-density population on a production landscape using camera traps and provide management strategies for conserving brown kiwi habitats within production landscapes.
- **Objective 2:** Investigate the capture rate of brown kiwi by camera traps, including how the capture rate may vary with the placements of camera traps in macro habitats, edge habitats and at different geographical locations, as well as seasonally variations in the southern part of Ponui Island.

- **Objective 3:** Provide strategies for using camera traps in brown kiwi management, including deployment patterns and sampling effort requirements for achieving adequate accuracy and efficiency.

Thesis outline

There are six chapters to this thesis. Chapter one provides an overview of the research background, aims and objectives. Chapter two conducts a literature review on the general information of the study species, the North Island brown kiwi, as well as the camera-trapping method. For the species, the general information includes the taxonomy, behaviour, and ecology of the North Island brown kiwi, as well as the current conservation pressures and management programs. For the camera-trapping method, the general information includes the history, development and application of camera traps, and the capture rates and sampling effort of using the camera-trapping method. Chapter three outlines the methods used in this thesis, including the camera trap data processing method, the use of generalised linear mixed models (GLMM) for data analysis, and the use of QGIS to visualise the results from camera traps. Chapter four presents the findings of this study, including the results of the GLMM and heat maps to show activity hotspots of brown kiwi. Chapter five discusses the findings on whether the camera-trapping method can be used for brown kiwi monitoring and information on brown kiwi habitat utilisation as well as management implications regarding their habitat utilisation on agricultural landscapes. This chapter also discusses what factors influence the camera traps capture rate of brown kiwi and the effect of the sampling efforts when using camera traps in fragmented habitats, and when reducing camera trap numbers randomly. Chapter six summarises the findings of the research and provides further research directions on management strategies of the North Island brown kiwi in agricultural landscapes and camera-trapping designs for future brown kiwi monitoring.

Chapter 2: Literature review

Study species

Kiwi are flightless birds of the genus *Apteryx* and belong to a unique bird family, the Apterygidae (Holzapfel *et al.*, 2008). They are the smallest of the extant Palaeognathe group, which primarily consists of gigantic terrestrial herbivores, such as the cassowary (*Casuarius spp.*) and emu (*Dromaius novaehollandiae*) in New Guinea and Australia, and the rhea (*Rhea spp.*) and ostrich (*Struthio camelus*) in South America and Africa, respectively. Furthermore, the group includes two recently extinct groups: the Madagascar elephant bird (*Aepyornithidae*) and the New Zealand moa (*Dinornithiformes*) (Mitchell *et al.*, 2014). Although moa and kiwi had coexisted in New Zealand, they were not the closest relatives. Recent DNA analyses suggest that moa were more closely related to the South American tinamous (*Tinamidae*), whereas kiwi were the closest relatives to the elephant bird. The Palaeognathae is classified based on their distinctive basal palate structure and separated from all other bird species that belong to the Neognathae (Phillips *et al.*, 2010). In addition to their unique taxonomic status, kiwi are endemic to New Zealand and have a cultural significance. Indigenous Māori people regard kiwi as taonga, or sacred natural treasures, all New Zealanders are self-referred to as kiwi. Kiwi is the unofficial national symbol in the country and known worldwide (Herbert & Daugherty, 2002).

Kiwi taxonomy

Understanding kiwi taxonomy is essential for their conservation. Defining the abundance and distribution of distinct taxa can identify the conservation units that need to be managed, hence maintaining genetic diversity. Without a solid understanding of the distribution of distinct taxa, undetected species may become extinct, and isolated populations may lose their ability to reproduce and adapt to environmental change and disease. Kiwi classification was based solely on morphological distinctions in the early years. However, the development of genetic technology has allowed the detection of distinguishing characteristics that are not visibly apparent. The most recent phylogenetic study recognises five species of kiwi: North Island brown kiwi, Okarito brown kiwi (*Apteryx rowi*), Southern brown kiwi (*Apteryx australis*), great spotted kiwi (*Apteryx haastii*) and little spotted kiwi (*Apteryx owenii*) (Burbidge *et al.*, 2003; Weir *et al.*, 2016). Weir *et al.* (2016) also supported Burbidge *et al.* (2003) finding that there were four genetically different and geographically separated groups or taxa within *Apteryx mantelli* (Northland, Coromandel, Western, and Eastern), and four additional taxa of southern brown kiwi (Haast, North Fiordland, South Fiordland, and Stewart Island). Furthermore, more in-depth research on the southern brown kiwi

showed impediments to gene flow at the landscape level (Weir *et al.* 2016). This approach would also split great spotted kiwi into four lineages: North West Nelson, Paparoa, Westport and Arthur's Pass great spotted kiwi. This is based solely on the recognition of geographical factors considered likely to impede gene flow in a manner comparable to that observed in southern brown kiwi (McLennan & McCann, 2002), however, no genetic investigations have been done to test this hypothesised great spotted kiwi population structure. Thus, there are a total of 14 known lineages proposed to exist in the genus *Apteryx*. Each lineage is termed a 'taxon' in management literature and is recognised as a distinct management unit (Germano *et al.*, 2018). The present management standards strongly prohibit any hybridisation between the management units in captivity and in the wild. This rigorous stance has led some populations to be deemed undesirable hybrids and removed from future conservation efforts. This specifically targets the hybrid offspring of birds from past translocations from different management units (Innes *et al.*, 2015, Undin *et al.*, 2021). In this thesis, the focused kiwi species is the North Island brown kiwi on Ponui Island, located in the Hauraki Gulf.

North Island brown Kiwi behaviour and ecology

Brown kiwi are flightless, lacking external tails and having small vestigial wings. They have lower body temperature compared to other birds, and the lowest basal metabolic rate of any bird measured to date. Both characteristics are adaptations to conserve energy and likely contributed to their inability to fly (Cunningham *et al.*, 2007). Additionally, dimorphism exists between the sexes, with males being significantly smaller than females and the latter having disproportional longer bills (Sales, 2005; Holzapfel *et al.*, 2008; Keast *et al.*, 2010). The brown kiwi possesses an outstanding sense of smell compared to most birds thanks to enlarged areas of the brain dedicated to the sense of smell (Corfield, 2009). Their bills are particularly effective at probing for food because their bill tips have specialized vibration and pressure-sensing nerve endings that allow them to detect invertebrate movements in the soil and on the surface in addition to a keen sense of smell (Cunningham *et al.*, 2007). In addition to soil invertebrates, their prey also includes native freshwater crayfish, such as koura (*Paranephrops spp.*), living in streams and rivers (Keast *et al.*, 2010).

Brown kiwi are predominantly nocturnal. They leave roosting sites to forage at dusk. During the day, they usually roost in hollow logs, soil burrows or under dense vegetation (McLennan *et al.*, 1987). Within the home range, a kiwi can have several roosting sites, and they usually roost alone or with their mate (Jamieson *et al.*, 2016). Brown kiwi have been documented as mostly

monogamous in some populations to having polygamy in some others (McLennan, 1988). Undin and Castro (2022) suggested that while North Island brown kiwi share some traits with monogamous birds, such as high parental care for offspring and well-developed olfaction, they also have many traits that are consistent with polygamy, such as uneven distribution and quality of resources and asynchronous and long breeding season. Hence, they concluded that the high flexibility in the North Island brown kiwi breeding system is underestimated, and that more research effort should be placed into using their flexible mating behaviour to improve their conservation management. When out foraging, a male makes far-carrying high pitch calls, and a female makes low pitch guttural sounds (McLennan, 1988).

North Island brown kiwi breeding ecology and activity patterns

The mating season normally starts in late autumn and early winter (May to June), and the egg-laying period can begin in early winter (June), with the peak laying phase occurring between midwinter (July) and mid-spring (October) and as late as midsummer (February) (Reid & Williams, 1975; Ziesemann *et al.*, 2011). Brown kiwi generally use freshly dug burrows or modify existing natural cavities, such as hollow tree bases or logs, for nesting. (Ziesemann *et al.*, 2011; Craig *et al.*, 2011). The female can lay up to two clutches per breeding season and up to two eggs in each clutch (Keast *et al.*, 2010; Ziesemann *et al.*, 2011). However, in some rare situations, brown kiwi females can lay up to seven eggs in a single breeding season in three different clutches (Colbourne, 2002). Compared to the body weight of a female bird, the North Island brown kiwi eggs are among the largest eggs of any bird species (Calder, 1991). After eggs are laid, male brown kiwi generally undertakes the incubation alone, and the incubation period is normally between 74 and 84 days (Sales, 2005). After hatching, chicks are precocial and are sustained by the energy provided by the remaining highly nutritious yolk for the first week (McLennan, 2004). Male parent birds leave the chicks shortly after hatching, and chicks start foraging independently at night after the first week and fully fledge at two to ten weeks week (McLennan, 2004). It is still unknown whether parents feed chicks before fledging (Ziesemann *et al.*, 2011).

North Island brown kiwi habitat utilisation

Brown kiwi was traditionally considered a dweller of New Zealand's native forests, the majority of which have been removed by agricultural exploitation and human settlement (Robertson and Colbourne, 2017). In a study at Waitangi Forest, Northland, Taborsky and Taborsky (1995) suggested that brown kiwi generally preferred native forest and successional vegetation rather than

exotic pine forest, road, pasture, and marshes during nocturnal activity. Their roosting sites during the daytime were usually in successional vegetation and wetlands. Most nest sites in their research were situated within 25 metres of native or successional vegetation. In the early weeks after hatching, chicks preferred using these areas during foraging when they could only move short distances. Taborsky and Taborsky (1995) also noted that regardless of whether habitats were anthropogenic or natural, brown kiwi usually selected habitats based on shelter sites and food availability. Jamieson *et al.* (2016) also believed that the quality of roosting sites (e.g., extent of protection against extreme weather) and distances to high-quality foraging sites might affect brown kiwi habitat selection. They discovered in their research that the brown kiwi population on Ponui Island preferred native forest habitats rather than scrub for roosting, although scrub areas had higher soil invertebrate biomass than forests, and most birds incorporated scrub in their core habitats where they spend most of their time. It was thought that avoidance of scrub was possibly a consequence of environmental factors; most scrub habitats on Ponui Island were located along the ridge where roosting birds would have poor shelter from the frequent cold and strong winds. (Jamieson *et al.*, 2016).

Other research indicated that, despite the above roosting preferences, kiwi are adaptable to a variety of habitats. Populations have been detected in exotic radiata pine (*Pinus radiata*) forests (e.g., Colbourne & Kleinpaste, 1984; Taborsky and Taborsky, 1991, 1992), and in mixed pasture and regenerating forest (e.g., Potter, 1989; Cunningham & Castro, 2011). Brown kiwi also actively use edge areas such as scrub-pasture and forest-pasture edges (e.g., Potter, 1989; Taborsky & Taborsky, 1995; Cunningham & Castro, 2011). In ecological terms, an edge is a transitional zone between two adjoining habitats, and depending on the study can have different areas (Harper et al. 2005). In this thesis, I have simplified this definition and consider an edge to be represented by the narrow line where two vegetation types meet. Kiwi on Ponui Island have been found to have a higher foraging success in open pasture (standard agricultural paddock) than other habitats, including forests (Cunningham & Castro, 2011). Since pasture is not far away from other habitats on Ponui Island, the forest- and scrub- pasture edges may play a crucial role in higher foraging success. Most of these suitable habitats exist in forest remnants that are located in production mosaic landscapes, such as farmland, mining land and exotic production forests that contain a variety of habitats within (Germano *et al.*, 2018). Pannel *et al.* (2020) found that sheep and beef farms are the most common production mosaic landscapes in New Zealand, comprising about 40% of the total land area, and possessing approximately 25% of the native vegetation of the country including both herbaceous (e.g., wetland and grassland) and woody vegetation (e.g., shrub and forest). Sheep and beef farms are also typically found in areas that are environmentally and climatically distinct from state

conservation land, such as low-elevation and warmer areas, and in areas that have been otherwise extensively deforested. This substantial indigenous vegetation found on these farms is currently not represented within conservation land, although it possesses great potential to serve as permanent habitat for brown kiwi and other native species (Pannell *et al.*, 2021). This has been confirmed in Northland by Blue and Blunden. (2010), who reported that 59% of the land is used for pastoral farming which contains 12.7% native forest, 13.6% scrub and 10% exotic forest. The country's conservation land in Northland occupies about 13.4% of the total land area in the region, and many forests on these lands have low-density concentrations of kiwi. In contrast, the highest concentrations of kiwi occur on pastoral farmlands and other private lands, such as lifestyle blocks, especially in the Bay of Islands (Blue & Blunden, 2010). In these production mosaic landscapes, landowners' production needs and goals may conflict with the best interests of kiwi conservation. A few issues are of particular concern:

- Production mosaic landscapes may pose greater threats to the bird populations than native forests as they contain not only the normal threats, such as introduced mammalian predators but also machinery, fire, and habitat loss or degradation.
- There is a lack of systematic support and guidance for kiwi management in native forest remnants on farmlands and in exotic production forests owned by the Crown, Māori and other individuals.
- There may be misunderstandings that kiwi conservation is incompatible with full production (Germano *et al.*, 2018).

Actions proposed for solving the above issues include:

- Provide landowners, Māori Trusts, company managers and conservation managers with information on the distribution of local kiwi populations and management priority zones.
- Provide landowners, Māori Trusts, company managers and conservation managers with information and support on the protection and mitigation measures of local bird populations (Germano *et al.*, 2018).

Because of these issues and proposed actions, in this thesis, I aim to determine the habitat utilisation of brown kiwi in a high-density very successful population on a high intensity production mosaic landscape, in the hope that it can provide general information on priority management areas on farmlands.

Brown kiwi status and agents for the decline

Before humans arriving in New Zealand, kiwi populations might have changed in response to natural events, such as volcano eruptions and glaciations (Craig *et al.*, 2011). The arrival of humans had a severe negative impact on all populations. For example, early Māori cleared vast areas of land by burning, hunted kiwi as food, and brought kiore rats (*Rattus exulans*) and dogs that competed for food or used kiwi as prey respectively (McLennan & Potter, 1992). Consequently, kiwi populations and habitats decreased everywhere in New Zealand (Keast *et al.*, 2010; Craig *et al.*, 2011). With the arrivals of Europeans, there were more lands acquired by settlers for agriculture and more mammalian predators introduced in the country (e.g., dogs, ferrets (*Mustela furo*), stoats (*Mustela erminea*)) and competitors (e.g., Norway rats (*Rattus norvegicus*), and ship rats (*Rattus rattus*)). Loss of habitat and predation on kiwi from mammalian predators worsened dramatically over time, leading to the continuous decline of all kiwi populations until today (Saunders & Norton, 2001; Holzapfel *et al.*, 2008; Keast *et al.*, 2010; Craig *et al.*, 2011).

To understand the agents of kiwi populations' decline and present threats, it is necessary to know the unique evolutionary history of the endemic species in the country. New Zealand separated from the Gondwana supercontinent around 80 million years ago before the terrestrial mammals could reach or establish in Zealandia, followed by a lengthy period of geographical isolation (Department of Conservation, 2020). Species have evolved in the insular environments leading to a large proportion of endemic species only found in New Zealand (e.g., kiwi, Tuatara (*Sphenodon punctatus*), North Island kōkako).

The high endemism draws a lot of recognition and interest in the conservation field worldwide. However, evolution in isolation also leads to several adverse consequences. One typical effect is that species lack effective defensive mechanisms against terrestrial mammals due to evolving without mammal presence (Monks *et al.*, 2019). For example, the principal cause of decline for most kiwi spp. populations is predation of chicks by stoats (Germano *et al.*, 2018). McLennan *et al.* (1996) suggested that the survival rate of kiwi chicks is about 6% without management of stoats but can be almost ten times higher in places where management programmes are implemented regularly. Adult kiwi may defend themselves with sharp claws and powerful kicks against stoats, but nothing can be used on larger mammalian predators, such as ferrets and dogs. The lack of sternums makes kiwi spp. suffocate easily and make them more vulnerable to dog attacks (Sales, 2005). Moreover, flightlessness makes them accessible prey for introduced mammalian predators (Hoare, 2006). Robertson *et al.* (2011) suggested that the average longevity of an adult brown kiwi in Northland is only around 13 to 14 years instead of 30 to 40 years in brown kiwi populations

elsewhere. This is primarily caused by dog predation. Because of the long lifespan and low reproduction rates of kiwi, the loss of adults reduces population recruitment significantly, which can potentially cause more damage than the loss of juveniles (Keast *et al.*, 2010; Craig *et al.*, 2011; Germano *et al.*, 2018).

Brown kiwi conservation and management programmes

In 1991, the Department of Conservation (DOC) issued the first edition of the Kiwi Recovery Plan and began implementing the Kiwi Recovery Programme alongside the Royal Forest and Bird Protection Society and the Bank of New Zealand. The initial focus of the recovery programme was on identifying the taxonomic status, population numbers, and distribution of the species. The programme also recognised the agents of population decline and highlighted introduced mammalian predators as the primary cause of the kiwi population decline. The first recovery phase was completed in 1996 and had many significant achievements. A particular achievement was the development of the Operation Nest Egg (ONE) programme, which greatly increased the survival rates of kiwi chicks by avoiding predation from mammalian predators (Butler & McLennan, 1991; Germano *et al.*, 2018). The fundamental idea of ONE is that eggs are collected from the wild and chicks are reared in captive facilities. Chicks are moved to a kiwi crèche at two weeks old. The crèche is either a predator-free island or a fenced area of land with all mammalian predators removed. They stay in the crèche until reaching 1000g, at which they are large enough to better defend themselves against stoats and are then released back into the wild (Colbourne *et al.*, 2005). In addition to ONE, more precise estimations were made on population size and distribution for each species; behavioural, ecological, and genetic differences between different kiwi species were also recognised during the first phase (Germano *et al.*, 2018).

From 1996 to 2008, the second term of recovery concentrated on developing technologies (e.g., ONE) and landscape-scale mammalian predator control via trapping or aerial application of 1080. There were five kiwi sanctuaries built across the country to conserve the most endangered species, Haast tokoeka and rowi, and three brown kiwi populations. During this phase, community-led kiwi recovery programmes grew in scale and number. The BNZ Save the Kiwi Trust was formed and became the formal partnership between BNZ, DOC and Forest & Bird (Robertson, 2003; Robertson & Colbourne, 2003). The third phase of the recovery programme, which was completed in 2017, centred on increasing management activities across a larger area and enabling local communities to manage their own kiwi populations. The focus has been on conserving kiwi as a crucial component of healthy ecosystems, with the expectation that kiwi conservation will also benefit other native

species (Germano *et al.*, 2018). As part of ONE programme, the development of the Kōhanga kiwi strategy was also a focus during this phase. This strategy shares the same concepts as ONE. The only difference is that captive birds live in predator-free Kōhanga sites for the rest of their life. When these sites have reached capacity, the original populations' offspring can be either used to maintain the existing populations, establish new sites, or return to the places where their ancestors were from (Craig *et al.*, 2011). Furthermore, this term saw a growth of community-led programmes, notably on the North Island, and greater security of the three most endangered species (little spotted kiwi, Haast tokoeka and rowi) provided by ONE (Germano *et al.*, 2018).

In 2018, Innes and Eppink. (2015) estimated that the brown kiwi population was about 25100 birds in total. Northland brown kiwi had the most birds, approximately 8600 birds, whereas Coromandel brown kiwi had the least birds, about 1900 birds. Eastern and Western had around 7000 and 7600 birds, respectively. Most brown kiwi populations are mainly distributed in Northland and several offshore islands in the Hauraki Gulf, such as Little Barrier Island and Ponui Island. Populations can also be found in western Hawke's Bay, Tongariro, Gisborne and other places in central North Island (Robertson, 2013).

Brown kiwi monitoring

The kiwi long-term recovery goal is to increase kiwi population to 100 000 individuals by 2030 (Germano *et al.*, 2018). There are period goals established in different sectors for achieving the long-term goal. For example, in kiwi management, more reliable monitoring tools are urgently needed to measure the growth rates of kiwi populations for all species; monitoring tools need to be more effective and cost-efficient for monitoring both kiwi and their predators and in managing the data collected. Improvements are also needed in people engagement, mana tangata need supporting tools to excise effective kaitiakitanga on kiwi, and other whānau-, hapū-, iwi- and community-led kiwi recovery projects also need tools to maximise the effectiveness of their projects (Germano *et al.*, 2018). All these goals point to an area in urgent need of development of the kiwi monitoring toolbox.

Monitoring evaluates long-term population changes by measuring the size and trend of a population (Goldsmith, 1991; Yoccoz, 2012) It is essential to measure the efficacy of management and use the results to advise and guide future recovery efforts. Currently, a limited number of methods can be used for monitoring brown kiwi effectively due to their nocturnal and cryptic behaviour, and extensive home ranges (Robertson & Fraser, 2009). To determine the age structure of the brown kiwi population in high-density populations, surveys carried out by trained kiwi dogs are most

effective. Kiwi dogs and their handler can find brown kiwi to capture them and determine their age. The age data are analysed to determine the survival rate of chicks and juveniles. If a high proportion (e.g., 30% or above) of juveniles is found in a brown kiwi population, it implies that predator control is successfully protecting their chicks (Robertson & Colbourne, 2003). The surveys can be repeated every three to five years (Robertson & Fraser, 2009). Radio telemetry, where radio frequency transmitters are placed on birds and the signal is monitored using a receiver, is regarded as the most accurate method for locating secretive species such as brown kiwi. After finding the birds, their movement pattern, reproduction status and survival can be monitored. Most radio-tracking is conducted from the ground, but brown kiwi at certain ages, such as juveniles and sub-adults, may travel long distances (e.g., 20 km or longer), and aircrafts may be used to detect transmitters' signals effectively and find their locations (Craig *et al.*, 2011).

The Kiwi Call Count Survey was developed in the mid-1990s and is the primary method for measuring abundance trends in brown kiwi populations (Robertson & Colbourne, 2003). It requires recording calls from brown kiwi during the dark moon phase from late May to June. Since female and male brown kiwi make distinctive calls, it is possible to identify the presence of males and females in an area. Brown kiwi pairs and groups call together (Corfield *et al.*, 2008), so the existence of duets in call surveys can inform the listeners of the presence of possible nesting adults. Moreover, because calls from territorial individuals are loud, it is possible to determine the direction of the call from up to 1.5 km away in a clear noiseless night (Robertson & Colbourne, 2003). Although this technique is effective for assessing presence or absence and documenting trends, it does not quantify the population abundance and is susceptible to observer bias (Craig *et al.*, 2011).

In addition to observer bias, existing monitoring tools may not be suitable for brown kiwi living at low densities or for other kiwi species such as tokoeka or the species that are readily disturbed, such as great spotted kiwi. In addition, call surveys are neither sensitive nor cost-effective in monitoring predator abundances at low density (e.g., stoats) and producing accurate kiwi monitoring outcomes simultaneously (Germano *et al.*, 2018). Habitats with access issues are difficult to survey and monitor with dog surveys and radio telemetry which are extremely labour-intensive and can be very expensive (Jahn *et al.*, 2021). For example, when using telemetry for brown kiwi monitoring, experienced kiwi specialists are required to attach the transmitters, and rangers need to monitor the birds with telemetry equipment. Due to battery consumption, transmitters must be changed annually, necessitating the same kiwi handling process every year and incurring a hefty cost from labour and equipment. One transmitter costs about NZ\$ 400 (Ellis & Marsland, 2022). With short-term financing cycles and increasing competition for DOC funding, it might be challenging to

maintain the current long-term commitment of work necessary to measure kiwi distributional changes and population trends using radio telemetry (Germano *et al.*, 2018).

Furthermore, some methods, such as radio telemetry, may have potential animal welfare issues. Birds have reportedly been caught by their transmitter while moving through vines. (Ellis & Marsland, 2022). Barron *et al.* (2010) also that transmitters have negative impacts on birds who wear them through their meta-study of comparing birds with/without these devices. Other welfare issues include that they are invasive to target species as they require capturing the birds physically (Craig *et al.*, 2011).

Engagement and advocacy are other important considerations that needs to be consistently incorporated into kiwi management in the future. For the past 25 years, advocacy programs have encouraged the public to change their behaviour, for example improving responsible pet ownership (especially for dogs), carrying out kiwi predator control, and increasing financial support for conservation programmes (Germano *et al.*, 2018). The development of these programmes relies on a variety of people including mana tangata, landowners, children, business owners and many other groups. Different people or groups have different values and perspectives on kiwi conservation; hence, the future improvement of these programmes need to have various tools to ensure an effective engagement with society. At present, in kiwi monitoring, lack of engagement is embodied in the lack of accessible training for monitoring skills for mana tangata or complicated training and handling procedures (e.g., telemetry) for younger generations and the wider public (Germano *et al.*, 2018). To ensure mana tangata can perform their duties as kaitiaki of kiwi and actively participate in decision-making, and younger generations can participate in kaitiakitanga in kiwi conservation and the public can connect with kiwi, a simple, accurate, cost-effective, and non-invasive tool needs to be developed and added to the current brown kiwi monitoring toolbox. Camera trapping may have the potential to fill in these gap. In this thesis, I aim to test whether the camera trapping method can be used as a new kiwi monitoring tool to provide reliable information and support kiwi protection and management on production landscapes.

Camera-trapping Method

Concept and development

Cameras are ubiquitous in modern society, recording every part of our lives. There is a long history of using cameras for professional reasons in subject areas such as medicine and astronomy, and photography has been recognised as a demystifying power in nature (O'Brien & Kinnaird, 2008). In recent years, the development of camera technology has made a valuable contribution to the

biological conservation field and has become a preferred method for sampling animal populations. Camera-trapping in the study of wild animals has undoubtedly increased the knowledge of their ecological interactions and, more significantly, population dynamics (O'Connell *et al.*, 2011). In the study of secretive and rare species, images provide evidence of identity and presence, also information about distribution, abundance, and behaviour (O'Brien & Kinnaird, 2008). The development of the camera trap as a scientific instrument has covered virtually the entire 20th century, the innovation speed has been determined by social and cultural preferences. For example, an increasing public concern for animal welfare has encouraged and sped up the use of non-invasive sampling methods (e.g., camera trapping). Technology developments in sectors such as electronic engineering have created most features (e.g., automation components, networked system, miniaturisation) of the modern camera trap. These have allowed practitioners to efficiently deploy camera traps to collect samples of various species in different environments (O'Connell *et al.*, 2011).

In 1913, George Shiras III became the first person to use a camera trap that allowed an animal to activate the camera and take a self-portrait (O'Brien & Kinnaird, 2008). The initial camera trap was composed of a flash system and a trip wire, and bait was often tied to the wire to attract animals to pull on the trip wire. Shiras successfully photographed many wild species, including American beavers (*Castor canadensis*), raccoons (*Procyon lotor*) and North American porcupines (*Erithizon dorsatum*) (O'Brien & Kinnaird, 2008). By the mid-Twentieth Century, the diminution of photographic equipment and the substitution of toxic magnesium flash powder with bulbs enabled further development of remote animal photography. During this time, several experiments were designed and published using remote cameras to capture wild animal activities (Kucera & Barrett, 2011).

Pearson (1959, 1960) created a camera-trapping system to monitor small mammals' activity patterns, specifically California voles (*Microtus californicus*). The major component of the system was a 16-mm film camera, which was operated one frame at a time so that hundreds of exposures could be taken without having to reset the system. There were two types of triggers used in the design. One used a treadle mounted on the ground, an electric switch was closed when a mouse crossed the treadle, and an image was shot. The other used a dark red-light beam positioned over the study site's ground, and an exposure was made when an animal interrupted the beam. A clock, thermometer, hygrometer, and ruler were also placed within the view of the camera. Individual mice were identified by checking ear tags and comparing the patterns of clipped fur. Although most photos were of voles, 26 species of other mammals, reptiles and birds were also captured and identified in the same study. Additionally, Pearson (1959, 1960) described the effects of relative

humidity and temperature on the activity of western fence lizards (*Sceloporus occidentalis*) and shrews (*Sorex spp.*) (Kucera & Barrett, 2011). Before the 1980s, camera-trapping was primarily a hobby of nature photographers. However, American game hunters started deploying camera traps to explore favourite hunting sites, and the industry emerged (O'Brien & Kinnaird, 2008).

In 1991, an automatic photographic system was developed and equipped with an infrared pulse beam as the trigger. When an animal interfered with the pulse beam, the infrared sensor delivered a signal to a customised automatic 35-mm camera with automatic control of exposure, a specialised flash and a quartz data-back to record the time and date on each image. The system was used to observe animals moving along paths and to identify pollinators visiting flowering plants day and night in Australia (Carthew & Slater, 1991). Griffiths and Van Schaik (1993a) highlighted the usefulness of remote cameras in the study of rainforest wildlife. They documented the avoidance of human-occupied areas and the altered activity patterns among Sumatra's larger mammals using remote photography. In 1995, camera traps were deployed to sample and identify individual tigers (*Panthera tigris*); the population abundance was estimated using the capture-recapture (CR) model for the first time in the Nagarahole National Park, India (Karanth, 1995). Numerous commercially made camera trap models are now available on the market, and major technology advances allow wildlife monitoring to become more efficient at a reasonable cost. For example, many camera traps can function for up to four months in the field, during which up to 20,000 photographs can be taken. Data are collected on-site and stored in small flashcards and can be extracted using card readers (Kucera & Barrett, 2011).

How do camera traps work?

Most modern camera traps equip a passive infrared sensor (PIR) to detect a change in heat and motion between a subject and its surroundings and an infrared or LED flash array to highlight the interest area. Different animals have different infrared heat features, and the PIR distinguishes this difference to activate the camera (Sollmann, 2018). However, a limitation exists in how PIR detects temperature changes between the target animal and its surroundings. When the temperature difference between the target animal and its background is larger than 2.7° C, camera trapping is optimal. Therefore, camera traps with PIR can be unreliable when the surrounding temperature drops within most mammals' body temperature range. Another disadvantage of PIR is that it can be activated by the movement of vegetation within the detection zone (Rovero *et al.*, 2013).

A detection zone is an area where the sensor of a camera trap can detect a target. It is not necessarily the same as the field of view of the camera, e.g., the actual image. Different camera trap

models have different detection zones. Some cameras have a small percentage of the field of view to match their detection zones. Some types have detection zones in conical shapes, while others have a combination of vertical axis zones and horizontal bands, depending on technological specifications. An interacting parameter to the detection zone is the trigger delay, the speed at which the camera shoots a photo when the sensor detects a moving target. A low trigger delay results in a rapid trigger speed that enhances the likelihood of a target being captured. In contrast, a high trigger delay results in a slow trigger speed that may cause missed targets. However, a high trigger delay can provide a larger detection zone.

There are two major groups of PIR camera traps based on flash technology. The majority on the market are PIR equipped with an infrared LED flash. The remainder are PIR fitted with a white flash, which also has two types of flash systems: white LED and Xenon (Swann *et al.*, 2011). Although both are available on the market, there was a significant decline in demand when the infrared LED flash system was promoted (Rovero *et al.*, 2013). Depending on the data to be collected, the type of habitat, and the target species, it is crucial to select the appropriate camera model to collect the required data, as not all models are acceptable for a particular study purpose. For example, for trap shy species, faster trigger speed and more discrete cameras are required to avoid frightening animals and obtain clearer images (Trolliet *et al.*, 2014). The types of camera traps used in this research and setup will be discussed in detail in the methodology chapter.

