The influence of illumination and moon phase on activity levels of nocturnal mammalian pests in New Zealand

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New Zealand (NZ) hosts several introduced mammalian pests that threaten native flora and fauna. Substantial time and money is spent controlling these pest populations with some success, but in order to attain the dream of a predator free NZ we must increase our effectiveness. We already know that nocturnal mammals worldwide alter activity levels in response to moon phase; understanding this behaviour can allow better control of their populations. Little is known as to how NZ's nocturnal mammalian pest activity levels change with moon phase or nocturnal illumination levels. If we can predict when pests will be most active then the deployment of pest control and monitoring could be more efficient and effective.

The main goal of the current study was to determine how moon phase and illumination affect the activity levels of nocturnal mammalian pests. The first step in this process was to analyse two large camera trap data sets from the Blue Mountains (Otago) and Hawkes Bay to assess the response of the pests to moon phase (measured illumination data was not available for these data sets). Next, a highly sensitive light meter, a Sky Quality Meter (SQM), was tested in the dark conditions of rural Banks Peninsula (Canterbury) to assess whether it could differentiate illumination levels between moon phases and canopy covers. This device was then used in conjunction with indirect indices of activity, using Waxtags™ and camera traps, on three field sites over three months to assess activity levels. The Banks Peninsula data, as well as data from the Blue Mountains and Hawkes Bay, were analysed using a generalized linear mixed model with a binomial distribution and a logit link function.

Moon phase was not able to fully explain the variation in pest activity within the camera trap data (from Hawkes Bay and the Blue Mountains), by including measured illumination levels in the Banks Peninsula study more of the variation in the data set was explained. Overall, the most interesting finding was that illumination does impact nocturnal mammalian pests and appears to affect activity levels more than moon phase or rain. These results suggest that as illumination levels decreased, pest activity levels increased. The second major finding was that SQM's can detect, even under very dark conditions, significant differences in illumination between moon phases and under different canopy covers. This research has several practical applications. First, SQM's were found to measure illumination in a biologically relevant way and would be useful in further ecological studies. Second, there was an implication for pest control in that monitoring these pests should be targeted during darker conditions, such as outside of the full moon and under canopy cover. Taking illumination into account may increase the efficiency and effectiveness of monitoring and control, bringing us one step closer to a predator free New Zealand.

Keywords: nocturnal mammalian pest, mammal, vertebrate, animal behaviour, illumination, light, moon phase, predator free, control, monitor.

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"The truth is, the natural world is changing and we are totally dependent on that world. It provides our food, water and air. It is the most precious thing we have and we need to defend it."
David Attenborough

"Sometimes life is like this dark tunnel, you can't always see the light at the end of the tunnel, but if you just keep moving, you will come to a better place."
General Iroh

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Chapter 1

General Introduction

In Aotearoa/New Zealand we pride ourselves on our lush flora and unique fauna. We have named ourselves after the kiwi (*Apteryx* spp.) and you'll find the last of a group of ancient reptiles here - tuatara (*Sphenodon* spp.), and a kakapo (*Strigops habroptila*), Sirocco, has even been dubbed the "Official Spokesbird for Conservation". Our natural environment is a large part of our culture and it is being threatened. Introduced mammalian pests have facilitated the disappearance of a number of populations of our native birds and lizards. The main pest mammals in NZ, possums (*Trichosurus vulpecula*), stoats (*Mustela erminea*), rats (*Rattus* spp.) and feral cats (*Felis catus*), all prey on native birds, often targeting eggs and chicks. On top of this these pests, as well as mice (*Mus musclus*), compete with native fauna for food resources as well (King, 2005). New Zealand was a very different place before their arrival and these pests continue to change the face of the islands. For example, possums can cause a gradual change in forest composition by selectively browsing on particular species of tree (Coleman, Green, & Polson, 1985; Cowan, Waddington, Daniel, & Bell, 1985; A. E. Fitzgerald, 1976). It should be no surprise, therefore, that we dream of a pest free New Zealand (NZ).

Millions of dollars are poured into monitoring, control and research to reduce the populations of these pests. This year, 2016, a goal has been set to be predator free by 2050. We are already known for our high standards of vertebrate pest control and monitoring, but we need to become significantly better if we are to achieve this goal. One aspect of predator biology often overlooked is the behaviour of these nocturnal animals. Significant research has analysed their preferences when it comes to food, dens, habitat and home ranges. We know that when rainfall is heavy and the wind is strong, that the pests are unlikely to venture out to forage, encounter monitoring devices or find poison baits. However, one factor that has had little consideration and impacts many nocturnal mammals worldwide is their response to moon phase and illumination levels. Previous studies in NZ and overseas suggest that the main pest mammals in NZ are likely influenced by lunar conditions and but have been unable to determine exactly how. Additionally, few studies have been able to measure illumination levels in a biologically significant way partly due to a lack of appropriate equipment. Meaning that illumination levels are often not considered as an impact on animal behaviour.

Accordingly, the goal of this thesis is to address these gaps by investigating the following research questions. The first research question uses two large data sets to assess the effect of moon phase on several nocturnal mammalian pests (possums, rats, cats, mice and stoats). Second, a Sky Quality Meter (SQM) is trialled as a potential tool to measure illumination levels in NZ's dark rural areas. I test the meter to determine whether it detects biologically significant changes in illumination levels between different cloud covers, canopy covers and moon phases. Last, the third research question applies the knowledge learned from the first research questions; Waxtags™ and camera traps measure pest activity levels and the SQM is utilised to measure illumination levels (a first for pest research in NZ) on Banks Peninsula, Canterbury.

The structure of this thesis is as follows. Chapter 2 considers how moon phase and illumination have been shown to impact animals around the globe and identifies our knowledge gaps when it comes to our main mammalian pests. Chapter 3 reviews our current pest monitoring and control methods in NZ. Chapter 4 reviews our current knowledge as to the ecology of our key pests. The aim of chapter 5 is to test the impact of moon phase on nocturnal mammalian pests using large data sets from the Blue Mountains and Hawkes Bay. Chapter 6 details the steps taken to test the Sky Quality Meter and describes the ways it was successful in measuring the difference in illumination levels between canopy covers and moon phase. Chapter 7 focuses on Waxtag™, camera trap and illumination data collected on Banks Peninsula, and discusses the statistical findings. Chapter 8 is an overall discussion exploring what we have learned about measuring illumination in a biologically significant way, how the pests are impacted by this and moon phase, the implications of this new knowledge and how this study can be improved in future research.

Chapter 2

Moon phase, illumination and animal behaviour

We have little understanding of how moon phase and illumination impact the activity levels of nocturnal mammalian pests in New Zealand (NZ). The five species we will focus on within this study are stoats (*Mustela erminea*), rats (*Rattus* spp.), cats (*Felis catus*), mice (*Mus musclus*) and possums (*Trichosurus vulpecula*). These animals are pervasive throughout the mainland and negatively impact native flora and fauna (see chapter 4). By understanding the complex needs of a species we are better able to manage their populations, and control operation can be focused more effectively when an animal's habits and activities are better understood (Marcum, Biggins, & Clarke, 2006). These five species and their changes in activity levels in relation to abiotic factors, moon phase and illumination, will be discussed in this literature review. We shall begin by exploring known factors to affect pest animal activity; such as home range, predators, weather, seasons, food availability, gender and intra-specific interactions. Then venture into greater detail as to the current state research on nocturnal mammals, highlighting the gap where our nocturnal mammalian pests lie.

A number of studies have considered how home range size impacts the areas that a pest may roam. For example, brushtail possums typically only forage in a small area of their home range each night (Paterson, Morris, Weston, & Cowan, 1995) but these areas overlap to a great extent among possums (Cowan & Clout, 2000) and once a possum establishes a home range it tends to be stable in both space and time. However in late summer to early autumn home ranges are often larger (Cowan & Clout, 2000). Also, home range is dependent on habitat type. Possums in forested areas may roam throughout 1-4 ha, but in pasture an individual's home range may be up to 60 ha (Cowan & Clout, 2000). Paterson et al. (1995) found that possums share the paddocks that cows forage in and that these pieces of paddock were closest to possum denning areas. Home range also changes post control because the remaining possums tend to reposition home ranges, although the effect is limited to within a few range lengths of the original (Cowan & Clout, 2000).

Another behaviour to consider is that of an animal's predators. A study by Pickett, Hik, Newsome, and Pech (2005) showed that in Australia possums were predated by foxes and when the fox population decreased that possums were far more likely to be active on the ground and increase their foraging behaviour. As previously mentioned possums have very few predators in NZ and thus may display similar behaviours to the Australian possums when their predator's population drops. Thus when developing methods of how to best control a pest we need to consider their interspecific interactions. For example, we might identify the density of feral cat populations (who compete with possums for prey) in the area and how this could affect the way in which the possums react to other factors; such as weather.

Like many animals, humans included, when the weather turns foul we tend to stay close to our dens. Paterson et al. (1995), Lennon (1998) and Jolly (1976) found that strong winds reduced possums activity, but B. Brockie and The New Zealand Ecology Division (1987) disagreed saying that strong winds do little to change possum activity patterns. B. Brockie and The New Zealand Ecology Division (1987) instead found that heavy frosts encouraged the animals to return to their dens. Both Jolly (1976) and Cowan and Clout (2000) agree that heavy rain decreased activity patterns, a possum may be reluctant to emerge from their den due to heavy rain for up to five hours. However, Paterson et al. (1995) could not prove that weather conditions other than wind affected possum activity.

We do know that seasonality plays a large part in a possum's diet and activity. For example, autumn is breeding season (Paterson et al., 1995). So, during this time a male possum will spend more of its time looking for mates and once a female is pregnant her demands for food will grow. Possum activity is high during this period. A possum's diet is also affected by the seasonal availability of food, such as the relative palatability of the evergreen foliage, as well as the availability of non-foliar (more nutritious) and foliar foods (less nutritious). According to Nugent, Sweetapple, Coleman, and Suisted (2000) possums seem to have an appetite for non-foliar foods, hinting that they prefer this food type and that perhaps it may affect possum reproductive success and thus local possum carrying capacity. Additionally, over longer periods of time a possum's diet may change because their intensive browsing has changed the composition of the vegetation (Nugent et al., 2000). Understanding their diets may allow us to predict the possum densities and how they may impact different habitats.

Another important component of pest behaviour is when they are most active within the day and night. Being nocturnal, possums spend most of the day in their dens and at night they spend about 1-2 hours foraging, the rest of the night is spent grooming, sitting or moving around (Cowan & Clout, 2000). Paterson et al. (1995) noted that possum activity was low in the first 1-2 hours after darkness, then tended to be highest between the dark hours of 11pm and 2am and after 4am activity dropped again. This trend suggests that the darkest periods of the night are the most favourable for a possum. However, on a moonlit night possums are more active on the ground (Cowan & Clout, 2000).

Stoats are also strongly nocturnal but may be active during the day if need be, they have high energy demands and thus need to hunt often (King & Powell, 2007). In NZ, stoats have been found to be active for on average 40 min at a time, totalling 8 hrs a day and in all seasons (King & Powell, 2007). Their activity has however been found to correlate with, primarily, ambient temperature and secondarily with reproductive condition. Studies have shown that outside of the breeding season stoats are likely to change the amount of time they spend inside their dens depending on air temperature (King & Powell, 2007). Their activity changing around breeding season is an intraspecific interaction but the interspecific interactions are just as important when controlling the pests. In a study by Murphy, Clapperton, Bradfield, and Speed (1998) the number of ship rats in an area were reduced via poison control, this success was marred when it was found that stoats replaced the rats in their diet with birds.

Ship (*Rattus rattus*), kiore (*R. exulans*) and Norway rats (*R. Norvegicus)* are known to forage on the ground (Pryde, Dilks, & Fraser, 2005) and in trees (Atkinson & Towns, 2005; Innes, 2005a, 2005b). This foraging occurs for the most part at night as they are strongly nocturnal. Seasonality also plays a part in rat populations and activities. Norway rat populations are lowest in spring and at their highest in autumn and early winter (Innes, 2005a). Norway rat females are polyoestrous and have been caught pregnant in all seasons (Innes, 2005a). The season can affect when they are best able to forage as night length varies throughout the year. The Norway rat makes up for shorter summer nights by foraging at an increased rate later in the night (Innes, 2005a). There are a number of creatures that include rats in their own nightly forage. Young kiore can be threatened by moreporks, kingfishers and weka. Kiore adults are often predated by cats and mustelids, and sometimes by ship rats (Atkinson & Towns, 2005). The life of a Norway rat can come to an abrupt end from cats, stoats, ferrets and harrier hawks (Innes, 2005a). Ship rats are also oft predated by cats, stoats and ferrets, but also by weasels and, rarely, moreporks (Innes, 2005b).

Bramley (2014) discusses that when kiore (*Rattus exulans*) and Norway rats (*Rattus norvegicus*) inhabit a similar area the presence of one is likely to impact the ranging behaviour and habitat use of the other. By tracking both rat species with VHF collars Bramley (2014) found that kiore rats have a much smaller home range than the Norway rats, which agrees with (Atkinson & Towns, 2005). In Bramley's study the mean distance travelled for female kiore rats was 0.18 ha and for males 0.14 ha, whilst female Norway rats travelled a mean of 5.13 ha and males 5.78 ha; a huge difference! Ship rats have different home range sizes again with males travelling between 7.5 and 11.4 ha and females between 0.27 ha and 0.89 ha

(Pryde et al., 2005). Rats have a strong drive to explore unfamiliar surroundings but exhibit neophobia to new objects in familiar surroundings – such as poison baits (Atkinson & Towns, 2005). Pryde et al. (2005) and Bramley (2014) remind the reader that the results of any study may differ to another due to differing field condition, such as season or habitat. Pryde et al. (2005) demonstrates this, explaining that with their study the home range of New Zealand South island dwelling rats appeared to have a much larger home range than those recorded in the North Island non-beech forests.

The house mouse is not as strongly nocturnal as rats, stoats and possums, for they prefer to feed at dusk and dawn (Ruscoe & Murphy, 2005). The food resources available to them affects a number of their behaviours. The breeding season is determined to a large extent by available resources such as food. So breeding tends to cease in winter for many populations as food is less abundant. However, females are capable of falling pregnant throughout the year if conditions are good. In the search for resources a mouse travels over its territory. In a study conducted in the Orongorongo valley home range averaged at a minimum of 0.6ha to a maximum of 2.62ha (B. M. Fitzgerald, Karl, & Moller, 1981). Travelling though one's territory can be dangerous as cats and stoats are the main predators for mice in NZ.

There are a number of similarities between the five pests included in this study. Possums, stoats, rats and mice are all nocturnal, are all affected by the season and forage on the ground. Stoats and cats do not generally forage in the trees but they are a common predator for rats, mice and juvenile possums. Understanding when they are most active, thus when they are most likely to predate on native wildlife, is valuable information. The ability to predict the behaviours of these animals may make pest control and monitoring more effective, therefore such behaviours should be considered when planning control operations. Yet little is understood as to how moon phase and illumination impact these pests.

Ambient light levels affect the reproduction, foraging and predator-prey interactions of nocturnal species (Kronfeld-Schor, Bloch, & Schwartz, 2013). There is a large amount of knowledge about nocturnal mammals and their reaction to moonlight and illumination, but a gap when it comes to how these factors affect the nocturnal behaviours of possums, and other key pests, in NZ. This knowledge is crucial for control operations, as success rates are largely determined by activity levels of the target species and environmental conditions strongly affect these activities (Digby, Towsey, Bell, & Teal, 2014). Hunters historically learned when and where their prey might be found. In order to successfully kill or trap an animal knowing where it will be and what it may be doing is vital. This is true for pest control as well, if we know when a pest is likely to be most active and what it will be doing we can more effectively target poisons and traps, and monitoring equipment too. There are best practice documents for the monitoring and control of all key pests. However, they are generic and don't address behavioural influences that can affect individual animal behaviour from night to night. A greater understanding of the impact of moon phase and illumination is needed to achieve local eradication of pest as we move towards a predator free New Zealand.

2.1 Moon phase and behavioural changes

Marcum et al. (2006) describe that by understanding the behaviours of a nocturnal mammal under different light levels we might increase our efficiency of finding the animal. There are a huge number of factors that affect the ways in which animals react to moonlight intensity: too much light or too little, foraging versus predation risk– there is a fine balance. Nocturnal mammals the world over exhibit curious activity patterns when it comes to the phase of the moon. Some creatures go so far as lunar phobia; displaying a strong aversion to full moonlit nights and reducing activity levels accordingly. Whilst others may be lunar philic, showing a significant preference for nights with high moonlight intensity.

The majority of nocturnal animals are lunar phobic, in fact less than a handful are lunar philic or lunar neutral. The copious number of studies carried out on nocturnal mammals has shown that a difference in moon phase or illumination can have a significant impact on an animal's activity; foraging may be reduced, movement might be restricted or vocalisations could decrease and vice versa (Gursky, 2003). For example, Johnson and De Leon (2015) found that rodents were more likely to give up food, i.e. reduce their foraging, when moonlight was high due to a perceived increase in predation risk. Predation risk is one of the most common explanations as to why an animal may change their activity with the level of illumination or moon phase. However, in a study by Gursky (2003), spectral tarsiers (*Tarsius spectrum*) became more active during the full moon regardless of the increase in predation risk. This could be because while their predators may be able to see them more easily, the tarsier is more likely to see the predator before the attack as well.

Predators often change their activity levels around the full moon such as the eagle owl (*Bubo bubo*) which increases its activity levels (Penteriani, Kuparinen, Delgado, Lourenco, & Campioni, 2011). The increase may be because it requires more time to search for prey because they are more concealed and wary. Penteriani et al. (2011) also mentions that foraging is not the only behavioural driver for animals. For example, to attract the attention of conspecifics the eagle owl (*Bubo bubo*) has a white patch on its throat that becomes visible when it calls. On nights with high light levels the white patch is more visible and so the owl tends to call more. Displays were found to be directly influenced by moonlight and on moonlit nights the owls were more active (Penteriani, Delgado, Campioni, & Lourenco, 2010).

Another predator that changes its activity levels in response to moon phase is the maned wolf (*Chrysocyon brachyurus*). Lima Sabato, Bandeira de Melo, Vaz Magni, Young, and Coelho (2006) compared the distance travelled by maned wolves between the new and full moon, they found that the wolves travelled significantly greater distances on the new moon than the full moon. Within this study nights with cloud cover were removed from the data set as they recognised its impact on illumination levels, however no light levels were actually recorded. The authors suggest that the change in the wolves behaviour is due to an anti-predator response displayed by their main prey; rodents. Most rodents reduce their activity on the full moon (Daly, Behrends, Wilson, & Jacobs, 1992; Leaver & Daly, 2003; Wolfe & Summerlin, 1989) and it seems the wolves follow suit in response to this change in prey availability.

Not all animals are bullied by their predators into being less active when there is more light to see by. In Gursky's (2003) study she found that spectral tarsiers (*Tarsius spectrum*) are in the minority among mammals as they are more active in the full moon. This is due in part to the foraging benefits as the tarsiers caught three times as many insects on full moon nights than on new moon nights. To make up for any increased predation risk the animals travelled in larger groups, thus having a higher likelihood of spotting a predator before an attack. One factor to consider is that because the tarsiers prey is more abundant on nights with high moonlight there was less intraspecific competition than may have been expected when individuals travel in groups. Another contributing factor is that spectral tarsiers may be more active during the full moon because they might be secondarily nocturnal (historically they may have been diurnal as they lack a tapetum lucidum to help them see in low light), which would help explain their lunar philic behaviour.

The inverse of lunar philia is the far more common phobia and is largely explained as an antipredator response. Gotthard (2000) details that for some species increased light means an opportunity to be more active, it could be that they may be more successful whilst foraging, however for many cases this is offset by the increased risk of predation. Indeed Rich and Longcore (2004) tells us that small rodents reduce their foraging time when moonlight intensity is high. Expanding on this, Kotler, Brown, Mukherjee, Berger-Tal, and Bouskila (2010) found that during the darker periods of the moon's cycle, rodents tend to forage and cache food, banking it for nights when moonlight and perceived predation risk is high. So, rodents exposed to higher light levels reduce their foraging and as light levels reduce, their foraging activity increases. The rodent in question, the gerbil (*Gerbilus andersoni allenbyi*), alters its activity levels during the lunar cycle in part due to predation risk of its main predator, the red fox (*Vulpes vulpes*). However, predators tend to catch up with their prey's latest avoidance scheme and the fox may modulate its own behaviour in response to the opportunities offered during the moon phases.

Another rodent predated by the red fox are wood mice (*Apodemus sylvaticus*). A study conducted on the mice used exposure to faecal odour of the red fox and moon phase to assess the impact predation risk has on food intake. The study found that on a full moon the mice ate significantly less food, like the previously mentioned gerbil, and avoided traps treated with predator faeces at a greater rate. The study concluded that an anti-predator response was indeed higher on full moon nights due to a greater perceived risk of predation (Navarro-Castilla & Barja, 2014). Indeed, the lunar neutral black-footed ferrets (*Mustela nigripes*) tended to reduce their activity during periods where their predator is most active regardless of moonlight intensity (Marcum et al., 2006).

A. J. Thomas and Jacobs (2013) found that predation strongly influences activity in several sympatric bat species. Mello, Kalko, and Silva (2013) conducted a similar study on bats and found that more bat species were captured on dark nights, meaning that they are likely lunar phobic. They did however find the bats activity highly variable within and among nights, and that when viewing this on a larger temporal scale lunar phobia may be observed; but this may not be the case on smaller temporal scales. Mello et al. (2013) points out that a great number of factors determine an animal's behaviour and a more holistic view gives less contradictory results. Also, in the study by Clarke, Chopko, and Mackessy (1996) the authors suggest that whilst moonlight may be an important factor for an animal, temperature, hunger levels and reproductive state could supersede it.

An example of this is the snowshoe hare *(Lepus americanus* Erxleben), its activity is heavily influenced by weather condition. Griffin, Griffin, Waroquiers, and Mills (2005) found that the perceived higher risk of predation came only with the snowy season and their activity decreased significantly on snowy full moon nights. There is also a potential gender difference. The number of sandflies (*Phlebotomus orientalis*) caught in traps decreased as the level of moonlight increased (Gebresilassie et al., 2015) but, twice as many females were caught on nights with no moon than on full moon nights. In the woolly opossum (*Caluromys philander*) there was a definite difference between male and female activity levels and the extent to which moon phase affected them. Julien-Laferriere (1997) found that female opossum activity was unaffected by moon phase and was, on average, consistently lower than male activity. However, male activity seemed to be regulated by moonlight, when moonlight was absent or low their activity was higher, hinting at lunar phobia. This theory fits with the woolly opossums' nocturnal predators (owls, and probably snakes or arboreal felids) some of which are visual hunters and thus may be more successful on well-lit nights

Some predators exhibit antipredator responses themselves. The adult prairie rattlesnake (*Crotalus viridis viridis*) avoided bright moonlight by sheltering under cover (Clarke et al., 1996). The authors hypothesised that this could be an antipredator response but it could be a reaction to their prey's nocturnal activity changes. It may be that the rodent prey is just too difficult to catch on well moonlit nights due to their tendency to hide away, thus their predators may do the same, especially if they themselves are also more vulnerable to predation during this time (Clarke et al., 1996). Also, in New Zealand the possum (*Trichosurus vulpecula*) is prey to the feral cat (*Felis catus*). The cat is an ambush predator that prefers small, dark, enclosed spaces. Perhaps this is why possums are partial to large, light and open spaces such as pastures (Parisi, 2011).

The limited research conducted on possums (*Trichosurus vulpecula*) in NZ found that they could be lunar neutral, phobic or even philic. Parisi (2011) suggested the likelihood is that possums are lunar neutral; her study did not find an increase in activity during the full moon period and did not discover that possums preferred dark or covered areas for foraging. This could be an anti-predator response, cats have been known to predate possums. However, a previous study by Dutton (2008) demonstrated that during full-moon phases *T. 10ulpecula's* activity levels increased but at new moon there was no change in activity levels. This disagrees with Parisi's findings, as well as the first study conducted on possum nocturnal activities by Lennon in 1998. Lennon (1998) found that bait consumption increased by 33% on dark nights on the forest edge compared to the edge of farmland. However, Parisi argues that Lennon's forest area is actually scrubland and that the activity levels of possums in some areas could have been higher merely due to higher levels of human disturbance (Parisi, 2011). These are the only three studies conducted specifically on New Zealand possum activity changes with moon phase and illumination, it is clear that there is some discrepancy between their findings. This may be due to factors such as differing tree canopy density between sites and studies. Lennon (1998) leans toward lunar phobia, Dutton (2008)and Parisi (2011) towards lunar philia.

Other species are definitively known to be lunar neutral, with moon phase not appearing to affect their activity levels. Veilleux, Jacobs, Cummings, Louis, and Bolnick (2014) found that the lemur (genus *Avahi*) has developed a keen eye for succulent young leaves under all nocturnal light environments. So moon phase and the level of illumination make little difference in the foraging levels of this animal. The same can be said for black-footed ferrets (*Mustela nigripes*); Marcum et al. (2006) found that the ferrets displayed no preference for light level and their activity did not change when light level fluctuated. However, the researchers propose that this constant level of foraging activity may be due to the high energy needs of the ferret. The ability to be active during higher light levels has its advantages, Marcum et al. (2006) suggests that higher light levels could be beneficial when learning one's home range, securing burrows and finding prey or mates.

On a final note, there is a relatively small body of literature that is concerned with a relationship between cats and moon phase or illumination. The information available is dominated by breeding activity, veterinary visits and some information on diurnal versus nocturnal activity. In Brooklyn, Haspel and Calhoon (1993) found that cats were predominantly nocturnal, gradually increasing their activity from 1300 to 2200 hours with no evidence of a peak at sunset. The authors found a peak at 0100 h and another at sunrise. It was suggested that the loss of sunset activity could be attributed to the animals avoiding humans and to a lack of dependence on prey as food (many of the cats studied scavenged from dumpsters).

In terms of the cat's biology two studies considered the impact day length has on females breeding cycle and found that cats have a defined anestrus period associated with day length. If illumination levels are higher more litters can be expected within a year (Hurni, 1981; E. Jones & Coman, 1982). Additionally, a fractional increase in cat visits to an emergency vet on fuller moon days (waxing gibbous to waning gibbous), compared with all other days was found by Wells, Gionfriddo, Hackett, and Radecki (2007). Whether it is illumination, moon phase or another factor causing this is unknown.

We have some understanding of how possums respond to the phase of the moon but it is still inconclusive. Research overseas has confirmed that moon phase is an important factor for nocturnal mammals but lunar phobia is largely an anti-predator response. Possums and stoats do not have any higher trophic predators in New Zealand so it is difficult to predict their behaviour with over a century since liberation.

2.2 Lunar Illumination and behavioural changes

Animal behaviours change not only with lunar phase but also with changes of illumination. The effect of illumination and lunar phase on animal activity are closely entangled. Each moon phase has a different level of illumination, so determining whether an animal's activity has changed due to moon phase or due to illumination is difficult. Julien-Laferriere (1997) was able to differentiate between the two by noticing that the opossum (*Caluromys philander*) was not more active on lighter parts of a night but rather had a continuous level of activity throughout the night, suggesting no illumination preference. There have been far fewer studies conducted on the impact of illumination than the impact of moon phase on activity. In order to increase the efficiency of finding a nocturnal animal we must understand it's behaviours under different light levels (Marcum et al., 2006).

I will discuss two particular sources of illumination at night; natural (moon and star light) and anthropogenic. Guo, Hu, Chen, Gao, and Du (2014) state that urban light seriously affects sky brightness and Rich and Longcore (2004) express concerns as to how urban light pollution affects non-human animals. Artificial illumination does not affect all animals but it can be beneficial or detrimental in many cases (Kyba, Ruhtz, Fischer, & Holker, 2011). Most of the studies concerned with urban light pollution tend to focus on negative impacts, such as the discussion by Digby et al. (2014) on how light pollution affects the little spotted kiwi (*Apteryx owenii*). They found that moon phase had no impact on the bird but with increased cloud cover the bird decreased vocal activity. The authors suggest this may be due to reflected urban light, which is more intense with cloud cover. Kyba et al. (2011) explains that urban light pollution can increase light levels by up to a factor of ten, depending on the distance to an urban centre and its size.

For some species, increased hours of high illumination can have a positive impact. Dwyer, Bearhop, Campbell, and Bryant (2013) discuss the benefits of anthropogenic illumination to a nocturnally foraging shorebird (the common redshank, *Tringa tetanus*). In this study they show that the redshank has increased foraging opportunities under the continuous artificial lighting on an estuary. On bright moonlit nights with an absence of cloud cover (in naturally illuminated areas) the redshanks were able to use visual rather than tactile foraging. Similarly, in areas with high anthropogenic illumination redshanks could forage for less time than those in darker areas that foraged largely by touch, which was more labour intensive. Individuals foraging in continuously artificially illuminated areas exhibited visually based foraging regardless of moon phase or cloud cover. The birds did not, however, actively seek illuminated areas, instead they showed high site fidelity and stayed in the areas they had originally been caught and collared in. This may be due to other factors that could not be recorded in this study such as social status and age.

A study that was specifically interested in the age of their subjects was conducted by Boldogh, Dobrosi, and Samu (2007). They considered the negative impacts of artificial illumination on house-dwelling bats, *Rhinolophus ferrumequinum*, *Myotis emarginatus* and *M. oxygnathus,* the impacts included a delay in the onset of emergence and significantly smaller juveniles. Artificial light disrupted the bats foraging routine and even an hour of illumination after dusk caused significant disruption in behaviour and growth. The authors warn that the bat populations could even fail altogether. A solution offered by the authors was to eliminate direct illumination during the breeding season. From these examples we can see how important it is to consider artificial sources of illumination. Thus in future studies on activity changes relating to illumination and pest mammals in New Zealand, anthropogenic light pollution should be considered and recorded.

Natural illumination is far more constant and has a less drastic effect on animals, as they have evolved with natural illumination changes, whereas artificial illumination has caused significant changes in night brightness only in the last century (Kyba et al., 2011). This is not to say that changes in natural illumination do not affect animals, quite the opposite. With increasing levels of illumination the nocturnal grey tree frog (*Hyla chrysoscelis*) decreased their activity and it took the frogs much longer to detect prey (from 1 minute in the control treatment to 3-4 minutes under the higher illumination treatments) (Buchanan, 1993). Conversely, for the western toad (*Bufo boreas)* as light levels decreased so did their activity levels. The toad reacted to ambient illumination by disappearing in the darkest times of the night (Hailman, 1984). The author defers saying factors, such as temperature, could be involved; however, Hailman (1984) feels that toad foraging activity and illumination are correlated.

A slightly more complex scenario was explored by Pizzatto, Child, and Shine (2008), who found it perplexing that the metamorphs (animals that are pre-metamorphosis) of the nocturnal cane toads (*Bufo marinus*) exhibited diurnal behaviour. Nocturnal adults with diurnal juveniles, an unusual phenomenon! One of the possibilities Pizzatto et al. (2008) explored was that the metamorphs, with simpler eyes than the adults, may require high light levels in order to see predators and prey. The metamorphs sadly often fell prey to conspecifics, the authors found that cannibalism was a common occurrence in the larger animals and that cannibalism was highest in the dark and at night. So, lighter times of the day were in fact safer for animals who would later turn to the darkness of the night for safety; which sounds very similar to the antipredator responses exhibited by lunar phobic animals. Pizzatto et al. (2008) think that the culprit could be an endogenous day-night rhythm that had not developed to the extent of the adults.

2.3 Lessons from the literature

When studying animal behaviour the goal is not only to discover the 'what' but also the 'why'. Why is an animal behaving in a certain manner? For example, why, if illumination is important, would an animal continue to be active in less than ideal conditions? One potential explanation could be multiple sensory organs. Goyret and Yuan (2015) discuss that many animals use multiple sensory organs when engaged in goal-directed activities, such as feeding. Meaning that an animal can rely on more than one sense in order to, for example, feed. So, if, when feeding, an animal relies on vision or smell to locate food and conditions are too dark to see, that animal may instead use smell to locate food. When considering our nocturnal pests we cannot assume that levels of illumination or moon phase are the only factors that will determine their activities. Illumination may be important but not necessary the most important factor. We can see that there are a large number of factors affecting the activity levels of animals however we can clearly see that moon phase and illumination levels do play a part for many creatures. The question is, how do these factors impact possums and other pest mammals in NZ? And can this information be used to increase the efficiency and effectiveness of pest control and monitoring?

Chapter 3

Monitoring and controlling pests in New Zealand

As detailed above possums, rodents, cats and stoats need to be eliminated before NZ's ecosystems can fully repair the damage made (Courchamp, Langlais, & Sugihara, 1999; B. M. Fitzgerald, Karl, & Veitch, 1991; Imber, West, & Cooper, 2003). The concept of a predator free NZ is often considered a pipe dream, we would need far better methods in order to even come close. Methods of pest control can be made more precise and accurate if we are able to predict when the pests will be most active. In this section I will outline the methods of pest monitoring and control currently and commonly used in NZ, as well as how understanding the animal's nocturnal behaviour can improve the success of the techniques.

A greater understanding of these pest behaviour is particularly relevant because in July, 2016 the New Zealand government set a target for mainland Aotearoa to be predator free by 2050. The project has set four goals to be achieved by 2025:

- "An additional 1 million hectares of land where pests have been supressed or removed through Predator Free New Zealand partnerships"
- "Development of a scientific breakthrough capable of removing at least one small mammalian predator from New Zealand entirely"
- "Demonstrate areas of more than 20,000 hectares can be predator free without the use of fences"
- "Complete removal of all introduced predators from offshore island nature reserves" (Office of the Minister of Conservation, 2016)

Minister Maggie Barry calls these goals ambitious (Office of the Minister of Conservation, 2016), ambiguous would be more accurate. At least we can rest assured that science will work its magic with a 'breakthrough' to save the day, just like the breakthroughs planned for combatting climate change.

The Department of Conservation (DoC) states that the government will fund the project with $7 million every year. This being additional to the $70 million already spent every year on predator control by a number of sectors (government, regional councils, OSPRI, businesses, iwi, communities and others) (Department of Conservation, 2016). An additional 10% funding does not appear to be a large enough investment for such an ambitious goal. The conservation spokesperson of the Green party (Kevin Hague) noted that the goal was welcomed but research showed it would cost closer to $9 billion to make New Zealand predator-free with current technology (Kirk, 2016).

A number of agencies contribute towards the millions of dollars spent (on research and direct control) annually on controlling pest mammals (Kerle, 2001). DoC, TBfree (previously known as the Animal Health Board, AHB), the National Pest Control Agency (NPCA), the Ministry of Agriculture and Forestry (MAF), Environment Canterbury (ECAN) and local and regional councils are some of the larger organisations involved. On a smaller scale - hunters, farmers, iwi and private landowners also contribute towards controlling these pests. TBfree even has a guide on pest control for landowners that can be found on the NPCA website.

A range of pest control measures are used to suppress pest populations, particularly in areas of high biodiversity and disease risk. DoC sustains possum control on about 10% of the 8.5 million hectares of conservation land by using both poisoning and trapping techniques (Department of Conservation & New Zealand Fur Council, 2015). Resources are limited and must be directed to areas where they can do the most good, these areas are determined using a variety of pest monitoring techniques. Such techniques do not show the true abundance of animals present, but they do give a relative indication of population trends and change over time. Other methods can provide an estimate of activity and some give results regarding the presence or absence of an animal.

Waxtags™ (Figure 3.1) are good for surveillance and assessing the presence and type of pests in an area, specifically possums and rodents (Department of Conservation, 2015). The equipment comprises of a piece of wax attached to a bright orange marker, which can then be attached to a tree (Figure 3.1) and there is a national protocol for use. A curious rat or possum may then bite the wax leaving an indent of its teeth behind with which the species can be accurately identified. Another index of relative abundance are tracking tunnels, where a non-toxic bait (e.g. peanut butter) encourages a rodent or mustelid to run through the tunnel, over paper and ink, leaving incriminating footprints behind and there also is a National protocol for use. Mark–recapture also gives an indication of abundance; an animal is caught, marked (or identified) and later detected by capture or sighting. This reveals population trends, such as survival rates, and also allows population sizes to be accurately estimated (Lettink & Armstrong, 2003). A similar measure is spotlighting, where animals are actively searched for and counted, particularly nocturnal animals whose bright eye shine gives them away under a spotlight. Camera traps spot nocturnal animals without the disruptive presence of a human; generally attached to a tree, the motion sensitive camera snaps an animal as it passes and

Figure 3.1 Wax tag 20 cm from the ground attached to a tree

allows individuals to be tracked, activity levels to be estimated, and give an indication of activity types.

VHF collars are used to monitor populations; such as assessing home range or individual animal reactions to a change in the environment. Leg-hold traps are used as a density indicator but they are labour intensive and have to be checked daily so as not to infringe on animal welfare laws , the traps are also bulky, expensive and you can get a lot of by-catch (M. D. Thomas, Brown, Maddigan, & Sessions, 2003). Catch per unit effort, e.g. trapping or shooting, also gives an indication as to the relative abundance and spread of a species. This links with fur recovery, where possums in particular are hunted and their pelts sold.

These monitoring techniques can be further improved when a greater understanding of the target animal's behaviour is achieved. We already do this in some ways, in a week with heavy rain there is little point in setting up monitoring or control when we know that our target animals reduce their activity in such conditions (Cowan & Clout, 2000; Jolly, 1976; Ward, 1978). Additionally, there is much still unknown about general animal behaviour around these monitoring devices. We have National Protocols to streamline pest control and monitoring, however, if mainland New Zealand is to be predator free by 2050 we need to understand much more about pest animal behaviour, particularly when they are at low densities. This includes how many animals are finding monitoring devices and interacting with them. Extensive research has shown that animal behaviour can be influenced by lunar conditions and by illumination levels (see chapter 2). So, if we can predict when a pest may be most active on a night to night basis, depending on moon phase or illumination levels, then monitoring data can be more accurately interpreted and the monitoring itself be made more efficient.

The next step is using this information to control the species in question. Poisons and trapping are the most common forms of control in NZ. Poisons can be distributed either via localised in bait stations or widespread by aerial control. Aerial control is best for remote areas (Parliamentary Commissioner for the Environment, 2011) and typically uses the poison 1080 (sodium fluoroacetate) mixed into bait. It is the most effective technique for rapid response pest control on a large scale (Department of Conservation, n.d.-a). Controlling large areas for pests is crucial during avian nesting season as it gives better odds that native birds, particularly ground nesters, will successfully raise a brood. Similarly in masting years, when some beech (*Nothafagus* spp.) trees release copious seeds, it is important to control pest populations lest they boom out of control as is currently happening in the "Battle for the Birds".

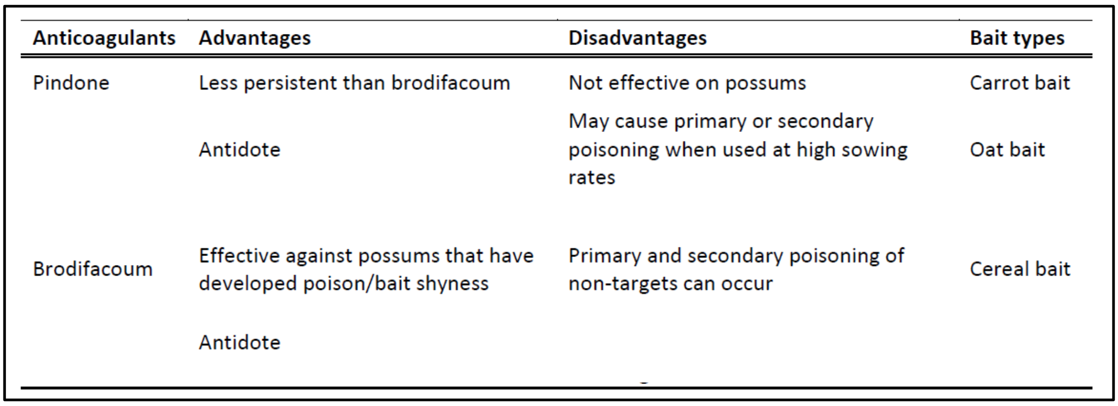
About 5% of NZ is treated with 1080 annually, the poison does not build up in the food chain, it is biodegradable and dilutes quickly in water. The poison is found naturally in many plants in Africa, Australia and South America (Department of Conservation, n.d.-a). 1080 largely targets possums and rodents. Secondary poisoning during campaigns against rabbits and rodents occurs, but only if the stoat or cat is hungry enough to eat enough quantities ,and to eat the liver and stomach of the prey to obtain a lethal dose (Department of Conservation, n.d.-b; King, 2005). The baits are often flavoured with cinnamon to attract pests but, importantly, deters birds. Aerial pest control has been shown to effectively reduce the populations of possums, rats and stoats simultaneously; the time frame needed is short and the cost is three times lower than ground control methods (Department of Conservation, n.d.-b). However, if a non-lethal dose is ingested the animal may survive to become bait shy, meaning they are less likely to interact with a novel substance like a poisoned bait in the future. Aerial control still outplays ground-based trapping though, because traps are more expensive, are harder to place in remote areas and often cannot cope with areas overrun with pests (Department of Conservation, n.d.-b).