Major applications of camera traps in monitoring mammals

Through the 1990s and early 2000s, most camera-trapping studies focused primarily on mammals. There were several common applications: (1) mammal inventories and endangered and secretive species detection (e.g., terrestrial rainforest mammals: Tobler *et al.* 2008, Rovero and De Luca, 2007), (2) estimation of relative abundance of cryptic mammals using capture rate of camera traps (e.g., tigers: O'Brien *et al.*, 2003, Carbone *et al.*, 2001), (3) estimation of abundance and density, recruitment and survival of recognisable individual species using Capture Mark-Recapture analysis (e.g., tigers: Karanth and Nichols, 1998, Karanth *et al.*, 2006), (4) occupancy modelling (e.g., Sumatra sun bear (*Helarctos malayanus*): Linkie *et al.*, 2007), (5) a series of species-specific studies on reproduction (e.g., wolf packs, juvenile lynx (*Felis lynx*)), activity patterns (e.g., ungulate: Tobler *et al.*, 2009; swamp rat (*Rattus lutreolus*): Meek *et al.*, 2012b) and disease monitoring (e.g., bare-nosed wombats (*Vombatus ursinus*): Borchard *et al.*, 2012).

Extended applications on avifauna

The first time a camera-trapping system that was used in avifauna research was in a study of wild turkey (*Meleagris gallopavo*) nest predation (O'Brien & Kinnaird, 2008). The system developed by Goetz (1981) consisted of a Polaroid camera fitted with exposure control, an automatic flash and film advance. After Goetz's research, several researchers have also used camera-trapping to study nest predation of avian species. For example, Laurance and Grant (1994) used camera traps and found nine species, including birds, mammals, and reptiles, that visited artificial nests on the ground. Through the videos captured in this study, the authors determined that white-tailed rats (*Uromys caudimaculatus*) were the major predator to ground bird nests in Australia. Major and Gowing (1994) also used camera traps and identified the ship rat as the most significant predator on the nests in trees in Australia (Kucera & Barrett. 2011).

Since the early 2000s, more camera-trapping applications have been used to estimate avian species richness and abundance and discover rare species, which has significantly contributed to avian conservation management (O'Brien & Kinnaird, 2008). Dinata *et al.* (2008) used camera traps for an avifauna monitoring programme in three study areas with various types of habitats, different degradation levels and conservation status in west-central Sumatra. They recorded nine species of birds during their monitoring period and discovered the highest bird species diversity (five species) was from a forest site within Kerinci Seblat National Park (KSNP), but also bordering a degraded forest that used to be a logging site. Camera traps also captured a Sumatran ground cuckoo (*Carpococcyx viridis*) inside an ex-logging area outside KSNP. This species is very cryptic as it had only been documented once since 1916. Therefore, it was important to use the results of these camera traps to raise the conservation status of the area that had ground cuckoos. This research demonstrated that combining routine monitoring with camera-trapping can have significant benefits in finding cryptic avian species and locating species in unexpected habitats that would not have been surveyed otherwise. Many other researchers (e.g., Holden. (2002), Smith *et al.* (2003), Colyn *et al.* (2017) and Roncal *et al.* (2019)) also agreed on the benefits of using camera traps in surveying cryptic avian species, which are difficult to survey either by call or sight.

Number of captures and capture rates

Using camera traps can provide an obvious result which is the count of independent photos of a certain species at a sampling site. A capture rate is obtained by dividing the number of photos by the sampling effort at that place (Sollmann, 2018). According to O'Brien *et al.* (2003), capture rate can be used as a relative abundance index, however, Sollmann *et al.* (2013) suggested that species

abundance and movement patterns, as well as habitat types and camera trap placement patterns and many other factors, can all affect capture rate. If the influence of abundance cannot be separated from the influence of other factors, it is inaccurate to conclude that differences exist in relative abundance across sampling sites, as differences may be caused by other confounding factors.

Instead of index of relative abundance, capture rate could be viewed as an activity index, where species activity at a site increase as more individuals use it and/or some individuals use it more often (Bowkett *et al.*, 2008, Srbek-Araujo & Chiarello, 2013, Sollmann, 2018). In this scenario, Foster *et al.* (2010) suggested that generalised linear mixed models (GLMMs) can be used to analyse capture rates, as this model essentially calculates the associations between the predictor and response variables. The capture rate is the response variable in this situation, and GLMMs are used to examine whether covariates recorded at camera traps and/or over time can account for variance in capture rates. Details of GLMMs and how to use the model will be discussed in the methodology chapter.

Sollmann *et al.* (2018) indicated that when interpreting covariate correlations, it is important to understand that these correlations can represent both ecological processes and sampling processes. For example, suppose that higher capture rates are obtained in scrubland than in pasture areas. In that case, this may indicate that target species use scrubland more often (an ecological process), or this may also indicate that it is easy to target trails and other features that animals prefer to use, thus increasing the likelihood of capturing them (a sampling process). The sampling process is directly related to the strategies of camera placement, which can have a considerable impact on the applicability and accuracy of photo-based information (Kolowski & Forrester, 2017). For example, occupancy models using photo presence/absence data rely on comprehensive information on the factors (e.g., camera placement) that may affect detection likelihood, allowing for including these factors in modelling efforts (Royle & Nichols, 2003). When using occupancy models on rare species with low detection probability, cameras sometimes need to be placed at sites favoured by target species to increase the probability and sample sizes (MacKenzie *et al.*, 2002, Sollmann *et al.*, 2012, Cusack *et al.*, 2015). Kolowski *et al.* (2021) mentioned that capture rates of other models designed to estimate species abundance are also influenced by different factors from different camera placement designs, and a lack of understanding of what and how these factors can affect capture rate could cause bias in the estimates.

Another issue with the camera trapping method is that it may take a long time to capture the target species by the camera (Trolle & Kery, 2005). The longer it takes, the greater the financial cost. Therefore, understanding what factors from camera placement designs can influence the capture

rate will help avoid potential bias or maximise capture rates or save costs. To date, most studies on this subject have concentrated mainly on mammals in new world tropics and on the impacts of various sizes of trails (e.g., roads, animal trails) on camera trap rates (Kolowski & Forrester, 2017). Much less is known about what factors of camera placement designs can influence the capture rate of flightless birds in different continents, and we know nothing about this subject on the North Island brown kiwi.

To achieve a comprehensive understanding of factors influencing capture rates of the North Island brown kiwi, it is crucial to know whether geographical features (e.g., waterholes, slope), macro habitats (e.g., forest, scrub) and seasonal variations will affect capture rates of the brown kiwi. For example, Cunningham and Castro (2011) used a handheld video camera and direct observation technique to study the North Island brown kiwi behaviour on Ponui Island. They indicated that more brown kiwi were recorded in summer than in winter. They believed one of the reasons could perhaps be that most male birds were incubating in winter and thus could not be recorded, hence, fewer brown kiwi were documented in videos in winter. Murphy *et al.* (2017) also found that season affected the detection of the ground-dwelling Madagascar wood-rail (*Mentocrex kioloides*).

As for geographical habitat features, in addition to trails, the North Island brown kiwi may have a range of preferences, which perhaps have varying degrees of influence on the capture rates of camera traps placed in different sites. For example, they may prefer using areas near streams or swamps because the damper and softer soil conditions make foraging easier (Cunningham & Castro, 2011). In addition, many other researchers have suggested that waterholes increase capture rates for different species (e.g., Galliformes and tinamous from Thornton *et al.* (2012); great curassows (*Crax rubra*) and tiger herons (*Tigrisoma lineatum*) from Montalvo *et al.* (2019)). The different types of macro habitats may also influence the capture rates of the North Island brown kiwi on Ponui Island, and this will be tested in this thesis.

There is one more factor, the definition of an independent event, which may also influence the capture rate and the results of analyses of camera trap data. An “event” often refers to an animal appearing in a site on a single occasion and being detected by the camera sensor and captured by the camera (Meek *et al.*, 2014). An independent event refers to repeated visits to a camera site by the same or different animal that are independent from each other. Deciding when a photo/video is independent from the previous necessitates establishing the independent time interval between successive photos or videos (Meek *et al.*, 2014). The optimal time interval for defining independent events has never been determined and is still under considerable debate in wildlife research and camera trap studies (Meek *et al.*, 2014, Sollmann *et al.*, 2018; Peral *et al.*, 2022). Since no camera

trap study has been conducted on kiwi, it is important to know how “independent events” that are defined based on different time intervals can influence capture rates and the subsequent statistical analyses.

Sampling effort

The sampling effort mainly consists of two crucial components: the distance between camera traps and the number of traps. The spacing between traps indicates the independence of observations at nearby sites, and determines the overall spatial coverage, which is important in determining whether the sampling spatial scale is appropriately designed for the target species (Meek *et al.*, 2014). For example, a typical capture-recapture study requires that cameras need to be placed far apart to capture enough individuals, yet close enough to ensure that each individual has some degree of detection probability (O’Brien & Kinnaird, 2011). According to Tobler and Powell (2013), camera traps should have a minimum spatial coverage of the area equating to one home range of the target species and be spaced no more than one home range radius apart from another. Meek *et al.* (2014) suggested that when a regular grid is used for the sampling design, the camera spacing can be reported as a single value. In this thesis, the sampling design is based on a 500 m x 500 m grid (25 ha per grid) designed for camera trapping on a feral cat study. More details about the sampling design will be discussed in the methodology section.

The number of camera trap sites is important in determining if the sampling effort is sufficient to detect an effect of a particular size. The number of sites is influenced by the desired levels of precision in relation to other elements that may affect the research, such as environmental heterogeneity and deployment costs (Meek *et al.*, 2014). Karanth *et al.* (2011) noted that due to the expense of field equipment, camera trap studies often only deploy one camera per site to increase the total sites sampled. Finding strategies that maximise efficiency (e.g., number and placement of traps) and accuracy (e.g., capture rates) is a vital step in improving camera trapping research since it is common to have limited resources (Guillera-Arroita & Lahoz-Monfort, 2012). In fact, it has been demonstrated that missed detections resulting from resource-constrained survey designs affect parameter estimations more than sampling error in habitat covariates related to a sampling unit, in which extra sampling effort can help minimise bias and enhance model predictions (Moilanen, 2002). Both Kirsten *et al.* (2015) and Colyn *et al.* (2017) mentioned that there is a lack of standardisation of sampling efforts using camera traps, particularly regarding monitoring parameters, such as the minimum size of the research area and the minimum number of cameras.

There are also many debates and criticisms about issues with standard protocols for the use of camera traps (e.g., Dillon and Kelly, 2007; Maffei and Noss, 2008; Foster and Harmsen, 2012). In New Zealand, there is no such research focused on the North Island brown kiwi. In addition, because the North Island brown kiwi can be found inhabiting fragmented habitats, and given the fact that habitat fragmentation is one of the most common environmental issues both in New Zealand (Koot *et al.*, 2022; Watchorn *et al.*, 2022; Greig *et al.*, 2022) and worldwide (Sánchez-Fernández *et al.*, 2022; Li *et al.*, 2022; Broekman *et al.*, 2022), there is a need for studies to investigate the protocol of conducting camera trapping surveys on the North Island brown kiwi living in fragmented habitats, how would the capture rates be influenced by these habitats? Due to the small sizes of some fragmented habitats and cost constraints, some sites probably could not fit or warrant many camera traps; how would this affect predictions from the same model used in larger projects? Hence, in this thesis, I aim to investigate how camera numbers can change the capture rate and predictions. I also aim to compare the difference in capture rates for cameras set up in fragmented and continuous habitats with the hope of providing baseline information in the sampling effort of using camera traps on brown kiwi.

Summary

This chapter illustrates that kiwi can inhabit various habitats, not only in indigenous forests but also in forest remnants on production landscapes. Among all types of production landscapes, beef and sheep farms are the most common ones in New Zealand. They contain a quarter of the native vegetation of the country, which makes them ideal kiwi habitats, especially in areas with high-density kiwi populations. However, the potential conflicts between kiwi conservation and production requirements need to be addressed, and all proposed solutions must be based on having information on priority management areas on the production landscape. Hence, a part of this thesis will be investigating kiwi habitat utilisation on a production landscape to provide such information. After reviewing current kiwi management and its monitoring tools, there is an urgent need to expand the existing monitoring toolbox. The future tools need to be sensitive to detect low-density populations, they need to be less labour-intensive and more cost-effective to deal with limited government funding issues, and they need to avoid potential animal welfare issues and encourage in-depth public engagement. Therefore, I aim to test whether the camera trapping method can fill in the gaps and provide reliable information on kiwi management since it has not been used on kiwi but has emerged as a regular wildlife monitoring method for other rare and threatened species around the world.

To better understand how to design an appropriate camera-trapping study on kiwi, it is important to explore some baseline guidance and there is currently no such information. The first critical step is understanding the relationship between camera placement designs and capture rates and what factors may influence capture rates. Capture rates are directly related to many parameter estimations, such as occupancy models and species richness surveys, and it is useful to know the influencing factors of whether these estimations intend to maximise capture rates or avoid potential bias or save costs. Therefore, a range of camera placement designs (placed in macro habitats, nearby geographical features, and seasons) will be tested in this thesis to see the most influential factors on capture rates. Although the time interval for defining independent events is not related to camera placement, this factor may also affect the capture rates and most importantly the prediction ability of statistical models. There are no guidelines regarding this topic on the camera trapping survey for kiwi.

The last part of the review focuses on the sampling effort by using the camera trapping method. At present, most of the relevant research is dedicated to exploring camera spacing and sampling period length. Studies to understand the minimum size of sampling areas and the minimum numbers of cameras required for effective surveys are equally important considering that habitat fragmentation is a common issue globally and kiwi are adaptable to living in small, fragmented habitats, and that there are limited resources for kiwi conservation. Hence, the final aims of the thesis are to (1) provide information on how camera numbers affect capture rates and model prediction ability from cameras placed in fragmented and continuous habitats, and (2) explore the effect of reducing camera traps in an area to detect the minimum number of cameras needed to achieve the same model prediction ability. In the next chapter, I will illustrate the methodology used in this study for examining whether the camera trapping method can be a reliable new monitoring tool to be added to the toolbox of kiwi management in New Zealand.

Chapter 3: Methodology

Study site

This research was conducted on Ponui Island in the Hauraki Gulf, approximately 30 kilometres east of east Auckland (Figure 3.1A). Most of the research activity was centred in the southern end of the island (about 600 ha) (Brown, 1979) (Figure 3.1B). The island is part of the rohe of the indigenous Māori tribe, Ngai Tai. Since 1853, the island has been owned by the Chamberlin family (Brown, 1979). Currently, the island is divided into three separate farms, North Ponui is owned by the Spencer family, Mid Ponui is owned by Richard Chamberlin and South Ponui is owned by Chamberlin's family (Miles and Castro, 2000, I. Castro pers. comm.). The island has been used for farming since the 1850s, and still has about two-thirds of the land predominantly used for sheep and beef farming.

The 1770 ha island is comprised of a series of high hills divided by steep gullies and swamp areas (Bellingham, 1979). The landscape is highly modified, with the northern half of Ponui consisting primarily of pasture and farmland, and the southern half consisting of forest remnants primarily of kauri (*Agathis australis*) and native broadleaf trees. The largest kauri forest fragment (250 ha) is in the centre of the island. The forest in Central Ponui has at times been fenced to allow the forest to regenerate (Brown, 1979), but when water becomes scarce farm animals are allowed in (I. Castro pers. Comm, 2023). The forest at the southern end has never been fenced and is regularly grazed by cattle (*Bos taurus*), sheep (*Ovis aries*) and donkeys (*Equus asinus*). There were 14 North Island brown kiwi translocated to the island at the request of Peter Chamberlin in 1964, six kiwi were from Little Barrier Island and the rest were from Waipoua forest in Northland (Miles & Castro, 2000; Colbourne, 2005). The exact number of individual brown kiwi on the island at present is unknown. Cunningham *et al.* (2007) estimated that the population density of brown kiwi was about one individual/ha, which was the highest density in New Zealand at the time. The population is likely to have lost around a quarter of the birds during a drought in 2020 (I. Castro pers. Comm, 2023).

The island is also home to numerous other indigenous birds, including kereru (*Hemiphaga novaeseelandiae*), kākā (*Nestor meridionalis*), New Zealand dotterel (tūturiwhatu *Charadrius obscurus*) and Australasian bittern (*Botaurus poiciloptilus*). In addition, there are various introduced birds, including Australian magpies (*Cracticus tibicen*), Indian mynas (*Acridotheres tristis*), and a small colony of galahs (*Eolophus roseicapilla*). Reptile species are not common, but two species have been spotted on the island, namely copper skinks (*Oligosoma aeneum*) and shore skinks (*O. smithi*) (Strang, 2018). The diversity of mammals is low on the island. In addition to sheep and

cows, other mammals include donkeys, rats (Polynesian *Rattus exulans* and ship), farm dogs and feral cats. Besides feral cats, there are no other mammalian predators for the North Island brown kiwi population. Although there are farm dogs, they are kept in kennels at night and work with farmers during the daytime, reducing losses through predation.

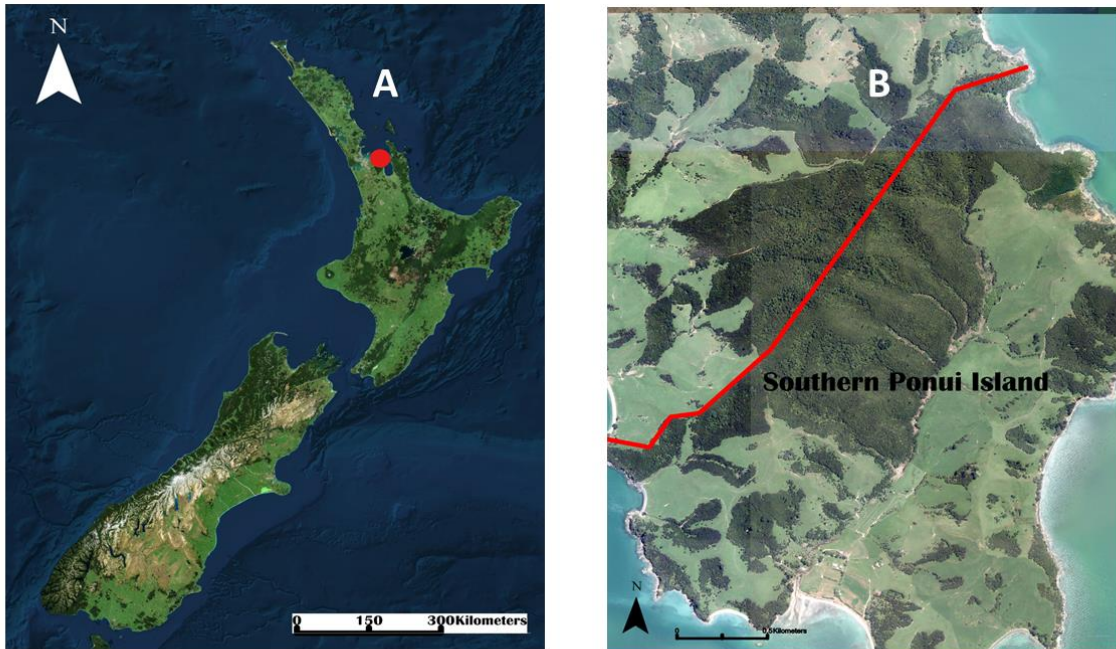


Figure 3.1. Location of the study site, Pomui Island. A. The red dot shows the location in the inner Hauraki Gulf, about 30km east of Auckland. B. The study site, in the southern part of Pomui Island (Southern Ponui Farm).

Data collection

Data set used in this study

The research in this thesis utilizes data collected during Kathryn Strang's PhD research that studied the behavioural ecology of feral cats on Ponui Island (2018). Part of her research investigated the utility of camera traps when studying feral cat activity. Because of the size of the feral cats, cameras were attached at a low height, which generated significant amounts of bycatch data containing brown kiwi. These data are what I am using in this thesis. The brown kiwi on the island has been the focus of long-term radio telemetry research led by the Massey University Kiwi Research Group. Therefore, many features of kiwi behaviour and distribution on Ponui Island are well known. Cameras were set up in 28 locations in a 500m x 500m sampling grid, and videos were collected from 2014 to 2017, covering a total of 39 months, 12,853 trap nights (Strang, 2018), and resulting in 1676 videos containing brown kiwi (using 30-minute interval for defining independent detection events). The method of original data collection used by Kathryn Strang is summarised in **Appendix B**.

Although the grid was originally designed based on the minimum size of feral cat home range in New Zealand (female: 15ha, male: 40 ha) (Fitzgerald and Karl, 1986) to minimise the possibility of

capturing the same individual on several other camera locations, it was also suitable for the brown kiwi population on Ponui Island for the same purpose. Ziesemann. (2011) conducted research on studying mating patterns and social organisation of the brown kiwi population on Ponui Island. In the research, she measured the home range size of the brown kiwi population using radio-tracking method and suggested that the annual home range size (95% isopleths) of male brown kiwi on Ponui was about 5.32 ha (estimated by the fixed kernel(KE)) and about 9.74 ha (estimated by the minimum convex polygon(MCP)); for female brown kiwi, the size was about 6.19 ha (KE) and about 13 ha (MCP). Home range sizes became smaller for both sexes during nesting season. During the breeding season, male birds had a home range of 3.66 ha (KE) and 9.75 ha (MCP), and female birds had an average home range of 3.81 ha (KE) and 12.79 ha (MCP). Although these camera trap data were collected a few years after the research of Ziesemann. (2011), the brown kiwi population was likely at carrying capacity and there were no large changes in the population during the two research periods. (I. Castro, 2022, pers. comm.). Hence, the video data should be suitable and valid for this research purpose. GPS coordinates of the 28 camera sites were recorded by a Garmin eTrex® 20x GPS device. The camera sites are shown in the map below (Figure 3.2).



Figure 3.2. The 28 camera traps were placed in a 500m x 500m grid throughout southern Ponui Island

Prior to my involvement with the data, videos were checked for all species presence including brown kiwi presence. If a kiwi was spotted in the video, kiwi-related data and video clip information were entered into an Excel spreadsheet. Information included camera location, number of individuals, date, time (hour and minute), whether the bird was wearing a transmitter, and if so, which legs it was attached to.

Data processing for this study

Classification of Macrohabitats

I classified the camera sites into three major macrohabitats namely scrub, forest, and pasture plus scrub edge. The first two habitat types and pasture habitat were classed by using Arc GIS. Map layers used for Arc GIS were from The New Zealand Land Cover Data Base (version 5.0) and were cropped and downloaded from the Land Resource Information System (LRIS) portal. After plotting onto the map, the forest habitat was classified into two types: broadleaf indigenous hardwoods and indigenous forest, Scrub and pasture habitats consisted of manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*) and high production exotic grassland respectively. The symbology function was applied to the map to distinguish habitats.

The third habitat was an edge habitat. The identification of edge habitat relied on how habitat patches are formed within a landscape since edges are typically described as boundaries between specific habitat patch types (Ries *et al.*, 2014). According to Cadenasso *et al.* (2003), patches can be defined at a range of scales, ranging from different plant species within a grassland to entire continents. Because of the scope of this research, I concentrated on patches of different land-use classes and vegetation types within production lands. These patches are generally small, with vegetation growing on the edge receiving more sunlight, larger temperature changes and lower humidity levels compared to vegetation growing inside of the patch. An "edge effect" is caused by these factors, which limit plant range in the bush by up to 60m (Veselkin *et al.*, 2021). Thus, I consider edge habitats in my research as areas within 50m either side of an edge between different habitats mentioned above.

To locate edge habitats and camera locations around these habitats, I used the buffer function in Arc GIS (located in the edit tool on the editor toolbar). A buffer was created by clicking the edge that had one or more camera traps, and the distance (50 m) for the buffer area around the target feature was entered into the system. Finally, if camera traps were found inside the buffer area, these locations would be defined as edge habitats.

Classification of geographical features, time intervals and seasons

Slope steepness was classified based on the New Zealand National Digital Elevation Model (DEM, North Island) with a resolution of 25 metres. The layer containing South Ponui Island was cropped and downloaded from LRIS and loaded into Arc GIS. The slope steepness was classed into three tiers: 0-8.5 degrees or gentle, 8.5-16.5 degrees or moderate and >16.5 degrees or steep (Bisht *et al.*, 2018). The symbology function was applied to the map to distinguish different slopes with different colours. Videos from camera locations in different slope levels were counted and recorded in Excel. The same DEM layer was used for classifying the aspects of these slopes. The aspect was defined as the clockwise surfaces of a slope measured from 0 to 360 degrees from the north. In general, the directions were categorised clockwise into north, north-east, east, south-east, south, south-west, west, and north-west. The directions were managed as 45 degrees groups (Cellek, 2021). Due to the small sample size, the aspects were classed into four categories: north (0-89°, 360°), east (90-179°), south (180-269°) and west (270-359°). Videos from camera locations in each category were counted and recorded in the same spreadsheet.

To locate swamp areas and surrounding camera locations, the NZ swamp polygons layer from the Topo 50 map was used in Arc GIS at first. However, the final map could not match the number of swamps in previous research from Ponui Island (e.g., Latham, 2006; Dixon, 2015). Therefore, to ensure accuracy, all 28 camera locations were tracked and found by following their GPS coordinates in June 2022, and the surroundings were checked for the presence of a swamp or other water features such as streams. The swamp boundary was clear and could be defined based on the predominant vegetation, raupo (*Typha orientalis*) (Latham, 2006; Dixon, 2015). The swamp areas and streams were mainly found at the bottom of gullies. Examples of swamp areas and streams around the camera sites can be seen in Figure 3.3.



Figure 3.3. Camera trap locations near swamp areas and streams

According to Strang. (2018), cameras were placed on and off trails. In my research, the camera locations were categorised into two groups: on trails and off trails. I confirmed the location of trails to the camera traps during the June 2022 visit to Ponui Island. Examples of trails and roads where some of the 28 cameras were located can be seen in Figure 3.4.



Figure 3.4. Camera trap locations on various sizes of major roads and animal trails.

Assigning independent events

To determine how time intervals of independent events would influence capture rates, I used Meek *et al.* (2014) and Sollmann. (2018) as guidance for choosing the time ranges. Both authors suggested that time intervals ranging from 10 minutes to 60 minutes had been used by researchers for different camera trap studies on various species. Therefore, I chose four cut-off points: 15 minute, 30 minute, 45 minute and 60 minute intervals to examine the effect of time interval on the camera trap rates. For example, when using 30 minute intervals, if a kiwi appeared in the detection zone of a camera for successive videos or reappeared in the detection zone within 30 minutes of the first video, only information and the number of birds from the first video were counted and recorded in a separate Excel spreadsheet. Observations separated by >30 minutes were categorised as independent and then used in the GLMM and used for calculating the capture rates. The primary field data (raw data) were classed into a separate Excel spreadsheet based on each time interval. Each spreadsheet had bird video count and all habitat information mentioned above and was loaded into GLMM to test the model prediction ability. The capture rates were calculated and compared for each time interval.

Seasonal variation in capture rates

To investigate seasonal variation influencing capture rates, I first checked the annual climate summary (2014 – 2016) from the National Institute of Water and Atmospheric Research (NIWA). The annual temperature for 2014 and 2015 was within 0.5°C of the annual temperature average. 2016 was claimed to have been the warmest year since 1909, with the annual temperature for Auckland and surrounding areas (e.g., Ponui Island) about 0.51°C above the annual temperature average. The annual rainfall for the three years was near normal (20% or less of the annual average) (NIWA, 2016). The four seasons used in my research were divided into spring (September to November), summer (December to February), autumn (March to May), and winter (June to August). Bird video count data were grouped together based on their month under different seasons.

Classification of fragmented and continuous habitats

The continuous habitat was classified based on the description from Brown (1979) who stated that there is one large kauri and broadleaf forest fragment (about 250 ha) in the middle of Ponui Island. This fragment was found and highlighted on the Arc GIS map (Figure 3.5).



Figure 3.5. The continuous habitat located in the central of Ponui Island consisted of the kauri forest and other broadleaf forests.

If the camera traps were placed in the highlighted area, they were counted as inside the continuous habitat. In turn, any camera site that was outside this area was inside the fragmented habitats. The raw data from the camera traps were classed into two separate data sets based on continuous and fragmented habitats and using 30-minute intervals for determining independent events. The two data sets were loaded into GLMM to test the relationship between these two camera placement strategies and model prediction ability.

Data processing for random reducing cameras

To understand the relationship between camera numbers and model prediction ability, and the minimum number of cameras for achieving the same model prediction ability as the original model (with 28 cameras), I removed some camera stations randomly from the original grid using the `RANDBETWEEN` function in excel. I started removing one camera trap from each macrohabitat and from each month randomly. This process was done ten times generating ten separate data sets and they were loaded into GLMM to test the model prediction ability. If the prediction ability was the same as the original model (with 28 cameras), the capture rates were then calculated and compared to check specific differences caused by camera reductions. The same procedure was repeated to remove one more camera each time until the model prediction ability collapsed.

Data analysis

Generalised Linear Mixed Model

I used the generalised linear mixed models code from the lme4 package in R to determine habitat utilisation of the brown kiwi population in southern Ponui Island and to test what factors would affect the number of kiwi videos recorded at different camera sites. These factors included: macrohabitats, geographical features and seasonal variations. The reason for using GLMM was based on the consideration of the independence of residuals. It is common that the data in many studies and surveys are arranged into clusters, such as genotypes, observers, dates and spatial locations. These clusters are part of a larger group of clusters, so instead of focusing on variation between clusters, it is more useful to determine how much variation there is among clusters. This is because the data may be structured by variation among clusters, but it is not included in the hypotheses. The non-independence of residuals is accounted for by absorbing the variation among clusters, only keeping the variation related to the predictors whose significance needs to be evaluated (Dawber, 2019). For example, in my research, I wanted to infer a relationship between camera trap placement in a macrohabitat and the number of bird videos collected by that camera. However, the video count data were clustered into different camera trap locations, which might introduce extra noise into the data analysis. Variation among trap locations can be absorbed by using GLMM, only keeping independent residuals related to macrohabitat types.

GLMM contains a mixture of random and fixed effects. Random effects are categorical explanatory factors that are used to predict variation among categories. These effects are known to affect the data but are not part of the hypotheses (Manning, 2007). Fixed effects are explanatory factors that are used to predict slopes or variations between categories. These effects are directly associated with the hypotheses (Manning, 2007). The table below (**Table 3.1**) shows the random and fixed effects in my research.

Table 3.1. Macrohabitats, geographical features and seasons related to the 28 trap sites used in this study that evaluated as predictors for the number of kiwi videos. These are the fixed effects. Camera location ID is the only random effect identified in this study.