Poison control also makes use of bait stations, a form of ground-based control. These need to be regularly refilled and there is the concern that in order for a possum to find the bait the possum may risk encountering a conspecific; often a negative reinforcement (Parliamentary Commissioner for the Environment, 2011). With aerial control the possum has to locate the bait distributed on the ground but with a bait station the animal risks being seen

(Parliamentary Commissioner for the Environment, 2011). Poison baiting can fail due to: sub-lethal toxic dosing, undersized sub-lethal baits, target failing to encounter baits and non-learned behavioural aversion to bait (D. R. Morgan, Batcheler, & Peters, 1986). Also, weather is a consideration as aerial poisons will not be dropped unless three fine nights are forecast, as rain reduces the effectiveness of the poison bait (Powlesland, Knegtmans, & Marshall, 1999; Stephens, 1992)

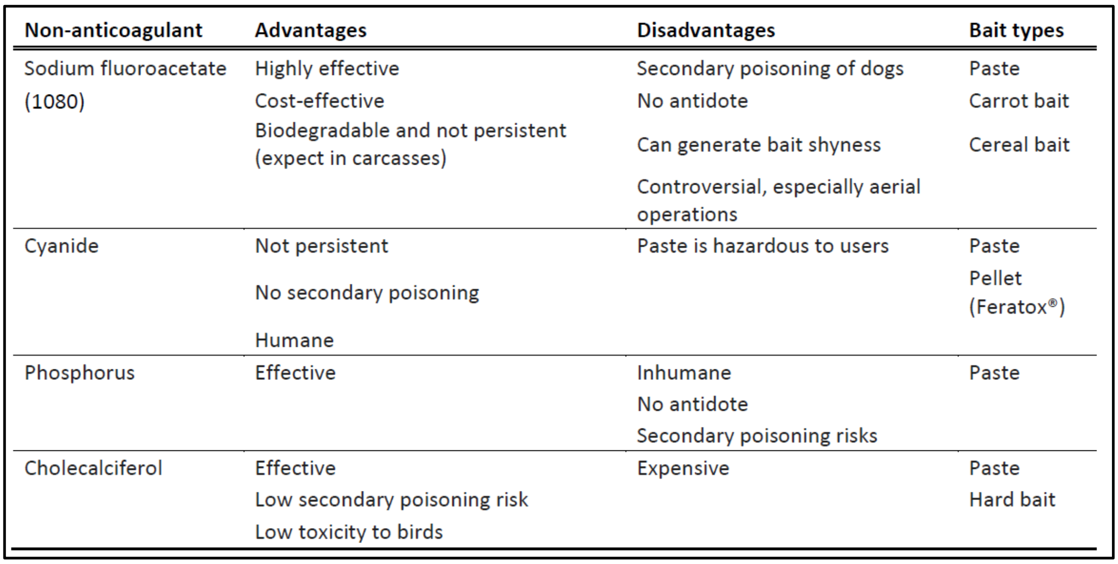
Additionally, there are several varieties of poisons that can be used in bait stations. Anticoagulants include Pindone (used in bait stations) and Brodifacoum (bait station and aerial control) but tend to be inhumane (Parliamentary Commissioner for the Environment, 2011) but do reduce the potential for bait shyness as the poison must build up over time before the animal is killed (Eason & Wickstrom, 1997) (Table 3.1). Cyanide is often used (Table 3.2) at bait stations as it is too lethal for aerial drops, also it can be more effective than 1080 for possums control but, cyanide is more expensive than 1080 (Parliamentary Commissioner for the Environment, 2011). Another poison used at bait stations is Cholecalciferol (Table 3.2), but it is expensive and considered less humane than faster-acting compounds (Parliamentary Commissioner for the Environment, 2011). Like 1080, Zinc Phosphide is relatively humane and Sodium Nitrate could be used in ground and aerial control (Parliamentary Commissioner for the Environment, 2011). Newer toxins included PAPP (para-aminopropiophenone), a gut toxin that targets stoats. PAPP was registered for use recently, in 2011; it specifically targets stoats and cats so is not a substitute for 1080 (Parliamentary Commissioner for the Environment, 2011).

Table 3.1 Anticoagulant baits as summarised by Sjoberg (2013)



Anticoagulants	Advantages	Disadvantages	Bait types
Pindone	Less persistent than brodifacoum	Not effective on possums	Carrot bait
	Antidote	May cause primary or secondary poisoning when used at high sowing rates	Oat bait
Brodifacoum	Effective against possums that have developed poison/bait shyness	Primary and secondary poisoning of non-targets can occur	Cereal bait
	Antidote		

Table 3.2 Non-anticoagulant baits as summarised by Sjoberg (2013)



Non-anticoagulant	Advantages	Disadvantages	Bait types
Sodium fluoroacetate (1080)	Highly effective Cost-effective Biodegradable and not persistent (expect in carcasses)	Secondary poisoning of dogs No antidote Can generate bait shyness Controversial, especially aerial operations	Paste Carrot bait Cereal bait
Cyanide	Not persistent No secondary poisoning Humane	Paste is hazardous to users	Paste Pellet (Feratox®)
Phosphorus	Effective	Inhumane No antidote Secondary poisoning risks	Paste
Cholecalciferol	Effective Low secondary poisoning risk Low toxicity to birds	Expensive	Paste Hard bait

The most common form of control for cats and stoats in NZ are baited/lured traps (Department of Conservation, 2011; Gillies et al., 2003; King, Flux, Innes, & Fitzgerald, 1996b). Trapping produces measurable results, such as the increased nesting of success of wrybills (*Anarhynchus frontalis*) after seasonally trapping predators (Keedwell, Maloney, & Murray, 2002). The concern with traps, however, is that the animal has to firstly find the trap and then interact with it. No matter how tasty the bait smells inside it, if an animal dislikes dark spaces then it is unlikely to go into a dark box. Traps are also sized for specific species, are labour intensive and individuals can become trap-shy. Additionally, control trapping can be costly – traps that do not kill require checking every day, and while kill traps approved by the Animal Welfare act (1999) can be set across larger areas and checked less regularly they still require a large investment (King, 2005). In fact, DoC spends more than $5 million every year on just stoat and rat trapping (Department of Conservation, n.d.-b)

Other potential methods of control that are being investigated include: predator proof fences, repellents, fertility control, use of trained pest control dogs and manipulation of diseases. Much newer techniques involve genetic engineering of vectors, which would carry pest specific bio-control agents; this is something that would require public consultation and as such will not be available for use in the near future (Parliamentary Commissioner for the Environment, 2011).

Alongside monitoring and control the implications of these actions should be considered. Yes, control means cats have been eradicated from nine NZ islands (King, 2005) and this control has increased bird numbers (Dowding & Murphy, 1993) but this may cause an imbalance in the current ecosystem. We do not know which predator impacts birds to the greatest degree, or to what extent predator diets can switch (e.g. when prey abundance changes), or which factors can cause rodent population release. In order to protect threatened birds pest control must target all predators: mustelids, rodents, cats and possums, it is too risky to leave any of them to chance (King et al., 1996b). Understanding this interaction of behaviours may aid the fight to a pest free NZ.

Each monitoring and control technique has developed in part due to recognising the behaviours of the target species; however, as detailed above there is a lack of research investigating animal behaviour around both monitoring and control devices. For example, we know that possums forage on the forest floor thus we spread poison baits upon it. We know that stoats are suckers for rabbit meat so we place it in traps. We understand that in masting years pests won't bother eating anything suspicious because alternative food is in such a high abundance, so we must control them beforehand. However, are some animals afraid of the dark? Will they feel safe entering a dark trap on a dark night? Is there a point during the moon's cycle that possums spend less time foraging on the forest floor? By understanding these pests' behaviours under different illumination levels and moon phase we can further fine tune our methods to be more effective and efficient.

Chapter 4

The ecology and history of nocturnal mammalian pests in NZ

As human populations began to grow in Aotearoa/New Zealand (NZ) so did the number of introduced animal pest species. Across the two islands pests include rabbits (*Oryctolagus cuniculus*), birds, eight different species of deer, fish, insects, mustelids (including stoats (*Mustela erminea*), rats (*Rattus* spp.), cats (*Felis catus*), mice (*Mus musclus*) and possums (*Trichosurus vulpecula*) (King, 2005). Saying we have a pest problem is an understatement. The pests posing the largest threat to our plants and birds include possums, stoats, rats and mice. These pests eat native birds (as eggs, hatchlings and chicks), they compete with native species for resources and can even change the structure of an ecosystem. In this chapter I will describe the general ecology of rats, possums, cats, mice and stoats in New Zealand and overseas, how they came to be here and give an overview as to their impact in NZ.

4.1 Rats (*Rattus* spp.)

There are three species of rats in New Zealand/Aotearoa, the pacific rat/ kiore (Rattus exulans), the Norway rat (Rattus norvegicus) and the ship rat (Rattus rattus) (Figure 4.1). Of these three, the only rat believed to have been intentionally introduced was the commensal living kiore (Atkinson & Towns, 2005). Māori settlers brought the rat to New Zealand in the 13th century, however the rat may have been introduced before this point (Golding & Harper, 2008). The two European rats, the Norway rat and ship rat, were accidentally introduced with European human settlement (Innes, 2005a, 2005b). The three species are a menace and

Figure 4.1 A comparison of rat species size in New Zealand (Department of Conservation, n.d.-i)

are actively controlled using traps and poison baits, and have been eradicated off numerous small offshore islands.

Despite control efforts rats remain a significant threat to New Zealand's mainland native biota, most worryingly by eating native birds and their eggs. The wide range of native fruits and plants this pest eats puts them in direct competition with a number of native species and each rat species presents its own particular threat. The kiore predate weta (native *Orthopteran)*, snails, frogs, tuatara (order *Sphenodontia*), birds and bats; their wide dietary range also includes native plants, seeds and flowers. On top of this kiore has cultural significance to some Māori iwi and thus DoC must consult these parties before beginning eradication programmes (Department of Conservation, 2006).

Ship rats are found worldwide and of the three rat species found in NZ ship rats are the most uniformly spread across the islands including in intact native forests (Innes, 2005b). Damage from the ship rat comes with its skill at climbing, giving them easy access to many bird nests where they will predate egg, hatchling and chick alike. Norway rats are the largest rat in NZ and thus are able to kill nesting adult seabirds and will readily prey on birds that live, nest or roost close to the ground (Department of Conservation, n.d.-i).

4.1.1 General ecology of Rats (*Rattus* spp.)

There are three different species of rat in New Zealand; kiore (*Rattus exulans*) ship rats (*Rattus rattus*) and the Norway rats (*Rattus norvegicus*) (Table 4.1). Whilst having many similar impacts on NZ's ecosystem, each has its own unique way of putting that little bit of extra pressure on NZ's already fragile ecosystem.

Kiore (*Rattus exulans)*:

This species is the smallest of the rats in NZ (Table 4.1) and is similar in appearance to the ship rat. Kiore are not known for eating birds like some of the other rats, but they do have a broad diet which includes weta (native *Orthopteran*), centipedes, spiders, earthworms, weevils, snails and cicadas. They also eat fruits, nuts, bark and rhizomes. There are some predators in New Zealand that feast upon kiore; moreporks (*Ninox novaeseelandiae*), Kingfishers (Family *Halcyonidae*), weka (*Gallirallus australis*), mustelids and cats (*Felis catus)*. Also, Māori peoples trapped the rats extensively as a food source and although not a huge contribution to their diet it is clear from archaeological digs that kiore were esteemed as food (Atkinson & Towns, 2005).

Table 4.1 Distinguishing characteristics of rodents in New Zealand (adapted from King and Powell (2007))

	Kiore ***Rattus exulans***	**Ship rat** ***Rattus rattus***	**Norway rat** ***Rattus norvegicus***	**House mouse** ***Mus musclus***
Adult weight (g)	Average: 60-80 Max: 180	Average: 120-160 Max: 225	Average: 200-300 Max: 450	Average: 15-20 Max: 30
Max head-body length (mm)	180	225	250	115
Fur on back	Brown	Grey-brown or black	Brown	Dull grey-brown
Fur on belly	White-tipped grey giving irregular colouring	Generally uniform grey, white or creamy white, rarely irregular colour.	Similar to kiore	Uniformly grey or white
Habits	Agile climber, digs small holes, nests largely on the ground, feeds on the ground and in trees, infrequent swimmer.	Very agile and frequent climber, rarely burrows, nests mostly in trees and shrubs, infrequent swimmer.	Burrows extensively, climbs far less frequently than other rats, nests underground, strong swimmer, is very wary.	Mainly ground dwelling though is a capable climber, nests in small holes.

Found worldwide, the rats were once widespread across New Zealand. They are now apparently confined to areas in Fiordland, Southland and south Westland. These rats live in a wide range of habitats; from grasslands, to shrublands and scrub to mature hardwood forests. The known altitudinal limit for kiore is 1300m and they are also known to feed along the intertidal zone along the sea shore. In NZ kiore reach higher densities in grasslands than they do in forests. This could be due to the dominance of ship and Norway rats over kiore, so they persist in grasslands but are not necessarily better off than they might be in the forests (Atkinson & Towns, 2005).

In these habitats the impact of kiore is evident, there is early evidence that kiore caused local extinctions such as three native frog species. Large, flightless invertebrates are particularly vulnerable to kiore such as tree weta (genus *Hemideina*) and landsnails. Kiore have also been charged with predating the eggs and juveniles of tuatara (*Sphenodon* spp.) and some bird species (e.g. Pycrofts petrel, *Pterodroma pycrofti*, and kakapo, *Strigops habroptilus*) (Atkinson & Towns, 2005).

Norway rat (*Rattus norvegicus)*:

The largest of the three rat species in New Zealand (Table 4.1), the Norway rat, is an adept invader and is found worldwide. By the 1850s this rat was common throughout the North and South islands. One of the aspects that make them so successful is their ability to breed all year round. They are able to do this in part because they are omnivorous and opportunistic, meaning that the Norway rat is adept at surviving in a great number of circumstances.

In New Zealand they are known to eat seeds, fruits, molluscs, insects and annelids amongst a range of other foods. It has been recorded that the Norway rat will also eat weta (native *Orthopteran*), bird eggs and young, as well as lizards. Norway rats were once prized as a food source for Māori but were soon reviled for their uncleanliness (Best, 1907). When foraging for food these rats tend to stick to a network of trails that run alongside vertical surfaces such as rocks or fallen timber, and males tend to travel farther than females.

In less human-dominated areas non-commensal populations prefer wetland habitats and have a much smaller presence in native forests, especially where less water is present. Commensal populations tend to live in areas where food is processed stored or dumped. The rats will occupy and forage in almost any form of structure; including rubbish heaps, sewers, wharves or industrial sites. They are also a commensal pest by destroying food stores, chewing plastic materials and carry diseases but above all the Norway rat is a predatory pest of native wildlife. Fortunately, competition with ship rats and predation by mustelids has cut their populations down from early invasion population highs (Innes, 2005a).

Ship rat (*Rattus rattus)*:

Sleek and slender (Table 4.1) the last rat to establish in NZ, the ship rat, is highly sensitive to light but not as visually acute as brushtail possums. Similar to the Norway rat and kiore the ship rat is a generalist omnivore and all year round it will eat both plant and animal foods (Daniel, 1973). Their diets are mainly based upon arthropods, including weta (native *Orthopteran*), but they will also eat native snails, birds and lizards in commensal living the rats will feed on any available food source, ranging from edible stored products to refuse. Individual ship rats feed on a small number of bird eggs, chicks and/or sitting adults but because the rats live in high densities, are ubiquitous and arboreal their impact on bird populations collectively is severe (Innes, 2005b).

Ship rat populations have a serious impact on New Zealand's ecosystem, they threaten native wildlife and seed survival of some plant species (Innes, 2005b). The animals live in native and exotic forests, urban parks and gardens, buildings and are most abundant in mature, diverse, lowland podocarp-broadleaved forests. Dwelling from coast to treeline the rats are rarely found at any higher elevations and never in alpine tussock. Marino, Brown, Waddington, Brockie, and Kelly (1992) state that ship rats and possums are the most pervasive and devastating agents of change in NZ due to their seed eating, bird devouring and invertebrate ingesting habits.

4.2 Brushtail possum (*Trichosurus vulpecula*)

Possums (*T. vulpecula)* were first introduced to New Zealand (NZ) from Australia as a way to bolster the local economy via the fur trade. In Australia possums are, for the most part, a valued low-density native animal. They can be considered an annoyance in urban areas where residents believe they rummage in rubbish but the animal is in fact endangered in the Northern Territories of Australia (Pavey & Ward, 2012). From 1837–1959 possums were imported and liberated into NZ, the government not only advocated by the process but supported it too. In fact, one of the acclimatisation societies at the time reported in a typical annual report that "We shall be doing a great service to this country in stocking these large areas [of rough bush hills] with this valuable and harmless animal" (Kerle, 2001, p. 13). Yet, by 1923 some New Zealanders were beginning to question the wisdom of introducing the animal as they noticed the damage possums caused to berry-bearing forest trees and in orchards.

The first study on the possible negative impacts of possums in New Zealand was conducted by H. B. Kirk in 1920, Kirk reported that "the damage to New Zealand forests is negligible" (Clout & Erickson, 2000b, p. 2). Only after roughly another 30 years did the full extent of damage possums were causing come to light and in 1947 the government issued penalties for harbouring or liberating them, and legalised the use of several poisons as a control method.

We now understand the devastation possums cause in New Zealand; Montague (2000) describes them as a major wild animal pest. Amongst the human populace they have a terrible reputation, and it is not hard to see why. In the native forests they have colonised, Podocarp (*Podocarpaceae*), Rata (*Metrosideros spp.*) and mixed hardwood forests, possums cause severe damage and often defoliate large areas causing dieback (Figure 4.2). This impact on the forest also means the creatures compete for the resources of berry-eating bird species (Kerle, 2001)

Figure 4.2 **Dieback in the mamuka/black tree fern (*Cyathea medullaris*) (left) caused by possum browsing, after two years of possum control the plant recovers (right) (Hutching, 2012).**

Figure 4.3 Possum scavenging an abandoned woodpidgeon/kereru (*Hemiphaga novaeseelandiae*) nest (Department of Conservation, n.d.-h)

Additionally possums also prey on the vulnerable eggs and chicks of native birds (Innes, Kelly, Overton, & Gillies, 2010), such as the kereru (Figure 4.3) and kokako (*Callaeas cinerea*). To add insult to injury possums also transmit bovine Tuberculosis – making them a serious threat to the beef and dairy industries. It cost our country NZ$41-52 million for control work in 2008 (Biosecurity New Zealand, 2009) and the pest is still prevalent across the islands. In 2009 possum populations in NZ were estimated still as high as 48 million (Warburton, Cowan, & Shepherd, 2009). That's roughly 10 possums for every person. Kerle (2001) suggests that eradication of this marsupial pest is improbable, however sustained control in TB and conservation hotspot areas remaining is essential to mitigate the impact on the environment and agricultural industry.

4.2.1 General ecology of the brushtail possum

In the northern Territories of Australia the common brushtail possum (Figure 4.4) is endangered (Pavey & Ward, 2012). It was only in the 1970's that ecological thinking of marsupials in Australia extended beyond the kangaroo, so the understanding of brushtail possum biology has only just begun to grow. Indeed the large majority of investigation into the common brushtail possum, has been conducted in New Zealand and largely due to its status as a pest species (Kerle, 2001).

Figure 4.4 Brushtail possum forms in New Zealand (King, 2005)

In Latin *Trichosurus* means 'hairy tail', hence their common name–brushtail, this feature distinguishes them from other species of possum. Other distinctive features are their pointed snout, long ears and broad, stout skull (Kerle, 2001). They weigh between 2-4kgs (Clout & Erickson, 2000a) are cat sized, nocturnal, arboreal and are a polygynous marsupial (Whyte, Ross, & Blackie, 2013). In New Zealand their mean life expectancy is 6.7 years (Kerle, 2001). However, Efford (2000) suggests that 90% of females and 80% of males die at 2-5 years. Brushtail possums are highly agile and have an accuracy of movement that suggests well-developed vision. Kerle (2001) explains that a possums' brain and eye structure have some specific visual specialisations that support this theory. This can be seen when shining a light on a possum at night, its eyes will glow unsettlingly, and this is due to the special reflective pigment layer set behind the retina called the tapetum lucidem. And, from personal experience, brushtails have a very bright eyeshine, meaning they have good night vision. As for the other senses, we can assume that they have a good sense of smell as one mechanism possums use to communicate is scent marking; also when interacting directly communication is visual and vocal (Kerle, 2001), these features are key to finding mates.

Efford (2000) comments on possum reproduction saying that, when left to their own devices, populations fluctuate at roughly 50% of their long-term average density. Efford continues by relating that there is little understanding as to what would control a possum population when left alone to this extent, explaining that competition and simple plant-herbivore dynamics do not seem to apply. Regardless of the reasons why, brushtail possums are now a plague upon the two mainland islands.

Estimates of brushtail possum populations across New Zealand have changed in the last few years, pre-2009 the common population estimation was 70 million (Kerle, 2001), however in a study by Warburton et al. (2009) the estimate is now 48 million. Brushtail possums have taken over New Zealand with relative ease in part because they are generalists and opportunists; they are arboreal folivores (Kerle, 2001). that will quickly take advantage of new food sources and will eat a wide range of foliar and non-foliar foods (Nugent et al., 2000). Indeed, depending on the season, non-foliar foods such as flowers and fruits may form the bulk of a possum's diet (Kerle, 2001; Nugent et al., 2000) and it may travel vast distances to find them (Cowan, 2001). This is because *T. vulpecula* is not as well adapted to the low-nutrient content of foliar foods and thus will supplement its diet with high energy/nutrient foods whenever possible (Nugent et al., 2000).

Figure 4.5 Possum and rat both preying on a thrush nest (Department of Conservation, n.d.-h)

To supplement the energy and nutrients in their diets possums have been known to feed on insects (Cowan & Moeed, 1987) and birds (M. D. Thomas et al., 2003; Whyte et al., 2013). There have been some suggestions that possums have ingested insects only accidentally but (Kerle, 2001) disagrees, saying that in New Zealand large quantities of insects have been found in the stomachs of possums. In fact they have been seen actively searching for fly larvae in leaf litter and congregating around lights to catch moths (Kerle, 2001). (Nugent et al., 2000) agrees by stating that in all possum habitats invertebrates will be eaten when available.

In contrast possums are known to actively predate bird nests (Figure 4.3 and 4.5). In fact they have caused the decline of several native bird species due to predation and by out-competing them for resources. Possums compete with hole-nesting birds, such as kiwi (*Apteryx spp.*), parakeets and saddlebacks (*Philesturnus carunculatus*), by occupying potential nesting spaces (Cowan, 2005). Of course, by consuming food resources such as fruit, flowers and insects the pests compete with other bird species too. Many sources confirm (Cowan, 2005; Innes et al., 2010; Kerle, 2001) that possum preference for some flowers and fruits causes considerable damage and endangers native fruit-eating bird species. Another significant effect possums have on bird populations is that they will actively predate on them (Figure 6). Cowan (2005) lists that possums will eat the eggs, nestlings and/or adults of native bird species such as the kōkako, kiwi, kāhu (*Circus approximans)*, fantail/piwakawaka (*Rhipidura fuliginosa*), kereru/kukupa (Fig. 3), and tītī/muttonbird (*Puffinus griseus*). There is a cruel circle to this scenario where greater access to highly nutritional food in turn can increase possum reproductive rates, thus local possum carrying capacity, meaning there are more possums to prey on New Zealand's birds (Cowan, 2005) .

Possums enhance their pest status in New Zealand as carriers of bovine Tuberculosis (bTB) (Butcher, 2000; Clout & Erickson, 2000b; Kerle, 2001; Paterson et al., 1995; Whyte, Ross, & Buckley, 2014; Whyte et al., 2013). BTB was likely first introduced to possum populations by livestock Kerle (2001) and the disease was first detected in a wild possum in NZ in 1967 (Coleman & Caley, 2000) or 1970 (Clout & Erickson, 2000b): whilst possums in Australia are not known to carry it. When Kerle (2001) published, bTB was found across 13% of the country and in 27 widely scattered locales. As of 2000 (Coleman & Caley, 2000) state that possum populations infected with TB occupied 23.6% of NZ which is where 75% of cattle infected with TB are found. We can see that the sources do not agree with each other, this extends to just how cattle may contract TB. Paterson et al. (1995) state that transmission of bTB occurs between possums and cattle as well as amongst possums; and that this transmission tends to occur where possum and cow habitat overlap. Unfortunately for the dairy industry, pasture plants, such as clovers and introduced grasses, are an attractive food source for possums (Nugent et al., 2000), and will exhibit territoriality over this habitat (Whyte et al., 2013).

Few sources say with confidence that possums directly transmit bTB to cattle. Yet, T. Porphyre, McKenzie, and Stevenson (2007) found that farm-to-farm spread of bTB was not an important infection mechanism, suggesting that possums were a more important vector. Coleman and Caley (2000) disagree with this, stating that there was no concrete evidence that possums were indeed infecting cattle. However, in the study by T. Porphyre et al. (2007) possums living in the forest near their study site were found to be a main source of bTB in the area, also TBfree has recorded video evidence of a cow nuzzling a possum, a close enough interaction to transmit the disease (TBfree, 2014). Yet, Butcher (2000) found no evidence of how TB may be transmitted from possums to cattle but then continues to say that the consensus is that inquisitive stock may encounter recently dead or dying possums and contract the disease. Getting involved in this debate is New Zealand First Member of Parliament Richard Prosser, stating that "54 possums testing positive for TB from 124,213 autopsies over nine years suggested possums were not a significant vector, let alone the single-most important vector as official channels are fond of repeating" (Price, 2015). We know for a fact that both possums and cattle can be infected with bTB but the literature does not concretely show whether possums directly transmit it to cattle or how they might do so.

Nevertheless, bTB is a significant problem for farmers; livestock, such as deer (Walter, Smith, Vanderklok, & VerCauteren, 2014) or cattle, found to be infected with bTB must, as decreed by TBfree, be slaughtered immediately, along with its fellows in the herd. This causes a financial loss to the farmer as the animals are slaughtered at a lighter weight and the farmer is unable to store young or stock from the infected herd. Also, the meat from bTB infected deer is has no value and the farmer shoulders all cost from testing the animals for bTB (Deer Industry New Zealand, n.d.). On top of this, as farmers are attempting to eradicate the disease in their own stock, possums may be re-infecting the pastures once more (Department of Conservation, n.d.-e). In fact, Whyte et al. (2013) state that until possums are eradicated from New Zealand there is little chance of doing the same for bTB. Yet, (Butcher, 2000) discusses that whilst possums are implicated as the major culprit there are other known animals that host TB such as deer, ferrets, hedgehogs, stoats, feral cats and feral pigs. However, the Department of Conservation (n.d.-e) stands firm that possums are considered the single greatest barrier to eradicating bTB from NZ livestock.

Another concern regarding the spread of bTB in NZ is that possums are often solitary creatures (Day, O'Connor, & Matthews, 2000). Socially their interactions are limited to agonistic, affiliative or sexual and often do not share a den, making the disease neither quickly nor easily passed between possums (Day et al., 2000). However, in the farmland-forest margin, dens are shared more frequently, where up to five possums have been found in the hollow of a willow tree (Cowan, 2005). Understanding possum denning behaviour is important because, as stated by Whyte et al. (2014), bTB transmission risk may differ between varying habitat types as there can be a difference is denning behaviour. Thus by understanding this aspect of possum behaviour we can better control its impact.

Possums spend the day in their dens and are strictly nocturnal (Cowan & Clout, 2000). And, according to Kerle (2001), they mostly nest above ground in epiphytes, or tree hollows; with the lack of predators some have taken to nesting in dense ground vegetation, under logs or tree roots as well as in other creature's burrows. Whyte et al. (2014) and Cowan and Clout (2000) agree stating that NZ possums den both above and underground. Similarly, in Australia, brushtail possums mostly den in the hollows of large eucalypts, but can be found in hollows of termite mounds, rabbit warrens and rock crevices (Kerle, 2001). In New Zealand forests possums generally use 5-10 different dens and will only actively defend them if they are using them.

Possums have been recorded moving from dens in forests to forage on pastureland, downhill this distance can be up to 1.5km (Cowan, 2005). Whyte et al. (2013) describes that males will tend to have a larger home range than females and that possum home range sizes are not fixed but adult possums do tend to occupy a home range for life. It seems their home ranges are dependent on population density, and, it is likely, on resource availability. In a low density population an individual may have a home range greater than 40 ha, which, according to Whyte et al. (2013) is quite large. Population density when considering home range is important for pest control because, as Whyte et al. (2013) explain: being able to predict the movements of pests allows weaknesses to be targeted and allows bait stations and traps to be placed more effectively.

More effective management also results from understanding the habitats in which possums live. In Australia the animals flourish in pasture, pine plantations and farmland where large trees have been left standing (Kerle, 2001), it takes little stretch of imagination to guess that possums in NZ are also successful in these habitats. In fact, Efford (2000) describes that possums are found in podocarp-broadleaved forests, beech forests and pine forests; with the highest densities of possum being found on the edge of forest and pasture. Efford does note however that is it unclear as to whether the latter is due to the nutrition of pasture foliage or the particular suitability of these forests. Indeed many sources agree that possums have invaded all but a few areas of NZ (Cowan, 2005; Hutching, 2012; Warburton et al., 2009). Kerle (2001) suggests this is due to their excellent manipulative skills, giving them the capacity to survive changes in their habitat more readily than other marsupials, such as the koala, might.

This ecological flexibility and the relative ease of life means that possum populations have boomed across New Zealand. Clout and Erickson (2000b) discuss that the possums' success in New Zealand can be distilled down to the animals' generalist habits, New Zealand's abundance of palatable and nutritious vegetation, the lack of competitors, parasites or predators allowing a population boom and lastly, human assistance. In Australia the possums main predator are foxes (Cowan & Clout, 2000). Cowan (2005) suggests that the impact of predation (by feral cats and stoats) on possum populations in NZ is unknown, however it is presumed to be less significant than human control or harvesting.

NZ possum population dynamics are so 'strong' that that their physiology now differs from their cousins in Australia. Kerle (2001) suggests that the NZ possum has adapted to the local conditions and now has a different skull size (correlating with air temperature). Kerle (2001) suggests this adaptation took place within a remarkably short amount of time, estimating that for some populations it occurred within as short a time as 30 generations.

There is no doubt in the eyes of New Zealanders that possums must be controlled. Several case studies have shown that with possum control comes a revitalisation of vegetation condition and significant increases in native animal populations (Norton, 2000; Parkes, Baker, & Ericksen, 1997; Powlesland et al., 1999; Veltman, 2000). Huge amounts of money have gone into possum control, more than any other pest eradication programme in NZ; the estimated regional council expenditure on pest management is $41-52 million per year (Biosecurity New Zealand, 2009). This cost is largely incurred due of bTB and possums destructive impact on not only native forests but also commercial pine plantations (Department of Conservation, n.d.-e).

Pine plantations are not free of the economic pressures hungry possums bring, the pests will browse on young trees, eating the main shoots and stripping their bark; at some sites half the trees can be killed (Department of Conservation, n.d.-e; Nugent et al., 2000). Butcher (2000) explains that a plantation is most at risk from possums up to 14 years of age and that these plantations are predominantly *Pinus radiata.* Butcher expands, stating that if 5% of *P. radiata* plantings were lost, the potential monetary loss in the year 2000 would be between NZ$282 and NZ$840 per/ha.

One form of control is being revitalised to manage possum populations and that is the fur trade. Recently the Department of Conservation and New Zealand Fur Council (2015) have shown that the (roughly) $10 million DoC spends per year on possum control could be reduced if the fur trade were increased. DoC's research shows that by combining trappers in the buffer zones knocking down possum numbers and DoC targeted pest control, possums re-invasion can be delayed by 2-3 years. Lou Sanson, Director General of Conservation at DoC, said

> *"Any delay in re-invasion will give New Zealanders' more bang for their buck – as well as precious extra time for our native plants and birds to recover. The fact that New Zealand businesses and local communities will also benefit from enabling more fur recovery operations is the icing on the cake."*

The fur industry in NZ currently generates $100 million to $150 million per year in retail sales and the industry employs about 1,500 workers (New Zealand Institute of Economic Research, 2014). According to Neil Mackie, chairman of the New Zealand Fur Council, there is an unfulfilled demand internationally for products using possum fur. The NZFC states that if their consent was allowed to double in volume not only would this contribute to the economy, provide employment and increase the production of possum-related clothing - it would also contribute to the health of native fauna and flora through the approximately two million possums killed every year (New Zealand Institute of Economic Research, 2014).

4.3 Stoats (*Mustela erminea*)

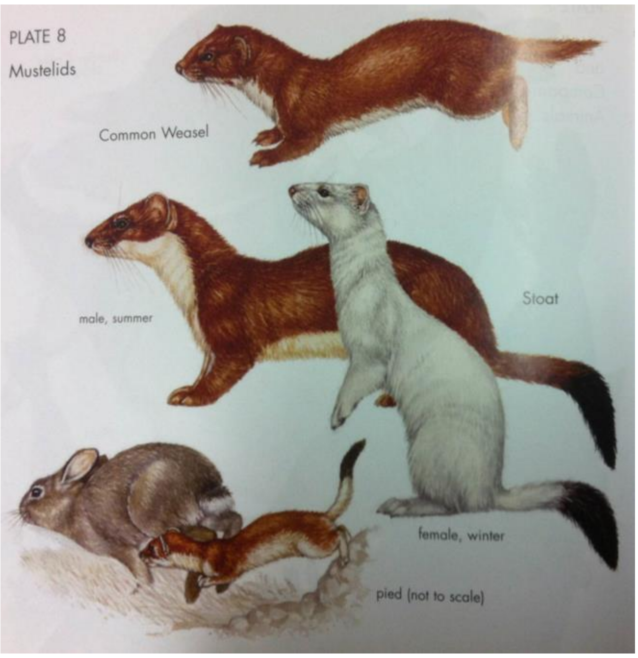


Figure 4.6 Stoats in New Zealand (King, 2005)

New Zealand is the only country where stoats *(Mustela erminea)* (Figure 4.6) are considered important introduced pests (King & Powell, 2007). They were introduced into NZ in the 1870's to control another introduced pest – rabbits (*Oryctolagus cuniculus)* (Department of Conservation, n.d.-j; King & Powell, 2007). Even at this time when the fragility of New Zealand ecology was not well understood ornithologists protested, pointing out the potential destructive nature of stoats on native bird populations. As predicted by ornithologists the mustelid did not restrict itself to rabbits nor the habitats it was introduced to, and by 1889-90 reports of stoats spreading far from any known release places flooded in. Stoats can live in any habitat where they may find prey; from beaches to farm pastures, to beyond the treeline. They are flexible and opportunistic, their prey includes native species and they are a significant threat to native birds. Stoats are known to prey on mohua (*Mohua ochrocephala*), kaka (*Nestor meridionalis*) and kakariki (C*yanoramphus auriceps*). Additionally, King and

Murphy (2005) mention that 94% of young brown Kiwi are lost to predation, about half of this caused by stoats. And it's not just ground dwelling birds at risk, being an adept tree climber stoats threaten birds nesting in tree-holes. New Zealand's long term bird residents are most at risk for they have not evolved the innate anti-predator behaviour that many other species have. The stoat does at least prey on other pest species, such as house mice, rabbits, hares, rats and possums (King & Murphy, 2005).

Considering the impact of stoats it is unsurprising that King (2005, p. 284) describes the 'liberation' of stoats into NZ as one of the "worst ecological mistakes ever made by European colonists in New Zealand". Pioneer explorers blamed the rapid decrease in native birds on stoats and they are still blamed today (although it seems possums are still public enemy number 1). There are some that argue on the stoat's behalf, saying the animal helps control rabbit and rat populations. This party suggests that when controlling stoats we should consider the consequences their reduced density will have on their prey populations, such as rats (King & Murphy, 2005).

4.3.1 General ecology of stoats

Introduced from Britain in the 19th century, New Zealand forests were a paradise with a well-stocked pantry for stoats, it also offered them shelter from harrier hawk and ferret hunting in more open areas. Their only competition for food has been from feral cats (*Felis catus*), morepork owls (*Ninox novaeseelandiae*) and bush falcons (*Falco novaeseelandiae*). Both predators of the stoats and the stoats themselves share prey in common: birds (Department of Conservation, n.d.-c, n.d.-d, n.d.-g, n.d.-k). Indeed King and Moody (1982) found that the most important class of food for stoats were birds (Figure 4.7).

Like possums, stoats are versatile in their diet and are able to switch prey to whatever is most abundant. However, stoats cannot get enough nutrition from prey (such as mice) alone, hence birds are a more preferable prey even when mice populations are very high. A number of studies found that, in forests, more than half of items eaten were birds (Alterio & Moller, 1997; King, Flux, Innes, & Fitzgerald, 1996a; Murphy et al., 1998) and insects (particularly weta (native *Orthopteran*)), other food items included rats, mice and possums (King & Powell, 2007).

Figure 4.7 Stoat scampering with a stolen chick in its mouth (New Zealand Times, 2014)

Numerous studies have found that stoats have a large impact on bird populations, in Iowa, USA, stoats were found to be responsible for some of the upland duck nests that failed (Fleskes, 1988). In Northern Norway stoats predate willow grouse and when rat populations are low stoat impact on willow grouse and other bird increases drastically (Myrberget, 1972). Also, in England, stoats were found to destroy 45% of curlew nests (Robson, 1998). King and Powell (2007) state that bird nests on the ground are particularly vulnerable to stoats and, compounding the threat to birds, stoats will also hunt day or night and require several feeding bouts to give them their daily energy requirements. Meaning that it would be rare for a bird to not be at risk from predation by stoats.

Stoats can range over huge areas and the distances they travel can be food dependant. Murphy and Dowding (1994) found that when prey, such as mice, populations are high stoat home ranges are lower than when prey is scarce and stoat densities trend upwards. Higher stoat densities mean smaller home ranges and less territoriality (King & Powell, 2007). Gender also plays a role; in males and females home range is determined by an interaction of body size and prey density. Larger stoats need larger home ranges (particularly when prey is scarce) and males tend to have larger home ranges than females, plus a male's home range changes with breeding season. Also, stoats in NZ tend to have larger home ranges than those studied in Scotland (King & Powell, 2007). Plus, within their home range a stoat will find a den, these sites tend to be dark and sheltered; such as holes in tree trunks or roots, piles of logs or ditches (King & Powell, 2007). Specifically in New Zealand it was found that stoats move from den to den and are known to occupy dens previously occupied by ferrets (King & Powell, 2007).