Predictor	Categories	Random or Fixed Effects
Camera location ID		Random
Macrohabitats	Forest	Fixed
	Scrub	Fixed
	Scrub and pasture edge	Fixed
Season	Spring	Fixed
	Summer	Fixed
	Autumn	Fixed
	Winter	Fixed
Slope	Gentle	Fixed
	Moderate	Fixed
	Strong	Fixed
Aspect	North	Fixed
	East	Fixed
	South	Fixed
	West	Fixed
Swamp	Around a swamp/water feature	Fixed
	Not around swamp/water	Fixed
Track	On a track/road	Fixed
	Not on a track/road	Fixed

If not using GLMM, random effects are usually treated as fixed effects and ignored on purpose during testing the hypothesis (Harrison *et al.*, 2018). The disadvantage is that if there are too many clusters of the random effects, these clusters will use a degree of freedom each to infer their cluster-specific means, and then the available capacity to examine fixed effects is very low due to the loss of the residual degrees of freedom (Harrison *et al.*, 2018). As mentioned above, GLMM infers variation among random effect clusters instead of variation between means. By doing so, only one degree of freedom is consumed by each inferred variance, allowing enough capacity for testing fixed effects-related hypotheses. The model used in this research was a simple mixed-effects consisting of a linear regression that takes into account the random intercept of the cluster. The different random intercepts for each cluster are fitted with a normal distribution of which variance is inferred by the model. By doing so, the model reflects how much the clusters change in intercept and only consumes one degree of freedom (Valletta & McKinley, 2018).

The lme4 package contains the lmer function specifically for variables showing Gaussian distribution and the glmer function for all generalised error distributions. For this research, glmer

function with Poisson distribution was used. Because the kiwi video count data did not show a Gaussian distribution, they matched with the assumption of the Poisson distribution which is defined as the distribution of count data of events that occur independently and randomly through time and space (Harrison *et al.*, 2018). These data are constructed of integers, with a lower bound of zero and up to infinite. The fixed effects are coded the same as the generalised linear model with Poisson distribution, the random intercept effect is introduced by coding “+ (1| random intercept)” which in my case is the camera location ID.

The Akaike Information Criterion (AIC) was used to determine the best model among a group of rival models. Because the AIC is not quantified in meaningful units of information, the AIC value of one model is not very useful (Dawber, 2019). But when this value is compared between models, the best model normally has the lowest AIC. This model comparison process is also known as model simplification (Harrison *et al.*, 2018). It is common to start by simplifying the model with the most explanatory variables and excluding any variable that is not significant and/or can lower the AIC of the model (Valletta & McKinley, 2018). For example:

- The full model with the most explanatory variables (m1) and one of the simplified models (m2) of this research were:
 - `m1<-glmer(Bird~Habitat+Season+Slope+Aspect+Swamp+Track+(1|Location),data=data1,family='poisson')`
 - `m2<-glmer(Bird~Habitat+Season+Slope+Aspect+Swamp+(1|Location),data=data2,family='poisson')`
- The ANOVA function was used to compare these two models to check whether the prediction ability of the model without “Track” as a predictor became better (lower AIC) than the full model (m1) and to check whether “Track” was significant by analysing the p-value of the simplified model (m2). If $p < 0.05$, “Track” would be a significant predictor of the model:
 - `anova (m1, m2)`

This process was continued by omitting the least significant predictor of the full model until the AIC value did not change anymore, suggesting that the significant predictors were the only ones left. In the end, the summary function in R was used for deriving the results of the final model. The result summary contains information about the estimate, standard error, z-value and p-value. The p-value is of particular importance as it indicates what category (e.g., scrub) of the predictor (e.g., macrohabitat) is significant when the p-value is less than 0.05.

Capture rate

The capture rates were calculated and plotted as bar charts for each category of the fixed effect predictors left in the final model, describing how the categories within each predictor influenced the likelihood of bird being found in a particular macrohabitat type, a specific season and a certain geographical feature after removing the effect of other non-significant fixed effect predictors. Due to the large dataset of brown kiwi videos for each category and predictor, the pivot table function in Excel was used to calculate the sum number of bird videos, the number of trap nights at each trap and the sum of the number of camera traps for each category. To ensure accurate and meaningful comparisons during statistical analysis, the collected data was standardized by dividing the sum number of videos by the trap nights at each trap site and this was divided by the sum number of camera traps. The duration of data collection was varied for this research, and standardization helped to mitigate any potential biases that could arise from such variations in sampling effort.

Heat maps in QGIS

Heat maps were also made using QGIS to visualise the influence of specific macrohabitat types and geographical features on brown kiwi capture rates. These maps were made by using a comma-separated values (CSV) Excel file that included the coordinates of camera locations and the kiwi capture rate (bird/night) at each location. The CSV file was loaded in QGIS via delimited text in the data source manager and the EPSG:4326-WGS 84 was used as the geometry coordinate reference system for making the camera location layer. The layer was then projected to Ponui Island image map layer, the habitat type layer and the slope level layer. Under the symbology of the location layer, graduated symbols were chosen and the column containing the capture rate was attached to these symbols. The method for symbology classification was based on the size of the symbol with natural breaks. From the map, the larger the dot, the higher the capture rate from that specific camera site.

Chapter 4: Results

Overview of the dataset

The dataset used in the original overall GLMM analysis and the heat maps (with 28 cameras operating) comprised a total of 1676 independent videos that were classed based on 30-minute intervals. When testing the effects of time interval for defining independent events on capture rates, the raw dataset was further classed based on 15-minute, 45-minute and 60-minute intervals, resulting in 1773 videos, 1595 videos and 1511 videos respectively. The dataset used in the continuous habitat analysis contained 523 independent videos (classed based on 30-minute intervals) that were collected by 13 cameras, and for fragmented habitat analysis, the dataset contained 1153 independent videos (classed based on 30-minute intervals) that were collected by 15 cameras. For the camera reduction analysis, all independent videos in the dataset were classed based on 30-minute intervals.

Overall model using 28 camera trap grids: Effects of macrohabitat type, season, and slope level on camera trap capture rates

Macrohabitat type, season, and slope level had a significant influence on the number of brown kiwi videos captured at a camera trap (Table 4.1). Camera traps placed in the forest, captured significantly more brown kiwi in videos than those located in edges or scrub (Table 4.2; Figure 4.1A). Most bird videos (average 1.46 ± 0.06 bird video/night/camera) were captured in winter, followed by autumn with an average of 1.37 ± 0.03 bird video/night/camera, then spring and summer with 1.15 ± 0.08 and 0.86 ± 0.06 bird videos recorded per camera per night respectively (Figure 4.1B). Cameras located on gentle slopes captured the most videos (approximately 1.46 ± 0.04 bird video/night/camera) while moderate slopes had the least (approximately 0.73 ± 0.09 bird video/night/camera) and steep slopes intermediate numbers (1.21 ± 0.06 bird videos captured per camera per night; Figure 4.1C).

Table 4.1. Results for the overall generalised linear mixed model with Poisson distribution looking at factors influencing the number of brown kiwi videos captured at camera trap sites. Independent detection events were classified based on 30-minute intervals. The table below contains the three major factors that were identified in the best model (habitat, season and slope), followed by the factors that were eliminated in each phase of a stepwise backwards elimination. The factors are listed in the order in which they were eliminated, and the AIC values of the model are shown for each elimination. *df* = degrees of freedom

Factor	df	Deviance	P-value	AIC
Overall model			<0.001	1689.9
Habitat	2	1686.0	<0.001	
Season	3	1755.2	<0.002	
Slope	2	1676.5	0.02	
Aspect	3	1670.6	0.63	1692.6
Swamp	1	1669.4	0.47	1695.4
Track	1	1670.2	0.25	1696.2

Table 4.2. Results of the best Generalised linear mixed model including estimate, standard error (Std. Error), z value and P-value to indicate significance levels for each category as a predictor of the number of brown kiwi videos captured at different camera sites. Independent detection events were classified based on 30 minutes intervals. The intercept includes the missing category for the reference factor: Habitat – Forest, Season – Autumn, Slope – Gentle.

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.99	0.25	11.95	<0.001
Habitat	Scrub	-1.15	0.26	-4.45	<0.001
	Scrub and pasture edge	-0.73	0.26	-2.78	0.005
Season	Spring	-0.07	0.10	-0.70	0.49
	Summer	-0.64	0.08	-8.27	<0.001
	Winter	0.21	0.10	2.05	0.04
Slope	Moderate	-0.70	0.22	-3.15	0.002
	Strong	-0.04	0.34	-0.11	0.91

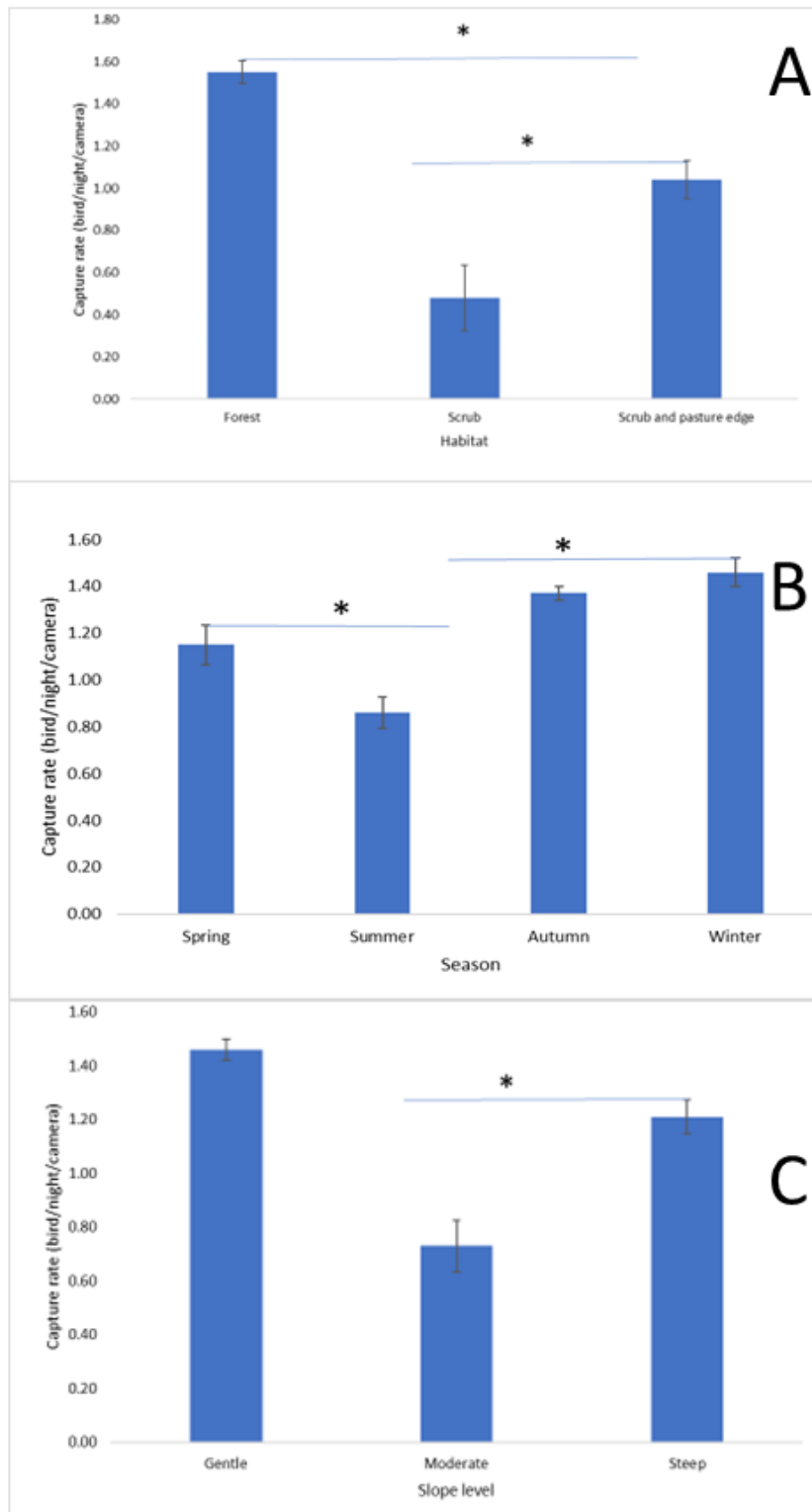


Figure 4.1. Capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the southern part of Ponui Island. A. effect of habitat on capture rate; B. effect of season on capture rate; C. effect of slope on capture rate. Stars denote significant differences.

Activity hot spots

Heat maps were made to show the capture rates of kiwi videos recorded at different camera trap sites in the landscape. During the whole survey period, each camera recorded at least one brown kiwi video. The highest capture rate was 1.74 ± 0.05 bird video/night/camera (Figure 4.2A). When I superimposed the landcover map, the major hotspots were mainly located in the forest habitats with a range from 1.27 ± 0.06 to 1.74 ± 0.05 video/night/camera (Figure 4.2B). Camera traps located in scrub and pasture edge habitats captured between 0.77 ± 0.02 and 1.27 ± 0.06 bird videos per night per camera. The lowest camera trap rates were from sites located in scrub habitats with most cameras recording between 0.23 ± 0.03 and 0.53 ± 0.05 video per night per camera. The slope map indicated that most kiwi activities were captured on gentle slopes ranging from 0.77 ± 0.02 to 1.74 ± 0.05 bird video/night/camera (Figure 4.2C). Both moderate and steep slopes had a couple of major hotspots, but they had a mixed level of capture of kiwi activities ranging from as low as 0.23 ± 0.03 bird videos per night per camera up to 0.77 ± 0.02 bird videos per night per camera.

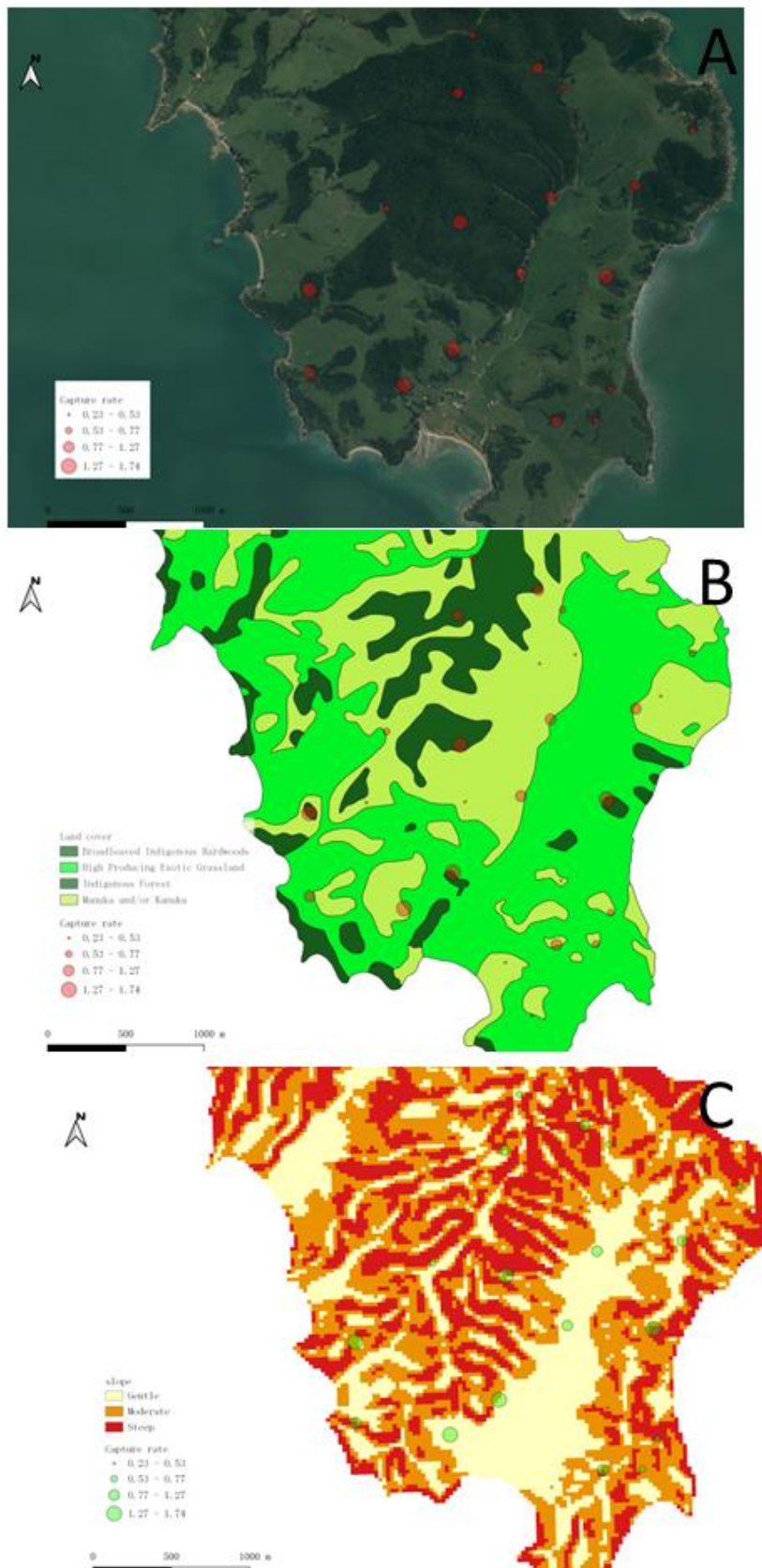


Figure 4.2. Heat map showing brown kiwi activity in the southern part of Pomui Island. A. activity from the 28 cameras placed in the 500m x 500m grid. The larger the point, the higher the capture rate of brown kiwi from the camera trap site; B. activity from the three major habitats: forest, scrub and scrub and pasture edge; C. activity from the three levels of slopes: gentle (0–8.5 degrees), moderate (8.5–16.5 degrees) and steep (>16.5 degrees).

Effects of time interval for defining independent events on capture rates

There were no significant differences in findings between capture rates estimated using 30-min, 15-min, 45-min or 60-min intervals to define independent events (Table 4.3). When analysing each predictor, all three models provided similar results for macrohabitats and slope levels and the same trends as the original model with 30 min intervals (Table 4.4; Figure 4.3A and Figure 4.3C).

Although all three models also provided the same trend for seasonal variations in capture rates, with the highest number of videos captured in winter and autumn, followed by spring and summer, the significant difference in capture rate between autumn and winter disappeared when sampling at 60 min intervals (Figure 4.3B; Table 4.4). After calculating the total capture rates of all 28 camera traps for each time interval, the capture rates decreased from about 0.81 ± 0.04 bird/night/camera using 15 min intervals to about 0.79 ± 0.06 bird/night/camera using 60-min intervals (Figure 4.4). This type of small decline could also be found within each category (e.g., forest) of each predictor from using 15 min intervals to 60-min intervals (Figure 4.3A, Figure 4.3B, Figure 4.3C).

Table 4.3. Results for the overall generalised linear mixed model with Poisson distribution looking at factors influencing the number of brown kiwi videos captured at camera trap sites, by sampling interval. The table contains the three major factors that were identified in the best model, habitat, season and slope, followed by the factors that were eliminated in each phase of a stepwise backwards elimination. The factors are listed in the order in which they were eliminated, and the AIC values of the model are shown for each elimination. *df* = degrees of freedom.

Interval	Factor	df	Deviance	P-value	AIC
15-min	Overall model			<0.001	1718.8
	Habitat	2	1714.7	<0.001	
	Season	3	1793.5	<0.001	
	Slope	2	1705.4	0.02	
	Aspect	3	1699.5	0.63	1721.5
	Swamp	1	1698.4	0.41	1724.4
	Track	1	1699.0	0.26	1725.0
45-min	Overall model			<0.001	1678.1
	Habitat	2	1674.8	<0.001	
	Season	3	1734.8	<0.001	
	Slope	2	1665.4	0.01	
	Aspect	3	1659.1	0.62	1681.1
	Swamp	1	1657.8	0.50	1683.8
	Track	1	1658.4	0.30	1684.4
60-min	Overall model			<0.001	1672.4
	Habitat	2	1668.5	<0.001	
	Season	3	1734.7	<0.001	
	Slope	2	1659.4	0.02	
	Aspect	3	1653.4	0.64	1675.4
	Swamp	1	1652.2	0.50	1678.2
	Track	1	1652.8	0.30	1678.8

Table 4.4. Results of the best Generalised linear mixed model include estimate, standard error (Std. Error), z value and P-value to indicate significance levels for each category as a predictor of the number of brown kiwi videos captured at different camera site, by sampling interval. The intercept includes the missing category for the factor; Habitat – Forest, Season – Autumn, Slope – Gentle.

Interval	Factor	Category	Estimate	Std. Error	z value	P-value
15-min	(Intercept)		3.05	0.25	12.09	<0.001
	Habitat	Scrub	-1.16	0.26	-4.46	<0.001
		Scrub and pasture edge	-0.72	0.26	-2.72	0.006
	Season	Spring	-0.10	0.10	-1.02	0.31
		Summer	-0.67	0.08	-8.66	<0.001
		Winter	0.20	0.10	1.98	0.04
	Slope	Moderate	-0.72	0.22	-3.22	0.001
		Strong	-0.06	0.34	-0.18	0.86
	45-min	(Intercept)		2.97	0.24	12.15
Habitat		Scrub	-1.14	0.25	-4.51	<0.001
		Scrub and pasture edge	-0.73	0.26	-2.87	0.004
Season		Spring	-0.05	0.10	-0.46	0.64
		Summer	-0.63	0.08	-7.93	<0.001
		Winter	0.20	0.10	1.94	0.05
Slope		Moderate	-0.70	0.22	-3.25	0.001
		Strong	-0.05	0.33	-0.15	0.88
60-min		(Intercept)		2.94	0.24	12.11
	Habitat	Scrub	-1.10	0.25	-4.41	<0.001
		Scrub and pasture edge	-0.73	0.25	-2.89	0.004
	Season	Spring	-0.04	0.10	-0.43	0.67
		Summer	-0.66	0.08	-8.30	<0.001
		Winter	0.19	0.10	1.83	0.07
	Slope	Moderate	-0.67	0.21	-3.13	0.002
		Strong	-0.04	0.33	-0.12	0.91

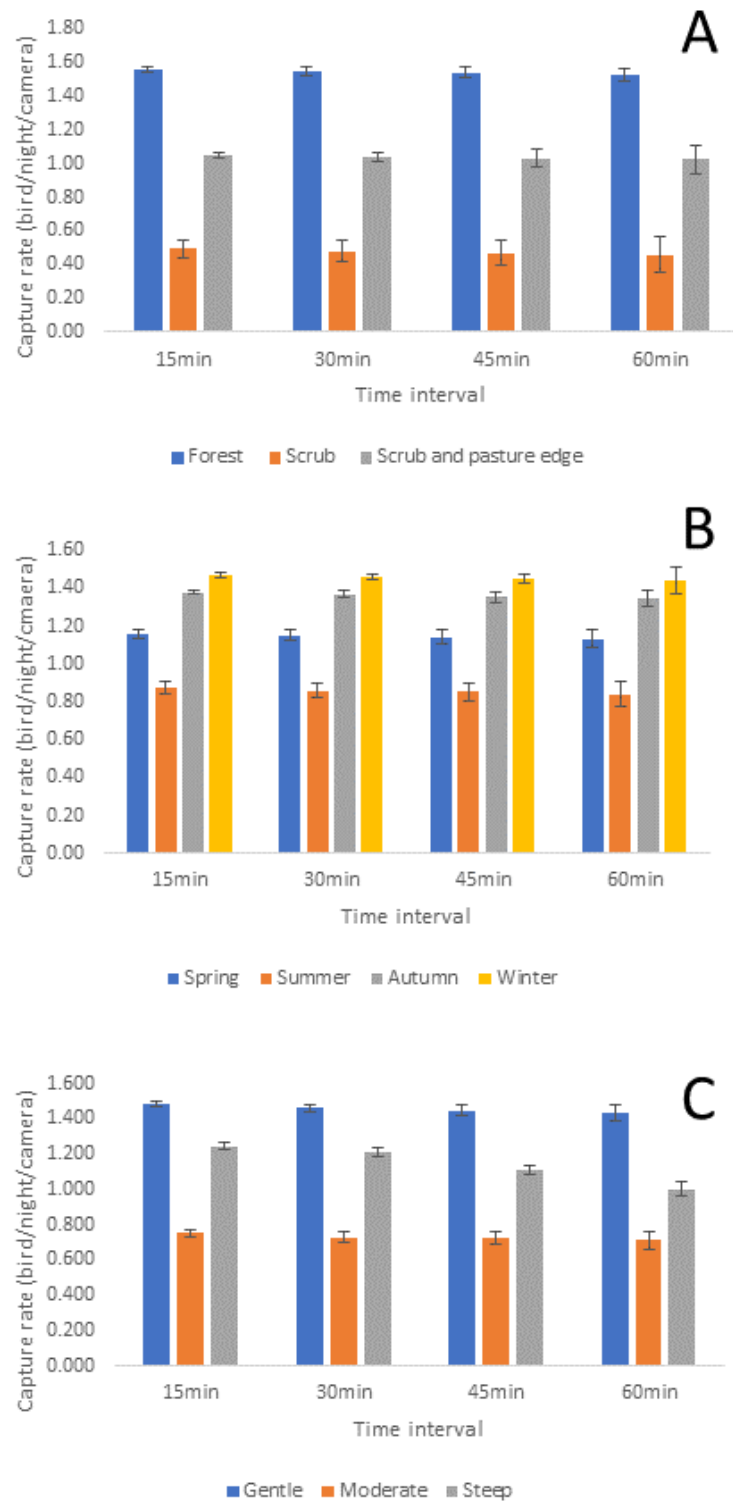


Figure 4.3. Difference between the capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the southern part of Ponui Island when independent detection events were classified based on different time intervals: 15min, 30min, 45min and 60min. A. effect of habitat on capture rate; B. effect of season on capture rate; C. effect of slope on capture rate.

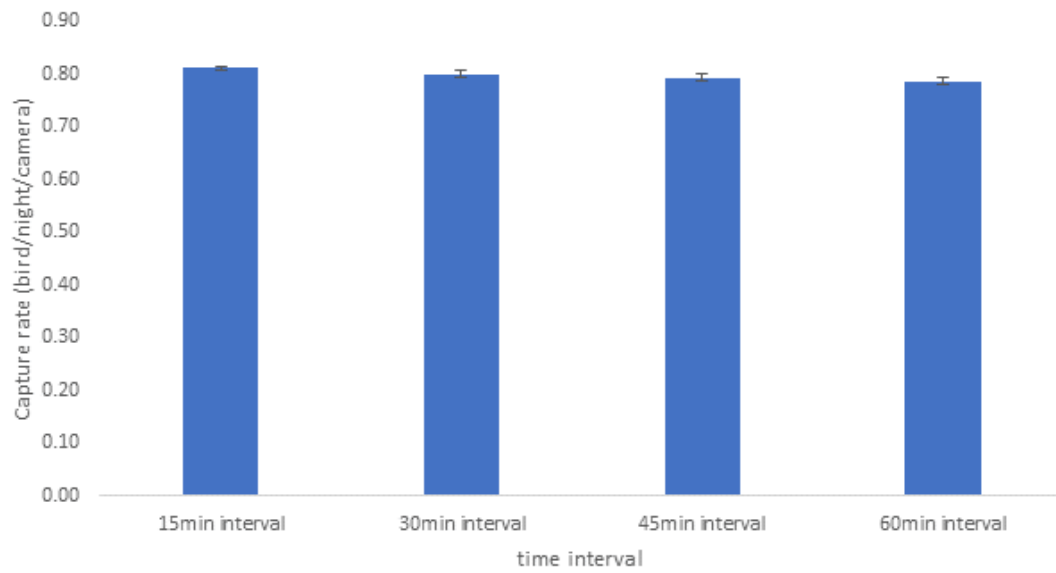


Figure 4.4 Capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the southern part of Ponui Island when independent detection events were classified based on different time intervals: 15 min, 30 min, 45 min and 60 min.

Results of camera traps located in continuous (n=13) and fragmented (n=15) habitats

The initial model had 28 cameras, and the capture rate was significantly different to that calculated from the 13 camera traps placed in the central continuous habitat (Table 4.5). Macrohabitat type and season were the two factors identified as having a significant influence on the number of kiwi videos (Table 4.5). Namely only forest and scrub were significant drivers on the number of kiwi videos, and winter became an unimportant category in the final model (Table 4.6).

There were 15 camera traps located in the surrounding fragmented habitats, and the model that used the video data collected from these locations lost some predictive power but generally remained the same as the original model and fitted the data better than the model of continuous habitat. The three predictors whose significance was identified in the original model—macrohabitat type, season and slope level—remained important factors influencing the number of videos captured at different camera trap sites within fragmented habitats (Table 4.5). The final model containing these three predictors was the best-fit model based on the lowest AIC value, and the final model itself was significant as well (Table 4.5). All three categories of the macrohabitat factor were significant, and three categories (summer, autumn, and winter) of the season factor remained significant as well (Table 4.6). Both gentle and moderate slopes were still important categories in the final model, but in this model, strong slopes became an important category affecting the number of videos recorded in fragmented habitats (Table 4.6).

Table 4.5. Results for the overall generalised linear mixed model with Poisson distribution looking at factors influencing the number of brown kiwi videos captured at camera trap sites located in the continuous and fragmented habitats in the southern part of Ponui Island. The table below contains the major factors that were identified in the best model, followed by the factors that were eliminated in each phase of a stepwise backwards elimination. The factors are listed in the order in which they were eliminated, and the AIC values of the model are shown for each elimination. *df* = degrees of freedom

Sampling effort	Factor	df	Deviance	P-value	AIC
Continuous habitats	Overall model			<0.001	846.7
	Habitat	2	838.3	0.008	
	Season	3	908.4	<0.001	
	Slope	2	832.0	0.33	847.96
	Aspect	3	826.9	0.16	848.88
	Swamp	1	821.9	0.65	847.93
	Track	1	821.8	0.83	847.77
Fragmented habitats	Overall model			<0.001	835.8
	Habitat	2	822.8	0.01	
	Season	3	826.5	<0.002	
	Slope	2	817.1	<0.001	
	Aspect	3	816.5	0.32	838.49
	Swamp	1	813.3	0.60	839.26
	Track	1	816.2	0.07	842.16

Table 4.6. Results of the best Generalised linear mixed model include estimate, standard error (Std. Error), z value and P-value to indicate significance levels for each category as a predictor of the number of brown kiwi videos captured at camera sites located in continuous and fragmented habitats in the southern part of Ponui Island. The intercept includes the missing category for the factor of continuous habitat: Habitat – Forest, Season – Autumn. The intercept includes the missing category for the factor of fragmented habitat; Habitat – Forest, Season – Autumn, Slope – Gentle.

Sampling effort	Factor	Category	Estimate	Std. Error	z value	P-value
Continuous habitat	(Intercept)		2.70	0.26	10.32	<0.001
	Habitat	Scrub	-0.84	0.28	-3.03	0.002
		Scrub and pasture edge	-0.31	0.32	-0.98	0.33
	Season	Spring	-0.26	0.14	-1.90	0.06
		Summer	-0.74	0.10	-7.52	<0.001
		Winter	0.23	0.14	1.71	0.09
Fragmented habitats	(Intercept)		3.31	0.54	6.14	<0.001
	Habitat	Scrub	-1.46	0.52	-2.81	0.005
		Scrub and pasture edge	-0.76	0.50	-1.52	0.03
	Season	Spring	0.09	0.15	0.63	0.53
		Summer	-0.46	0.13	-3.55	<0.001
		Winter	0.16	0.15	1.06	0.02
	Slope	Moderate	-1.12	0.35	-3.17	0.002
	Strong	-2.88	1.30	-2.22	0.03	

Since the fragmented habitats model kept an almost intact prediction ability, the capture rate of each category was calculated and further compared. The highest number of bird videos were still recorded in the forest habitat with an average of 1.24 ± 0.01 birds/night/camera, followed by 0.96 ± 0.02 and 0.57 ± 0.05 birds/night/camera in the scrub and pasture edge habitats and scrubs (Figure 4.5A). The highest number of videos captured by all 15 camera traps still occurred in winter with an average of 1.11 ± 0.02 birds/night/camera, followed by spring and then autumn with about 0.93 ± 0.06 and 0.91 ± 0.02 birds/night/camera respectively. Like the original model with 28 camera traps, the fewest videos were also recorded in summer with an average of 0.73 ± 0.08 birds/night/camera (Figure 4.5B). The capture rates on steep slopes were significantly lower than on gentle and moderate slopes, with only 0.47 ± 0.05 birds/night/camera (Figure 4.5C). Gentle and moderate slopes had an average of 1.31 ± 0.03 and 0.99 ± 0.04 bird videos recorded per night per camera (Figure 4.5C).

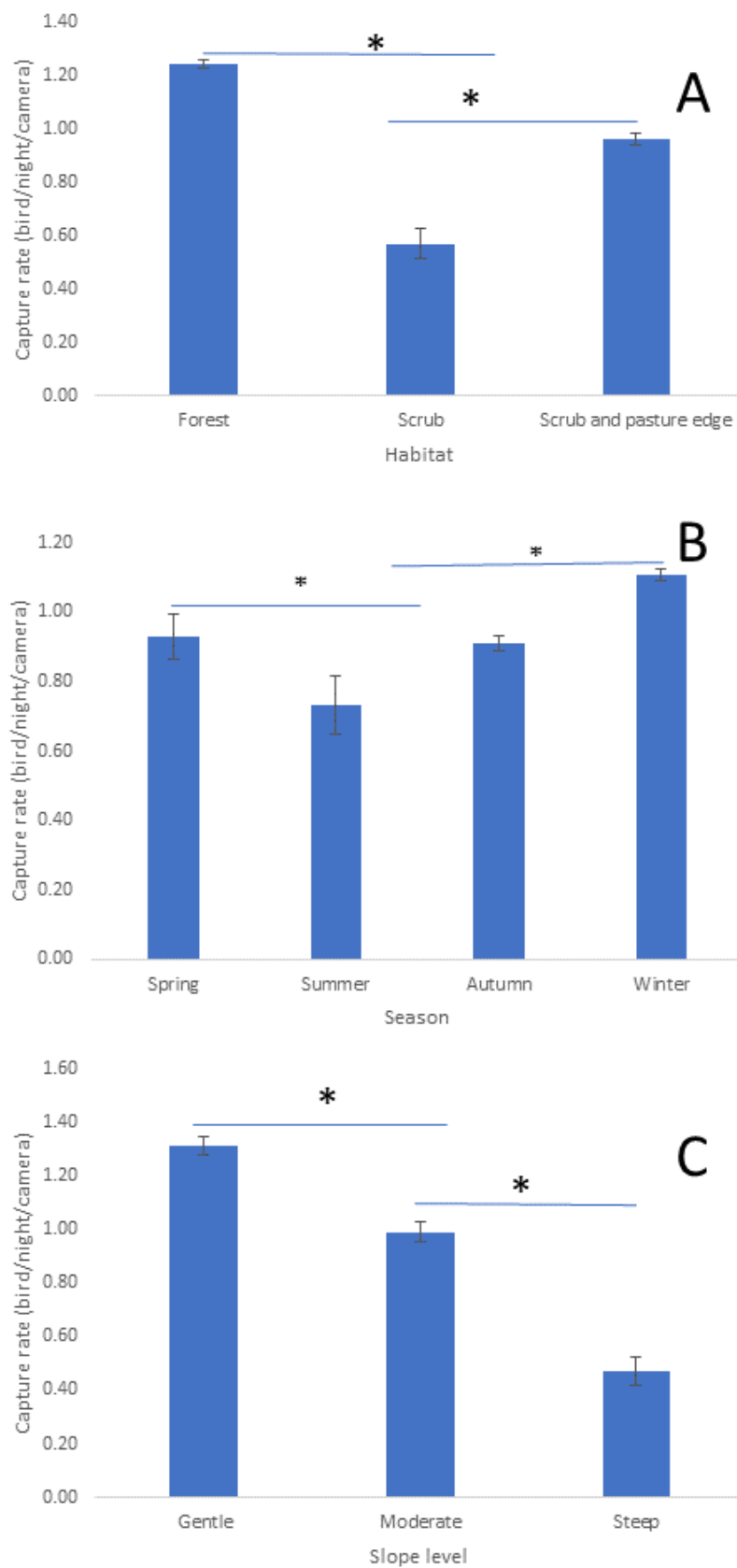


Figure 4.5. Capture rate of brown kiwi (bird/night/camera) \pm SD from camera traps set up in the fragmented habitats section of the Southern Pomui Island. A. effect of habitat on capture rate; B. effect of season on capture rate; C. effect of slope on capture rate. Stars denote significant differences.

Activity hot spots in fragmented habitats

There were more brown kiwi captured on average on camera traps in fragmented habitats than in the entire study site, with the highest being 1.74 ± 0.03 bird video/night/camera (Figure 4.6A). The major activity hot spots were still mainly located in the forest habitats and scrub and edges habitats with most cameras capturing between 0.89 ± 0.05 and 1.74 ± 0.03 kiwi videos per night per camera (Figure 4.6B). The camera traps that were placed in scrub did not capture many brown kiwi, with a range from 0.37 ± 0.08 to 0.89 ± 0.05 birds per night per camera for most trap locations (Figure 4.6B). Gentle and moderate slopes had many more activity hotspots than steep slopes, the range for these two levels of slope was mainly between 0.89 ± 0.05 and 1.74 ± 0.03 birds/night /camera (Figure 4.6C). The steep slopes had two major hotspots, one was between 1.25 ± 0.04 and 1.74 ± 0.03 birds/night/camera, and the other was between 0.5 ± 0.02 and 0.89 ± 0.05 birds/night/camera.

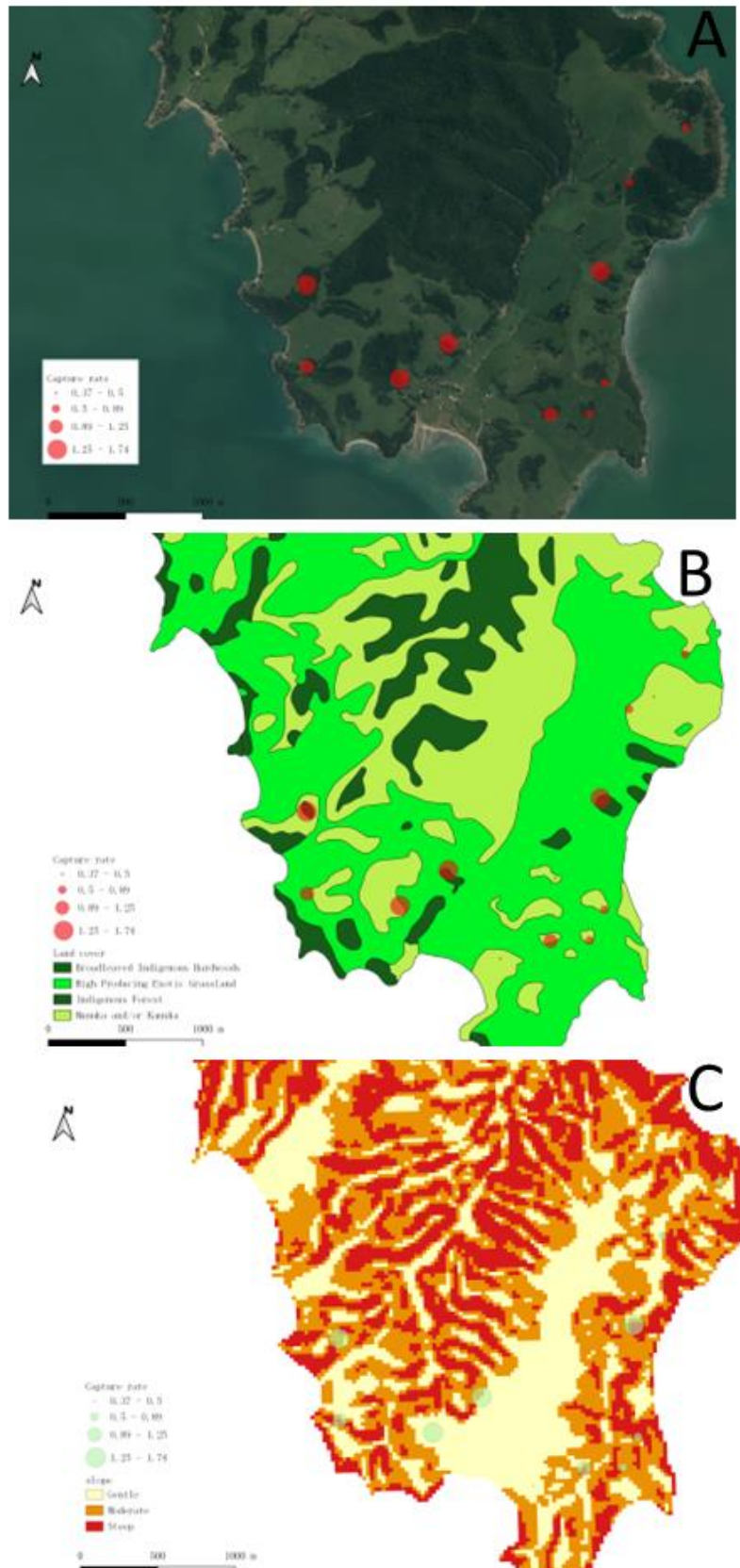


Figure 4.6. Heat map showing brown kiwi activity from the camera traps set up in the fragmented habitats section of Southern Ponui Island. A. activity from cameras placed in the 500m x 500m grid in the fragmented habitats. The larger the point, the higher the capture rate of brown kiwi from the camera trap site; B. brown kiwi activity from three major habitats: forest, scrub and scrub and pasture edge; C. brown kiwi activity from the three levels of slopes: gentle (0–8.5 degrees), moderate (8.5–16.5 degrees) and steep (>16.5 degrees).

Results of randomly reducing camera traps

I gradually reduced the number of camera traps by one camera from each habitat every month. By the time I removed three cameras, there was a significant change in the results of the models. (GLMM results: Table 4.7; Table 1 and Table 2 of Appendix A). After the removal of three cameras per habitat per month, there was one model that could not detect slope as an important driver influencing kiwi video numbers (Table 3 of Appendix A). Although the rest of the models included macrohabitat types, season and slope levels in the best-fit models, over half of the models did not identify scrub and pasture edge habitats as a significant category influencing the number of kiwi videos (Table 3 of Appendix A). Almost all models did not include the winter category as an influential category in the final models (Table 3 of Appendix A). After removing four camera traps from each habitat every month, most of the final models' predictive abilities collapsed, with most only identifying season as the most important factor for the number of videos captured at different trap sites (Table. 4.7; Table 4 of Appendix A).

Table 4.7. Results of random reducing the number of camera traps for 10 times until the original model collapse.

Number of camera reductions from each habitat	Repeat times	Times reaching same results as original model	Percentage reaching same results as original model
1	10	10	100%
2	10	10	100%
3	10	9	90%
4	10	2	20%

I recalculated capture rates after repeating this procedure of removing cameras randomly ten times and repeated the calculation of GLMMs. The forest habitat had the highest capture rates among all macrohabitat types, followed by the edge habitats that had much higher capture rates than the scrub habitats for most times under each reduction (Figure 4.7A, 4.7B, 4.7C). For seasonal variations, the highest capture rates still occurred in winter, although the winter category was not significant in most of these final models (Figure 4.8A, 4.8B, 4.8C). Autumn had slightly lower capture rates than winter and higher than spring, and summer still had the lowest capture rates among all seasons (Figure 4.8A, 4.8B, 4.8C). As for capture rates from different slope levels, moderate slopes still had much lower capture rates than the gentle slopes and the steep slopes, and the capture rates on the gentle slopes were still slightly higher than the steep slopes (Figure 4.9A, 4.9B, 4.9C). These graphs shared the same trend as the capture rate graph of the original 28-camera trap placement, which also confirmed that the predictive ability of these three types of camera removal models was the same as the original model.

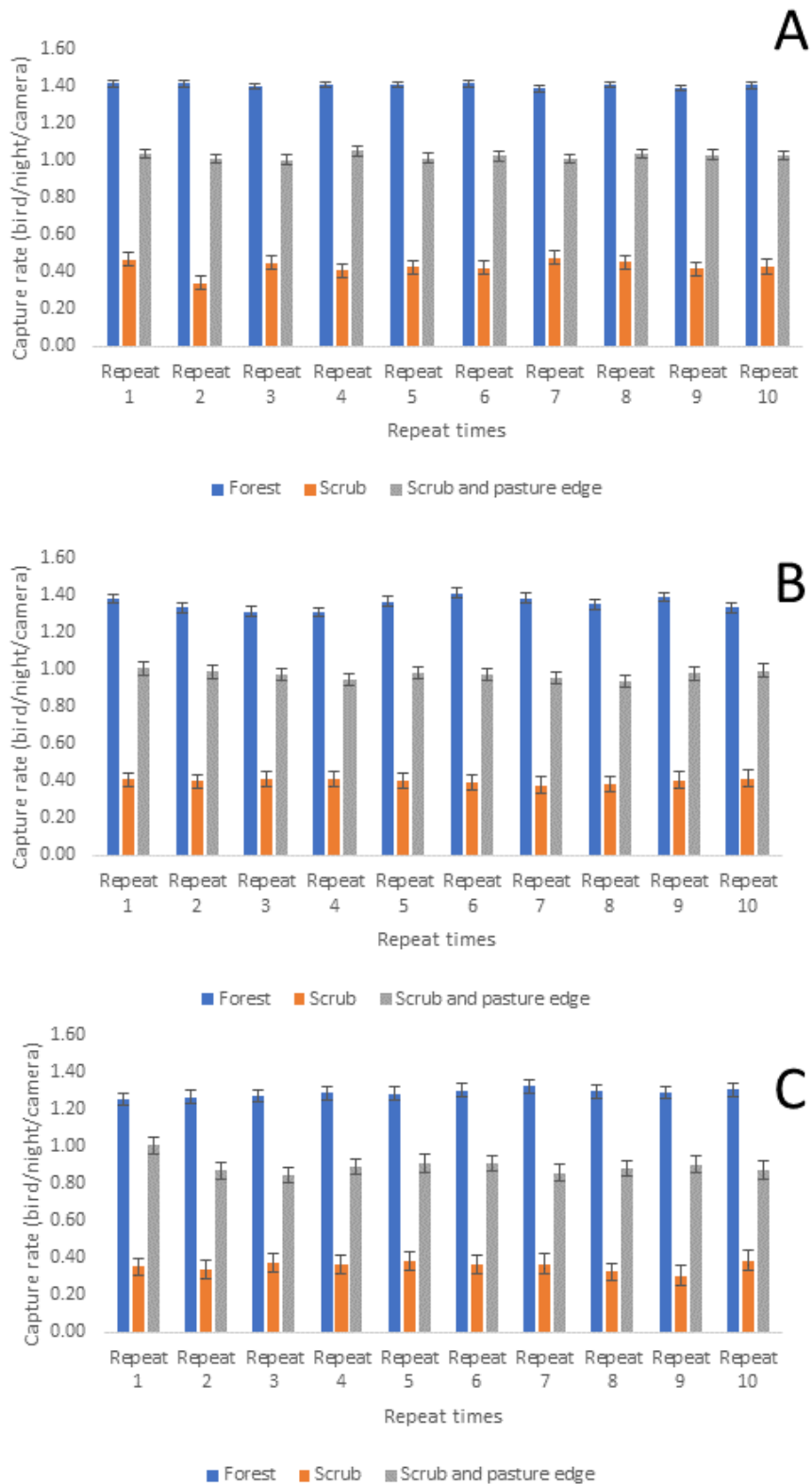


Figure 4.7. Capture rates \pm SD of brown kiwi from camera traps set up in the three main habitats in the southern part of Ponui Island after randomly reducing cameras and repeating for 10 times. A. effect on capture rate after randomly reducing 1 camera from each habitat every month; B. effect on capture rate after randomly reducing 2 cameras from each habitat every month; C. effect on capture rate after randomly reducing 3 cameras from each habitat every month.

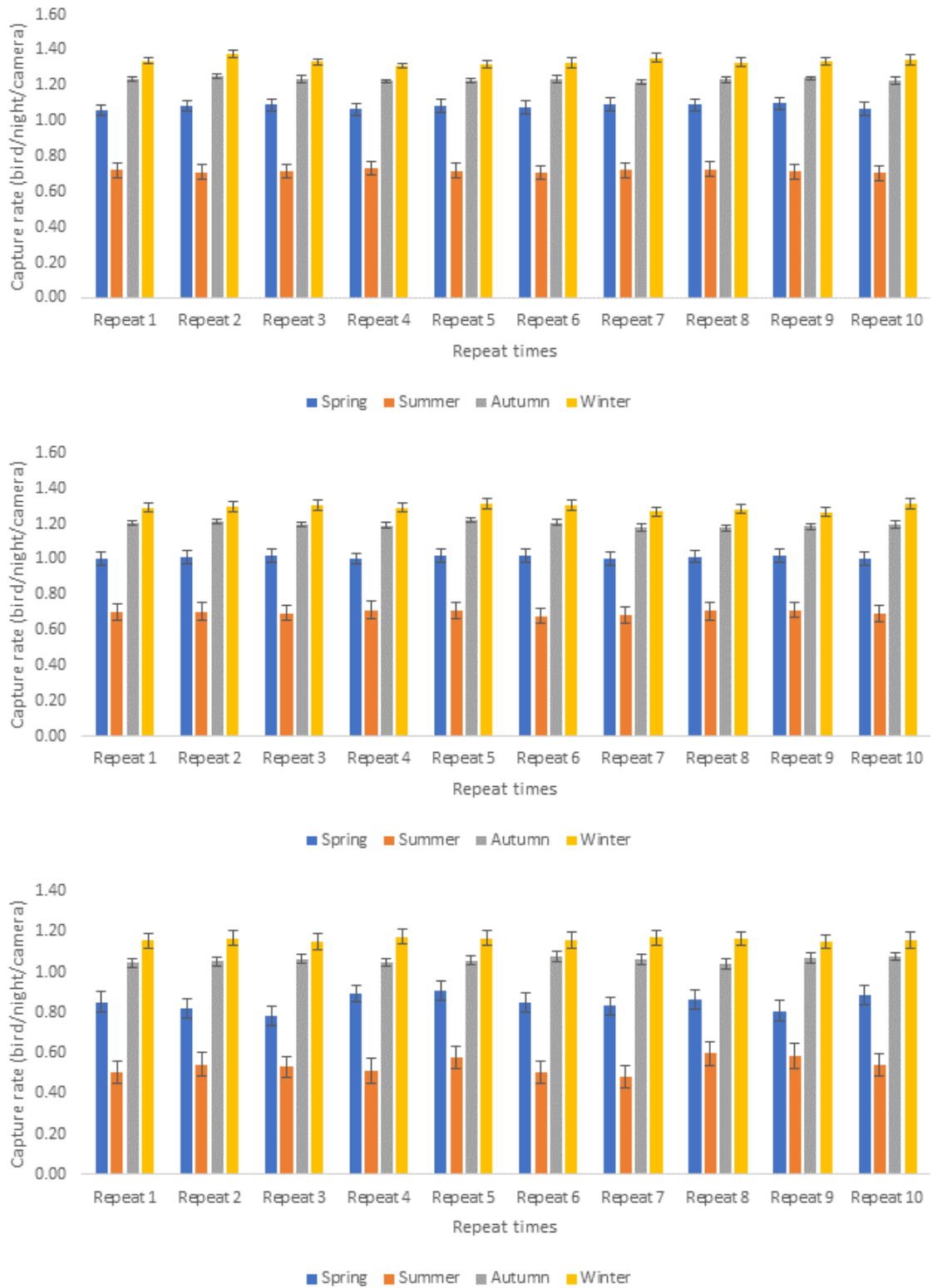


Figure 4.8. Capture rate \pm SD of brown kiwi from camera traps set up in different seasons in the southern part of Ponui Island after randomly reducing cameras and repeating for 10 times. A. effect on capture rate after randomly reducing 1 camera from each habitat every month; B. effect on capture rate after randomly reducing 2 cameras from each habitat every month; C. effect on capture rate after randomly reducing 3 cameras from each habitat every month.

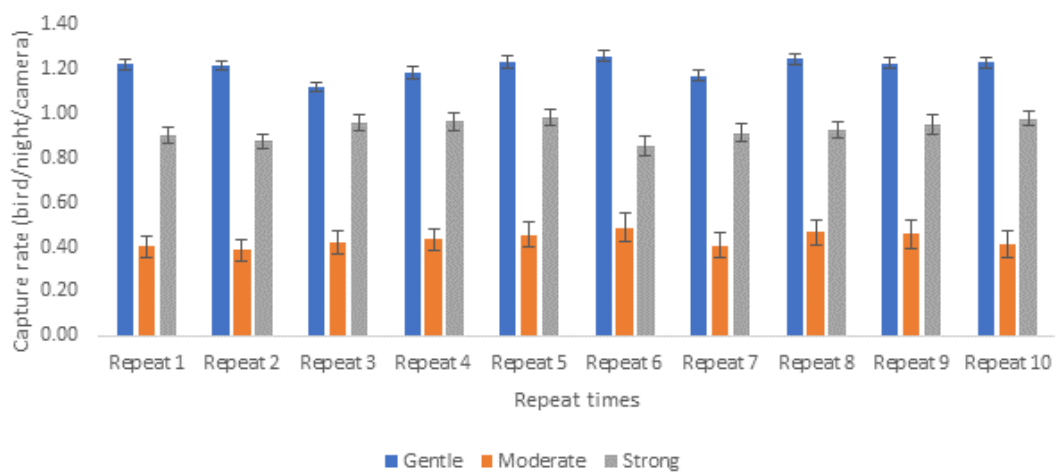
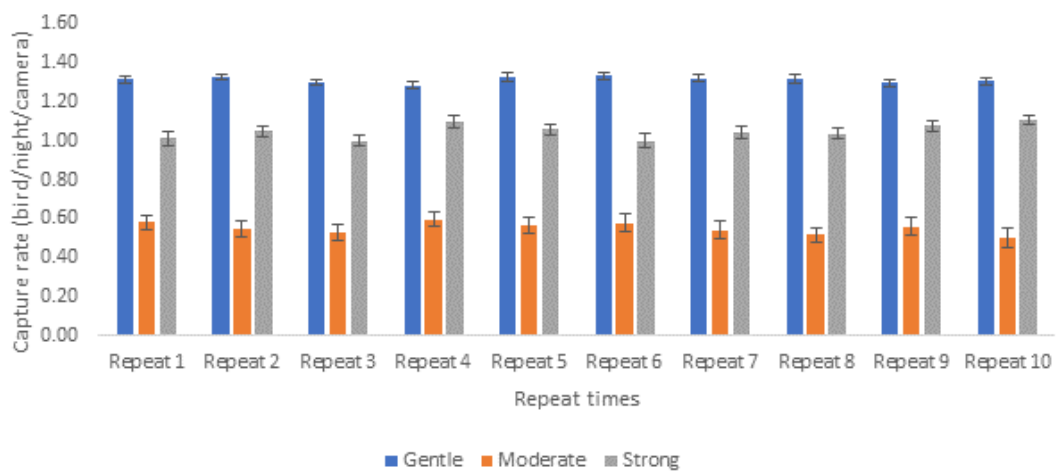
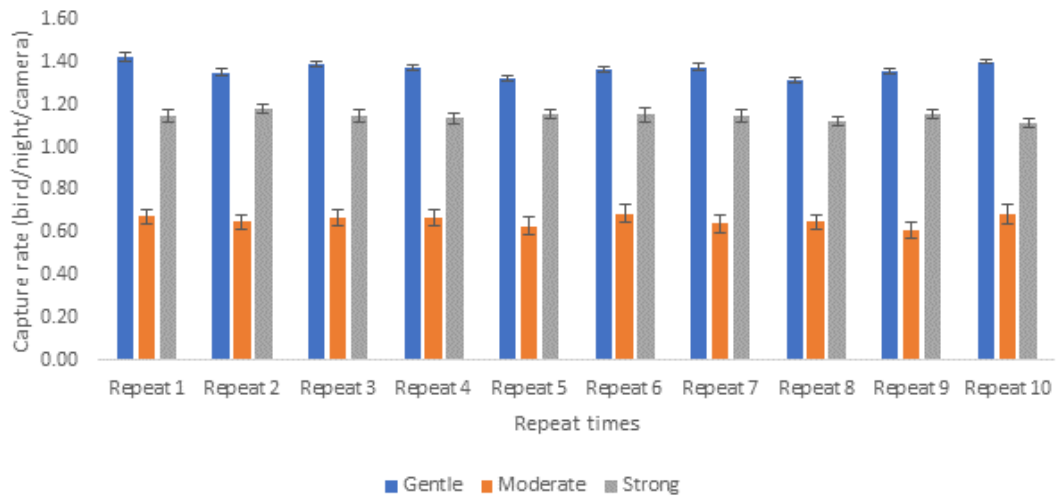


Figure 4.9. Capture rate \pm SD of brown kiwi from camera traps set up in different slope levels in the southern part of Ponui Island after randomly reducing cameras and repeating for 10 times. A. Effect on capture rate after randomly reducing 1 camera from each habitat every month; B. effect on capture rate after randomly reducing 2 cameras from each habitat every month; C. effect on capture rate after randomly reducing 3 cameras from each habitat every month.

Summary

This chapter summarised all the results of this research. Deploying all 28 cameras in the southern part of Ponui Island, I found that macrohabitat type, season and slope level were important factors in influencing the number of kiwi videos captured at different camera trap locations. Within macrohabitats, forests had the most kiwi activity hotspots and the highest capture rates, followed by scrub and pasture edge habitat and scrub habitat had the lowest capture rates and the fewest activity hotspots. Within the season factor, capture rates in winter and autumn were much higher than in spring and summer. Within the three slope levels, gentle slopes had the highest capture rates and the most major activity hotspots, followed by steep slopes. The lowest capture rates occurred on moderate slopes. After testing the influence of different time intervals for defining independent events on changing the number of kiwi videos, there were no major effects on the GLMM prediction ability, however, using different time intervals did slightly affect the total capture rates of all cameras, with the smallest interval producing the highest capture rates.

When only analysing the results from camera traps placed in the continuous habitat, the GLMM lost most of its predictive power by only identifying two factors, macrohabitat type and season, as being significant in the best-fit model. Even within these two factors, a few categories (e.g., scrub and pasture edge habitat, winter) became nonsignificant in the final model. When only keeping camera traps in the fragmented habitats, the GLMM results remained almost the same as the original model results. The graphs for capture rate and the heat maps of fragmented habitats showed similar trends to the original 28-camera placement except for the slope level factor. The steep slopes had the lowest capture rates and the least activity hotspots instead of moderate slopes from the original placement. From randomly reducing camera traps in the southern part of Ponui Island, I found that the GLMM lost its prediction ability completely after omitting three camera traps or more from each habitat every month. The predictive power of the model was best kept when removing up to two camera traps from each habitat every month.

Chapter 5: Discussion

In this chapter, I will discuss the main findings regarding habitat utilization and the influential factors of capture rate of brown kiwi using camera traps in a high-density population on a production landscape. The influential factors include the effects of camera trap placements in different macro habitats, edge habitats, and geographical locations, as well as seasonal variations in the southern part of Ponui Island. The sampling efforts for brown kiwi monitoring using camera traps will also be examined. The management implications of camera trap usage in future brown kiwi monitoring and management will be explored, along with the implications of brown kiwi habitat utilization for future management strategies. Finally, I will provide strategies for camera trap deployment patterns and the required sampling effort to achieve accurate and efficient brown kiwi management.

Camera trapping can be used for monitoring the North Island brown kiwi

Camera trapping assumes that the number of captures is related to the density of the animals in the survey area. Considering this assumption, according to my model predictions and heat maps, there were different proportions of brown kiwi found in each type of macrohabitat. Birds were mainly captured in forest habitats, followed by scrub and pasture edges and few birds were found in scrub habitats suggesting that brown kiwi uses those habitats in the same proportions. In general, these results were quite comparable with the predictions of brown kiwi nocturnal habitat utilisation on Ponui Island from Dixon (2015) using radio telemetry during the same period. Dixon (2015) studied bird populations located mainly in the gullies of the central continuous habitat and used the same macrohabitat types as this study. He classed his study habitats into four types: forest, scrub, pasture and swamp, and indicated that part of the scrub habitat from his study consisted of an edge habitat often bordering with pasture. Dixon (2015) found that most birds were found in forests, followed by the scrub and pasture edge habitats. Few birds were located in pasture and swamp.

These results provided confidence in using the camera trapping method for monitoring brown kiwi, especially their habitat utilisation. Other researchers also suggested that the camera trapping method can be used as a long-term monitoring tool for different rare and cryptic terrestrial birds such as tinamous (Roncal *et al.*, 2019), Salvadori's pheasant (*Lophura inornate*) and the Sumatran ground cuckoo (*Carpococcyx viridis*) (Dinata *et al.*, 2008). Although the camera trapping method can generate useful predictions for brown kiwi habitat use, precautions need to be taken when using differences in camera trap rates to represent habitat selection and use. Microhabitat and

geographical features need to be thoroughly considered and modelled to account for their influence on trap rates. Potentially, animals may frequently visit unfavourable habitats to obtain valuable resources, such as water (Bowkett *et al.*, 2007; Grotta-Neto *et al.*, 2020). In this study, the influential geographical features were modelled to see how they would affect capture rates.

Brown kiwi nocturnal habitat use from camera trapping method

Many bird species would select suitable habitats based on their survival and fitness, the primary requirement includes avoiding predation and having a high food availability (Harms *et al.*, 2017). For example, Niedzielski and Bowman (2016) found that wild turkeys selected agricultural lands and deciduous forests as major habitats because of the access to reliable food sources, especially in autumn and winter, and protection from predation. Dixon (2015) also noted that invertebrate availability (invertebrate weight per pitfall trap) was the most influential factor in determining brown kiwi habitat utilisation. Cunningham & Castro (2011) found that nearly a quarter of brown kiwi invertebrate prey was obtained in the forest leaf litter which makes forests a major foraging ground. Later research reinforced this opinion. Dixon (2015) suggested that brown kiwi preferred a variety of protein-rich invertebrate food items, such as Coleoptera and Arachnida, which were quite abundant throughout the year in forest environments in the southern part of Ponui Island. Gibbs and Clout (2003) mentioned that forest habitats usually provide a dense cover for the ground-dwelling kiwi, which was useful in protecting them against aerial predators (e.g., the extinct Haast's eagle (*Hieraaetus moorei*) during kiwi evolution). Except for the dense forest cover above them, brown kiwi on Ponui Island prefer forest habitats also because of the large number of tree burrows (Dixon, 2015). Jamieson *et al.* (2016) indicated that birds mainly used burrows in forests because roosting in burrows can provide more protection than roosting on the ground's surface, which would be especially vital for their survival during the cold and wet winter months.