One token in the birds favour is that stoats have short lifespans – meaning they have high and variable rates of birth and death. Unfortunately when you combine this with their naturally unstable populations, as well as a density and distribution that is largely controlled by food it means that stoats have a substantial resistance to human management. Stoat numbers are reduced to a small extent by non-human means; falcons (*Falco novaseelandiae),* wekas (*Gallirallus a. australis)*, feral cats and potentially ferrets attack them, but this impact is not enough to affect their general numbers. The impact that stoats have on the New Zealand environment is unfortunately far greater, particularly during beech seed production years (masts); the seeds are eaten by rodents whose populations grow and are then consumed by stoats which allows them to breed prolifically (King & Powell, 2007).

4.4 Mice (*Mus musculus*)

Mice (*Mus musculus)* were accidentally introduced and were first recorded in NZ in 1824 when a ship, the *Henrietta*, wrecked on Ruapuke island. The mammal is found worldwide and is claimed to be the most extensively distributed mammal other than humans and can now be found across all of New Zealand (Ruscoe & Murphy, 2005). They readily invade urban areas as well as native and exotic environments, their populations are found to be highest in areas with dense ground cover. Their habitat choice is oft a trade-off between food resources available and predator avoidance, their main predators in NZ being cats (*Felis catus*) and stoats (*Mustela ermina)*. Mice, like stoats, rats and possums, have a highly flexible diet; which is one of the reasons mice have been able to colonise most of the planet. In New Zealand Lepidoptera (caterpillars) are the most common food group eaten by mice, but they do also eat weta (native *Orthopteran)*, spiders, beetles and plant life (Miller & Webb, 2001). Mostly nocturnal and feeding at dusk and dawn; mice have been known to eat small eggs and nestlings but there is seldom an association between mice and nest predation (Ruscoe & Murphy, 2005).

The threat they pose to native bird species is through competition for resources and as a food source to pests that predate not only them but native birds as well. To explain, in autumn and winter mouse populations can increase drastically due to the sudden increase in food from the heavy seed fall of beech spp. particularly in the South Island. This in turn increases the density of mouse populations which increases their bird-eating predator – stoats (*Mustela ermine*a) (King & Powell, 2007; Ruscoe & Murphy, 2005). One might argue that in order to protect our native birds we could focus on decreasing mouse populations so as to reduce the impact of stoat predation. Methods of control are hindered in New Zealand due to the sheer numbers of mice and their high reproductive rate, they are even more difficult to eradicate than rats however, they can be controlled using commercial poisons, fumigation, trapping and repellents (Ruscoe & Murphy, 2005).

4.4.1 General ecology of mice

The house mouse has a long thing tail, round ears, large black eyes and a pointed muzzle with long whiskers and are brown-grey with a white belly (Table 4.1, Figure 4.8). Predators are avoided through keen sense of smell and hearing. These senses also aid foraging for food and recognising conspecifics (Ruscoe & Murphy, 2005).

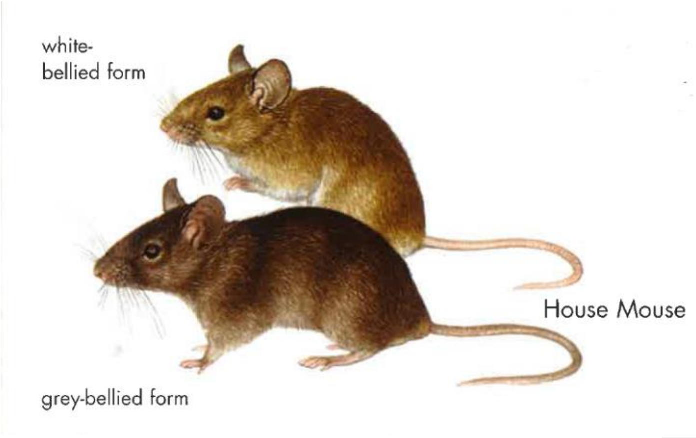


Figure 4.8 House mouse (*Mus musclus*) (King, 2005)

The house mouse has a flexible diet; commonly including lepidopetrans and other insects, lizards, birds and a range of seed species. Mice are able to eat small birds and nestlings but are seldom found predating nests. Populations may spike when there is a sudden increase in food such as heavy seedfall (such as beech mastings). Known to feed at dusk and dawn, they are largely nocturnal (Ruscoe & Murphy, 2005).

Found in both native and exotic temperate forests their highest populations are reached when there is a fair amount of ground cover. Urban areas are also common habitats; houses, farm buildings, rubbish dumps and factories being the most common (Ruscoe & Murphy, 2005). Mice will travel large tracts of land to gather resources and/or find mates, with a variation of home range found to be between 0.08 to 2.6 ha (with males having larger home ranges than females) (Marino et al., 1992). Mouse territories are so large and complex that Marino et al. (1992) suggests they may not meet conspecific neighbours often.

Apart from humans, mice are probably the widest spread mammals on Earth. They are found throughout the North and South Islands, largely through accidental transport by humans. They are significantly more difficult to eradicate than rats but their greatest impact on New Zealand's ecosystem is through competition with birds for fruits and seeds (Ruscoe & Murphy, 2005).

4.5 Feral cats (*Felis catus*)

Figure 4.9 Domestic cat inspecting its avian prey (Dr_Relling, 2009)

Cats are the most popular companion animal in New Zealand, in part because they are considered easier to care for than dogs. However, their human owners seem unable to fully cope with their cats' breeding rate, this has exacerbated the growing numbers of feral cats in NZ (Aguilar, Farnworth, & Winder, 2015). It has been estimated that the population of domestic cats in NZ is higher than 1.4 million, with about 48-52% of homes having at least one cat (Aguilar & Farnworth, 2013; S. A. Morgan et al., 2009). To the cat lover this may not seem a problem, but in fact the impact of house cats on the environment is a national and global concern (Lepczyk, Mertig, & Liu, 2004; S. R. Morgan, 2002; Woods, McDonald, & Harris, 2003). We cannot regard them as solely our cuddly companions. They are efficient bird killers (Figure 4.9) (Gillies & Clout, 2003; Harper, 2004; King et al., 1996b; S. A. Morgan et al., 2009) and their drive to kill is independent of hunger, it is pure instinct. (Barratt, 1998; B. M. Fitzgerald & Turner, 2000) Cats have had a huge impact on NZ's ecology and are continuing to do so. Whole populations of birds (Galbreath & Brown, 2004; Kuschel, 2012) and lizards (Stack, 1874; Thomson, 2011) have been wiped out by cats. NZ has far less variety when it comes to mammalian prey than other areas of the world, which leads to pressure on other food sources and birds become a larger part of their diet (B. M. Fitzgerald & Turner, 2000).

Due to this feral cats have been controlled alongside other mammalian pests for decades (King, 2005) but, their populations continue to be large enough to negatively impact the islands fragile ecosystems.

4.5.1 General ecology of feral cats

Figure 4.10 A juvenile lagomorph falls prey to a cat (Alex T., 2012)

Cats were introduced to both the New Zealand (NZ) mainland and a number of offshore islands for pest control, companions and some as gifts. On Mangere Island, in the Chathams, cats were used to control rabbits (Figure 4.10) but, unfortunately eliminated at least two species of seabirds and most forest birds by 1950 (Department of Conservation, n.d.-f). The European ships that landed in NZ from 1779 onwards had a crew of cats to control rodents and on occasion a cat would be made as a gift to inhabitants of an island. When Cook first visited NZ he gave as a gift two cats to Māori at Tolaga bay (Gillies & Fitzgerald, 2005). Cook was also considerate enough to leave cats at Tahiti, Ulietea and Huaheine (Beaglehole, 1961). Years after these events feral cats became established, most likely by the 1830's. By 1860 the cats were 'very numerous' and farmers began importing cats from the cities to help control the rabbit problem (Gillies & Fitzgerald, 2005). Over time the cat population in New Zealand has expanded. A survey of domestic cat numbers was conducted in 1990 and New Zealand was found to have the second highest per capita proportion of cats at 1.2 million (with Austria coming in top at 12.3 million cats) (Bradshaw, 1992).

Feral cats are now distributed throughout the three main islands of NZ. Historically they have been present on at least 31 islands but have been eradicated or have died out from about 14 of these (King, 2005). Similar to possums, rats, mice and stoats the feral cat is relatively flexible in the areas it will live. Ranging from pastures, sand dunes, scrub, tussock, pine plantations, podocarp-broadleaf forests and native forests (King, 2005). An important factor to consider is that in a high emission climate change scenario the amount of suitable habitat for feral cats could increase in NZ (Aguilar et al., 2015). Within these habitats the mean home range for feral males is between 155-2083 ha and the home range females is roughly half that (between 45.8 – 1109 ha) in New Zealand (Gillies & Fitzgerald, 2005). The density and distribution of females is largely due to food abundance, whereas the range size of males is mainly determined by density and distribution of females (Liberg, Sandell, Pontier, & Natoli, 2000).

In terms of size and weight, females tend to be 70-80% smaller than males, although feral cats in the south are larger than those in the north (Gillies & Fitzgerald, 2005). Both genders have similar colour patterns and variations found in domestic cats are also present in feral cats, in fact when it comes to morphology the domestic and feral cats are indifferent. There are however, a few distinguishing traits of New Zealand's feral cats; most are short haired and they can be a basic striped tabby, blotched tabby, black, grey, ginger or tortoiseshell. The feet, throat and belly can have white patches (Gillies & Fitzgerald, 2005; King et al., 1996a). These patterns allow them to fade into virtually any background however, when searching for them at night their glass green eyeshine gives them away. This bright shine is due to a highly developed tapetum lucidem, giving them fantastic night vision. The feral cat also has highly sensitive hearing, to the extent that they can hear the ultrasonic calls of rodents (Bradshaw, 1992), allowing cats to catch rodents more effectively.

On the mainland cats largely feed on rats, as well as rabbits (mostly smaller juveniles that are more easily caught), sometimes on possums, and occasionally on stoats, hedgehogs and carrion (Gillies & Fitzgerald, 2005). Cats' effectiveness at catching pests has long afforded them a place in man's domain; however, the ecological concern is that cats cannot curb their killer instinct and will often predate on birds and other vulnerable natives; such as lizards and invertebrates (Gillies & Clout, 2003; S. R. Morgan, 2002).

To assess how great a concern should be raised as to their impact, a number of studies investigated the actual number of birds preyed upon by cats. A study based in Auckland found that 40.7% of prey were rats and 25.5% were mice (Gillies & Clout, 2003). Similarly, in Wellington 34.5% of prey were mice and in Christchurch's Travis Wetland 37.7% of prey were mice (S. R. Morgan, 2002). However, a study in Browns bay found that only 3.6% of prey caught were rodents. In all of these studies birds were the second most common prey item. Additionally, in the Kauri-podocarp forests of Northland rats were frequently found in the guts of cats, and rabbit remains were often found closer to farmland areas (Gillies & Clout, 2003)

In a study by King et al. (1996b) 13 cat guts examined were found with a greater proportion of arthropods, large mammals (rabbits and possums) and mice than birds. Other prey types have also been found with a higher rate of occurrence than birds. In terms of percentage frequencies of occurrence rabbits and possums (23%) (King et al., 1996b) and invertebrates (69% and (King et al., 1996b) 54% (Middlemiss, 1995)) were found more often than birds in cat guts. A point to consider is that King et al.'s (1996b) study disagreed with some previously mentioned by stating that rats were found to a lesser extent than other prey.

Feral cats do prey on a number of creatures other than birds and the degree to which cats negatively impact birds is disputed. However, the fact remains that any predation on endangered birds in New Zealand cannot be tolerated (Morgan et al. 2009). In tussock grasslands the frequency of occurrence (%)of a feral cat preying on a bird has ranged between 56% (King, 2005) to 23% (Middlemiss, 1995) in Central Otago, with a distinctly higher rate recorded in Te Wharau: 59% (King, 2005). In a forest the frequency of occurrence (%) has been found to be between 23% (King et al., 1996b) and 12% (A. Fitzgerald & Karl, 1979). Additionally, in 10 dietary studies of mainland feral cats, birds were found in more than 20% of the samples collected (King, 2005)

Cats consume a wide variety of prey but they do still predate on a number of different bird species, mostly passerines (Bramley, 1996; King et al., 1996b; Murphy, Keedwell, Brown, & Westbrooke, 2005). Natives such as piwakawaka/fantail (A. Fitzgerald & Karl, 1979), tūī (*Prosthemadera novaeseelandiae*) (Fitzgerald, Vietch & Karl, 1991), Raoul Island banded dotterel (*Charadrius bicinctus*) (Murphy et al., 2005), and Kereru/New Zealand pidgeon (A. Fitzgerald & Karl, 1979) are preyed upon. Cats have also restricted the Stewart Island coastal breeding NZ dotterel (*Charadius obscurus obscurus*) to alpine tops (Dowding & Murphy, 1993) and lizard populations plummeted after the introduction of cats (Stack, 1874; Thomson, 2011). Ground feeding and nesting birds are particularly vulnerable (Sanders & Maloney, 2002). Kiwi suffer at the claws of cats who largely prey on chicks and juveniles (Department of Conservation, n.d.-f; Gillies et al., 2003; McLennan et al., 1996). On Stewart island cats (introduced there in the 1800s) are a significant predator for kakapo (*Strigops habroptilus*)

(Powlesland, Roberts, Lloyd, & Merton, 1995) with their remains found in cat scats (Karl & Best, 1982).

Cats have even been responsible for the disappearance of whole populations. The most well know story being the Stephen's island wren (*Xenicus lyalli*), which were supposedly discovered and exterminated by the lighthouse keepers cat in 1894, but more likely a number of cats on the island (Galbreath & Brown, 2004; Kuschel, 2012). The North Island saddleback /tieke (*Philesturnus rufusater*), pied tit/miromiro (*Petroica macrocephala*), tui (*Prosthemadera novaeseelandiae*) and kakariki/red-crowned parakeet (*Cyanoramphus novaezelandiae*) were eliminated on Cuvier Island, off the Coromandel coast, mostly through predation by cats (Department of Conservation, n.d.-f). On Stewart Island the endemic brown teal (*Anas aucklandica chlorotis*) has become extinct (Hayes & Williams, 1982), and weka (*Gallirallus australis scotti*) have almost been exterminated (Harper, 2004). However, rabbits have often been controlled by cats to almost the point of extermination (Gillies & Fitzgerald, 2005) and in some cases rats and mice are well controlled by cats (B. M. Fitzgerald & Turner, 2000).

Indeed, there are a number of cats famed for their pest control abilities. A number of cats have been 'employed' by the Prime Minister of the United Kingdom as 'Chief Mouser to the Cabinet Office' at 10 Downing Street (The Guardian, 2016; The Telegraph, 2016; Wikipedia, 2016) and 'Towser' even made it into the Guinness book of records for catching a known 28,899 mice during her lifetime as a mouser in the Glenturret Distillery, Scotland (BBC News, 2014; Purr'n'Fur, n.d.). This skill in rodent control is why we must take care when controlling cats. Detrimental flow on effects can occur, such as an increase in rats or other predators, which could be harmful to birds (S. A. Morgan et al., 2009). Until all predators have been exterminated we must keep a careful balance. There is, of course, no doubt that cats must be stopped from killing birds: even if it means a loss of dignity (Figure 4.11 and 4.12).

Figure 4.11 **CatBibs™ are very effective at reducing the number of birds caught by domestic cats (Calver, Thomas, Bradley, & McCutcheon, 2007), photo retrieved from imgur (2015).**

Figure 4.12 **Bright collars have been shown to reduce a cat's effectiveness at catching birds (Hall, Fontaine, Bryant, & Calver, 2015), photo retrieved from Kiwi Cat Collars (2015).**

Chapter 5

Research question 1: Using big data sets to assess the effect of moon phase and illumination on nocturnal mammalian pests

5.1 Introduction

Carl Sagan once said "you have to know the past to understand the present" (Mandelo, 2012), and he being generally acclaimed as one of the greatest scientists of the 20th century I am inclined to agree with him. In this section we explore two historical data sets, with the aim that they will help reveal the nocturnal secrets of rats (*Rattus spp.*), possums (*Trichosurus vulpecula*), mice (*Mus musclus*), stoats (*Mustela erminea*) and cats (*Felis catus*). The activity of these pests was recorded in both the North and South Islands of NZ as part of previous research based at Lincoln University. Through inspecting this data we have been able to shed further light on whether pests in NZ change their activity levels in response to moon phase. Unfortunately we were unable to include illumination in this section as the data available was too coarse to reveal any trends. Additionally, other information which would have helped reveal the factors impacting pest activity were unavailable to us; such as vegetation type, cloud cover and canopy cover. However, even without this information we were able to glean some understanding of how moon phase impacts these pests. The findings from this historical data helped lead the present study into pest activity levels and give us insight into two factors which have some impact on their activity levels; moon phase and illumination.

5.2 Data from the Blue Mountains, West Otago, 2014

5.2.1 Methods

Study site:

This data was collected in October 2013 and January 2014 (41 nights total) within the Rankleburn forest, Blue Mountains, West Otago and coordinated by Elaine Murphy (Murphy et al., 2014). Infrared cameras (27 LTL Acorn 5210A and 6 Bushnell Trophy cam on their default factory settings) were installed 400m apart along a line with 400m between the lines (Figure 5.1). The cameras were set near a re-setting toxin delivery device (Spitfire) (Figure 5.2). The DOC200 traps were baited with rabbit meat or eggs to attract stoats. The other species considered were brushtail possums (*Trichosurus vulpecula*), ship rats (*Rattus rattus*), pacific rats/ kiore (*R. exulans*), Norway rats (*R. norvegicus*) and mice (*Mus musclus*). Tracking pads were used to identify animals that entered the trap but did not trigger the spitfire sensor.

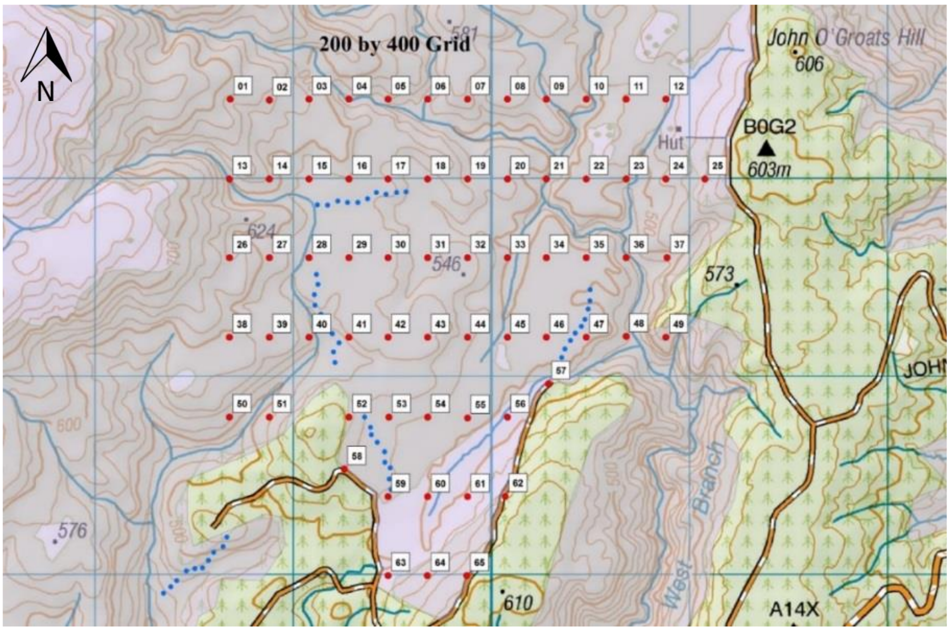


Figure 5.2 **Map of the PAPP 40% Spitfire field trial, Blue Mountains, West Otago (Murphy et al., 2014)**

Figure 5.1 **Light green specks indicate small amounts of PAPP 40% toxin in a triggered Spitfire DOC200 boxes (Murphy et al., 2014)**

Data analysis:

Activity outcomes (presence/absence) were modelled for each individual species using a generalized linear mixed model (GLMM) with a binomial distribution and a logit link function. Camera ID and day No. were treated as repeated measures as they are not true replicates but instead considered random effects (Bengsen et al., 2014). In an attempt to explain the variations in activity the following fixed effects were entered into the full model:

- Total rain between sunset and sunrise for the Blue Mountains region (retrieved from Metservice, from the Gore weather station (46.112S 168.888E))
- Moon phase (one day on either side of each phase (i.e. 3 days total): full, first quarter, new, third quarter)
- Presence (0 or 1) – dependent variable
- Illumination levels (retrieved from timeanddate.com/moon/) as a fixed effect but removed due to collinearity

To ensure model accuracy, collinearity was controlled before derivation of the full model. Collinearity was achieved by removing one variable from each pair of explanatory variables that were strongly correlated with each other. The final explanatory fixed variables were moon phase and total overnight rain (mm). Illumination was not used here because the illumination data was not precise enough to accurately represent on the ground illumination conditions and correlated strongly with moon phase.