Scrub and pasture edge was used by brown kiwi nearly as often as the forest habitat; this high utilisation of edge habitats on Ponui Island had also been observed by Cunningham and Castro (2011). Their research suggested birds had higher foraging success in edge habitats than in scrub habitats alone and that kiwi foraging in pasture edges were five times more successful at catching prey than birds foraging in the forest. This may be because the edge habitats can protect them against aerial predators by having aerial cover from the scrub and still supply abundant food sources from pasture. According to Gibbs (2000), juvenile kiwi with access to both pasture and seral vegetation had a much higher survival rate than birds that did not have such access. Data from Robertson & Colbourne (2022) showed that the main factor in the population decline of Rakiura

tokoeka at Mason Bay, Stewart Island was reduced food availability which was caused by the decrease of pasture edges as the native flora regenerated. Fertiliser applied on the pasture might have resulted in high soil fertility and soil invertebrate density. The exotic short grassland had been converted back to native species, such as flax (*Linum usitatissimum*) and mānuka (*Leptospermum scoparium*) scrub, for the past 30 years. The authors suggested that this made foraging difficult for Rakiura tokoeka and was reflected in a 7.5% decrease in the average weight of adult birds over the habitat change period, despite the population density also decreasing by 30% over the same period.

Kiwi is not the only species that prefers edge habitats. Takahē (*Porphyrio hochstetteri*), another iconic flightless New Zealand bird species, also has the same preference for scrub and pasture edges. Baber and Craig (2003) noted that the takahē population on Tiritiri Matangi Island favoured grass tracks and bordering scrub habitats, spending about 93% of their foraging time in these areas, suggesting edge habitats contain substantial food sources. In addition, the scrub provided protection against the Australasian harrier (*Circus approximans*). Barbaro *et al.* (2014) suggested that bird insectivory was higher at edge habitats than in the interiors even though insect herbivory was more common in vegetation in the interiors. They believed that the availability of insect larvae in the leaf litter in the edges could be higher than in the interiors because of increased tree productivity and higher leaf quality in the sunny edges. They also noted that ground-foraging insectivorous birds, such as kiwi, are known to rely on soil invertebrates, which are often found in forest interiors due to drier soils at edge habitats. This could explain the higher utilisation of forest habitat in my research. Compared to forest and scrub and pasture edge habitats, scrub habitats seem to be utilised far less frequently by brown kiwi on Ponui Island. This finding agrees with previous research on kiwi habitat utilisation on Ponui Island (e.g. Dixon, 2015; Jamieson *et al.*, 2016), with Dixon (2015) noting that birds would select forest habitats over scrub habitats if access to pasture edges is limited.

However, Taborsky and Taborsky (1995) suggested that brown kiwi found in Waitangi forest preferred using scrub habitat during their nocturnal activities, and they believed that scrubs had more prey items than other habitats in the region. Many other kiwi researchers suggested that juvenile kiwi have a clear habitat preference for scrub with a common hypothesis being that scrub offers sufficient protection from aerial predators with many shelter sites (Chan, 1999; Gibbs, 2000; Shapiro 2005). Shapiro (2005) conducted his research on Ponui Island and found that the understory of forest habitats was relatively sparse due to browsing from sheep and cattle, which limited shelter sites to hollow logs and burrows that might be occupied mainly by adult male birds. Most chicks

were located on the ridges primarily comprised of regenerating scrub which provided a dense understory and cover and many shelter opportunities (Shapiro, 2005).

Another possible reason for kiwi chicks to select scrub habitats more frequently was that the overall food availability was higher than in other habitats on Ponui Island for juvenile kiwi, as a significantly higher number of spiders and wētā were collected in pitfall traps placed in scrub than in other habitats (Shapiro, 2005). Wilson (2013) also confirmed the scrub habitat had a higher biomass of crawling invertebrates than other habitats on Ponui Island. The apparent difference in habitat utilisation between adult and young brown kiwi may be attributable to their varying beak length, which may lead to differences in food availability for different age groups in the same habitat (Swennen *et al.*, 1983; Gibbs, 2000; Cunningham, 2006). Hence, juvenile brown kiwi may prefer scrub because of more surface crawling invertebrates as their easy prey items, which is not necessary for adult birds. Jamieson *et al.* (2016) suggested that the avoidance of scrub habitat by adult birds on Ponui Island was largely due to a consequence of environmental factors. As mentioned above, scrub habitat is mainly found along the tops of ridges, which often have strong and cold winds. Roosting birds would have little protection from these factors. Although juvenile kiwi prefer scrub, there was no evidence that adult brown kiwi selected nest sites in scrub, so that chicks can have ready access to these habitats after leaving the nest (Gibbs, 2000). Therefore, scrub habitats on Ponui Island were not used by brown kiwi, especially adults, as often as other habitats.

What factors influence the capture rate of camera trap on brown kiwi

Habitat

As Grotta-Neto *et al.* (2020) suggested, the capture rate of camera traps may be related to the habitat use of the species, which is perhaps related to different species-specific behaviours and activities. For example, foraging, travelling, and roosting of brown kiwi may differ in intensity or only occur in a particular habitat type. Thus, as illustrated above, brown kiwi on Ponui Island showed a preference for forest and edge habitats based on their foraging preference and probably antipredator behaviour, these two habitats are thus likely to have high capture rates. Moreover, capture rates may decrease as vegetation density, especially understory, increases. Both Kolowski and Forrester (2017) and Moll *et al.* (2020) showed that high understory vegetation density and/or obstructed viewshed (full or partial) of camera traps reduced the capture rates of various mammal species in North America. Hofmeester *et al.* (2017) reported that the effective detection distance of camera traps decreased for multiple species in dense understory compared with sparse understory in forest habitats. Both Shapiro (2005) and Latham (2006) noted that forest habitat on Ponui Island

had more leaf litter on the ground and less dense understory vegetation than the scrub habitat. The abundant leaf litter was thanks to the numerous kauri and taraire (*Beilschmiedia tarairi*) trees in the forests, and the sparse understory was due to trampling and browsing from cattle and donkeys. Therefore, the higher capture rate in forest and edge habitats was probably due to the sparse understory and abundant leaf litter (food source), whereas the lower capture rate in scrub was caused by the dense understory layers and lack of leaf litter.

Season

The seasonal variation in capture rates may be partially due to changes in foraging behaviour. On Ponui Island, both the overall invertebrate availability and the species that brown kiwi prefer consuming follow a similar seasonal pattern, with surface-dwelling grassland invertebrates such as field crickets (Formicidae) being preferred during the summer and invertebrates from the forest during the winter (Dixon, 2015). Based on the dry weight and the number of invertebrates found by Dixon (2015), the overall availability of invertebrates reached its peak in summer and was at its lowest in winter. Although summer had the highest invertebrate availability, most invertebrates occurred on pasture where camera traps were not placed. Hence the lowest capture rate was found in summer. Furthermore, since pasture had abundant invertebrates, it might possibly make foraging easier and reduce the foraging time, which might also reduce the chance of capturing bird videos, especially for cameras set up in the scrub and pasture edge habitats.

In turn, birds might need a longer foraging time to catch sufficient invertebrates from autumn to winter when invertebrates' availability decreases and might shift their foraging ground to forests. Hence, the high capture rate in forest habitats in winter and in autumn may be due to the longer foraging leading to a higher chance of recording birds. Another factor that affected the capture rates was the breeding season. Brown kiwi on Ponui Island normally started breeding in winter and breeding peaked in spring (Ziesemann *et al.*, 2011). During the breeding season, male birds alone engage in the long period of incubation, and the overlapping clutches and long incubation period reduce the daily activity level of many males, which ultimately will reflect on reduced camera capture rates, especially in spring. In contrast, female birds are likely to mate with several males (Undin and Castro, 2022) and this may result in more activity during the late autumn and early winter as they search for possible mates.

Slope level and aspect

The slope level was a good predictor of the capture rate of camera traps, and I suggest this is because the slope may play a significant role in microclimatic variables that influence the distribution and growth of plants (Sukmasuang *et al.*, 2022). Slope can also affect the amount of solar energy plants receive, the soil moisture, and other microclimatic factors influencing the distribution of birds, which ultimately may affect the capture rate of camera traps (Girma *et al.*, 2017). In this thesis, the highest capture rate was on gentle slopes. This might be because more solar radiation could reach these areas to facilitate vegetation growth and increase the amount of leaf litter as well as invertebrate availability. This could help brown kiwi to have a high foraging efficiency, and it was easier for birds to move around compared with steeper slopes, so more energy could be conserved (Luo *et al.*, 2019). Lesser rhea (*Rhea pennata*) also displays the same preference for habitats located in flat areas based on a similar reason, that is, easier access to a high-quality foraging ground (Iranzo *et al.*, 2021). The steep slopes on Ponui Island also had quite high capture rates of brown kiwi, possibly because of their preference for burrow locations. Burrow-nesting birds, such as Cook's petrel (*Pterodroma cookii*) (Rayner *et al.*, 2007), thin-billed prion (*Pachyptila belcheri*) (Catry *et al.*, 2003) and grey petrel (*Procellaria cinerea*) (Bell *et al.*, 2013) prefer nesting on steep slopes because free-draining soil can provide better drainage for burrows and prevent flooding in burrows. Furthermore, unfenced flat areas were likely to attract more livestock than steep slopes, grazing would cause a large amount of vegetation cover loss that might expose bird to predators, and trampling would cause more severe damage directly to the nesting areas (Rayner *et al.*, 2007).

The model results from this study showed that aspect was not an important driver of capture rates. The data from Taborsky and Taborsky (1995) indicated that the aspect of a nesting place was unimportant for the brown kiwi populations in the Waitangi Forest. Jamieson *et al.* (2016) also discovered no significant correlation between the aspect of kiwi burrow entrance and utilisation on Ponui Island. However, the aspect of roosting sites is important for many bird species, such as little auk (*Alle alle*) (Keslinka *et al.*, 2019) and many parrots (Psittaciformes) (Davis *et al.*, 2012), because exposure to solar radiation can influence the thermal conditions of the roosting sites. On Ponui Island, due to the close canopy, not many places could receive direct sunlight (Jamieson *et al.*, 2016).

Swamp/Water features

I found that the presence of swamps or other water features, such as streams, was not predictive of the capture rates of brown kiwi. My results were broadly similar to the previous study on Ponui Island, but they contradicted other research on different ground-dwelling bird species. Dixon (2015) found that brown kiwi on Ponui Island had a low utilisation of swamp habitats and suggested that might be due to the small proportion of swamp habitats (4%) within the study site. Although my study site was larger than his, most swamp habitats overlapped in the same area. Thus, the small proportion of swamp habitats in the study site could be the reason for its insignificant influence on the capture rates of camera traps. Furthermore, Dixon (2015) and Jamieson *et al.* (2016) suggested that kiwi on Ponui Island probably actively avoided swamp habitats leading to low usage of these habitats. I think that one of the reasons for the North Island brown kiwi avoidance of swamps or other water features could be avoiding mortality through their bill being sucked down by water pressure in areas where there is lots of water. There were two cases of birds dying from being unable to draw their bills off the ground on Ponui Island, both within meters of a wet area (I. Castro, 2023, pers. comm.). Hence, brown kiwi on Ponui Island might stay away from water features if they do not have to use them. Therefore, these features were not important factors in influencing capture rates. However, the study results contradicted many other research results (Shah and Shama, 2020; Sukmasuang *et al.*, 2023). For example, Sukmasuang *et al.* (2022) found that the camera trap capture rates of the Siamese fireback (*Lophura diardi*), a ground-dwelling species belonging to the Galliformes, were most influenced by nearby local streams. They noted that the capture rates increased when the camera placement was closer to the water source.

Track presence

The location of camera traps (on or off tracks) did not affect the capture rates of kiwi significantly in this study. The probability of capturing a species on or off tracks may vary between locations, maybe due to the presence of predators or other species or variation in habitats (Blake and Mosquera, 2014). Murphy *et al.* (2017) found that there was a low detection probability on tracks of ground-dwelling birds, such as Madagascar crested ibis (*Lophotibis cristata*) and Red-breasted Coua (*Coua serriana*), when the feral cat activity was high in the same area in a Madagascar rainforest. They believed that these birds actively avoided using trails due to their major predators, feral cats, also using the same trails. On Ponui Island, Strang (2018) indicated that the camera traps had high capture rates of feral cats on trails, and the same camera locations were also used for collecting bycatch data of brown kiwi. Therefore, even though kiwi did use trails, they might nevertheless avoid ones used heavily by cats. The probability of a species utilising trails and

roads may also vary depending on the difficulty of travelling in the forest, which may in turn rely on the understory vegetation density (Di Bitetti *et al.*, 2014). As mentioned above, the forests on Ponui Island do not have dense layers of understory vegetation, so kiwi could move freely in forests. In addition, high food availability on forest grounds might also attract them to forage while moving around.

Sampling effort when using camera traps

Camera traps in fragmented habitats

According to the GLMM results and heat maps, camera traps placed in fragmented habitats generated the same model predictions as the original models and showed similar patterns of heat maps as the full camera traps placement, whereas camera traps placed in continuous habitats had lower predictive ability. An important reason could be that in a fragmented agro-forest landscape, such as Ponui Island, edge effects are the primary determinant of the predation intensity of insects for insectivorous birds at a smaller scale (Barbaro *et al.*, 2012), and brown kiwi had more nocturnal activities in these habitats. Moderate degrees of fragmentation are anticipated to provide high structural heterogeneity favouring predator and prey survival, providing stable predator-prey relationships (Cooper *et al.*, 2012). These spatial discontinuities in mosaic production landscapes formed by the edges between pasture and forests could be considered “keystone structures” that complement resources for insectivorous birds like brown kiwi (Barbaro and van Halder, 2009). In addition, a shorter distance from fragmented habitats to continuous native forest remnants is also crucial for insectivorous birds exploring surrounding fragmented habitats (Clough *et al.*, 2009). In this research, this could be found on the heat maps for fragmented habitats, higher capture rates were mostly found close to the continuous habitats.

Reduced number of camera traps and time interval for sampling independence

My results suggested that when reducing more than three cameras from each habitat every month, GLMM would lose its prediction ability completely. Since the original grid cell was one camera per 25 ha, the grid cell after reducing three cameras from each habitat would become one camera per 37 ha for maintaining 90% of the model predicting power. If the exact same prediction ability as the original grid needs to be preserved, the grid cell size should not increase beyond 32 ha/ camera trap. The different time intervals (from 15 minutes to 60 minutes) used for extracting independent videos did not influence the prediction ability of the GLMM, hence, using 30-minute intervals should be sufficient for the video extraction process.

Implications of using camera trapping method in kiwi management

Increase the scale of future kiwi management

As demonstrated above, the camera trapping method has the potential to generate valuable and reliable monitoring results for brown kiwi, especially for their nocturnal habitat utilisation. If this method is added to the current kiwi management toolbox, it may solve a few issues that the current management is facing. Camera trapping has great benefits over other sampling methods such as radio-tracking and live trapping in that they can collect highly accurate data without disturbing the animal or requiring the researcher to be present. In certain aspects, these data are preferable to human observations because they can be reviewed by other researchers, unlike live-trapping or other observational data (Swann *et al.*, 2011). For example, Silveira *et al.* (2003) compared track count with camera-trapping and mentioned that although both methods can assess abundance throughout time and space, camera-trapping can link to analysis of habitat use, activity patterns and reproductive information. With more sophisticated survey designs in the future (Blount *et al.*, 2021), the camera trapping method could assist in shaping large-scale kiwi conservation strategies. In recent years, researchers have already used camera traps to document the occurrence of unexpected species in human-dominated landscapes (Athreya *et al.*, 2013), monitor biodiversity (Steenweg *et al.*, 2017) and assess how wildlife reacts to changes in human activity and compare production landscapes to natural habitats (Gallo *et al.*, 2017). If nationwide camera trapping activities can be coordinated and standardised, this method could contribute to a comprehensive regional and national kiwi conservation agenda.

Kiwi birds play a crucial role in biodiversity and often appear and inhabit farmland as far as the area has a variety of habitats (is a mosaic of landscapes) rather than being a monoculture of pasture. Now, there is an increased focus and value on integrating biodiversity into the farm planning process and management decisions in New Zealand. On-farm biodiversity is critical for New Zealand's economy and cultural identity. It helps farms operate sustainably, enhances resilience against climate extremes, and supports ecosystem functions. However, current biodiversity management falls short of transformative change (Norton & Reid 2013). Increasing structural diversity through indigenous species reintroduction reduces environmental risks and improves farm resilience (Dominati *et al.* 2019). This is essential for the viability of farms, rural communities, and national economic security (Maseyk *et al.* 2019). Recognizing environmental limits and sustaining natural capital, including indigenous biodiversity, is crucial for overall well-being (Rockström *et al.* 2009). Farm plans in New Zealand serve as crucial mechanisms for planning, managing, and addressing environmental risks within the regulatory framework. Farm plans consider the farm's

capabilities and assets while complying with regional council requirements (Manderson et al. 2007). The next step for farm plans is to explicitly incorporate indigenous biodiversity assets to enhance farm resilience (Maseyk et al. 2019). Internationally, there is a growing recognition of the need to expand land evaluation to include indigenous biodiversity, sustainability, and ecosystem services. The future direction of farm plans lies in their evolution towards encompassing these aspects, aligning with the global call for sustainable land management (FAO 2007).

In New Zealand, current whole farm plans are primarily focused on building on-farm resilience to mitigate the effects of severe weather events and promote sustainable land use practices (Mackay 2007). While these plans do consider the presence/absence and quantity of indigenous biodiversity, they do not adequately address biodiversity quality or assess the impact of farm activities on biodiversity or its contribution to the farm system and ecosystem services (Mackay 2007). Therefore, expanding the scope of whole farm plans to explicitly incorporate indigenous biodiversity as a template is a suitable approach to address these limitations and enhance biodiversity management on farms. Maseyk *et al.* (2019) suggested a six-step approach to evolve current whole farm plans to achieve the ideal integration outcomes and a large amount of data is needed to support this approach (for example, stocktaking of on-farm indigenous flora and fauna assets and conditions, and monitoring changes in indigenous species assets). Camera traps have the potential to be an effective data collection tool not only for kiwi living in production landscapes but also for other indigenous species inhabiting the same farm.

Increase community engagement in kiwi conservation

Images and films captured by camera traps are effective public engagement tools for raising awareness about significant conservation areas, endangered species, and the conservation goals of local and national governments. A single image distributed via social media can reach millions of people with crucial conservation messages. Blount *et al.* (2021) posted photographs from camera traps and updates of their project on Instagram and Facebook, where a single photo could be viewed by more than 25,000 people within five days. Opportunities for public engagement extend to citizen science initiatives, in which the public deploys cameras or identifies species in camera trap photographs (Adler *et al.*, 2020). Many large-scale camera-trapping initiatives, such as eMammal, the Urban Wildlife Information Network and EUROMAMMALS, have made progress through citizen science programmes and multi-city partnership initiatives (Blount *et al.*, 2021).

It is necessary to have a simple training process if a wide range and long-term engagement want to be guaranteed. Li *et al.* (2012) found that a week of training was sufficient for their volunteers to become proficient in setting up and operating camera traps and collecting data. Lasky *et al.* (2021) also stated that the training process for using camera traps is relatively simple and the training process can be very efficient in training a significant number of volunteers for larger citizen conservation projects, especially with the help of online training. They also noted that volunteers from different cultures, ages and occupations have improved wildlife knowledge, enhanced science efficacy and most importantly, strengthened relationships with nature and a sense of belonging and place (Lasky *et al.*, 2021). In New Zealand's case, the strong connection with nature and place is crucial in encouraging all New Zealanders to connect and look after our national icon (Ministry for the Environment, 2022).

Lower costs in the long term and less observer bias

Some researchers (e.g., O'Brien & Kinnaird, 2008; Link *et al.*, 2022) mentioned that there were high initial expenses of using camera traps, but long-term expense would be less. Lasky *et al.* (2021) pointed out that the financial expenditure for using camera traps on their citizen science project was less than what would have been incurred for hiring professionals to conduct the project over a long term, particularly due to reductions in travel expenditure when sampling large areas. Link *et al.* (2022) suggested that observer bias can be significantly reduced by using verifiable data (images and videos) to identify diurnal and nocturnal species and their activities with the same accuracy and efficiency. Camera trapping can be used to sample several large areas simultaneously and sometimes to serve dual monitoring or survey purposes, such as feral cat survey data used for brown kiwi habitat utilisation in this research (Link *et al.*, 2022). These features can reduce a large amount of staff effort, which will ultimately reduce the project costs (Li *et al.*, 2012).

Implications of brown kiwi habitat utilisation in future management

As mentioned above, brown kiwi use multiple habitats based on the various benefits to their fitness and survival. An important factor relating to their survival is predation from mammalian predators. There were two favourite habitats shown in my research which were forest and scrub and pasture edge habitats, and several researchers (e.g., Basse *et al.*, 1999; Gibbs & Clout, 2003) suggested that stoats are the most dominant predators in both forest and edge habitats. Basse *et al.* (1999) found that stoat populations are highest in forests when kiwi chicks have just become independent, and they may outnumber chicks by up to ten to one during this period. At some edge habitats, especially with the presence of rabbits, all three mustelid species (stoats, ferrets, and weasels) can be found,

and the predation pressure on kiwi chicks would be more intense (King, 1990). In addition to stoats, feral cats are another potential predator in the forest (Gibbs and Clout, 2003; Strang, 2018). They have a strong preference for staying close to watercourses (Gibbs and Clout, 2003), and can often be located on ridges and wide trails or roads on Ponui Island (Strang, 2018). In addition to their main prey, feral cats may change prey and seek more common species in different seasons and are very likely to prey upon any species that are active at the same time (Garvey, 2016). For example, if they are more active at night, even in locations where rats are the major prey target, this could still lead to high predation rates on other nocturnal prey species, such as juvenile brown kiwi (Wilson, 2013).

Predator control is the key, and the first step to ensuring brown kiwi can survive and thrive in these two macrohabitats (forest and edge habitats) on production landscapes (Jamieson *et al.*, 2016). For stoat control, integration of regular stoat trapping and aerial 1080 poison before brown kiwi nesting season and during mast year in beech forest habitats should be enough to ensure long-term high survival rates for brown kiwi populations in both forest and edge habitats (Steffens *et al.*, 2022). As for feral cat control, especially on Ponui Island, more effort should be placed into forest habitat in autumn because most female cats give birth during this period, which imposes greater energy demands and may result in increased nocturnal predation in order to supply enough food (Strang, 2018). Another important aspect relating to their fitness is sufficient food sources, Dixon (2015) noted that brown kiwi inhabiting Pipe gully on Ponui Island had lower weight than kiwi from other gullies, and had significantly lower hatching success than other gullies, with hatching success rate being 50% compared to 60% and 67% in Kauri Bush and Red Stony Hill gully respectively. He suggested that this habitat may be less ideal for brown kiwi, to the point that it hinders their ability to maintain weight and reproduce. He suggested that the reason may be the lack of pasture around this habitat, which may reduce food availability. Hence, future kiwi management should concentrate on establishing kiwi populations in mosaic production landscapes with extensive native forest patches.

Sheep and beef farms already have advantage in often containing considerable amounts of native forest and grassland vegetation (Pannell *et al.*, 2021). In recent years, these farms have received increasing pressure, such as low wool prices and growing demand for environmentally friendly and low carbon footprint products (Tait *et al.*, 2016; Hilborn *et al.*, 2018). To maintain profitability and social license, this sector will need to reduce its environmental impact (Norton *et al.*, 2020). In this context, if the substantial amounts of native forests on these farms are managed properly, they not

only have the potential to help mitigate some of these problems but will enhance biodiversity and become ideal habitats for kiwi and other species and could eventually provide financial benefits to farmers (Young *et al.*, 2014). As examples of such management, Dodd *et al.* (2011) noted the retention and improvement of the connectivity between patches of native forests on farms, along with mammalian pest control and control of livestock entering the forests.

However, these activities certainly require the consideration of trade-offs between productivity and conservation for agricultural industries. Therefore, it is vital for the government to establish an independent national verification system particularly focusing on farm biodiversity management and outcomes and demonstrating that farmers are doing what they claim to be doing (Williams *et al.*, 2019). Then, they can add more value to their products and sell based on New Zealand's environmental and sustainability story on the global market and maintain their social license in the country (Norton *et al.*, 2020). Most international standards of agricultural sustainability address conservation and biodiversity management, such as the identification and protection of priority habitats, and the management of threatened species and invasive species (Englund & Berndes, 2015). After following these standards, farmers have benefitted from enhanced brand image and position, expanded markets and improved product prices (Norton *et al.*, 2020). In our case, this will be a win-win strategy for both kiwi management and agricultural industries, as more farmers will be encouraged to participate in this verification system, more kiwi habitats will be retained and even be restored, more birds will be protected within these habitats, and more farmers can sell products under the brand of real "kiwi made".

Camera trap deployment strategies for future brown kiwi monitoring and management

For future kiwi monitoring using camera traps, several recommendations can be made to maximize capture rates based on the above findings. Firstly, camera traps should be placed in forests and/or edge habitats with an open understory. This habitat type provides suitable conditions for kiwi activity and increases the chances of capturing them on camera. Secondly, for brown kiwi monitoring, I suggest deploying camera traps during autumn and winter, and if used in summer, they should be placed in pasture and other habitats. Spring should be avoided as it may have lower capture rates. Additionally, when setting up camera traps in areas with similar topography to Ponui Island, it is advisable to place them on both gentle and steep slopes to maximize capture rates of brown kiwi. However, the aspect does not seem to be a major influencing factor. Furthermore, it is important to explore how the distance between the location of camera traps and water features

affects the likelihood of detecting kiwi in future management. Lastly, combining on- and off-trail camera placement strategies in future monitoring can offer a more comprehensive understanding of brown kiwi activity at a specific location.

Camera trap sampling efforts for future brown kiwi monitoring and management

Sampling efforts in fragmented habitats and implications of fragmented habitats for brown kiwi management

If the goal is to maximize capture rates of kiwi on camera traps, I suggest increasing the number of traps placed in fragmented habitats near continuous habitats. This approach can increase the chances of capturing kiwi movement and behaviour in areas with habitat fragmentation. To a certain extent, my results showed that fragmented habitats could attract brown kiwi during their nocturnal activities. This suggested that retaining semi-natural pockets of native forests on pasture-based commercial agricultural landscapes could be important for kiwi conservation, especially for their dispersal. Innes et al. (2022) classified North Island brown kiwi as high gap limited species because they have never been observed crossing pasture or water gaps of more than 500 m, and Potter (1990) also indicated that they could travel for about 300 m between patches of native forests. The poor dispersal ability is least likely to help them establish in new, secure areas distanced by 5 km of water or pasture from original populations. Hence, they have a strong demand for wildlife corridors and translocations to facilitate their dispersal (Innes et al., 2022).

Many researchers (e.g., Fischer et al., 2010; Le Roux et al., 2017; Waite, 2012) suggested that the scattered trees within the fragmented habitats in agricultural landscapes can be essential in building vegetated wildlife corridors for forest birds with poor dispersal ability, such as brown kiwi. Ruffell and Didham (2017) noted that even without enough mature native forests, exotic pine plantations may be sufficient to connect the isolated habitats of these birds. Although fragmented habitats from my research and others showed the potential to be promising stepping stones for kiwi dispersal, the current focus should still be placed on increasing safe habitats on the mainland to avoid creating corridors from good habitats to poor habitats, which could cause bird population decline especially if dispersed birds are unable to successfully breed in the new sites due to their vulnerability to mammal predation on eggs and chicks (McArthur et al., 2019).

Sampling efforts of using reduced number of cameras and time intervals for sampling independence

As mentioned above, if future brown kiwi monitoring and management needs to use camera traps with the same grid system, the grid cell size should not increase beyond 32 ha/ camera trap. It is useful to know this threshold when the grid cell size needs to be expanded and still needs to remain valid for the research purpose, because some areas within a study site may not be suitable for using camera traps due to their susceptibility to livestock and/or human interference, and/or some mechanical issues causing cameras to break down in the field (Glen et al., 2016). As for time intervals used for extracting independent videos, using 30-minute intervals should be sufficient for the video extraction process without affecting the prediction ability of the GLMM.

In this thesis, most of the time was spent on filtering videos containing moving cattle or vegetation, and because there were four different time intervals, the same dataset was filtered four times. If the same or similar practice is needed to be repeated in future kiwi monitoring, it will likely impose a considerable labour expense on kiwi management. To be more efficient in analysing videos or images in the future, semi-automated or even automated identification photo or video data analysis techniques should be considered. Norouzzadeh et al. (2018) built deep convolutional neural networks to recognise, classify, and analyse the activities of 48 species present in the Snapshot Serengeti dataset with 3.2 million images. The deep neural networks identified animals automatically with an accuracy greater than 93.8%. If the network only classified images that it was confident in, it could identify animal images for 99.3% of the data with the same accuracy (96.6%) as volunteers filtering manually. It was estimated that this would save more than 8 years (40 hours/week) of volunteer effort for the same dataset (Norouzzadeh et al., 2018). Kays et al. (2018) suggested that although the identification is not always accurate, filtering photos or videos by species before sending them for further analysis still could considerably improve the efficiency of the data extraction process. The significant amount of labour effort can be allocated to other essential scientific tasks and enables data extraction possible for camera-trap programmes that are unable to recruit enough volunteers or with limited funding. This is particularly important for future kiwi monitoring and management. For future camera trap studies on kiwi, it would be useful to try to use multiple cameras at a single grid cell and set up a calibration target to explore estimating the relative abundance of kiwi with the help of the newest developed R package, spaceNtime. In the meantime, this data set should be used to calculate density using more traditional methods such as the Royle-Nichols model (Royle and Nichols, 2003) and the Binomial-N-mixture model. Given that

some birds had transmitters and were identifiable, spatial capture recapture models should also be applied to the data to investigate their usefulness in assessing density in this well-known population.

Summary

This chapter first demonstrated that the camera trapping method had great potential to monitor kiwi in the future and generate reliable information, such as habitat utilisation. The nocturnal habitat utilisation results produced by camera traps and analysed using GLMM were very comparable with the results produced by using radio telemetry and analysed using GLMM during the same period on Ponui Island. Based on the habitat utilisation results, I found that the brown kiwi population on Ponui Island had a high utilisation of forest and edge habitats and a much lower utilisation of scrub habitats. This was probably because of the high food availability and sufficient aerial predator protection in the first two habitat types. The locations of most scrub habitats were along the tops of ridges, strong winds, and other harsh environmental factors, and less food availability could make this type of habitat on Ponui Island less attractive to kiwi. Because of the potential of using camera traps in monitoring kiwi, I concluded three major implications for future kiwi management: (1) the increase of the scale of kiwi management and low costs in the long term, (2) the increase of community engagement in kiwi conservation, and (3) lower observer bias. Furthermore, based on my findings on kiwi habitat utilisation, the key steps for managing the North Island brown kiwi on production landscapes would be intensive predator control within forests and edge habitats bordering pasture on agricultural lands, maintaining and increasing the number of native forest patches on farms and control of livestock entering the forests. An independent national verification system focusing on farm biodiversity management and outcomes should be established to support and prove that farmers are following the plans.

In addition to macrohabitat types, two factors were identified as major drivers in influencing capture rates of camera traps: season and slope level. The seasonal variation in capture rates might be partially due to the change in foraging behaviour and camera trap locations and partially due to the breeding season. The variation in capture rates caused by different slope levels might be due to the strength of solar radiation, which could cause differences in vegetation growth and leaf litter quantity and quality that eventually could affect invertebrate availability and lead to more kiwi foraging activities in these areas. The preference for burrow locations to prevent flooding could be another reason brown kiwi prefer different slope levels. Different time intervals for defining independent events did not affect the prediction ability of the GLMM but slightly affected the

capture rates. It was time-consuming to classify video data based on different time intervals repeatedly; semi-automated or even automated identification photo or video data analysis techniques should be considered in the future. When comparing camera traps set up in fragmented habitats and continuous habitats, the GLMM retained much better predicting power. To a certain extent, this indicated that fragmented habitats could attract brown kiwi during their nocturnal activities and suggested that retaining semi-natural pockets of native forests on pasture-based agricultural landscapes could be important for kiwi conservation, especially for their dispersal. According to the results of reducing camera traps, the grid cell size could expand to 32 ha/ camera trap to preserve a 100% prediction ability as the original grid cell size.

Chapter 6: Conclusion

Kiwi are one of the representative endemic species of biodiversity in New Zealand and a crucial indicator of ecosystem health. Besides being a national icon, kiwi also have great values in Māori culture. Since humans arrived in New Zealand, kiwi populations have started to decline mainly because of the introduction of mammalian predators and habitat loss. For the past 30 years, kiwi management programmes, such as the Operation Nest Egg programme, have successfully boosted kiwi populations, especially the North Island brown kiwi. But most of these programmes were conducted on a small scale, such as in kiwi sanctuaries or state conservation lands. For future kiwi recovery and management programmes, the focus needs to be placed on increasing management activities across a larger area and enabling local communities to manage their own kiwi populations. Although kiwi were traditionally considered a dweller of New Zealand's native forests, the majority of which have been removed by agricultural exploitation and human settlement (Robertson and Colbourne, 2017), there are some species, especially the North Island brown kiwi, that can live in a variety of habitats, including exotic forests, regenerating forests and pasture. Since the primary land use in New Zealand is pastoral farming, especially sheep and beef farms, and these lands are normally at low-elevation and warmer areas and often have significant amounts of indigenous vegetation, hence, there is a great potential for these agricultural lands to be permanent kiwi habitats. However, landowners' production goals and demands may conflict with the best interests of kiwi conservation on these agricultural lands. Thus, it is necessary to provide landowners with detailed information on the distribution and activities of local kiwi populations and management priority zones.

Furthermore, effective management programmes are the key to successful recovery for all kiwi species and populations, and kiwi monitoring plays a crucial part in measuring the effectiveness. The future monitoring tools need to be sensitive to detect low-density populations, they need to be less labour-intensive and cost-effective to deal with limited government funding issues, and they need to be avoiding potential animal welfare issues and encourage in-depth public engagement. In recent years, the camera trapping method has emerged as a regular wildlife monitoring method for many rare and threatened species around the world. It has all the features of a future kiwi monitoring tool, but there has been no exploration of the camera trapping method for studying any kiwi species. Meanwhile, internationally, there is a lack of standardisation of deployment patterns and sampling efforts using camera traps, particularly with regard to monitoring parameters, such as the minimum size of the research area and the minimum number of cameras, and no such studies with the North Island brown kiwi have been conducted in New Zealand. In addition, brown kiwi are

often found living in small fragmented habitats, especially in Northland. Therefore, it is important to compare the difference in capture rates between camera traps set up in fragmented and continuous habitats in order to establish a baseline for future camera trap sampling efforts on brown kiwi.

As such, the central aims of this thesis are to investigate whether camera-trapping can detect brown kiwi in a way that can be used to monitor their habitat utilisation in a production landscape, to identify the factors that can influence the capture rate of camera traps on brown kiwi in a high-density population, and to inform management strategies for future brown kiwi management. This study was conducted at the southern end of Ponui Island, located in the Hauraki Gulf. The central aims of this thesis are divided into three objectives, which are addressed and answered accordingly:

Objective 1: Investigate the habitat utilisation of brown kiwi in a high-density population on a production landscape using camera traps and provide management strategies for conserving brown kiwi habitats within production landscapes.

Objective 2: Investigate the capture rate of brown kiwi by camera traps, including how the capture rate may vary with the placements of camera traps in macro habitats, edge habitats and at different geographical locations, as well as seasonally variations in the southern part of Ponui Island.

Objective 3: Provide strategies for using camera traps in brown kiwi management, including deployment patterns and sampling effort requirements for achieving adequate accuracy and efficiency.

Objective 1. Findings of brown kiwi habitat utilisation on agricultural landscapes using camera traps and management implications for future brown kiwi conservation

The brown kiwi video data collected from the three types of macro habitats (forest, scrub, and scrub and pasture edge) were analysed using the GLMM and heat maps, and capture rates (bird/night/camera) were also calculated for each habitat. The main findings were that forest habitats were used more often by brown kiwi, followed by scrub and pasture edge habitats, and scrub habitats were used less frequently compared to the other two habitats. Predator avoidance behaviour and food availability are the most important factors in selecting suitable habitats among many bird species (Harms *et al.*, 2017), and this is probably true for brown kiwi. Forest habitats contained large amounts of protein-rich invertebrate food items, such as Coleoptera and Arachnida, throughout the year. These invertebrates are an important part of the brown kiwi diet. Thus brown

kiwi preferred foraging in forests, which increased the usage of forest habitats. The dense canopy cover in forests could protect brown kiwi against aerial predators, and large amounts of tree burrows could provide dry and safe roosting sites for the birds. These benefits were most likely the reason for the high usage of forest habitats.

Scrub and pasture edge habitats were used slightly less often than forest habitats. The similar high usage of the edge habitats to forest habitats was probably due to the same reasons, aerial predation avoidance and food availability. However, food availability might be the dominant reason because abundant food sources could come from pasture and the high availability of insect larvae in the leaf litter at edge habitats due to the high productivity of high-quality leaves from vegetation growing along the edges. Scrub habitats were used the least often. This might be due to adult brown kiwi choosing forests and pastures when foraging, so fewer bird activities could be captured by cameras set up in scrubs. Furthermore, most scrub habitats were at the tops of ridges, where brown kiwi often experienced strong and cold winds. Hence fewer birds may select these areas as roosting sites. Thus, the least brown kiwi videos were captured in scrub habitats, reflecting the least usage of this type of habitat among the brown kiwi population on Ponui Island.

After comparing the nocturnal habitat utilisation findings from this study to other studies on North Island brown kiwi habitat utilisation, especially the findings from Dixon (2015) conducted by using radio telemetry at the same study sites during the same time, the camera trapping method generated similar predictions on brown kiwi nocturnal habitat use as with using radio telemetry. This proved that the camera trapping method could be used for brown kiwi monitoring, especially in studying their habitat utilisation. Using the camera trapping method in brown kiwi monitoring can benefit future brown kiwi management by increasing management scales, improving community engagement and monitoring accuracy and reducing long-term costs. The habitat utilisation findings from this study suggested that the key steps of managing brown kiwi on agricultural lands would be intensive predator control within forests and edge habitats bordering pastures, maintaining and increasing the number of native forest patches on farms and control of livestock entering the forests.

Objective 2. Camera traps placement and capture rates

Based on the results from the GLMM, the most influential factors affecting capture rates of brown kiwi were the presence of different types of macro habitats, season and slope levels of the camera sites. When cameras were set up in forest and edge habitats, high capture rates could be achieved. This was probably due to the abundant food items from leaf litter in these two habitats, as well as sparse understory layers, which would increase the viewable area of the cameras to capture more

bird videos. During summer, the capture rates of brown kiwi were the lowest, and the reason might be that brown kiwi spent more time foraging for field crickets on pastures, but cameras were not set up on pastures. Although some cameras were placed on the scrub and pasture edges, because of the abundant ground-dwelling invertebrates on pastures during summer, it might make brown kiwi foraging easier and reduce their foraging time, causing a reduction in capture rates in summer. During autumn and winter, brown kiwi switched their foraging ground to forests because of their invertebrate preference. They would also spend more time foraging due to the low invertebrate availability during these two seasons. Therefore, these reasons might lead to high capture rates of camera traps, especially the cameras placed in forests. Camera traps set up during spring had lower capture rates than in autumn and winter. This was probably caused by the reduction of male birds' activities due to the incubation for breeding during spring.

The slope level of camera trap sites was also an important factor in influencing capture rates. Both gentle and steep slopes had higher capture rates than cameras on moderate slopes. For gentle slopes, this could be due to the fact that these areas would receive more sunlight, allowing for an increase in the growth of vegetation, an increase in leaf litter, and ultimately an increase in insect availability and foraging activities in these places. Steep slopes properly had free-draining soil, which could prevent flooding in burrows. Hence, brown kiwi might roost in burrows on steep slopes, which could potentially lead to high capture rates if camera traps were placed close to these burrows. The aspects of camera trap sites were not recognised as an important factor in influencing capture rates. A possible reason could be that the close canopy in the study site blocked solar radiation from many places, which would not influence the thermal condition of many roosting sites and bird activities in different aspects of the study site. Other factors, such as the presence of swamps and tracks, were not identified as important drivers in affecting capture rates, which was probably due to predator avoidance behaviour.

Objective 3. Camera trap deployment strategies and sampling effort in future brown kiwi management

For future brown kiwi monitoring and management, if the purpose of using camera traps is to maximise the capture rates of brown kiwi, this study suggested that camera traps should be placed in forests and edge habitats bordering pastures. Camera traps should be operating during autumn and winter, and they should be placed mainly on gentle slopes or steep slopes if possible. The time intervals, ranging from 15 minutes to 60 minutes, used for identifying independent events did not

influence the GLMM prediction ability. Thus, using 30-minute intervals should be sufficient for the video extraction process. However, to save labour effort and cost in the future, semi-automated or even automated identification photo or video data analysis techniques should be considered when extracting camera trap data.

Based on the results from GLMM and heat maps, camera traps set up in fragmented habitats kept much more model prediction ability than in the continuous habitat. One of the potential reasons could be that edge effects were intense in fragmented habitats, which increased the predation intensity of insectivorous birds at a smaller scale. Thus, brown kiwi had higher activity levels in these habitats and more chances for cameras to capture them. Other potential reasons could be that there were slightly more cameras set up in fragmented habitats than in continuous habitats, and some fragmented habitats were close to the continuous habitat, which increased the utilisation of these surrounding fragmented habitats. These results suggested that more efforts should be placed on sampling fragmented habitats when using camera traps for monitoring brown kiwi. Moreover, these results also indicated that fragmented habitats could attract brown kiwi during their nocturnal activities, which further suggested that preserving fragments of native forests on agricultural lands is crucial for brown kiwi conservation and management in the future, particularly with regard to their dispersal.

Based on the results from GLMM, when camera traps were randomly reduced by more than three cameras (grid cell size changed from 25 ha/camera to 37 ha/camera) from each habitat every month, the GLMM lost its prediction ability completely. Knowing this threshold is helpful in brown kiwi management and research. For example, due to the limited number of cameras or broken cameras in the field, the grid cell size sometimes must be increased, and this threshold can ensure that the management protocol remains valid.

Limitations

- Due to the use of by-catch camera trap data, one of the limitations of my research was that I could not increase one or more cameras within each grid cell. Kolowski *et al.* (2020) suggested that grid-based camera trapping projects could benefit from using multi-cameras within each cell by minimising unknown or unmeasured microhabitat factors from areas out of the field of view of a single camera trap. Other benefits of using a multi-camera placement within a single grid cell include that it has been demonstrated to be a cost-effective approach for monitoring elusive species (Galvez *et al.*, 2016), such as brown kiwi,

improving their detection probability (Stokeld *et al.*, 2016; Evans *et al.*, 2019) and reducing bias in occupancy estimation (MacKenzie and Royle, 2005; Neilson *et al.*, 2018).

- A further constraint of using bycatch data for camera trap analysis is the lack of capability to investigate the influence of trail length and width on the capture rate of brown kiwi.
- Despite capturing a significant amount of brown kiwi behavior data, such as courting and fighting, through the use of camera traps, the analysis of these behaviors was not feasible within the scope of this thesis due to time constraints.

Future research

- Further research should focus on using camera traps to estimate the relative abundance of the North Island brown kiwi. A useful approach would be to incorporate a calibration target in front of the camera. This would enable the capture of images or videos that reveal the movements and sizes of animals, allowing for the estimation of the distance between the animal and the camera. By knowing the viewable area of the camera trap, it becomes possible to estimate the relative abundance of animals without natural markings, such as the brown kiwi, using the advanced R package *spaceNtime* (Moeller *et al.* 2022).
- Camera trap studies generate a large volume of data, and processing and analyzing this data can be challenging. Future research should consider using artificial intelligence (AI) to help with data processing and should also focus on testing the accuracy of using AI in data processing.
- Further research should also focus on the influence of cameras on recorded brown kiwi, including factors such as camera-emitted light, olfactory cues and mechanical noise. The significance of these influential factors may become particularly evident in behavioral studies, where the accurate attribution of behavioral changes to specific environmental factors is crucial.

Overall summary

Based on the findings of this study, it is clear that camera trapping can be an effective tool for monitoring brown kiwi populations and studying their habitat utilization. The study revealed that forest habitats were preferred by brown kiwi due to the abundance of food sources and protection against aerial predators. Scrub and pasture edge habitats also showed significant usage, while scrub

habitats were used less frequently. These findings have important implications for brown kiwi management and conservation efforts. It suggests that intensive predator control within forests and edge habitats, as well as maintaining and increasing the number of native forest patches on agricultural lands, are key steps in managing brown kiwi populations. Furthermore, the study highlights the need to deploy camera traps in forests and edge habitats to maximize capture rates.

The study also identified influential factors affecting capture rates, such as the presence of different macro habitats, seasonality, and slope levels. These findings can inform camera trap placement strategies, recommending cameras to be set up in forests and edge habitats during autumn and winter, preferably on gentle or steep slopes. In addition, the study emphasized the importance of sampling fragmented habitats and preserving fragments of native forests on agricultural lands. The results indicated that fragmented habitats attract brown kiwi during their nocturnal activities, emphasizing the significance of these habitats for brown kiwi conservation and dispersal.

Overall, these findings contribute valuable insights for brown kiwi management and provide guidance for future camera trap monitoring efforts. By implementing the recommended strategies, we can enhance the effectiveness of conservation measures and work towards the successful recovery and long-term survival of brown kiwi populations in New Zealand.

Reference list

- Adler, F. R., Green, A. M., & Şekercioglu, Ç. H. (2020). Citizen science in ecology: a place for humans in nature. *Annals of the New York Academy of Sciences*, 1469(1), 52-64.
- Athreya, V., Odden, M., Linnell, J. D., Krishnaswamy, J., & Karanth, U. (2013). Big cats in our backyards: persistence of large carnivores in a human dominated landscape in India. *PLoS One*, 8(3), e57872.
- Baber, M. J., & Craig, J. L. (2003). The relationship between foraging behaviour and habitat use by South Island takahe (*Porphyrio hochstetteri*) on Tiritiri Matangi Island. *Notornis*, 50(2), 59-66.
- Barbaro, L., & Van Halder, I. (2009). Linking bird, carabid beetle and butterfly life-history traits to habitat fragmentation in mosaic landscapes. *Ecography*, 32(2), 321-333.
- Barbaro, L., Giffard, B., Charbonnier, Y., Van Halder, I., & Brockerhoff, E. G. (2014). Bird functional diversity enhances insectivory at forest edges: a transcontinental experiment. *Diversity and Distributions*, 20(2), 149-159.
- Barbaro, L., Brockerhoff, E. G., Giffard, B., & Van Halder, I. (2012). Edge and area effects on avian assemblages and insectivory in fragmented native forests. *Landscape ecology*, 27(10), 1451-1463.
- Barron, D. G., Brawn, J. D., & Weatherhead, P. J. (2010). Meta-analysis of transmitter effects on avian behaviour and ecology. *Methods in Ecology and Evolution*, 1(2), 180-187.
- Basse, B., McLennan, J. A., & Wake, G. C. (1999). Analysis of the impact of stoats, *Mustela erminea*, on northern brown kiwi, *Apteryx mantelli*, in New Zealand. *Wildlife Research*, 26(2), 227-237.
- Bell, E. A., Bell, B. D., Sim, J. L., & Imber, M. J. (2013). Notes on the distribution, behaviour and status of grey petrel (*Procellaria cinerea*) on Antipodes Island, New Zealand. *Notornis*, 60(4), 269-278.
- Bisht, S., Chaudhry, S., Sharma, S., & Soni, S. (2018). Assessment of flash flood vulnerability zonation through Geospatial technique in high altitude Himalayan watershed, Himachal Pradesh India. *Remote Sensing Applications: Society and Environment*, 12, 35-47
- Blake, J. G., & Mosquera, D. (2014). Camera trapping on and off trails in lowland forest of eastern Ecuador: does location matter?. *Mastozoología Neotropical*, 21(1), 17-26.
- Blount, J. D., Chynoweth, M. W., Green, A. M., & Şekercioglu, Ç. H. (2021). COVID-19 highlights the importance of camera traps for wildlife conservation research and management. *Biological Conservation*, 256, 108984.
- Blue, L., & Blunden, G. (2010). (Re) making space for kiwi: beyond 'fortress conservation' in Northland. *New Zealand Geographer*, 66(2), 105-123.
- Bowkett, A. E., Rovero, F., & Marshall, A. R. (2008). The use of camera-trap data to model habitat use by antelope species in the Udzungwa Mountain forests, Tanzania. *African journal of ecology*, 46(4), 479-487.
- Brockerhoff, E. G., Burns, B., Shaw, W., Deconchat, M., & Hock, B. (2006). Forest biodiversity: identifying the issues and opportunities for management. In *New Zealand Institute of Forestry Conference, 2023 April, Te Papa, Wellington, New Zealand*.
- Broekman, M. J., Hilbers, J. P., Schipper, A. M., Benítez-López, A., Santini, L., & Huijbregts, M. A. (2022). Time-lagged effects of habitat fragmentation on terrestrial mammals in Madagascar. *Conservation Biology*, 36(5), e13942.
- Brown, E. A. (1979). Vegetation and flora of Ponui Island, Hauraki Gulf, New Zealand. *Tane*, 25, 5-16.

- Brown, M. A., Stephens, R. T., Peart, R., & Fedder, B. (2015). Vanishing nature. *Facing New Zealand's biodiversity crisis*. Auckland, Environmental Defence Society.
- Burbidge, M. L., Colbourne, R. M., Robertson, H. A., & Baker, A. J. (2003). Molecular and other biological evidence supports the recognition of at least three species of brown kiwi. *Conservation Genetics*, 4(2), 167–177.
- Butler, D.; McLennan, J.A, 1991: Kiwi recovery plan. Threatened Species Recovery Plan2. Department of Conservation, Wellington. 35 p.
- Cadenasso, M. L., Pickett, S. T., Weathers, K. C., & Jones, C. G. (2003). A framework for a theory of ecological boundaries. *BioScience*, 53(8), 750-758.
- Carthew, S. M., & Slater, E. (1991). Monitoring animal activity with automated photography. *The Journal of Wildlife Management*, 689-692.
- Catry, P., Campos, A., Segurado, P., Silva, M., & Strange, I. (2003). Population census and nesting habitat selection of thin-billed prion *Pachyptila belcheri* on New Island, Falkland Islands. *Polar Biology*, 26, 202-207.
- Cellek, S. (2021). The Effect of Aspect on Landslide and Its Relationship with Other Parameters. In *Landslides*. IntechOpen.
- Chan, T. (1999). *Habitat Selection by Northern Brown Kiwi Chicks (Apteryx Mantelli) in Trounson Kauri Park, Northland* (Doctoral dissertation, University of Auckland).
- Clough, Y., Putra, D. D., Pitopang, R., & Tschardtke, T. (2009). Local and landscape factors determine functional bird diversity in Indonesian cacao agroforestry. *Biological Conservation*, 142(5), 1032-1041. 2.
- Clout, M. N. (2002). Biodiversity loss caused by invasive alien vertebrates. *European Journal of Wildlife Research*, 48, 51.
- Colbourne, R., & Kleinpaste, R. (1984). North Island brown kiwi vocalisations and their use in censusing populations. New Zealand Wildlife Service.
- Colbourne, R. (2002). Incubation behaviour and egg physiology of kiwi (*Apteryx* spp.) in natural habitats. *New Zealand journal of ecology*, 129-138.
- Colbourne, R. (2005). Kiwi (*Apteryx* spp.) on offshore New Zealand islands. *Department of Conservation Research and Development Series*, 208, 23.
- Colbourne, R., Bassett, S., Billing, T., McCormick, H., McLennan, J., Nelson, A., & Robertson, H. (2005). The development of Operation Nest Egg as a tool in the conservation management of kiwi. *Science for Conservation*, 259, 24 pages. Department of Conservation, Wellington, New Zealand.
- Cooper, J. K., Li, J., & Montagnes, D. J. (2012). Intermediate fragmentation per se provides stable predator-prey metapopulation dynamics. *Ecology Letters*, 15(8), 856-863.
- Colyn, R. B., Campbell, A. M., & Smit-Robinson, H. A. (2017). The application of camera trapping to assess Rallidae species richness within palustrine wetland habitat in South Africa. *Ostrich*, 88(3), 235-245.
- Colyn, R. B., Radloff, F. G. T., & O'Riain, M. J. (2018). Camera trapping mammals in the scrubland's of the Cape Floristic Kingdom—the importance of effort, spacing and trap placement. *Biodiversity and Conservation*, 27, 503-520.
- Corfield, J., Gillman, L., & Parsons, S. (2008). Vocalizations of the North Island brown kiwi (*Apteryx mantelli*). *The Auk*, 125(2), 326-335.
- Corfield, J. R. (2009). *Evolution of the brain and sensory systems of the kiwi* (Doctoral dissertation, University of Auckland).

- Craig, E., Gardiner, C., Renwick, N., & Sporle, W. (2011). Taxon plan for Northland brown kiwi (*Apteryx mantelli*): strategic plan for Northland brown kiwi, 2010–2019 and beyond. Department of Conservation, Whangarei. 56 p.
- Croxall, J.P., Butchart, S.H.M., Lascelles, B.G., Stattersfield, A.J., Sullivan, B., Symes, A. and Taylor, P.D. 2012: Seabird conservation status, threats and priority actions: a global assessment. *Bird Conservation International* 22(1): 1–34. <https://doi.org/10.1017/S0959270912000020>
- Cusack, J. J., Dickman, A. J., Rowcliffe, J. M., Carbone, C., Macdonald, D. W., & Coulson, T. (2015). Random versus game trail-based camera trap placement strategy for monitoring terrestrial mammal communities. *PloS one*, 10(5), e0126373.
- Cunningham, S., Castro, I., & Alley, M. (2007). A new prey-detection mechanism for kiwi (*Apteryx* spp.) suggests convergent evolution between paleognathous and neognathous birds. *Journal of Anatomy*, 211(4), 493-502.
- Cunningham, S. J., Castro, I., & Potter, M. A. (2009). The relative importance of olfaction and remote touch in prey detection by North Island brown kiwis. *Animal Behaviour*, 78(4), 899-905.
- Cunningham, S. J., & Castro, I. (2011). The secret life of wild brown kiwi: studying behaviour of a cryptic species by direct observation. *New Zealand Journal of Ecology*, 209-219.
- Davis, A., Taylor, C. E., & Major, R. E. (2012). Seasonal abundance and habitat use of Australian parrots in an urbanised landscape. *Landscape and Urban Planning*, 106(2), 191-198.
- Dawber, J. (2009). Generalised linear mixed models and its application in R. Retrieved from *Generalised linear mixed models and its application in R (canterbury.ac.nz)*
- De Leo, G. A., & Levin, S. (1997). The multifaceted aspects of ecosystem integrity. *Conservation ecology*, 1(1).
- Di Bitetti, M. S., Paviolo, A., & De Angelo, C. (2014). Camera trap photographic rates on roads vs. off roads: location does matter. *Mastozoología neotropical*, 21(1), 37-46.
- Dillon, A., & Kelly, M. J. (2007). Ocelot *Leopardus pardalis* in Belize: the impact of trap spacing and distance moved on density estimates. *Oryx*, 41(4), 469-477.
- Dinata, Y., Nugroho, A., Haidir, I. A., & Linkie, M. (2008). Camera trapping rare and threatened avifauna in west-central Sumatra. *Bird Conservation International*, 18(1), 30-37.
- Dixon, T. (2015). *What they do in the shadows: habitat utilisation and diet of brown kiwi (Apteryx mantelli) adults within a high-density island population*. Master of Science Thesis, Massey University).
- Dodd, M., Barker, G., Burns, B., Didham, R., Innes, J., King, C., ... & Watts, C. (2011). Resilience of New Zealand indigenous forest fragments to impacts of livestock and pest mammals. *New Zealand Journal of Ecology*, 35(1), 83-95.
- Dominati, E. J., Maseyk, F. J., Mackay, A. D., & Rendel, J. M. (2019). Farming in a changing environment: Increasing biodiversity on farm for the supply of multiple ecosystem services. *Science of the total environment*, 662, 703-713.
- Dymond, J. R., Shepherd, J. D., Newsome, P. F., & Belliss, S. (2017). Estimating change in areas of indigenous vegetation cover in New Zealand from the New Zealand Land Cover Database (LCDB). *New Zealand Journal of Ecology*, 41(1), 56-64.
- Ellis, S., & Marsland, S. (2022). Sounding out the nest. *New Zealand Journal of Ecology*, 46(1), 1-11.
- Englund, O. and Berndes, G. (2016). How do Sustainability Standards Consider Biodiversity? In *Advances in Bioenergy* (eds P.D. Lund, J. Byrne, G. Berndes and I.A. Vasalos).

- Esri. (n.d.). *Creating a buffer around a feature*. Retrieved from *Creating a buffer around a feature Help ArcGIS for Desktop*
- Evans, B. E., Mosby, C. E., & Mortelliti, A. (2019). Assessing arrays of multiple trail cameras to detect North American mammals. *PloS one*, *14*(6), e0217543.
- Fischer, J., Stott, J., & Law, B. S. (2010). The disproportionate value of scattered trees. *Biological Conservation*, *143*(6), 1564-1567.
- Food and Agriculture Organization of the United Nations. (2007). *Land Evaluation: Towards a Revised Framework*. FAO.
- Forbes, Y. (2009). *Natal dispersal, habitat selection and mortality of North Island brown kiwi (Apteryx mantelli) at the Moehau kiwi sanctuary, Coromandel* (Doctoral dissertation, Auckland University of Technology).
- Foster, R. J., Harmsen, B. J., & Doncaster, C. P. (2010). Habitat use by sympatric jaguars and pumas across a gradient of human disturbance in Belize. *Biotropica*, *42*(6), 724-731.
- Foster, R. J., & Harmsen, B. J. (2012). A critique of density estimation from camera-trap data. *The Journal of Wildlife Management*, *76*(2), 224-236.
- Gallo, T., Fidino, M., Lehrer, E. W., & Magle, S. B. (2017). Mammal diversity and metacommunity dynamics in urban green spaces: implications for urban wildlife conservation. *Ecological Applications*, *27*(8), 2330-2341.
- Garvey, P. (2016). *Interspecific competition and olfactory communication between New Zealand's invasive predators: unravelling and exploiting stoat behaviour for conservation* (Doctoral dissertation, University of Auckland).
- Gálvez, N., Guillera-Arroita, G., Morgan, B. J., & Davies, Z. G. (2016). Cost-efficient effort allocation for camera-trap occupancy surveys of mammals. *Biological Conservation*, *204*, 350-359.
- Germano, J., Barlow, S., Castro, I., Colbourne, R., Cox, M., Gillies, C., Hackwell, K., Harawira, J., Impey, M., Reuben, A., Robertson, H., Scrimgeour, J., Sporle, W., & Yong, S. (2018). *Kiwi recovery plan 2018–2028 Mahere whakaora kiwi 2018–2028*. Threatened species recovery plan, 64, 60. Department of Conservation (New Zealand).
- Gibbs, S. (2000). *Distribution, habitat use and survival of immature North Island brown kiwi (Apteryx australis mantelli) at Trounson Kauri Park* (Doctoral dissertation, University of Auckland).
- Gibbs, S. J., & Clout, M. N. (2003). Behavioural vulnerability of juvenile brown kiwi: habitat use and overlap with predators (p, 17). Wellington, New Zealand: Department of Conservation. DOC Science Internal Series 102.
- Girma, Z., Mamo, Y., Mengesha, G., Verma, A., & Asfaw, T. (2017). Seasonal abundance and habitat use of bird species in and around Wondo Genet Forest, south-central Ethiopia. *Ecology and Evolution*, *7*(10), 3397-3405.
- Glen, A. S., Anderson, D., Veltman, C. J., Garvey, P. M., & Nichols, M. (2016). Wildlife detector dogs and camera traps: a comparison of techniques for detecting feral cats. *New Zealand Journal of Zoology*, *43*(2), 127-137.
- Goldsmith, F. B. (2012). *Monitoring for conservation and ecology* (Vol. 3). Springer Science & Business Media.
- Greig, H. S., McHugh, P. A., Thompson, R. M., Warburton, H. J., & McIntosh, A. R. (2022). Habitat size influences community stability. *Ecology*, *103*(1), e03545.
- Griffiths, M. (1993). Camera-trapping: a new tool for the study of elusive rain forest animals. *Tropical biodiversity*, *1*, 131-135.