The fixed variables remaining were entered into the model (rain and moon phase). The least significant variables were dropped (rain) and the analysis re-run. The model with the most significant variables and with the lowest AIC (Akaike's Information Criterion) score was selected as the final model.

After the final model was selected the LS means function was used to extract the mean activity for each moon phase and give us the probability of detection of a pest (or all pests on the combined model). Next, a multiple species model compared the mean of pest activity (rats, mice, possums, stoats and combined) each moon phase against each other moon phase.

All analyses were run using R i386 3.2.2 software (R Core Development Team 2010). For the GLMMs, the "lme4" package (Bates, Machler, Bolker, & Walker, 2015) was used, and for multiple comparisons the "multcomp" package (Hothorn, Bretz, Westfall, & Heiberger, 2008) was used.

5.2.2 Results:

Moon Phase

No significant difference was found in activity levels between moon phases for the individual pest species nor when all pest activity was combined (Figure 5.3-7). The error bars overlap considerably, indicating that moon phase does not have a significant effect on pest activity levels. Consequently, the standard error for each analysis was reasonably large, and the sample statistics do not adequately represent the population parameter.

Stoat, mice and rat activity did not change significantly between moon phases, however during the full moon stoats, rats and mice were less active (Figure 5.4, 5.5 and 5.7). Possums were least active in the last quarter and their activity increased slightly on full moon (Figure 5.6). In the total pest activity analysis the full moon showed the least amount of activity but the difference between the moon phases was small (Figure 5.3); the difference in probability of detection between a full moon and the other phases was 0.02–0.06. Unfortunately, detection was low overall with activity clustered around several camera traps.

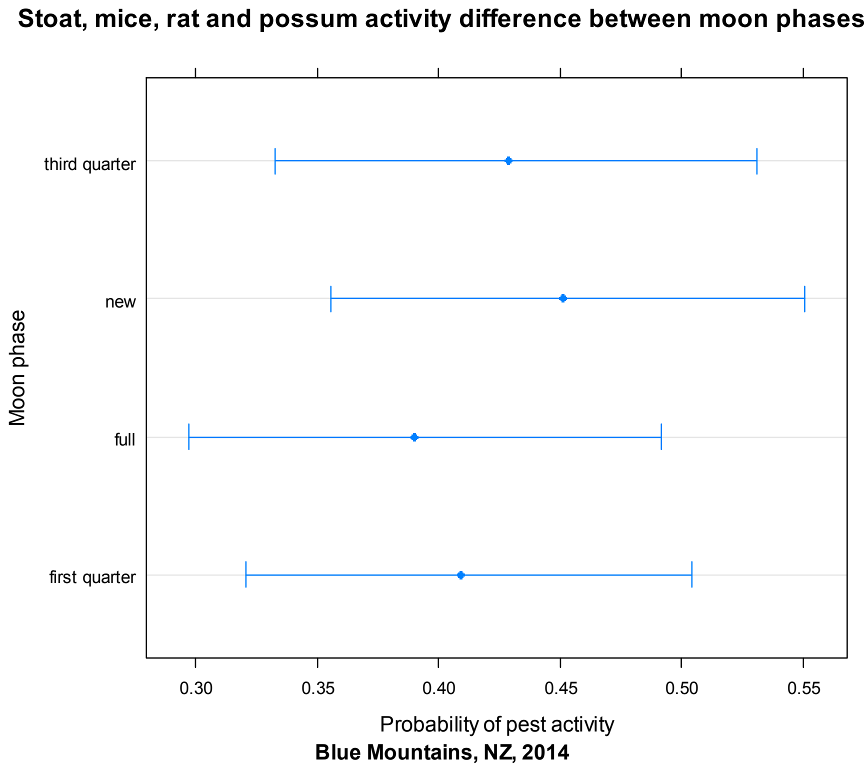


Figure 5.3 A comparison of least-square means between stoat, mice, rat, and possum presence and moon phase as predicted from the general linear

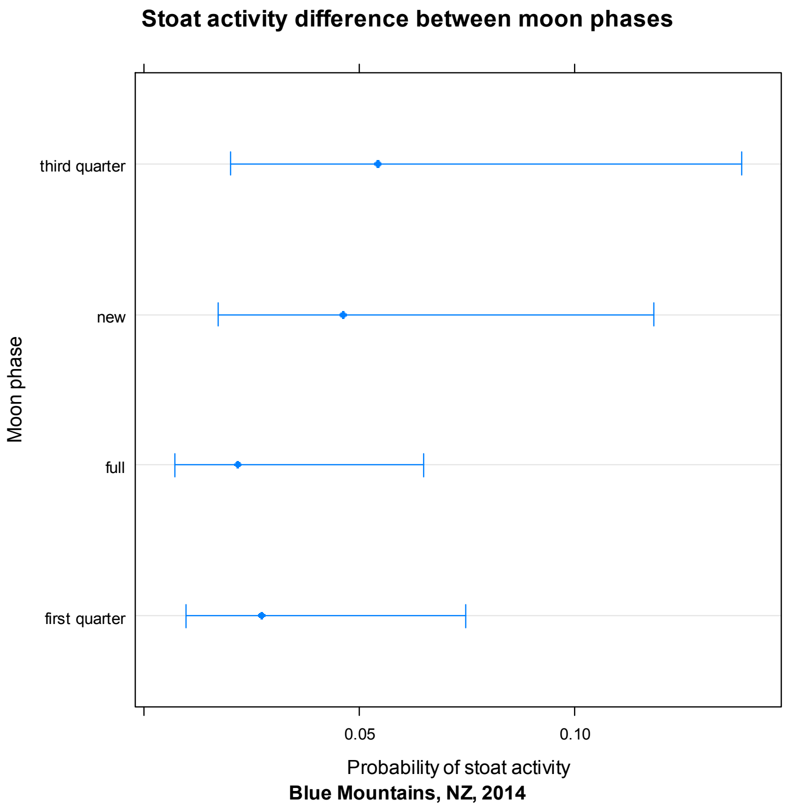


Figure 5.5 A comparison of least-square means between stoat presence and moon phase as predicted from the general linear model.

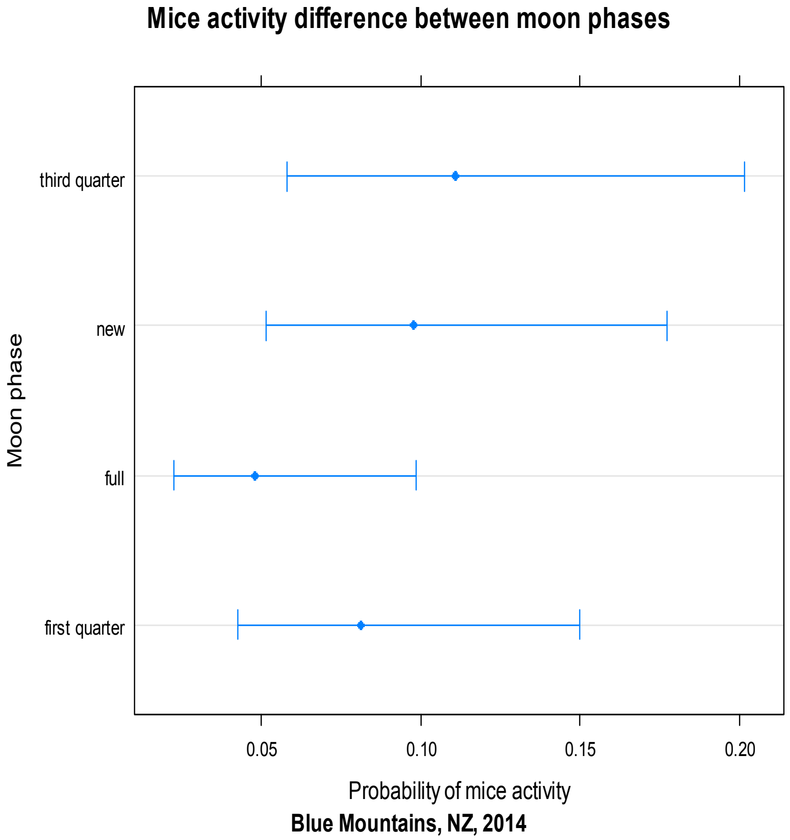


Figure 5.4 A comparison of least-square means between mice presence and moon phase as predicted from the general linear model.

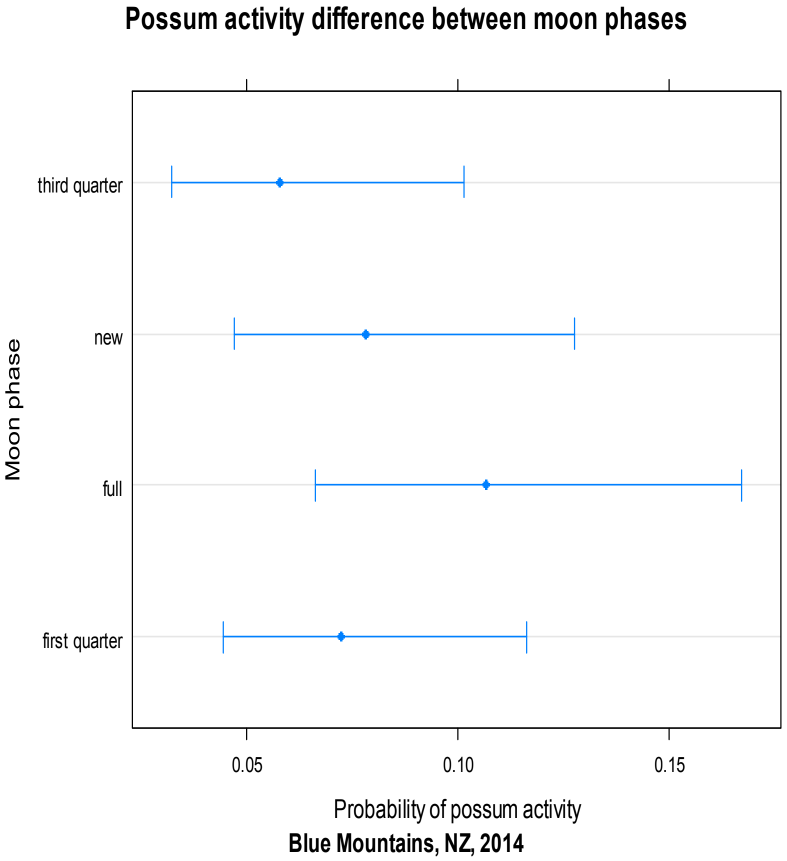


Figure 5.6 **A comparison of least-square means between possum presence and moon phase as predicted from the general linear model.**

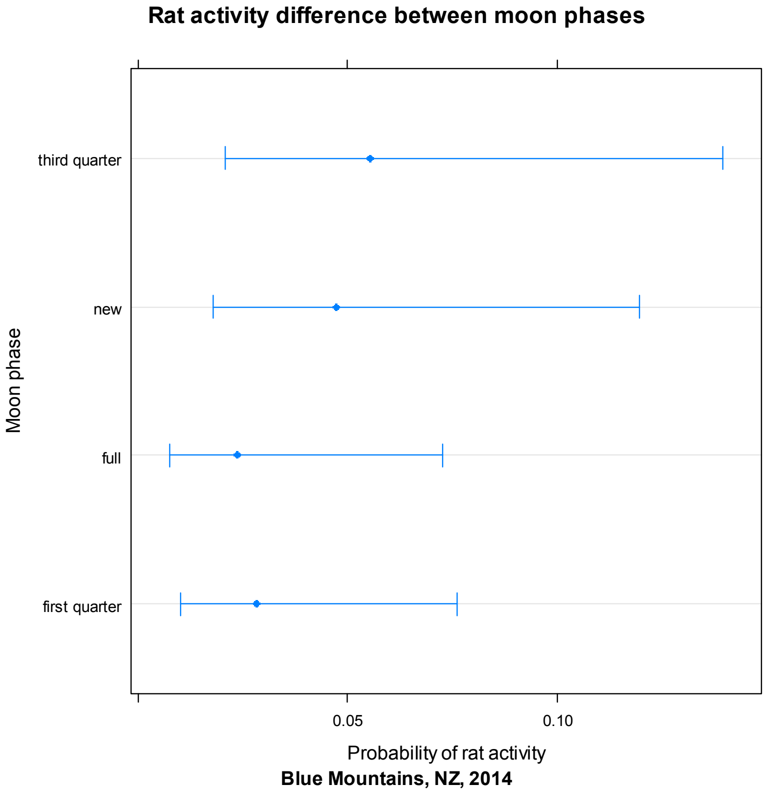


Figure 5.7 **A comparison of least-square means between rat presence and moon phase as predicted from the general linear model.**

Camera activity

Within each data set some cameras detected a higher number of pests (Tables 5.2 – 5.6). The cameras were always set in the same location. Vegetation type may have influenced detection but this data was unavailable.

Rainfall

During the sampling period (27/08/2013-2/12/2014) one night experienced 11mm of rain and more than half the time rainfall was under 2mm (Figure 5.8). Rainfall was not a significant predictor variable but we did observe some patterns. For pests combined the lowest probability of detection was between 0.5–2 mm, with 0–0.5 mm and 2–10 mm with similar rates (Table 5.1). Rates of detection were higher under heavy rainfall but detections were overall lower on these nights. Additionally, these detections were all on the same night and on the first quarter. The highest detection rates of mice were when rainfall was lowest (16.52%) and this detection rate was roughly halved (8.33%) during the heaviest rainfall experienced. Possums showed a steadier decline in detection rates as rainfall increased. All individual pests had higher detection rates on lower rainfall nights (Table 5.1).

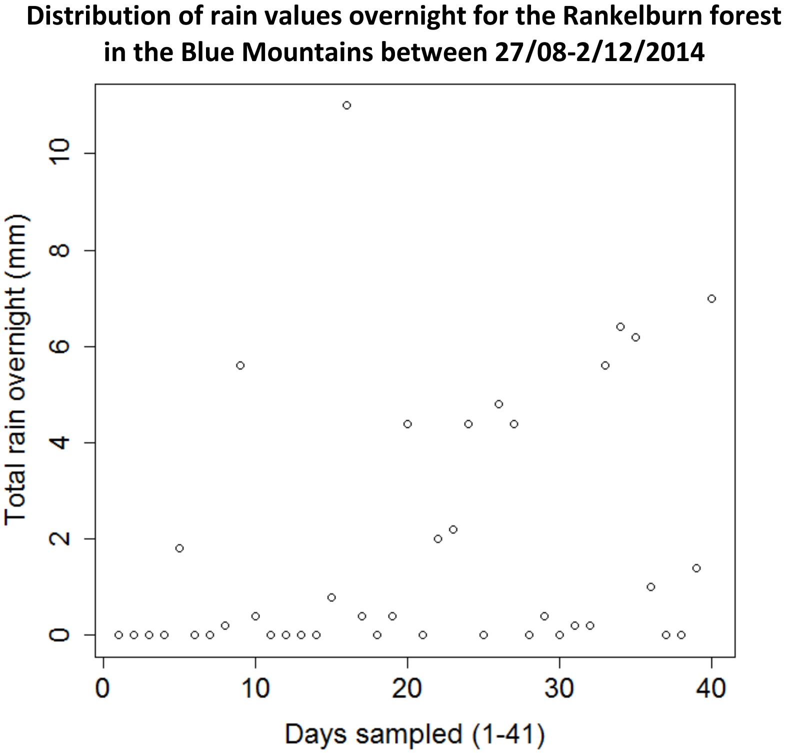


Figure 5.8 **Total nightly rainfall between 27/08/2013-2/12/2014 within the Rankleburn forest, Blue Mountains, West Otago**

Table 5.1 The impact of rainfall on the probability of detection of possums, rats, mice, stoats and the total impact on all pests detected in the Blue Mountains, Otago (2014). Presence/absence indicates number of images captured.

	Total rain at night (mm)			
All pests:	**0-0.5mm**	**>0.5-2mm**	**>2-10mm**	**>10-15mm**
absence	295	73	125	12
presence	233	37	95	10
*	78.98%	50.68%	76.00%	83.33%
	Total rain at night (mm)			
Mice:	**0-0.5mm**	**>0.5-2mm**	**>2-10mm**	**>10-15mm**
absence	557	113	221	24
presence	92	17	39	2
*	16.52%	15.04%	17.65%	8.33%
	Total rain at night (mm)			
Rats:	**0-0.5mm**	**>0.5-2mm**	**>2-10mm**	**>10-15mm**
absence	449	103	195	21
presence	57	7	25	1
*	12.69%	6.80%	12.82%	4.76%
	Total rain at night (mm)			
Possums:	**0-0.5mm**	**>0.5-2mm**	**>2-10mm**	**>10-15mm**
absence	549	123	243	24
presence	74	7	17	2
*	13.48%	5.69%	7.00%	8.33%
	Total rain at night (mm)			
Stoats	**0-0.5mm**	**>0.5-2mm**	**>2-10mm**	**>10-15mm**
absence	490	103	195	21
presence	60	7	25	1
*	12.24%	6.80%	12.82%	4.76%
* Probability of detection (%)				

Table 5.2 **All pests detected by camera traps on each moon phase in the Blue Mountains, Otago (2014). Highlights denote higher detections.**

All pests presence detected by moon phase and camera									
Camera	**First quarter**	**Full**	**New**	**Last quarter**	**Camera**	**First quarter**	**Full**	**New**	**Last quarter**
1	0	0	0	1	**12**	1	1	4	0
2	0	0	0	0	**13**	0	0	0	1
3	0	0	0	0	**14**	1	0	0	1
4	0	0	1	0	**15**	1	2	4	1
5	8	3	7	6	**16**	0	0	0	0
6	2	0	1	1	**17**	0	0	0	0
7	0	0	1	2	**18**	0	0	0	0
8	1	1	0	1	**19**	7	8	8	7
9	1	0	0	1	**20**	0	0	0	0
10	0	0	1	0	**21**	0	0	0	2
11	0	0	1	1	**22**	1	0	1	1

Table 5.3 **Possums detected by camera traps on each moon phase in the Blue Mountains, Otago (2014). Highlights denote higher detections.**

Possums presence detected by moon phase and camera									
Camera	**First quarter**	**Full**	**New**	**Last quarter**	**Camera**	**First quarter**	**Full**	**New**	**Last quarter**
1	1	4	1	2	**14**	0	2	2	1
2	0	0	1	0	**15**	0	0	3	1
3	0	2	0	0	**16**	0	0	1	0
4	3	2	1	4	**17**	2	1	0	0
5	3	1	0	0	**18**	2	0	0	0
6	0	0	0	0	**19**	1	2	0	1
7	2	2	1	1	**20**	0	2	0	0
8	4	0	2	0	**21**	0	0	0	0
9	3	4	4	1	**22**	0	3	0	0
10	3	2	3	2	**23**	0	0	1	1
11	0	1	0	0	**24**	0	1	0	1
12	0	0	1	0	**25**	2	1	2	1
13	2	0	0	0	**26**	0	0	2	1

Table 5.4 **Stoats detected by camera traps on each moon phase in the Blue Mountains, Otago (2014). Highlights denote higher detections.**

Stoat presence detected by moon phase and camera									
Camera	**First quarter**	**Full**	**New**	**Last quarter**	**Camera**	**First quarter**	**Full**	**New**	**Last quarter**
1	0	0	0	1	**12**	1	1	4	0
2	0	0	0	0	**13**	0	0	0	1
3	0	0	0	0	**14**	1	0	0	1
4	0	0	1	0	**15**	1	2	4	1
5	8	3	7	6	**16**	0	0	0	0
6	2	0	1	1	**17**	0	0	0	0
7	0	0	1	2	**18**	0	0	0	0
8	1	1	0	1	**19**	7	8	8	7
9	1	0	0	1	**20**	0	0	0	0
10	0	0	1	0	**21**	0	0	0	2
11	0	0	1	1	**22**	1	0	1	1

Table 5.5 **Rats detected by camera traps on each moon phase in the Blue Mountains, Otago (2014). Highlights denote higher detections.**

Rat presence detected by moon phase and camera									
Camera	**First quarter**	**Full**	**New**	**Last quarter**	**Camera**	**First quarter**	**Full**	**New**	**Last quarter**
1	0	0	0	1	**12**	1	1	4	0
2	0	0	0	0	**13**	0	0	0	1
3	0	0	0	0	**14**	1	0	0	1
4	0	0	1	0	**15**	1	2	4	1
5	8	3	7	6	**16**	0	0	0	0
6	2	0	1	1	**17**	0	0	0	0
7	0	0	1	2	**18**	0	0	0	0
8	1	1	0	1	**19**	7	8	8	7
9	1	0	0	1	**20**	0	0	0	0
10	0	0	1	0	**21**	0	0	0	2
11	0	0	1	1	**22**	1	0	1	1

Table 5.6 Mice detected by camera traps on each moon phase in the Blue Mountains, Otago (2014). Highlights denote higher detections.

Mice presence detected by moon phase and camera									
Camera	First quarter	Full	New	Last quarter	Camera	First quarter	Full	New	Last quarter
1	1	1	0	0	**14**	0	0	0	0
2	1	1	2	2	**15**	1	0	0	0
3	6	1	7	6	**16**	1	1	1	1
4	0	0	0	0	**17**	1	0	0	1
5	2	2	3	2	**18**	0	0	0	0
6	4	3	1	3	**19**	2	2	3	7
7	2	0	2	1	**20**	3	1	4	3
8	0	0	0	0	**21**	0	1	2	0
9	1	0	3	2	**22**	0	0	0	0
10	1	0	1	3	**23**	0	0	2	0
11	1	0	1	1	**24**	1	2	1	0
12	1	0	0	0	**25**	7	5	3	2
13	2	0	5	1	**26**	5	1	4	6

Summary of results:

We found that rain had no significant impact on pest activity levels but there was a trend with heavier rainfall equating to lower activity levels. This trend was prevalent for possums, stoats, rats and mice, as well as for the total pest activity analysis.

For all analyses there was no significant preference for moon phase – indicating that the pests could be lunar neutral. However, without an idea of site vegetation, canopy cover or accurate illumination data we cannot say for sure that the pests are in fact lunar neutral.

5.3 Data from Hawkes Bay, 2014:

5.3.1 Methods

About the data:

In 2014, Margaret Nichols coordinated a study on ferrets, stoats and feral cats in order to learn how to control them better (*Nichols* & *Glen*, n.d.). Detections for ferrets and stoats were too few to be used in this study, but there were enough cat detections (722). Eighty camera traps (settings unknown) were placed 500m apart on two pastoral properties in Hawke's bay from January 1st to March 22nd 2014 (74 nights total). The two pastoral properties (Toronui and Waitere Stations) had small patches of native bush throughout (Glen, Anderson, Veltman, Garvey, & Nichols, 2016). Toronui Station had no recent history of predator control (so served as the control) and Waitere Station served as the treatment area. The cameras were deployed for a three-week period from early April through to early June to monitor mammalian pest predator populations, specifically cats (*Felis catus*), ferrets (*Mustela furo*) and stoats (*Mustela erminea*). 80 Reconyx PC 900 (RECONYX Inc, Holmen, Wisconsin) cameras (40 at each site) were set to take three photos per trigger over the nine weeks. A lure of ferret odour and rabbit meat was placed 1.5m in front of the camera and secured with a tent peg. The cameras were mounted on wooden stakes, with the base 5cm from the ground, in a grid with 500m spacing; however there was a lenience of 100m if hazardous terrain or close proximity to livestock or roads were encountered. Three weeks of intensive predator removal followed, concluding with three weeks of post-removal monitoring.

Data analysis:

Activity outcomes (presence/ absence) were modelled for the individual species using a generalized linear mixed model (GLMM) with a binomial distribution and a logit link function. Camera ID and day number were treated as repeated measures (Bengsen et al., 2014). Only data between the hours of sunset and sunrise were considered. In an attempt to explain the variations in activity the following fixed effects were entered into the full model:

- Total rain between sunset and sunrise for the Hawke's bay region (retrieved by Metservice from the Te Pohue station (39.237S 176.687E))
- Moon phase (one day on either side of each phase (i.e. 3 days total):full, new, first quarter, third quarter)
- Illumination
- Presence (0 or 1) – dependent variable

To ensure model accuracy collinearity was controlled before derivation of the full model. Collinearity was achieved by removing one variable from each pair of explanatory variables that were strongly correlated to each other. The final explanatory variables were moon phase and the total rain overnight (mm). Unlike the previous data set, illumination was used in this model, it still correlates strongly with moon phase but less so than in the previous analysis. The Illumination data retrieved here is fairly coarse and cements why further illumination data was needed.

The remaining variables were entered into the model. The least significant variables were dropped (rain and illumination) and the analysis re-run. The model with the most significant variables (moon phase) and with the lowest AIC (Akaike's Information Criterion) score was selected as the final model.

The LS means function was used on the final model to extract the mean activity for each moon phase and give us the probability of detection of cats. Stoats and ferrets were not tested as the rate of detection was too low for the models to converge. Next, a model compared the mean of cat activity on each moon phase against each other moon phase.

All analyses were run using R i386 3.2.2 software (R Core Development Team 2010). For the GLMMs, the "lme4" package (Bates et al., 2015) was used, and for multiple comparisons, the "multcomp" package (Hothorn et al., 2008) was used.

5.3.2 Results:

Moon Phase

There is an overall effect of moon phase on cat detection, the multiple comparisons test indicated that the third quarter is significantly different to the new moon (p= 0.0456, SE = 1.6066, CI =95%). None of the other moon phases showed a significant difference in detection of the predator (Figure 5.9).

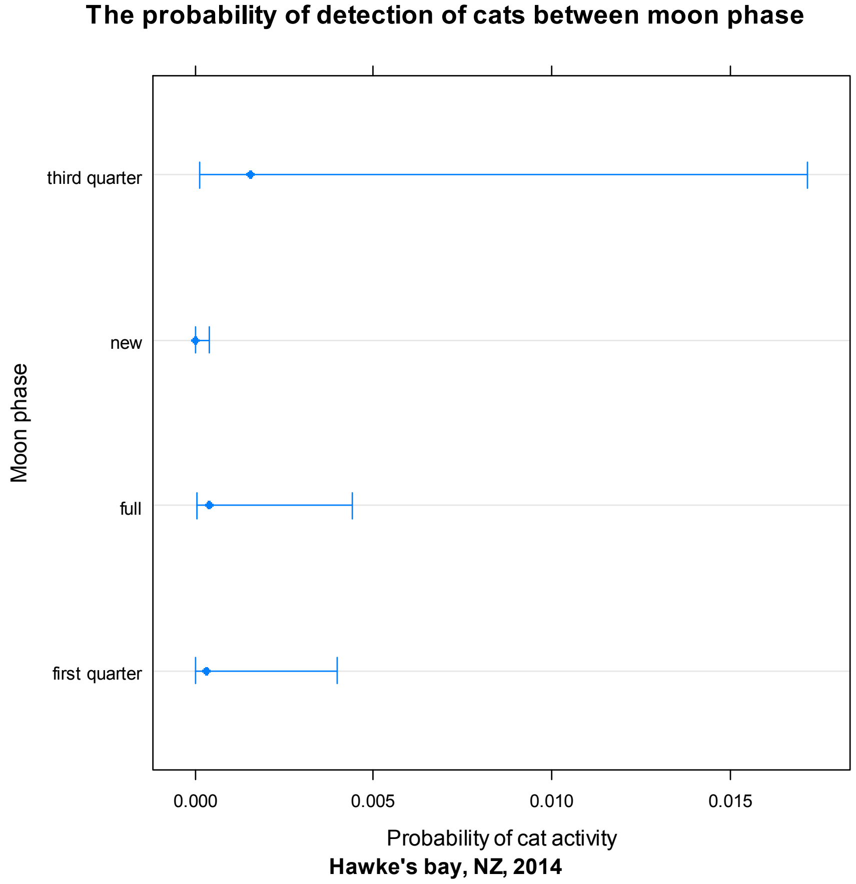
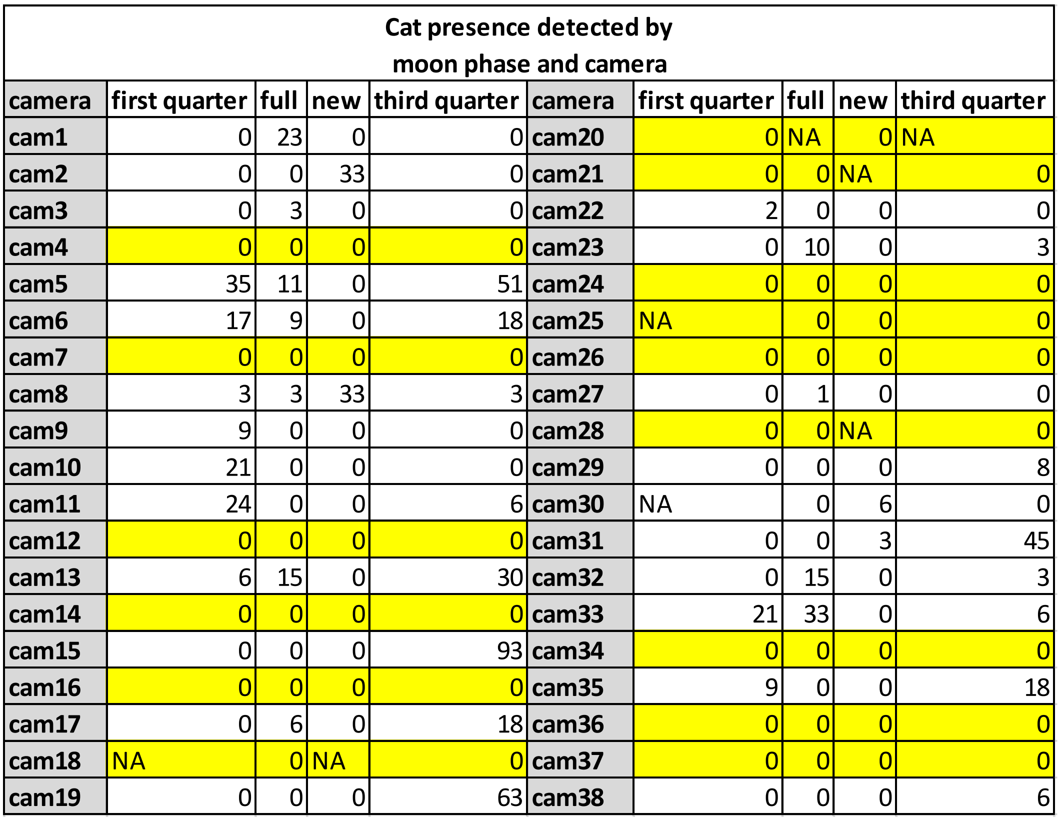


Figure 5.9 **A comparison of least-square means between cat presence and moon phase as predicted from the general linear model.**

Camera activity

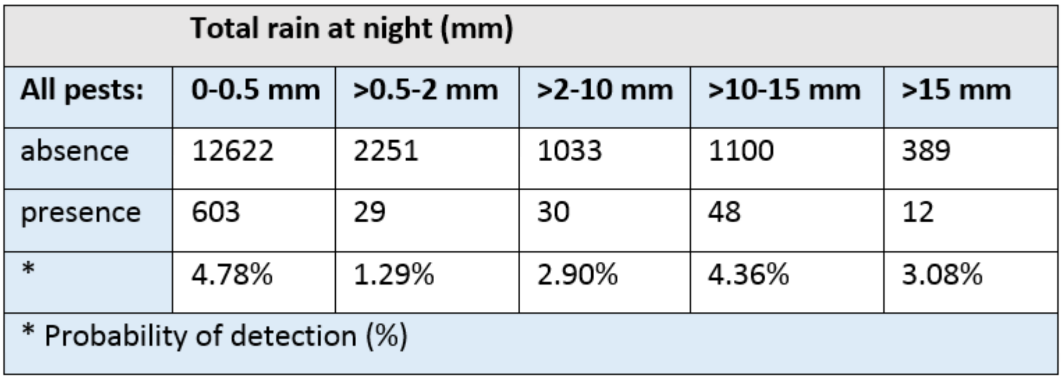
Some cameras did not record any activity. This could be due to other factors not able to be considered such as differences in slope between sites. For example 'cam5' recorded 51 instances of cat activity whilst camera 28 recorded zero presence (Table 5.8).

Table 5.7 Cats detected by camera traps on each moon phase in the Blue Mountains, Otago (2014)



Cat presence detected by moon phase and camera									
camera	first quarter	full	new	third quarter	camera	first quarter	full	new	third quarter
cam1	0	23	0	0	cam20	0	NA	0	NA
cam2	0	0	33	0	cam21	0	0	NA	0
cam3	0	3	0	0	cam22	2	0	0	0
cam4	0	0	0	0	cam23	0	10	0	3
cam5	35	11	0	51	cam24	0	0	0	0
cam6	17	9	0	18	cam25	NA	0	0	0
cam7	0	0	0	0	cam26	0	0	0	0
cam8	3	3	33	3	cam27	0	1	0	0
cam9	9	0	0	0	cam28	0	0	NA	0
cam10	21	0	0	0	cam29	0	0	0	8
cam11	24	0	0	6	cam30	NA	0	6	0
cam12	0	0	0	0	cam31	0	0	3	45
cam13	6	15	0	30	cam32	0	15	0	3
cam14	0	0	0	0	cam33	21	33	0	6
cam15	0	0	0	93	cam34	0	0	0	0
cam16	0	0	0	0	cam35	9	0	0	18
cam17	0	6	0	18	cam36	0	0	0	0
cam18	NA	0	NA	0	cam37	0	0	0	0
cam19	0	0	0	63	cam38	0	0	0	6

Table 5.8 The impact of rainfall on the probability of detection of cats detected in Hawkes Bay, 2014



Total rain at night (mm)					
All pests:	**0-0.5 mm**	**>0.5-2 mm**	**>2-10 mm**	**>10-15 mm**	**>15 mm**
absence	12622	2251	1033	1100	389
presence	603	29	30	48	12
*	4.78%	1.29%	2.90%	4.36%	3.08%
* Probability of detection (%)					

Rainfall

Rainfall was not a significant predictor variable. During the sampling period (January 1st to March 22nd 2014) there was one night where it rained a total of 22.2mm, more than half of the time rainfall was under 2mm (Figure 5.10). Cat presence decreased on nights with higher rainfall. There was a slight increase in cat activity on three nights where it rained between 10-15mm, and all occurred on the third quarter; the phase when cat activity was highest (Table 5.8). The number of detections overnight in relation the amount of rainfall was not significant, however we did observe some patterns. On a night with low rainfall (0 – 0.5 mm) a camera has a 4.78% chance of capturing a cat whilst on a night with heavier rainfall (>15 mm) the chance of this predator being caught on camera is 3.08% (Table 5.7).

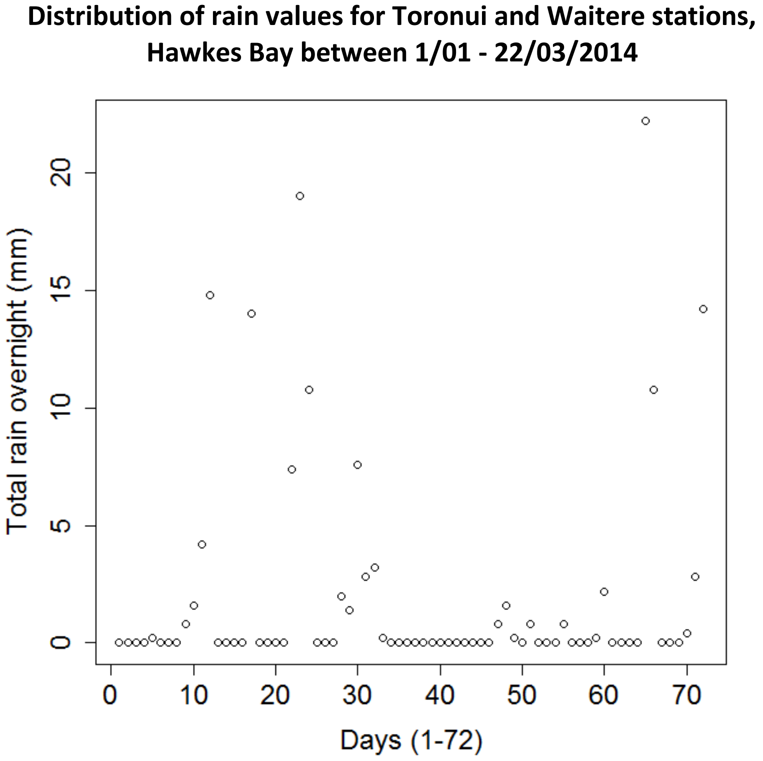


Figure 5.10 **Total rainfall for the 72 nights between 1/01 - 22/03/2014 at the two field sites, Tornui and Waitere Station in Hawkes Bay.**

Summary of results:

Moon phase had a significant impact on the activity levels of cats. Within this study period it was far more likely to encounter the predator during the moons third quarter and far less likely to detect a predator on the new moon. The third quarter and new moon had a significantly different detection rate of the predator (Figure 5.9). This result is different to that found in the previous data set and does not align itself with labelling the pests as lunar philic, phobic or neutral – perhaps lunar influenced would best describe the pest's reactions.

Rain had an impact on pest activity but was not significant. Illumination showed little effect on predator activity however this may be because the data was not fine enough. There was a large difference between some cameras detection rates, this may be due to factors or conditions unknown to us.

5.4 Discussion:

This chapter set out with the aim of assessing the effect of moon phase on nocturnal mammalian pest activity. Two data sets collected for other purposes were examined, one from the Blue Mountains in Otago and the other from Hawke's Bay. Both data sets utilised camera traps to measure indices of activity but each focussed on different pests. The Blue Mountains data set concentrated on possums (*Trichosurus vulpecula*), rats (*Rattus spp.*) and mice (*Mus musclus*). While the Hawke's bay data set focussed on stoats (*Mustela erminea*), feral cats (*Felis catus*) and hedgehogs (*Erinaceus europaeus*). However, only cats were considered within this study as detections rates for stoats and hedgehogs were too small. In this section I will discuss the findings within both data sets, compare the two and identify areas of potential improvement.

5.4.1 Pest activity in the Blue Mountains, West Otago, 2014:

Contrary to expectations, this study did not find a significant impact of moon phase on pest activity levels. There was no difference between moon phases and the only trend found was in possums. They were marginally less active on the last quarter and their activity began to increase towards the full moon before dropping down again as it reached the first quarter. At most we can suggest that possums are lunar influenced, clearly there is some relationship going on but it is not strong enough to make any grand statements.

When possum, rats and mice were combined into one data set, the analysis showed the least amount of activity on the full moon but the difference between the moon phases was minor. Possible explanations for this might be that the sample size was too small and perhaps the pest's behaviours are too different from each other for a combined model to expose any trends.

An important biologically relevant finding was that as rainfall increased pest activity tended to decrease. This result is in agreement with several studies which have showed that heavy rain decreased activity patterns of possums (Cowan & Clout, 2000; Jolly, 1976; Wayne et al., 2006).

For all analyses (each pests individually and the combined analysis) there was no significant preference for moon phase, indicating that possums, rats and mice could be lunar neutral. However, without an idea of other explanatory variables, such as site vegetation, canopy cover or accurate illumination data, we cannot say for sure that the pests are in fact lunar neutral.