- Grotta-Neto, F., Peres, P. H., Piovezan, U., Passos, F. C., & Duarte, J. M. (2020). Camera trap feasibility for ecological studies of elusive forest deer. *Wildlife Society Bulletin*, 44(3), 640-647.
- Guillera-Arroita, G., & Lahoz-Monfort, J. J. (2012). Designing studies to detect differences in species occupancy: power analysis under imperfect detection. *Methods in Ecology and Evolution*, 3(5), 860-869.
- Harms, T. M., Murphy, K. T., Lyu, X., Patterson, S. S., Kinkead, K. E., Dinsmore, S. J., & Frese, P. W. (2017). Using landscape habitat associations to prioritize areas of conservation action for terrestrial birds. *PLoS One*, 12(3), e0173041.
- Harrison, X. A., Donaldson, L., Correa-Cano, M. E., Evans, J., Fisher, D. N., Goodwin, C. E., ... & Inger, R. (2018). A brief introduction to mixed effects modelling and multi-model inference in ecology. *PeerJ*, 6, e4794.
- Herbert, J., & Daugherty, C. H. (2002). Genetic variation, systematics and management of kiwi (*Apteryx spp.*). Pages 10-33 in Overmas, F. (ed.) *Some early 1990s studies in kiwi (Apteryx spp.) genetics and management*. Department of Conservation Science and Research Internal Report 191. Department of Conservation, Wellington.
- Hilborn, R., Banobi, J., Hall, S. J., Pucylowski, T., & Walsworth, T. E. (2018). The environmental cost of animal source foods. *Frontiers in Ecology and the Environment*, 16(6), 329-335.
- Hoare, J. M. (2006). Novel predators and naïve prey: how introduced mammals shape behaviours and populations of New Zealand lizards. (Doctoral thesis, Victoria University of Wellington)
- Hofmeester, T. R., Rowcliffe, J. M., & Jansen, P. A. (2017). A simple method for estimating the effective detection distance of camera traps. *Remote Sensing in Ecology and Conservation*, 3(2), 81-89.
- Holzapfel, S., Robertson, H. A., McLennan, J. A., Sporle, W., Hackwell, K., & Impey, M. (2008). Kiwi (*Apteryx spp.*) recovery plan: 2008–2018. Threatened Species Recovery Plan, 60. Department of Conservation, Wellington. 71 p.
- Humphreys, A. M., Govaerts, R., Ficinski, S. Z., Nic Lughadha, E., & Vorontsova, M. S. (2019). Global dataset shows geography and life form predict modern plant extinction and rediscovery. *Nature Ecology & Evolution*, 3(7), 1043-1047.
- Innes, J., Eppink, F. V., & Robertson, H. A. (2015). *Saving a national icon: Preliminary estimation of the additional cost of achieving kiwi population stability or 2% growth*. Landcare Research Manaaki Whenua.
- Innes, J., Miskelly, C. M., Armstrong, D. P., Fitzgerald, N., Parker, K. A., & Stone, Z. L. (2022). Movements and habitat connectivity of New Zealand forest birds. *New Zealand Journal of Ecology*, 46(2), 1-21.
- Iranzo, E. C., Traba, J., Mata, C., Acebes, P., & Malo, J. E. (2021). Habitat structure and association with ungulates drive habitat selection and grouping behaviour of lesser rhea (*Rhea pennata* subsp. *pennata*). *Austral Ecology*, 46(1), 86-97.
- Jahn, P., Ross, J. G., MacKenzie, D. I., & Molles, L. E. (2022). Acoustic monitoring and occupancy analysis: Cost-effective tools in reintroduction programmes for roroa-great spotted kiwi. *New Zealand Journal of Ecology*, 46(1), 3466.
- Jamieson, S. E., Castro, I., Jensen, T., Morrison, K. W., & Durrant, B. (2016). Roosting preferences of North Island brown kiwi (*Apteryx mantelli*). *The Wilson Journal of Ornithology*, 128(4), 857 - 866.
- Kanka, P., Sukmasuang, R., Duengkae, P., & Siripattaranukul, K. (2023). Abundance and physical factors affecting the appearance of selected terrestrial birds in Khao Yai National Park using camera trapping. *Biodiversitas Journal of Biological Diversity*, 24(1).

- Karanth, K. U. (1995). Estimating tiger *Panthera tigris* populations from camera-trap data using capture—recapture models. *Biological conservation*, 71(3), 333-338.
- Karanth, K. U., & Nichols, J. D. (2011). Estimating tiger abundance from camera trap data: field surveys and analytical issues. *Camera traps in animal ecology: methods and analyses*, 97-111. (Vol. 271). A. F. O'Connell (Ed.). New York: Springer.
- Kays, R., Tilak, S., Kranstauber, B., Jansen, P. A., Carbone, C., Rowcliffe, M. J., ... & He, Z. (2010). Monitoring wild animal communities with arrays of motion sensitive camera traps. *arXiv preprint arXiv:1009.5718*.
- Keast, J., Kelly, T., Moorhouse, H., Tan, J., & Wei, S. Y. (2010). Conservation of the North Island Brown Kiwi (*Apteryx mantelli*): current approaches, the successes and limitations, and proposals to ensure long term continuity. *School of Biological Sciences, Victoria University of Wellington, Wellington, New Zealand*.
- Keslinka, L. K., Wojczulanis-Jakubas, K., Jakubas, D., & Neubauer, G. (2019). Determinants of the little auk (*Alle alle*) breeding colony location and size in W and NW coast of Spitsbergen. *PLoS One*, 14(3), e0212668.
- King, C. M. (1990). *'The Handbook of New Zealand Mammals.'* Oxford University Press: Auckland.
- Kolowski, J. M., & Forrester, T. D. (2017). Camera trap placement and the potential for bias due to trails and other features. *PloS one*, 12(10), e0186679.
- Kolowski, J. M., Oley, J., & McShea, W. J. (2021). High-density camera trap grid reveals lack of consistency in detection and capture rates across space and time. *Ecosphere*, 12(2), e03350.
- Koot, E. M., Morgan-Richards, M., & Trewick, S. A. (2022). Climate change and alpine-adapted insects: modelling environmental envelopes of a grasshopper radiation. *Royal Society Open Science*, 9(3), 211596.
- Kucera, T. E., & Barrett, R. H. (2011). *A History of Camera Trapping*. In O'Connell, A.F., Nichols, J.D., Karanth K.U. (eds) *Camera Traps in animal Ecology*. Springer, Tokyo. https://doi.org/10.1007/978-4-431-99495-4_2
- Lasky, M., Parsons, A., Schuttler, S., Mash, A., Larson, L., Norton, B., ... & Kays, R. (2021). Candid Critters: Challenges and solutions in a large-scale citizen science camera trap project. *Citizen Science: Theory and Practice*, 6(1), 4.
- Latham, J. E. (2006). *The ecology of ship rats (Rattus rattus) on Ponui Island: implications for North Island brown kiwi (Apteryx mantelli)* (Doctoral dissertation, University of Auckland).
- Lee, W., McGlone, M., & Wright, E. (2005). Biodiversity inventory and monitoring: a review of national and international systems and a proposed framework for future biodiversity monitoring by the Department of Conservation. *Landcare Research contract report LC0405/122*.
- Le Roux, D. S., Ikin, K., Lindenmayer, D. B., Manning, A. D., & Gibbons, P. (2018). The value of scattered trees for wildlife: Contrasting effects of landscape context and tree size. *Diversity and Distributions*, 24(1), 69-81.
- Li, D., Yang, Y., Xia, F., Sun, W., Li, X., & Xie, Y. (2022). Exploring the influences of different processes of habitat fragmentation on ecosystem services. *Landscape and Urban Planning*, 227, 104544.
- Li, S., McShea, W. J., Wang, D., Huang, J., & Shao, L. (2012). A direct comparison of camera-trapping and sign transects for monitoring wildlife in the Wanglang National Nature Reserve, China. *Wildlife Society Bulletin*, 36(3), 538-545.
- Link, A., Alvarez-Solas, S., Blake, J., Campos, F., Espinosa, S., Medrano-Vizcaino, P., ... & Valenzuela, L. (2022). Insights into the habits of the elusive nocturnal curassow (*Nothocrax urumutum*). *Ornitología Neotropical*, 33(1), 74-78.

- Lu, Y., Wang, R., Zhang, Y., Su, H., Wang, P., Jenkins, A., ... & Squire, G. (2015). Ecosystem health towards sustainability. *Ecosystem Health and Sustainability*, 1(1), 1-15.
- Luo, G., Yang, C., Zhou, H., Seitz, M., Wu, Y., & Ran, J. (2019). Habitat use and diel activity pattern of the Tibetan Snowcock (*Tetraogallus tibetanus*): a case study using camera traps for surveying high-elevation bird species. *Avian Research*, 10(1), 1-9.
- Mackay, A. D. (2007). Specifications of whole farm plans as a tool for affecting land use change to reduce risk to extreme climatic events. Horizons Regional Council.
- MacKenzie, D. I., Nichols, J. D., Lachman, G. B., Droege, S., Andrew Royle, J., & Langtimm, C. A. (2002). Estimating site occupancy rates when detection probabilities are less than one. *Ecology*, 83(8), 2248-2255.
- MacKenzie, D. I., & Royle, J. A. (2005). Designing occupancy studies: general advice and allocating survey effort. *Journal of Applied Ecology*, 42(6), 1105-1114.
- Maffei, L., & Noss, A. J. (2008). How small is too small? Camera trap survey areas and density estimates for ocelots in the Bolivian Chaco. *Biotropica*, 40(1), 71-75.
- Manaaki Whenua Landcare Research (n.d.). *Slope*. Retrieved from *Steepness of Slope » Maps » Our Environment (scinfo.org.nz)*
- Manderson, A. K., Mackay, A. D., & Palmer, A. P. (2007). Environmental whole farm management plans: Their character, diversity, and use as agri-environmental indicators in New Zealand. *Journal of Environmental Management*, 82(3), 319-331.
- Manning, C. (2007). Generalized Linear Mixed Models (illustrated with R on Bresnan et al.'s dative data). See https://nl.p.stanford.edu/manning/course/lin_g289/GLMM.pdf (accessed 22 February 2015).
- Maseko, M. S., Ramesh, T., Kalle, R., & Downs, C. T. (2017). Response of Crested Guinea-fowl (*Guttera edouardi*), a forest specialist, to spatial variation in land use in iSimangaliso Wetland Park, South Africa. *Journal of Ornithology*, 158, 469-477.
- Maseyk, F. J., Dominati, E. J., & Mackay, A. D. (2019). More than a 'nice to have': integrating indigenous biodiversity into agroecosystems in New Zealand. *New Zealand Journal of Ecology*, 43(2), 1-12.
- McArthur, N., Boulton, R. L., Richard, Y., & Armstrong, D. P. (2019). The role of pine plantations in source-sink dynamics of North Island robins. *New Zealand Journal of Ecology*, 43(1), 1-9.
- McGlone, M. S. (1989). The Polynesian settlement of New Zealand in relation to environmental and biotic changes. *New Zealand Journal of Ecology*, 12, 115-129.
- McLennan, J. A., Rudge, M. R., & Potter, M. A. (1987). Range size and denning behaviour of Brown Kiwi, *Apteryx australis mantelli*, in Hawke's Bay, New Zealand. *New Zealand Journal of Ecology*, 97-107.
- McLennan, J. A. (1988). Breeding of north Island brown kiwi, *Apteryx australis mantelli*, in Hawke's Bay, New Zealand. *New Zealand Journal of Ecology*, 11, 89-97.
- McLennan, J. A., Dew, L., Miles, J., Gillingham, N., & Waiwai, R. (2004). Size matters: predation risk and juvenile growth in North Island brown kiwi (*Apteryx mantelli*). *New Zealand Journal of Ecology*, 28(2), 241-250.
- McLennan, J., & McCann, T. (2002). Genetic variability, distribution and abundance of great spotted kiwi (*Apteryx haastii*). Pages 35-55 in Overmars, F. (ed.) *Some early 1990s studies in kiwi (Apteryx spp.) genetics and management*. Department of Conservation Science and Research Internal Report 191. Department of Conservation, Wellington.

- McLennan, J., & North, H. (1997). *Ecology of brown kiwi and causes of population decline in Lake Waikaremoana catchment*. New Zealand: Department of Conservation.
- McLennan, J. A., & Potter, M. (1992). Distribution, population changes and Management of brown kiwi in Hawke's bay. *New Zealand Journal of Ecology*, 16(2), 91-102.
- McLennan, J. A., Potter, M., Robertson, H., Wake, G., Colbourne, R., Dew, L., ... & Reid, J. (1996). Role of predation in the decline of kiwi, *apteryx spp.*, in New Zealand. *New Zealand Journal of Ecology*, 20(1), 27-35.
- Meek, P. D., Ballard, G., Claridge, A., Kays, R., Moseby, K., O'Brien, T., ... & Townsend, S. (2014). Recommended guiding principles for reporting on camera trapping research. *Biodiversity and conservation*, 23, 2321-2343.
- Mere Roncal, C., Middendorf, E., Forsyth, A., Cáceres, A., Blake, J. G., Almeyda Zambrano, A. M., & Broadbent, E. N. (2019). Assemblage structure and dynamics of terrestrial birds in the southwest Amazon: a camera-trap case study. *Journal of Field Ornithology*, 90(3), 203-214.
- Mitchell, K. J., Llamas, B., Soubrier, J., Rawlence, N. J., Worthy, T. H., Wood, J., ... & Cooper, A. (2014). Ancient DNA reveals elephant birds and kiwi are sister taxa and clarifies ratite bird evolution. *Science*, 344(6186), 898-900.
- Moeller, A. K., Lukacs, P. M., & Horne, J. S. (2018). Three novel methods to estimate abundance of unmarked animals using remote cameras. *Ecosphere*, 9(8), e02331.
- Moeller, A.K., Lukacs, P.M. (2022). spaceNtime: an R package for estimating abundance of unmarked animals using camera-trap photographs. *Mammalian Biology* 102, 581–590.
- Moeller, A. K., Waller, S. J., DeCesare, N. J., Chitwood, M. C., & Lukacs, P. M. (2023). Best practices to account for capture probability and viewable area in camera-based abundance estimation. *Remote Sensing in Ecology and Conservation*, 9(1), 152-164.
- Moilanen, A. (2002). Implications of empirical data quality to metapopulation model parameter estimation and application. *Oikos*, 96(3), 516-530.
- Moll, R. J., Ortiz-Calo, W., Cepek, J. D., Lorch, P. D., Dennis, P. M., Robison, T., & Montgomery, R. A. (2020). The effect of camera-trap viewshed obstruction on wildlife detection: implications for inference. *Wildlife Research*, 47(2), 158-165.
- Monks, J. M., Nelson, N. J., Daugherty, C. H., Brunton, D. H., & Shine, R. (2019). Does evolution in isolation from mammalian predators have behavioural and chemosensory consequences for New Zealand lizards?. *New Zealand Journal of Ecology*, 43(1), 1-13.
- Murphy, A. J., Farris, Z. J., Karpanty, S., Kelly, M. J., Miles, K. A., Ratelolahy, F., ... & Golden, C. D. (2018). Using camera traps to examine distribution and occupancy trends of ground-dwelling rainforest birds in north-eastern Madagascar. *Bird Conservation International*, 28(4), 567-580.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403(6772), 853-858.
- Naturespy. (2015). *New 2015 bushnell trophy cam aggressor review 119776-119774*. Retrieved from *New 2015 Bushnell Trophy Cam Aggressor Review - NatureSpy*
- Neilson, E. W., Avgar, T., Burton, A. C., Broadley, K., & Boutin, S. (2018). Animal movement affects interpretation of occupancy models from camera-trap surveys of unmarked animals. *Ecosphere*, 9(1), e02092.
- Nichols, J. D., Bailey, L. L., O'Connell Jr, A. F., Talancy, N. W., Campbell Grant, E. H., Gilbert, A. T., ... & Hines, J. E. (2008). Multi-scale occupancy estimation and modelling using multiple detection methods. *Journal of Applied Ecology*, 45(5), 1321-1329.

- Nichols, J. D., & Karanth, K. U. (2011). *Camera traps in animal ecology: methods and analyses* (Vol. 271). A. F. O'Connell (Ed.). New York: Springer.
- Niedzielski, B., & Bowman, J. (2016). Home range and habitat selection of the female eastern wild turkey at its northern range edge. *Wildlife Biology*, 22(2), 55-63.
- NIWA National Climate Centre. (2014). *The year 2014: Near normal rainfall and near average temperatures for most of the country*. Retrieved from *2014_Annual_Climate_Summary.pdf* (*niwa.co.nz*)
- NIWA National Climate Centre. (2015). *The year 2015: Sunny for most, drier than normal for some*. Retrieved from *2015_Annual_Climate_Summary_Final.pdf* (*niwa.co.nz*)
- NIWA National Climate Centre. (2016). *The year 2016: New Zealand's warmest on record*. Retrieved from *2016_Annual_Climate_Summary_Final_0.pdf* (*niwa.co.nz*)
- Norouzzadeh, M. S., Nguyen, A., Kosmala, M., Swanson, A., Palmer, M. S., Packer, C., & Clune, J. (2018). Automatically identifying, counting, and describing wild animals in camera-trap images with deep learning. *Proceedings of the National Academy of Sciences*, 115(25), E5716-E5725.
- Norton, D. A., Suryaningrum, F., Buckley, H. L., Case, B. S., Cochrane, C. H., Forbes, A. S., & Harcombe, M. (2020). Achieving win-win outcomes for pastoral farming and biodiversity conservation in New Zealand. *New Zealand Journal of Ecology*, 44(2), 1-9.
- Norton, D., & Pannell, J. (2018). Desk-top assessment of native vegetation on New Zealand sheep and beef farms. *Beef+ Lamb New Zealand. New Zealand*, 1, 32.
- O'Brien, T. G., Kinnaird, M. F., & Wibisono, H. T. (2003). Crouching tigers, hidden prey: Sumatran tiger and prey populations in a tropical forest landscape. In *Animal Conservation Forum* (Vol. 6, No. 2, pp. 131-139). Cambridge University Press.
- O'Brien, T. G., & Kinnaird, M. F. (2008). A picture is worth a thousand words: the application of camera trapping to the study of birds. *Bird Conservation International*, 18(S1), S144-S162.
- Pannell, J. L., Buckley, H. L., Case, B. S., & Norton, D. A. (2021). The significance of sheep and beef farms to conservation of native vegetation in New Zealand. *New Zealand Journal of Ecology*, 45(1), 1-11.
- Pawson, S. M., Ecroyd, C. E., Seaton, R., Shaw, W. B., & Brockerhoff, E. G. (2010). New Zealand's exotic plantation forests as habitats for threatened indigenous species. *New Zealand Journal of Ecology*, 342-355.
- Perry, G. L., Wilmshurst, J. M., & McGlone, M. S. (2014). Ecology and long-term history of fire in New Zealand. *New Zealand Journal of Ecology*, 157-176.
- Peral, C., Landman, M., & Kerley, G. I. (2022). The inappropriate use of time-to-independence biases estimates of activity patterns of free-ranging mammals derived from camera traps. *Ecology and Evolution*, 12(10), e9408.
- Peters, M. A., Hamilton, D., Eames, C., Innes, J., & Mason, N. W. (2016). The current state of community-based environmental monitoring in New Zealand. *New Zealand Journal of Ecology*, 40(3), 279-288.
- Phillips, M. J., Gibb, G. C., Crimp, E. A., & Penny, D. (2010). Tinamous and moa flock together: mitochondrial genome sequence analysis reveals independent losses of flight among ratites. *Systematic biology*, 59(1), 90-107.
- Pierce, R. J., Gardiner, C., Moodie, H., Robertson, H. A., & Sporle, W. (2006). Sustainable management of brown kiwi and other threatened birds in Northland. *Wildlife Consultants, Report No, 1193*.
- Potter, M. A. (1989). *Ecology and reproductive biology of the North Island brown kiwi (Apteryx australis mantelli)*. (Doctoral dissertation, Massey University).

- Potter, M. A. (1990). Movement of North Island brown kiwi (*Apteryx australis mantelli*) between forest remnants. *New Zealand Journal of Ecology*, 17-24.
- Rayner, M. J., Hauber, M. E., & Clout, M. N. (2007). Breeding habitat of the Cook's Petrel (*Pterodroma cookii*) on Little Barrier Island (Hauturu): implications for the conservation of a New Zealand endemic. *Emu-Austral Ornithology*, 107(1), 59-68.
- Reid, B. E., & Williams, G. R. (1975). *The Kiwi*. In G. Kuschel (Ed.), *Biogeography and ecology in New Zealand* (pp. 301-330). Holland: The Hague.
- Reid, N. (2013). *Nature and farming: Sustaining native biodiversity in agricultural landscapes*. Csiro Publishing.
- Ries, L., Fletcher Jr, R. J., Battin, J., & Sisk, T. D. (2004). Ecological response to habitat edges: Mechanisms, Models, and Variability Explained. *Annual Review of Ecology, Evolution, and Systematics*, 35, 491.
- Robertson, H. A., Colbourne, R. M., Graham, P. J., Miller, P. J., & Pierce, R. J. (2011). Experimental management of brown kiwi *Apteryx mantelli* in central Northland, New Zealand. *Bird Conservation International*, 21(2), 207-220.
- Robertson, H. A. (2013). Updated 2017. North Island brown kiwi. In: Miskelly CM ed. New Zealand birds online. www.nzbirdsonline.org.nz.
- Robertson, H. A., Colbourne, R., & McLennan, J. (2017). *Kiwi best practice manual*. Wellington: Department of Conservation, 109p.
- Robertson, H. A., Colbourne, R. M., Graham, P. J., Miller, P. J., & Pierce, R. J. (2011). Experimental management of brown kiwi *Apteryx mantelli* in central Northland, New Zealand. *Bird Conservation International*, 21(2), 207-220.
- Robertson, H. A., Colbourne, R., & McLennan, J. (2017). *Kiwi best practice manual* (p, 109). Wellington: Department of Conservation.
- Robertson, H. A., & Colbourne, R. M. (2022). Habitat loss drives population decline and reduced mass of Rakiura tokoeka (*Apteryx australis australis*, Stewart Island brown kiwi,) at Mason Bay, Stewart Island/Rakiura. *Notornis*, 69, 147-157.
- Robertson, H. A., & Fraser, J. R. (2009). Use of trained dogs to determine the age structure and conservation status of kiwi *Apteryx* spp. populations. *Bird Conservation International*, 19(2), 121-129.
- Roche, P. K., & Campagne, C. S. (2017). From ecosystem integrity to ecosystem condition: a continuity of concepts supporting different aspects of ecosystem sustainability. *Current Opinion in Environmental Sustainability*, 29, 63-68.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., ... & Foley, J. A. (2009). A safe operating space for humanity. *Nature*, 461(7263), 472-475.
- Rovero, F., Zimmermann, F., Berzi, D., & Meek, P. (2013). " Which camera trap type and how many do I need?" A review of camera features and study designs for a range of wildlife research applications. *Hystrix. the Italian Journal of Mammalogy*, 24(2), 148- 156.
- Royle, J. A., & Nichols, J. D. (2003). Estimating abundance from repeated presence-absence data or point counts. *Ecology*, 84(3), 777-790.
- Ruffell, J., & Didham, R. K. (2017). Conserving biodiversity in New Zealand's lowland landscapes: does forest cover or pest control have a greater effect on native birds? *New Zealand Journal of Ecology*, 41(1), 23-33.
- Sales, J. (2005). The endangered kiwi: a review. *Folia Zoologica*, 54(1-2), 1-20.

- Saunders, A., & Norton, D. A. (2001). Ecological restoration at mainland islands in New Zealand. *Biological Conservation*, 99(1), 109-119.
- Sánchez-Fernández, M., Barrigón Morillas, J. M., Montes González, D., & de Sanjosé Blasco, J. J. (2022). Impact of Roads on Environmental Protected Areas: Analysis and Comparison of Metrics for Assessing Habitat Fragmentation. *Land*, 11(10), 1843.
- Shah, S. B. (2021). *Bird diversity and factors affecting bird abundance at Dullu Municipality, Dailekh, Nepal* (Doctoral dissertation, Tribhuvan University).
- Shapiro, L. M. (2005). *Diet overlap and potential competition between North Island brown kiwi chicks (Apteryx mantelli) and ship rats (Rattus rattus) for limited resources on Ponui Island, New Zealand*, Master of Science thesis, Massey University.
- Silveira, L., Jácomo, A. T., & Diniz-Filho, J. A. F. (2003). Camera trap, line transect census and track surveys: a comparative evaluation. *Biological conservation*, 114(3), 351-355.
- Si, X., Kays, R., & Ding, P. (2014). How long is enough to detect terrestrial animals? Estimating the minimum trapping effort on camera traps. *PeerJ*, 2, e374.
- Smith, D. A. E., Smith, Y. C. E., & Downs, C. T. (2017). Seasonal habitat requirements of Lemon Dove (*Aplopelia larvata*) in coastal forest: camera-trap surveys of a reclusive species. *African Zoology*, 52(4), 199-207.
- Sollmann, R. (2018). A gentle introduction to camera-trap data analysis. *African Journal of Ecology*, 56(4), 740-749.
- Sollmann, R., Furtado, M. M., Hofer, H., Jácomo, A. T., Tôrres, N. M., & Silveira, L. (2012). Using occupancy models to investigate space partitioning between two sympatric large predators, the jaguar and puma in central Brazil. *Mammalian Biology*, 77(1), 41-46.
- Sollmann, R., Mohamed, A., Samejima, H., & Wilting, A. (2013). Risky business or simple solution Relative abundance indices from camera-trapping. *Biological Conservation*, 159, 405-412.
- Srbek-Araujo, A. C., & Chiarello, A. G. (2013). Influence of camera-trap sampling design on mammal species capture rates and community structures in southeastern Brazil. *Biota Neotropica*, 13, 51-62.
- Steenweg, R., Hebblewhite, M., Kays, R., Ahumada, J., Fisher, J. T., Burton, C., ... & Rich, L. N. (2017). Scaling-up camera traps: Monitoring the planet's biodiversity with networks of remote sensors. *Frontiers in Ecology and the Environment*, 15(1), 26-34.
- Steffens, K. E., Malham, J. P., Davies, R. S., & Elliott, G. P. (2022). Testing the effectiveness of integrated pest control at protecting whio (*Hymenolaimus malacorhynchus*) from stoat (*Mustela erminea*) predation in beech forest (Nothofagaceae). *New Zealand Journal of Ecology*, 46(1), 113.
- Stokeld, D., Frank, A. S., Hill, B., Choy, J. L., Mahney, T., Stevens, A., ... & Gillespie, G. R. (2015). Multiple cameras required to reliably detect feral cats in northern Australian tropical savanna: an evaluation of sampling design when using camera traps. *Wildlife Research*, 42(8), 642-649.
- Strang, K. E. (2018). *The ecology of feral cats (Felis catus) on a New Zealand offshore island: considerations for management*. (Doctoral dissertation, Massey University).
- Sullivan, J. J., & Molles, L. E. (2016). Biodiversity monitoring by community-based restoration groups in New Zealand. *Ecological Management & Restoration*, 17(3), 210-217.
- Swann, D.E., Kawanishi, K., Palmer, J. (2011). Evaluating Types and Features of Camera Traps in Ecological Studies: A Guide for Researchers. In: O'Connell, A.F., Nichols, J.D., Karanth, K.U. (eds) *Camera Traps in Animal Ecology*. Springer, Tokyo.

- Swennen, C. L. L. M., De Bruijn, L. L. M., Duiven, P., Leopold, M. F., & Marteiijn, E. C. L. (1983). Differences in bill form of the Oystercatcher *Haematopus ostralegus*; a dynamic adaptation to specific foraging techniques. *Netherlands Journal of Sea Research*, *17*(1), 57-83.
- Taborsky, B., & Taborsky, M. (1991). Social organization of North Island Brown Kiwi: Long-term pairs and three types of male spacing behaviour. *Ethology*, *89*(1), 47-62.
- Taborsky, B., & Taborsky, M. (1992). Spatial organization of the North Island Brown Kiwi *Apteryx australis mantelli*: sex, pairing status and territoriality. *Ibis*, *134*(1), 1-10.
- Taborsky, B., & Taborsky, M. (1995). Habitat use and selectivity by the brown kiwi (*Apteryx australis mantelli*) in a patchy environment. *The Auk*, *112*(3), 680-689.
- Tait, P., Saunders, C., Guenther, M., & Rutherford, P. (2016). Emerging versus developed economy consumer willingness to pay for environmentally sustainable food production: A choice experiment approach comparing Indian, Chinese and United Kingdom lamb consumers. *Journal of Cleaner Production*, *124*, 65-72.
- Taylor, B. D., Goldingay, R. L., & Lindsay, J. M. (2013). Horizontal or vertical? Camera trap orientations and recording modes for detecting potoroos, bandicoots and pademelons. *Australian Mammalogy*, *36*(1), 60-66.
- Tobler, M. W., & Powell, G. V. (2013). Estimating jaguar densities with camera traps: problems with current designs and recommendations for future studies. *Biological Conservation*, *159*, 109-118.
- Trolle, M., & Kery, M. (2005). *Camera-trap study of ocelot and other secretive mammals in the northern Pantanal*. *Mammalia* *69*, 405-412.
- Trolliet, F., Vermeulen, C., Huynen, M. C., & Hambuckers, A. (2014). Use of camera traps for wildlife studies: a review. *Biotechnologie, Agronomie, Société et Environnement*, *18*(3), 446-454.
- Tyukavina, A., Hansen, M.C., Potapov, P.V., Krylov, A.M. and Goetz, S.J. (2016), Pan-tropical hinterland forests. *Global Ecology and Biogeography*, *25*: 151-163.
- Undin, M., Hills, S. F., Lockhart, P. J., & Castro, I. (2021). Gaps in genetic knowledge affect conservation management of kiwi (*Apteryx*) species. *Ibis*, *163*(4), 1155-1174.
- Undin, M., & Castro, I. (2022). Predicting breeding systems to guide conservation strategies: A kiwi example. *Ethology*, *128*(7), 538-549.
- United Nations. (1992). *Convention on Biological Diversity*, 17 July 1992. United Nations, New York. Reprinted in: *Environmental Policy and Law* *22*: 251- 258.
- Valletta, J. J., & McKinley, T. J. (2018). *Statistical modelling in R*. Retrieved from *Statistical modelling in R (exeter-data-analytics.github.io)*
- Veselkin, D. V., Korzhinevskaya, A. A., & Podgaevskaya, E. N. (2021). The Edge Effect on the Herb Dwarf Shrub Layer of Suburban Anthropogenically Fragmented Southern Taiga Pine Forests. *Russian Journal of Ecology*, *52*, 446-454.
- Waitangi Tribunal. (2011). *Ko Aotearoa tēnei: a report into claims concerning New Zealand law and policy affecting Māori culture and identity*. New Zealand. Waitangi Tribunal Waitangi Tribunal reports.
- Waite, E. M. (2012). *The role of large, isolated trees in supporting urban biodiversity* (Doctoral dissertation, University of Otago).
- Watchorn, D. J., Cowan, M. A., Driscoll, D. A., Nimmo, D. G., Ashman, K. R., Garkaklis, M. J., ... & Doherty, T. S. (2022). Artificial habitat structures for animal conservation: design and implementation, risks and opportunities. *Frontiers in Ecology and the Environment*, *20*(5), 301-309.

- Wegge, P., Pokheral, C. P., & Jnawali, S. R. (2004). Effects of trapping effort and trap shyness on estimates of tiger abundance from camera trap studies. In *Animal Conservation Forum* (Vol. 7, No. 3, pp. 251-256). Cambridge University Press.
- Weingarth, K., Zeppenfeld, T., Heibl, C., Heurich, M., Bufka, L., Daniszová, K., & Müller, J. (2015). Hide and seek: extended camera-trap session lengths and autumn provide best parameters for estimating lynx densities in mountainous areas. *Biodiversity and Conservation*, 24, 2935-2952.
- Weir, J. T., Haddrath, O., Robertson, H. A., Colbourne, R. M., & Baker, A. J. (2016). Explosive ice age diversification of kiwi. *Proceedings of the National Academy of Sciences*, 113(38), E5580-E5587.
- White, D. J., Ramón-Laca, A., Amey, J., & Robertson, H. A. (2018). Novel genetic variation in an isolated population of the nationally critical Haast tokoeka (*Apteryx australis* 'Haast') reveals extreme short-range structure within this cryptic and flightless bird. *Conservation Genetics*, 19, 1401-1410.
- Whittingham, M. J., Percival, S. M., & Brown, A. F. (2002). Nest-site selection by golden plover: why do shorebirds avoid nesting on slopes?. *Journal of Avian Biology*, 33(2), 184-190.
- Williams, J., Smith, R., Ball, A., Reid, N., & Kahn, L. (2019). Harmonisation of on-farm metrics for sustainability assessment of Australian agricultural industries. *Farm Policy Journal*, 16 (3), 15-22.
- Wilson, A. L. (2014). *The triumphs, challenges and failures of young North Island brown kiwi (Apteryx mantelli): a study of behaviour, growth, dispersal and mortality*. Master of Science thesis, Massey University.
- Young, J. M., Saul, G., Behrendt, R., Byrne, F., McCaskill, M., Kearney, G. A., & Thompson, A. N. (2014). The economic benefits of providing shelter to reduce the mortality of twin lambs in south-western Victoria. *Animal Production Science*, 54(6), 773-782.
- Zhang, J., Pannell, J. L., Case, B. S., Hinchliffe, G., Stanley, M. C., & Buckley, H. L. (2021). Interactions between landscape structure and bird mobility traits affect the connectivity of agroecosystem networks. *Ecological Indicators*, 129, 107962.
- Ziesemann, B., Brunton, D. H., & Castro, I. C. (2011). Nesting success and breeding ecology in a high-density population of Brown Kiwi (*Apteryx mantelli*). *Emu-Austral Ornithology*, 111(2), 148-154.

Appendix A

GLMM with Poisson distribution results for overall models after randomly reducing cameras from each habitat in every month and repeating for 10 times and results for the 10 best GLMMs

Table 1. GLMM results for randomly reducing 1 camera from each habitat in every month and results for the best GLMMs after repeating 10 times.

Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1336.7		Overall model			<0.001	1394.2	
Habitat	2	1332.8	<0.001			Habitat	2	1383.0	<0.001		
Season	3	1369.7	<0.001			Season	3	1423.8	<0.001		
Slope	2	1326.7	0.006			Slope	2	1377.8	0.01		
Aspect	3	1317.3	0.89	1339.3		Aspect	3	1371.5	0.49	1395.5	
Swamp	1	1317.0	0.53	1343		Swamp	1	1371.6	0.11	1397.6	
Track	1	1317.9	0.26	1343.9		Track	1	1373.0	0.07	1399.0	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.04	0.28	12.11	<0.001	(Intercept)		2.78	0.25	11.27	<0.001
Habitat	Scrub	-1.24	0.28	-4.38	<0.001	Habitat	Scrub	-1.01	0.25	-4.03	<0.001
	Scrub and pasture edge	-0.94	0.29	-3.23	0.001		Scrub and pasture edge	-0.39	0.26	-1.52	0.13
Season	Spring	-0.04	0.12	0.36	0.72	Season	Spring	-0.14	0.12	-1.21	0.23
	Summer	-0.62	0.09	-6.92	<0.001		Summer	-0.57	0.08	-6.76	<0.001
	Winter	0.13	0.12	1.07	0.29		Winter	0.09	0.12	0.80	0.43
Slope	Moderate	-0.85	0.25	-3.48	0.001	Slope	Moderate	-0.55	0.22	-2.54	0.01
	Strong	-0.08	0.37	-0.22	0.83		Strong	-0.12	0.34	1.23	0.22
Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1407.3		Overall model			<0.001	1397.4	
Habitat	2	1404.0	<0.001			Habitat	2	1392.1	<0.001		
Season	3	1444.1	<0.001			Season	3	1454.5	<0.001		
Slope	2	1394.3	0.02			Slope	2	1382.6	0.03		
Aspect	3	1388.3	0.67	1410.3		Aspect	3	1377.4	0.63	1399.4	
Swamp	1	1387.2	0.55	1413.2		Swamp	1	1376.9	0.27	1402.9	
Track	1	1388.0	0.27	1414.0		Track	1	1377.3	0.20	1403.3	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.08	0.25	12.19	<0.001	(Intercept)		2.94	0.26	11.54	<0.001
Habitat	Scrub	-1.15	0.26	-4.43	<0.001	Habitat	Scrub	-1.14	0.26	-4.35	<0.001
	Scrub and pasture edge	-0.79	0.26	-3.02	0.003		Scrub and pasture edge	-0.59	0.27	-2.23	0.03
Season	Spring	-0.09	0.11	-0.79	0.43	Season	Spring	-0.01	0.11	0.09	0.93
	Summer	-0.61	0.09	-6.97	<0.001		Summer	-0.65	0.09	-7.31	<0.001
	Winter	0.13	0.11	1.12	0.26		Winter	0.35	0.11	3.09	0.002
Slope	Moderate	-0.74	0.22	-3.35	<0.001	Slope	Moderate	-0.71	0.23	-3.16	0.002
	Strong	-0.14	0.36	-0.39	0.69		Strong	-0.20	0.34	-0.59	0.56
Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1336.7		Overall model			<0.001	1373.5	
Habitat	2	1332.8	<0.001			Habitat	2	1365.9	<0.001		
Season	3	1369.7	<0.001			Season	3	1399.8	<0.001		
Slope	2	1326.7	0.006			Slope	2	1357.7	0.05		
Aspect	3	1317.3	0.89	1339.3		Aspect	3	1355.1	0.39	1377.1	
Swamp	1	1317.0	0.53	1343		Swamp	1	1352.3	0.66	1378.3	
Track	1	1317.9	0.26	1343.9		Track	1	1352.8	0.40	1378.8	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.04	0.28	12.11	<0.001	(Intercept)		2.95	0.25	11.65	<0.001
Habitat	Scrub	-1.24	0.28	-4.38	<0.001	Habitat	Scrub	-1.06	0.26	-4.04	<0.001
	Scrub and pasture edge	-0.94	0.29	-3.23	0.001		Scrub and pasture edge	-0.72	0.26	-2.73	0.006
Season	Spring	-0.04	0.12	0.36	0.72	Season	Spring	-0.15	0.11	-1.36	0.17
	Summer	-0.62	0.09	-6.92	<0.001		Summer	-0.49	0.09	-5.67	<0.001
	Winter	0.13	0.12	1.07	0.29		Winter	0.21	0.11	1.91	0.06
Slope	Moderate	-0.85	0.25	-3.48	0.001	Slope	Moderate	-0.65	0.23	-2.88	0.004
	Strong	-0.08	0.37	-0.22	0.83		Strong	-0.01	0.34	0.01	0.99

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1369.9	
Habitat	2	1363.6	<0.001		
Season	3	1442.3	<0.001		
Slope	2	1354.4	0.05		
Aspect	3	1351.7	0.44	1373.7	
Swamp	1	1349.5	0.50	1375.5	
Track	1	1349.3	0.61	1375.7	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.89	0.26	11.28	<0.001
Habitat	Scrub	-1.03	0.26	-3.94	<0.001
	Scrub and pasture edge	-0.55	0.27	-2.07	0.04
Season	Spring	-0.19	0.11	-1.65	0.10
	Summer	-0.61	0.09	-6.92	<0.001
	Winter	0.38	0.11	3.30	<0.001
Slope	Moderate	-0.57	0.23	-2.46	0.01
	Strong	-0.09	0.33	-0.26	0.80

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1370.4	
Habitat	2	1358.8	<0.001		
Season	3	1397.4	<0.001		
Slope	2	1353.8	0.05		
Aspect	3	1350.2	0.46	1372.2	
Swamp	1	1350.2	0.11	1376.2	
Track	1	1348.3	0.41	1377.3	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.99	0.25	11.82	<0.001
Habitat	Scrub	-1.01	0.26	-3.88	<0.001
	Scrub and pasture edge	-0.63	0.26	-2.40	0.02
Season	Spring	-0.26	0.12	-2.17	0.07
	Summer	-0.50	0.09	-5.82	<0.001
	Winter	0.08	0.12	0.68	0.50
Slope	Moderate	-0.69	0.22	-3.09	0.002
	Strong	-0.04	0.34	-0.12	0.90

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1403.8	
Habitat	2	1394.9	0.002		
Season	3	1480.6	<0.001		
Slope	2	1387.2	0.05		
Aspect	3	1384.1	0.66	1406.1	
Swamp	1	1382.5	0.87	1408.5	
Track	1	1384.5	0.16	1410.5	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.92	0.26	11.19	<0.001
Habitat	Scrub	-1.03	0.27	-3.84	<0.001
	Scrub and pasture edge	-0.67	0.27	-2.46	0.01
Season	Spring	-0.03	0.11	-0.26	0.80
	Summer	-0.80	0.09	-8.99	<0.001
	Winter	0.25	0.11	2.23	0.03
Slope	Moderate	-0.64	0.23	-2.76	0.006
	Strong	-0.17	0.35	-0.48	0.63

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1377.2	
Habitat	2	1370.8	<0.001		
Season	3	1412.0	<0.001		
Slope	2	1368.4	0.005		
Aspect	3	1358.8	0.78	1380.8	
Swamp	1	1358.1	0.51	1384.1	
Track	1	1357.8	0.69	1385.8	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.01	0.27	11.07	<0.001
Habitat	Scrub	-1.13	0.28	-4.04	<0.001
	Scrub and pasture edge	-0.87	0.29	-3.05	0.002
Season	Spring	-0.09	0.12	0.79	0.43
	Summer	-0.52	0.09	-5.78	<0.001
	Winter	0.40	0.12	3.41	<0.001
Slope	Moderate	-0.93	0.24	-3.79	<0.001
	Strong	-0.20	0.36	-0.55	0.58

Table 2. GLMM results for randomly reducing 2 cameras from each habitat in every month and results for the best GLMMs after repeating 10 times.

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1076	
Habitat	2	1065.2	0.01		
Season	3	1164.9	<0.001		
Slope	2	1062.3	0.05		
Aspect	3	1057.8	0.70	1079.8	
Swamp	1	1056.5	0.71	1082.5	
Track	1	1056.5	0.76	1082.5	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.05	0.33	9.24	<0.001
Habitat	Scrub	-1.22	0.35	-3.51	<0.001
	Scrub and pasture edge	-0.84	0.36	-2.31	0.02
Season	Spring	-0.21	0.13	-1.63	0.10
	Summer	-0.77	0.09	-8.37	<0.001
	Winter	0.29	0.13	2.29	0.02
Slope	Moderate	-0.80	0.29	-2.75	0.006
	Strong	-0.19	0.67	-1.03	0.30

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1076.4	
Habitat	2	1031.3	<0.001		
Season	3	1069.0	<0.001		
Slope	2	1022.8	0.03		
Aspect	3	1018.8	0.37	1040.8	
Swamp	1	1015.8	0.77	1041.8	
Track	1	1015.8	0.71	1041.8	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.08	0.38	8.18	<0.001
Habitat	Scrub	-1.42	0.37	-3.87	<0.001
	Scrub and pasture edge	-0.75	0.38	-1.94	0.05
Season	Spring	-0.03	0.14	1.60	0.11
	Summer	-0.66	0.10	-6.63	<0.001
	Winter	0.17	0.17	-0.39	0.70
Slope	Moderate	-0.90	0.33	-2.72	0.006
	Strong	-0.12	0.44	0.49	0.63

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1084.1	
Habitat	2	1059.0	0.05		
Season	3	1115.7	<0.001		
Slope	2	1054.7	0.05		
Aspect	3	1059.4	0.09	1082.4	
Swamp	1	1059.1	0.77	1085.1	
Track	1	1059.5	0.71	1085.5	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.74	0.32	8.68	<0.001
Habitat	Scrub	-0.74	0.34	-2.15	0.03
	Scrub and pasture edge	-0.52	0.33	-1.54	0.12
Season	Spring	-0.20	0.14	-2.19	0.03
	Summer	-0.48	0.09	-5.37	<0.001
	Winter	0.27	0.13	2.09	0.04
Slope	Moderate	-0.72	0.30	-2.41	0.02
	Strong	-0.08	0.41	-0.20	0.84

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1106.4	
Habitat	2	1096.3	<0.001		
Season	3	1125.9	<0.001		
Slope	2	1088.3	0.04		
Aspect	3	1088.0	0.11	1110	
Swamp	1	1083.3	0.26	1111.3	
Track	1	1082.7	0.40	1112.7	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.88	0.24	12.05	<0.001
Habitat	Scrub	-0.94	0.25	-3.80	<0.001
	Scrub and pasture edge	-0.54	0.25	-2.21	0.03
Season	Spring	-0.12	0.12	-1.02	0.31
	Summer	-0.41	0.10	-4.35	<0.001
	Winter	0.33	0.12	2.72	0.006
Slope	Moderate	-0.65	0.21	-3.11	0.002
	Strong	-0.20	0.36	-0.57	0.57

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1063.8	
Habitat	2	1060.6	<0.001		
Season	3	1108.2	<0.001		
Slope	2	1050.7	0.02		
Aspect	3	1045.0	0.48	1067	
Swamp	1	1043.1	0.44	1069.1	
Track	1	1043.6	0.30	1069.6	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.15	0.27	11.73	<0.001
Habitat	Scrub	-1.27	0.28	-4.53	<0.001
	Scrub and pasture edge	-0.66	0.28	-2.36	0.01
Season	Spring	-0.12	0.13	0.92	0.36
	Summer	-0.84	0.11	-7.62	<0.001
	Winter	0.09	0.15	0.63	0.53
Slope	Moderate	-0.81	0.24	-3.42	<0.001
	Strong	-0.28	0.39	-0.72	0.47

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1102	
Habitat	2	1084.6	0.03		
Season	3	1134.0	<0.001		
Slope	2	1081.9	0.04		
Aspect	3	1081.8	0.23	1103.8	
Swamp	1	1079.8	0.13	1105.8	
Track	1	1078.4	0.35	1106.4	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.91	0.27	10.81	<0.001
Habitat	Scrub	-0.89	0.28	-3.20	0.001
	Scrub and pasture edge	-0.62	0.27	-2.26	0.02
Season	Spring	0.09	0.14	0.64	0.52
	Summer	-0.71	0.10	-7.16	<0.001
	Winter	0.10	0.15	0.68	0.5
Slope	Moderate	-0.70	0.24	-2.89	0.004
	Strong	-0.03	0.35	-0.09	0.93

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1105.2	
Habitat	2	1092.6	0.02		
Season	3	1107.0	<0.001		
Slope	2	1091.0	0.04		
Aspect	3	1086.5	0.57	1108.5	
Swamp	1	1084.7	0.68	1110.7	
Track	1	1084.9	0.52	1110.9	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.86	0.28	10.18	<0.001
Habitat	Scrub	-1.00	0.29	-3.45	<0.001
	Scrub and pasture edge	-0.67	0.29	-2.32	0.02
Season	Spring	-0.13	0.14	-0.93	0.35
	Summer	-0.48	0.11	-4.39	<0.001
	Winter	0.07	0.15	0.46	0.64
Slope	Moderate	-0.76	0.25	-3.05	0.002
	Strong	-0.11	0.39	0.29	0.77

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	1086.1	
Habitat	2	1077.5	0.004		
Season	3	1144.0	<0.001		
Slope	2	1070.4	0.03		
Aspect	3	1067.2	0.88	1089.2	
Swamp	1	1067.3	0.36	1093.3	
Track	1	1066.8	0.62	1094.8	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.01	0.29	10.44	<0.001
Habitat	Scrub	-1.07	0.29	-3.66	<0.001
	Scrub and pasture edge	-0.84	0.30	-2.76	0.005
Season	Spring	-0.02	0.12	-0.16	0.87
	Summer	-0.73	0.10	-7.26	<0.001
	Winter	0.45	0.13	3.42	<0.001
Slope	Moderate	-0.67	0.25	-2.63	0.009
	Strong	-0.14	0.37	-1.45	0.15

Table 3. GLMM results for randomly reducing 3 cameras from each habitat in every month and results for the best GLMMs after repeating 10 times.

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	741.3	
Habitat	2	727.4	0.01		
Season	3	758.0	<0.001		
Slope	2	722.2	0.02		
Aspect	3	719.9	0.73	742	
Swamp	1	718.5	0.96	744.5	
Track	1	722.1	0.06	748.1	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.14	0.27	11.50	<0.001
Habitat	Scrub	-1.07	0.28	-3.79	<0.001
	Scrub and pasture edge	-0.70	0.29	-2.44	0.01
Season	Spring	-0.11	0.18	-2.28	0.02
	Summer	-0.72	0.15	-4.83	<0.001
	Winter	0.11	0.19	0.62	0.54
Slope	Moderate	-0.64	0.24	-2.70	0.007
	Strong	-0.15	0.49	-0.32	0.75

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	789.5	
Habitat	2	775.2	0.007		
Season	3	809.2	<0.001		
Slope	2	768.3	0.04		
Aspect	3	767.9	0.45	789.9	
Swamp	1	766.5	0.27	792.5	
Track	1	768.1	0.10	794.1	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.18	0.30	10.62	<0.001
Habitat	Scrub	-1.08	0.31	-3.45	<0.001
	Scrub and pasture edge	-0.61	0.30	-2.02	0.04
Season	Spring	-0.13	0.17	-1.37	0.17
	Summer	-0.77	0.12	-6.56	<0.001
	Winter	0.21	0.19	-1.09	0.28
Slope	Moderate	-0.73	0.27	-2.72	0.006
	Strong	-0.20	0.40	-0.49	0.63

Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	726.1		Overall model			<0.001	749.4	
Habitat	2	708.5	0.05			Habitat	2	733.1	0.03		
Season	3	723.8	<0.001			Season	3	752.4	<0.001		
Slope	2	704.6	0.80	728.56		Slope	2	734.5	0.02		
Aspect	3	707.4	0.35	729.41		Aspect	3	728.2	0.61	750.2	
Swamp	1	707.3	0.08	733.26		Swamp	1	727.3	0.35	753.25	
Track	1	706.1	0.16	734.1		Track	1	729.8	0.07	755.8	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.77	0.36	7.61	<0.001	(Intercept)		2.99	0.33	9.04	<0.001
Habitat	Scrub	-0.95	0.38	-2.49	0.01	Habitat	Scrub	-0.91	0.34	-2.71	0.007
	Scrub and pasture edge	-0.68	0.37	-1.84	0.07		Scrub and pasture edge	-0.48	0.34	-1.42	0.16
Season	Spring	-0.12	0.19	-0.64	0.52	Season	Spring	-0.14	0.21	-2.07	0.04
	Summer	-0.51	0.12	-4.31	<0.001		Summer	-0.56	0.12	-4.85	<0.001
	Winter	0.18	0.22	-0.78	0.43		Winter	0.28	0.23	-1.22	0.22
Slope	Moderate	-0.46	0.32	-1.44	0.15	Slope	Moderate	-0.98	0.28	-3.53	<0.001
	Strong	-0.06	0.53	0.12	0.91		Strong	-0.07	0.52	0.14	0.89

Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	700.1		Overall model			<0.001	747.3	
Habitat	2	699.8	<0.001			Habitat	2	731.6	0.01		
Season	3	757.4	<0.001			Season	3	739.8	0.004		
Slope	2	683.3	0.04			Slope	2	734.9	0.01		
Aspect	3	681.0	0.47	702.99		Aspect	3	728.5	0.50	750.5	
Swamp	1	678.9	0.52	704.88		Swamp	1	726.7	0.47	752.7	
Track	1	678.5	0.99	705.0		Track	1	726.2	0.80	753.2	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.34	0.26	12.91	<0.001	(Intercept)		2.62	0.32	8.13	<0.001
Habitat	Scrub	-1.36	0.27	-4.97	<0.001	Habitat	Scrub	-0.83	0.32	-2.60	0.009
	Scrub and pasture edge	-0.57	0.26	-2.20	0.03		Scrub and pasture edge	-0.30	0.34	-0.89	0.37
Season	Spring	-0.17	0.14	-2.58	0.01	Season	Spring	-0.06	0.19	-0.32	0.75
	Summer	-0.98	0.14	-6.80	<0.001		Summer	-0.26	0.11	-2.28	0.02
	Winter	0.06	0.15	-0.39	0.69		Winter	0.30	0.20	1.49	0.14
Slope	Moderate	-0.71	0.23	-3.11	0.002	Slope	Moderate	-0.64	0.28	-2.24	0.03
	Strong	-0.05	0.43	-1.26	0.21		Strong	-0.11	0.43	0.74	0.46

Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	797.3		Overall model			<0.001	747.3	
Habitat	2	787.4	0.004			Habitat	2	735.5	0.008		
Season	3	784.4	<0.001			Season	3	784.4	<0.001		
Slope	2	784.4	0.02			Slope	2	732.1	0.05		
Aspect	3	779.3	0.44	801.3		Aspect	3	729.0	0.38	751.0	
Swamp	1	777.1	0.47	803.1		Swamp	1	726.5	0.42	752.5	
Track	1	776.6	0.81	804.6		Track	1	726.3	0.54	753.3	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.09	0.32	9.54	<0.001	(Intercept)		2.71	0.35	7.81	<0.001
Habitat	Scrub	-1.10	0.32	-3.39	<0.001	Habitat	Scrub	-1.08	0.35	-3.04	0.002
	Scrub and pasture edge	-0.68	0.34	-1.99	0.05		Scrub and pasture edge	-0.57	0.35	-1.60	0.11
Season	Spring	-0.07	0.16	0.41	0.68	Season	Spring	-0.02	0.18	-0.11	0.91
	Summer	-0.63	0.12	-5.09	<0.001		Summer	-0.94	0.15	-6.35	<0.001
	Winter	0.10	0.19	-0.53	0.59		Winter	0.44	0.18	2.38	0.02
Slope	Moderate	-0.84	0.28	-3.02	0.002	Slope	Moderate	-0.84	0.30	-2.83	0.005
	Strong	-0.11	0.51	0.21	0.83		Strong	-0.25	0.47	-0.52	0.60

Factor	df	Deviance	P-value	AIC		Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	724		Overall model			<0.001	784.1	
Habitat	2	717.7	<0.001			Habitat	2	769.3	0.02		
Season	3	773.0	<0.001			Season	3	808.0	<0.001		
Slope	2	709.2	0.02			Slope	2	767.6	0.04		
Aspect	3	703.5	0.67	725.5		Aspect	3	763.6	0.51	785.6	
Swamp	1	702.7	0.38	728.7		Swamp	1	764.5	0.07	790.5	
Track	1	705.1	0.08	731.1		Track	1	762.1	0.37	791.1	
Factor	Category	Estimate	Std. Error	z value	P-value	Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.37	0.29	11.76	<0.001	(Intercept)		2.98	0.31	9.65	<0.001
Habitat	Scrub	-1.23	0.30	-4.13	<0.001	Habitat	Scrub	-1.01	0.32	-3.17	0.001
	Scrub and pasture edge	-0.63	0.29	-2.16	0.03		Scrub and pasture edge	-0.54	0.32	-1.70	0.09
Season	Spring	-0.15	0.18	-4.63	<0.001	Season	Spring	-0.05	0.17	-2.73	0.006
	Summer	-0.93	0.13	-7.13	<0.001		Summer	-0.56	0.12	-4.80	<0.001
	Winter	0.28	0.18	-1.54	0.12		Winter	0.15	0.17	0.91	0.36
Slope	Moderate	-0.77	0.25	-3.07	0.002	Slope	Moderate	-0.80	0.27	-2.97	0.003
	Strong	-0.40	0.43	0.93	0.35		Strong	-0.22	0.41	-0.53	0.60

Table 4. Generalised linear mixed model with Poisson distribution results for overall models after randomly reducing 4 cameras from each habitat in every month and repeating for 10 times and results for the 10 best GLMMs.

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	443.1	
Habitat	2	424.6	0.04		
Season	3	438.1	<0.001		
Slope	2	420.3	0.40	444.3	
Aspect	3	423.0	0.21	445	
Swamp	1	422.2	0.06	448.2	
Track	1	421.5	0.08	449.5	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.14	0.00	1006.53	<0.001
Habitat	Scrub	-1.01	0.00	-475.57	<0.001
	Scrub and pasture edge	-0.02	0.00	-10.12	<0.001
Season	Spring	-0.18	0.00	-83.78	<0.001
	Summer	-0.54	0.00	-255.42	<0.001
	Winter	0.46	0.00	219.22	<0.001

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	493.4	
Season	3	487.3	0.004		
Habitat	2	474.5	0.95	498.5	
Slope	2	477.3	0.2	499.3	
Aspect	3	477.9	0.32	500.9	
Swamp	1	474.8	0.52	501.8	
Track	1	474.4	0.86	502.4	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.23	0.20	11.37	<0.001
Season	Spring	-0.02	0.23	-0.07	0.94
	Summer	-0.38	0.18	-2.16	0.03
	Winter	0.63	0.28	-2.21	0.03

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	475.6	
Habitat	2	460.6	0.02		
Season	3	506.5	<0.001		
Slope	2	453.8	0.55	477.8	
Aspect	3	459.9	0.06	481.9	
Swamp	1	454.1	0.22	482.1	
Track	1	456.0	0.06	484.0	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.69	0.33	8.24	<0.001
Habitat	Scrub	-1.04	0.41	-2.55	0.01
	Scrub and pasture edge	-0.85	0.40	-2.14	0.03
Season	Spring	-0.20	0.22	-1.37	0.17
	Summer	-0.53	0.14	-3.88	<0.001
	Winter	0.54	0.20	2.71	0.01

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	500.2	
Season	3	509.2	<0.001		
Habitat	2	486.6	0.3245	510.61	
Slope	2	484.6	0.89	511.6	
Aspect	3	485.1	0.86	512.7	
Swamp	1	485.7	0.25	513.7	
Track	1	484.4	0.90	514.4	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		1.96	0.20	9.97	<0.001
Season	Spring	-0.06	0.21	0.74	0.46
	Summer	-0.40	0.20	-2.03	0.04
	Winter	1.03	0.30	3.43	<0.001

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	419.4	
Habitat	2	401.2	0.04		
Season	3	456.6	<0.001		
Slope	2	399.7	0.51	422.7	
Aspect	3	401.6	0.36	423.6	
Swamp	1	398.6	0.65	424.6	
Track	1	398.4	0.90	424.4	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.81	0.37	7.56	<0.001
Habitat	Scrub	-1.12	0.47	-2.41	0.01
	Scrub and pasture edge	-0.65	0.45	-1.44	0.15
Season	Spring	-0.14	0.31	-2.75	0.006
	Summer	-0.68	0.16	-4.24	<0.001
	Winter	0.24	0.29	0.82	0.41

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	453.6	
Season	3	494.6	<0.001		
Habitat	2	432.1	0.64	456.1	
Slope	2	433.7	0.28	457.7	
Aspect	3	434.7	0.32	458.7	
Swamp	1	431.5	0.60	459.5	
Track	1	433.1	0.17	460.1	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.15	0.35	6.20	<0.001
Season	Spring	0.31	0.30	1.03	0.31
	Summer	-0.80	0.14	-5.89	<0.001
	Winter	0.63	0.49	-3.30	<0.001

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	504.2	
Habitat	2	482.1	0.007		
Season	3	499.3	<0.001		
Slope	2	489.0	<0.001		
Aspect	3	482.4	0.08	505.4	
Swamp	1	474.8	0.10	507.8	
Track	1	478.9	0.86	509.6	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.39	0.49	4.85	<0.001
Habitat	Scrub	-0.45	0.44	-1.03	0.03
	Scrub and pasture edge	-0.17	0.52	-0.91	0.002
Season	Spring	-0.03	0.32	2.58	0.01
	Summer	-0.59	0.13	-4.38	<0.001
	Winter	0.08	0.33	-0.24	0.81
Slope	Moderate	-0.76	0.41	-1.85	0.05
	Strong	-0.09	0.56	0.88	0.38

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	516.8	
Habitat	2	401.0	0.003		
Season	3	463.4	<0.001		
Slope	2	400.2	0.04		
Aspect	3	406.7	0.88	517.7	
Swamp	1	405.7	0.42	520.7	
Track	1	402.2	0.08	523.2	

Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		3.03	0.32	9.60	<0.001
Habitat	Scrub	-0.83	0.35	-2.35	0.02
	Scrub and pasture edge	-0.50	0.36	-1.38	0.17
Season	Spring	-0.33	0.15	-2.25	0.02
	Summer	-0.71	0.10	-6.94	<0.001
	Winter	0.08	0.15	0.55	0.58
Slope	Moderate	-0.88	0.29	-3.07	0.002
	Strong	-0.31	0.52	0.78	0.38

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	440.2	
Season	3	498.3	<0.001		
Habitat	2	425.6	0.07	441.7	
Slope	2	421.4	0.61	443.4	
Aspect	3	422.0	0.68	445.9	
Swamp	1	420.6	0.71	446.6	
Track	1	423.3	0.09	449.3	
Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.60	0.3155	8.247	<0.001
Season	Spring	-0.57	0.4693	-4.201	<0.001
	Summer	-1.08	0.1766	-6.105	<0.001
	Winter	0.06	0.4168	-1.814	0.07

Factor	df	Deviance	P-value	AIC	
Overall model			<0.001	467.2	
Habitat	2	455.4	<0.001		
Season	3	490.4	<0.001		
Slope	2	446.3	0.55	470.3	
Aspect	3	449.6	0.71	471.6	
Swamp	1	442.5	0.14	472.1	
Track	1	440.3	0.84	474	
Factor	Category	Estimate	Std. Error	z value	P-value
(Intercept)		2.59	0.32	8.22	<0.001
Habitat	Scrub	-1.20	0.40	-2.99	0.003
	Scrub and pasture edge	-0.33	0.38	-0.86	0.39
Season	Spring	-0.26	0.24	-1.06	0.29
	Summer	-0.61	0.16	-3.92	<0.001
	Winter	0.70	0.25	2.84	0.005

Appendix B

From 2014 to 2017, camera trap video was gathered over 39 months, totaling 12,853 trap nights. Between January 2014 and August 2015, Bushnell® Trophy Cam cameras (6 to 12 cameras) were placed in the field and relocated monthly, surveying 27 sites. Between September 2015 and March 2017, there were 12 Bushnell® Trophy Cam cameras and 16 Bushnell® Aggressor cameras set up in 28 fixed locations in a 500m x 500m sampling grid (Strang. 2018). The Trophy Cam cameras were 2014 models and the Aggressor cameras were 2015 models. In general, they have very similar specifications, but a few features make the Aggressor model slightly better than the 2014 Trophy Cam model (NatureSpy. 2015)

- Trigger speed is slightly faster, it is estimated that the 2014 model has a trigger speed of 0.2 seconds and the trigger speed for the 2015 model is within 0.2 seconds.
- Detection distance for the 2015 model (about 30.5m) is further than the 2014 model (about 27.5m)
- A significant improvement in image quality, the 2014 model has a resolution of 8 MP, whereas the 2015 model has a resolution of 14 MP. However, there are no changes in video quality, both models have a video quality of 1080p widescreen full HD. Thus, this difference was unlikely to cause any bias since only videos were used during the survey period (NatureSpy. 2015).

According to Strang (2018), the majority of the cameras were attached to sturdy tree trunks at a height of about 30 cm above the ground and placed along paths. The area in front of the camera was cleared of branches, grass and other debris that might block the detection zone of the camera. All cameras were programmed to record video for 30 seconds, with a one-second interval. Every month, SD cards and batteries were inspected and replaced. There were seven live traps for feral cats placed between January 2015 and January 2017 overlapping with seven camera sites. Those locations were baited with feral cat lures for 798 trap nights in total, other locations were not baited during the research. Moreover, cameras were placed on and off trails. When cameras were placed on the trails, she classed these trails by length and width for her research. The length was classed into three categories: short, medium and long. The thresholds were: <100m, 100-399m and >400m respectively. The width was also classed into three categories: narrow, medium and wide. The thresholds were: <1m wide, 2-3m wide and >4m wide.