5.4.2 Pest activity in Hawke's Bay, 2014:

One interesting finding here was that cats are significantly more likely to be detected on the last quarter and are highly unlikely to be detected on a new moon (p= 0.0456, SE = 1.6066, CI =95%, Figure 5.9). There are several possible explanations for this unexpected result. Perhaps this is a goldilocks effect, on the last quarter it may be not too dark, not too light but just right. It seems more likely however that variables other than moon phase were impacting the cat's activity, such as weather conditions. We know that rain reduces cat activity and the results here support this. On nights with higher rainfall cat presence decreased, not significantly but a trend was clear. These results are consistent with data obtained in Harper (2007) and in Haspel and Calhoon (1993); both found feral cat activity reduced significantly as precipitation increased. Higher rainfall also decreases the activity of a cats' prey, as was shown from Murphy's data presented earlier, an additional factor that would discourage cats' from foraging (Churcher & Lawton, 1987).

Other than rain we had no data available regarding conditions such as vegetation, temperature, illumination or cloud cover. A number of studies conclude that rain and temperature significantly impact feral cat activity levels. For example, (Haspel & Calhoon, 1993) found feral cats were more active as temperature increased. It could be that during Nichol's data collection temperatures were more favourable, by happenstance, on the last quarter, and vice versa on a new moon (when activity decreased). Or it could be that there were higher levels of rain on a new moon, which would also reduce the temperature, compounding a cats desire to find shelter.

Cat hunting activity is influenced by shelter and by habitat. The extinction of cats on Campbell Island has been attributed, in part, to a lack of shelter (Harper, 2007). So, shelter is important, but finding prey is too. Where a cat is most active is often determined by where prey densities are highest. In a study by B. M. Fitzgerald & Karl (1986), cats were found to be most active on the flat valley floor, while in a study by Harper (2007), steeper slopes were prowled more regularly. We do now know that cat activity is influenced by moon phase, which might be as important as these other variables.

Moon phase explained more of the variation in the data than rainfall did. These results do not suggest that cats are lunar philic, phobic or neutral – perhaps lunar influenced would best describe the cats' behaviour. A potential explanation for this unclear result is that of the two sites used one had recently undergone predator control, thus was used as a treatment site. The data set was not separated into control and treatment thus this could not be taken into account. What it could mean in terms of activity around the moon phases is that the treatment site would likely have fewer prey animals than the control. Thus cats may have moved out of the controlled area or were more active looking for the less dense prey population.

5.4.3 Overall discussion for the Blue Mountains and Hawkes Bay data sets:

In this investigation, the aim was to assess whether moon phase has an impact on the behaviour of possums, rats, mice and cats. It appears rats, possums and mice may be lunar neutral, while cats could be lunar influenced. There were a number of factors which made it difficult to present a clear picture of what is impacting these pests. Some of the camera traps detected significantly more pests than others and a number of potential explanatory variables were not able to be included.

Unfortunately, detection was low overall with activity clustered around several camera traps. This disparity in detections could be due to the habitat surrounding each trap. Information on vegetation, illumination and canopy cover were not included in these data sets thus they could not be tested for. For example, we know that nocturnal mammals change their behaviour in different vegetation types, so this may explain the disparity between pest detection at different trap locations. Possums and rats are prey to a number of animals in other parts of the world and avoiding risk areas is a common anti-predator response. Pickett et al. (2005) suggest that tall grasses and shrubs may hide the predator of a possum or rat; and whilst they face a much smaller threat of predation here, this behaviour may continue to be present. This theory is contrary, however, to evidence showing that the lack of predators has changed possum behaviour; some possums have moved from the trees and have taken to nesting in dense ground vegetation or under logs(Kerle, 2001). So, it may be that in areas with low detections it was not predator avoidance but perhaps there was a lack of potential dens in the area, if habitat data had been included in the data sets this would have been investigated.

This train of thought applies to food sources as well. In the study by Lennon (1998) there were three walnut trees within sight of the bait station, erected to measure indices of activity of possums. Lennon (1998) suggests that the poor results achieved from this bait station may have been due to the more favoured feeding ground nearby; the walnut trees. A similar scenario may have played out here, where the pests may have been attracted to a food source nearby that resulted in individuals being more active within the area of one camera than another. Although both studies used bait to lure the animals to the cameras (the Blue Mountains study used rabbit meat or eggs, the Hawkes Bay study used ferret odour or rabbit meat) and one assumes this would attract the pests at a similar rate to any other interesting foods in the area, as well as override any avoidance of the new object (the camera). So, perhaps it was other variables within a camera traps area that caused some traps to record more activity than others.

One such variable which has been known to impact nocturnal mammalian activity is illumination (Gursky, 2003; Kronfeld-Schor et al., 2013; Marcum et al., 2006). For example Johnson and De Leon (2015) found that rodents were more likely to give up food, i.e. reduce their foraging, when light levels were high, due to a perceived increase in predation risk. We were unable to obtain adequate illumination data in order to apply it here, and even if it was available we would have been unable to account for canopy cover's impact on ground illumination levels. It may be that the cameras with higher levels of detections were all under canopy cover and thus would consistently have lower illumination levels that sites without it.

There are some significant limitations in the studies conducted on this topic to date. Studies should be undertaken to explore how variables which interact with any potential impact from moon phase, such as canopy cover, cloud cover and illumination, influence nocturnal mammalian pests. Inclusion of site descriptive variables would allow a more thorough analysis of pest activity and may result in clearer conclusions being drawn. Accurate 'on the ground illumination' levels would have been incredibly valuable for these analysis. Several studies have attempted to measure this factor but have struggled to do so in a biologically significant way (Dutton, 2008; Gilbert & Boutin, 1991; Lennon, 1998; Parisi, 2011). A natural progression of this work is to investigate methods of measuring illumination, this would shed light on how the activity levels of nocturnal mammalian pests might be affected. These limitations will be addressed within the second research question (refining methods of measuring on the ground illumination), and the third research question will consider the impact of canopy cover, cloud cover and vegetation.

5.5 Acknowledgements

I would like to thank Margaret Nichols and Elaine Murphy who generously gave permission for their data to be analysed as a part of this research.

Chapter 6

Research question 2: Measuring illumination in a biologically meaningful way exploring methodologies

6.1 Introduction

Previous research tends to focus on a nocturnal mammal's response to moon phase, and have either discounted, or been unable to measure, illumination levels. There are good reasons for this, measuring the amount of light at ground level is not easy. Moon phase and levels of illumination are often closely correlated and are difficult to interpret separately. Considering all this, the ability to state whether an animal is lunar philic, phobic or neutral tends to be incredibly valuable information on its own. However, in New Zealand we need to have a robust knowledge of mammalian pest's nocturnal behavioural patterns in order to reduce their populations more effectively. If we were able to measure illumination levels with reliable equipment it would make collecting illumination data far more realistic. Currently there are some studies that have successfully measured light levels in a biologically applicable way, but most of these focus on the impact of urban light pollution (Gil, Honarmand, Pascual, Pérez-Mena, & Garcia, 2015; Goyret & Yuan, 2015; Rich & Longcore, 2004). We need a light meter that can measure in dark areas with little to no light pollution, as well as withstand New Zealand's often harsh weather conditions. A standardized method that can measure on the ground illumination in a biologically significant way would be a useful tool in the field of animal behaviour and ecology. This section attempts to show whether the Sky Quality Meter is up to the task.

6.2 Methods

To explore illumination levels a super sensitive light meter was used, a common light meter (such as the HOBO H8 Pro series) is not sensitive enough to pick up the low levels of light considered in this study (Parisi, 2011). I used a Sky Quality Meter (SQM) used by astronomers to measure sky brightness (Unihedron, n.d.). The SQM was recommended by a number of scientists, one being Steve Butler who runs the Dark Sky Group of the Royal Astronomical Society of NZ and uses a SQM themselves and find it of similar power to their own more advanced spectrometer (S. Butler, pers. comm., November 5, 2015). The recently retired senior technician at the Mt John Observatory, Alan Gilmore, also endorses the SQM. There are two SQMs at Mt John and they use them to measure the brightness of moonless skies each month to record long-term changes (A. Gilmore, pers. comm., November 3, 2015). The device measures in magnitudes per square second of arc (mag/arcsec^2) and considers how dark the sky is. So the higher the value the darker the night. The nomogram (Figure 6.1) compares sky brightness in mag/arcsec^2 to micro candelas per square meter, here you can see that as the mag/arcsec^2 get larger conditions are darker. For example, on a night of approximately

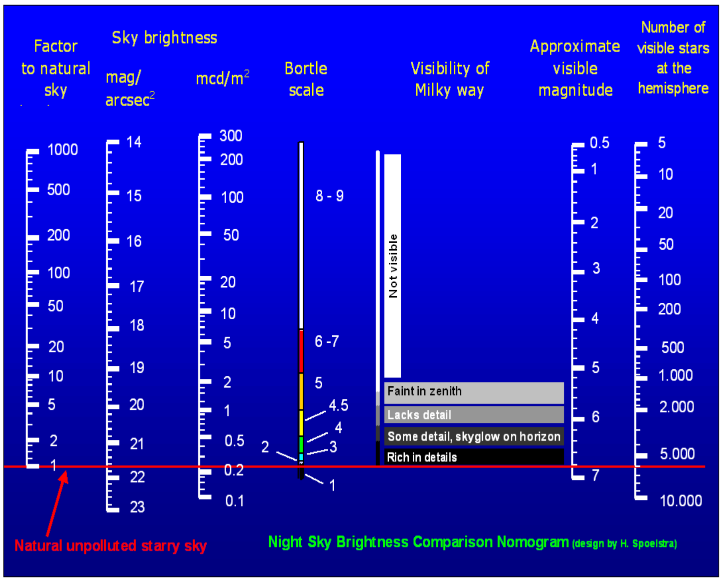


Figure 6.1 Night Sky Brightness Nomogram (Spoelstra, n.d.)

Figure 6.2 Study sites to be used for the field trials, Banks Peninsula. (Map data Google, 2015)

22 mag/arcsec^2 the Milky Way should be clearly visible, whereas below 19.5 mag/arcsec^2 the feature will be invisible to our eyes

The specific model used in this study is the SQM-LU-DL, a USB enabled data-logging light meter (Unihedron, n.d.). Illumination levels were read throughout the night every five minutes over two months for five nights on each moon phase (full, first quarter, last quarter and new) at two field sites on Banks Peninsula (Figure 6.2). The sites were in Okuti Valley (647443.74 m E, 5150398.84 m S (UTM)) and on the Waipuna saddle (643600.55 m E, 5158486.66 m S (UTM)), closed and open canopy readings were taken at each site for each moon phase. The impact on levels of illumination under different densities of cloud cover and canopy cover was considered.

6.2.1 Data analysis

The maximum observed illumination (mag/arcsec^2) levels per hour were used in a linear mixed model. The following fixed effects were entered into the full model:

- Moon phase (full, first quarter, new, third quarter)
- Time (from sunset to sundown)
- Cloud cover (0, 2, 4, 7, 8, 9 Octas–retrieved by Metservice, from the Christchurch international Airport NZ)
- Canopy cover (open and closed)

The fixed variables were entered into the model. All non-significant variables were dropped and the analysis re-run. Time was dropped first, then cloud cover. Accordingly, the final explanatory fixed variables were moon phase and canopy cover. An ANOVA comparing the models was run, the model with the most significant variables and with the lowest AIC (Akaike's Information Criterion) score was selected as the final model. Finally, the LS means function was used to extract the mean illumination values for both moon phase and canopy cover.

All analyses were run using R i386 3.2.2 software (R Core Development Team 2010). For the linear model, the "lme4" package was used (Bates et al., 2015).

6.3 Results

The illumination data collected was found to be right skewed, this was not unexpected as our focus is on the darker (higher) values. The decision was made that the data would not be transformed to be more normal as the linear models are capable of dealing with skewed data.

The greatest variation in time was between the hour immediately before sunrise, 5am, and 10pm at night (average hourly difference = 3.92 mag/arcsec^2) (Table 6.1). The linear models showed time was non-significant in describing illumination variations throughout the night. Meaning an overall illumination value per night would be sufficient when applying illumination data in an ecological study.

Table 6.1 Average hourly illumination between sunset and sunrise for Okuti Valley Reserve (closed canopy) and Waipuna Saddle (open canopy) between 13/02 – 9/04/16.

Average Illumination (mag/arcsec2)	
8pm	19.53
9pm	20.88
10pm	21.13
11pm	21.01
12am	20.34
1am	20.83
2am	21.09
3am	21.10
4am	20.20
5am	17.22

The final linear model included only moon phase and canopy cover, time and cloud cover were found to be non-significant. The analysis showed clear evidence that canopy cover (open and closed) and moon phase (new, full, first quarter, last quarter) significantly impact illumination levels ($p = <0.001$). The multiple R-squared for this model was 0.9569 and the adjusted R-squared was 0.9566 including a good fit. An interaction term did not improve the model so both moon phase and canopy cover were left in as individual variables.

The lsmeans package visualised the difference between the means for each moon phase and for each level of canopy cover. There was a significant difference in illumination levels between the full moon and all the other phases (Figure 6.3). Mean illumination levels for the full moon rest around 17 mag/arcsec^2 (Figure 6.4). First quarter, last quarter and new moons record a darker 22-24 mag/arcsec^2. Supporting our findings in the linear model showing the difference in means between an open canopy and a closed canopy displays a distinct difference between the two (Figure 6.5). Under an open canopy it is likely to be significantly lighter than under a closed canopy.

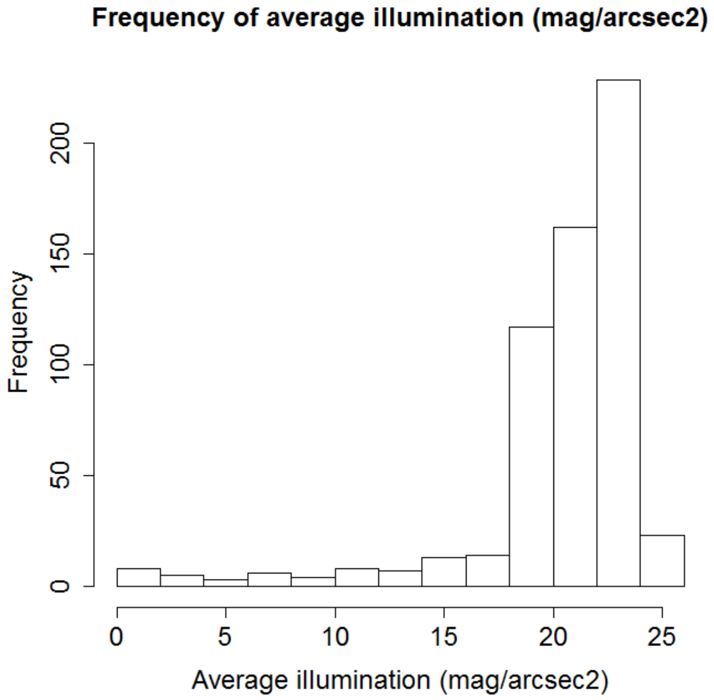


Figure 6.4 **Frequency of average illumination levels between sunset and sunrise for Okuti Valley Reserve (closed canopy) and Waipuna Saddle (open canopy) between 13/02 – 9/04/16.**

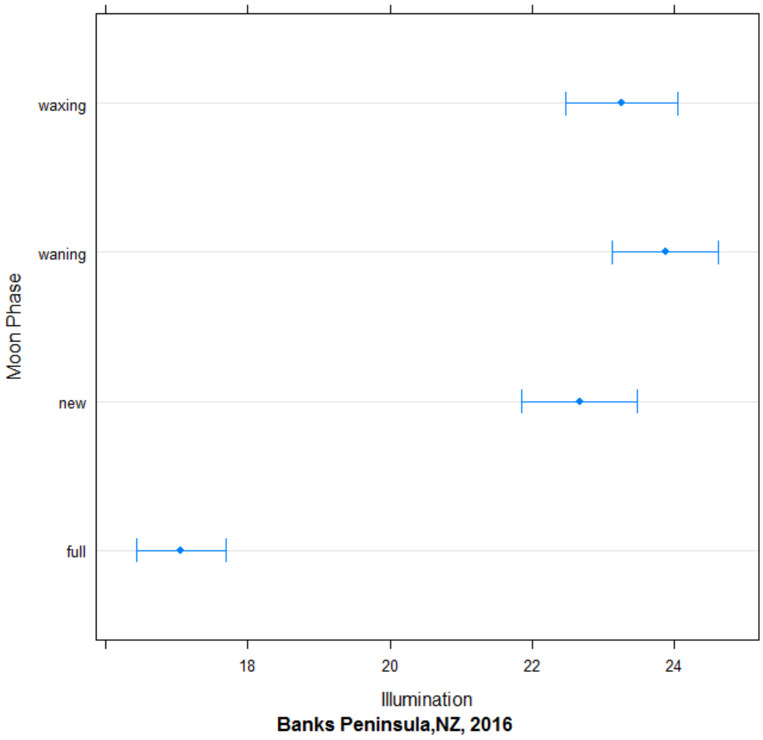


Figure 6.3 **Average hourly illumination levels between sunset and sunrise vary significantly between the full moon and the three other phases.**

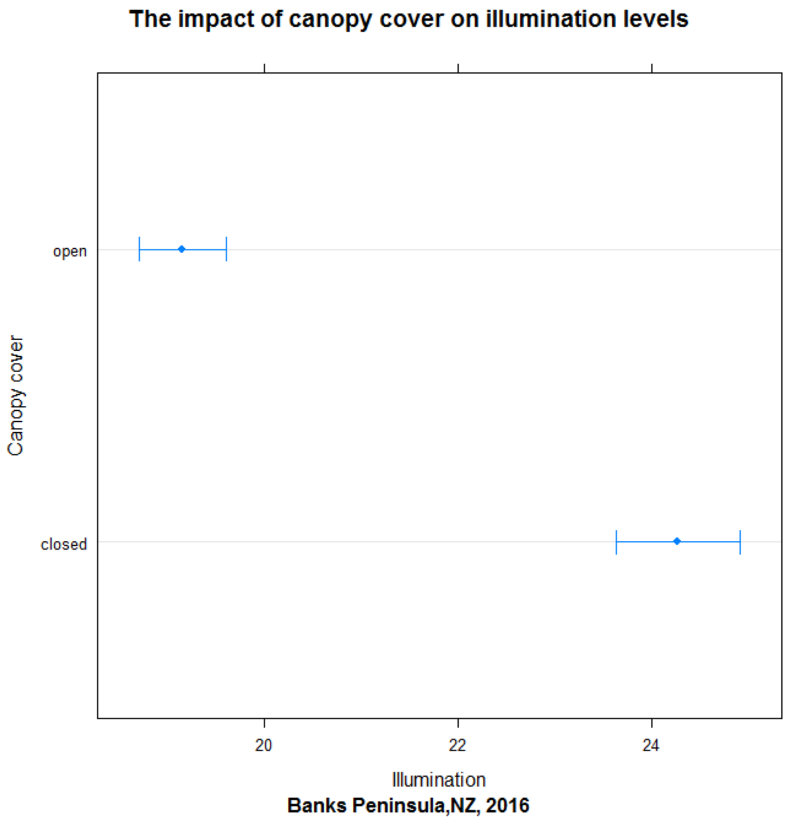


Figure 6.5 Average hourly illumination levels between sunset and sunrise vary significantly between open and closed canopy cover.

6.4 Discussion

This study set out with the aim of assessing how effectively a Sky Quality Meter (SQM) could measure on the ground illumination levels and measure differences during different moon phases and under open and closed canopies. The tool (inside a waterproof casing) was attached to a stake, often with twine, and exposed to the elements of Banks Peninsula; where, as residents there know, conditions can be harsh. Yet the set up survived every storm and all gale force winds to deliver it's packet of detailed data through an easy to use computer program (Unihedron Device Manager).

The SQM has proved that it can detect the differences in illumination between both canopy cover densities and moon phases. In fact 96% of the variation in illumination levels were accounted for in a model with both explanatory variables (multiple R^2 = 0.9569). These findings suggest that the SQM is able to detect the light differences between the moon phases and between canopy covers. There was also no significant interaction suggesting that canopy cover and moon phase should be considered independently.

Unsurprisingly, closed canopy was found to be significantly darker than open under all moon phases, meaning that conditions did not become too dark for the meter to measure as occurred in previous studies (see chapter 2). Additionally, the full moon was shown to produce much lighter conditions than the other moon phases. What was surprising was that the new moon, first quarter and last quarter were very similar in their illumination levels, whilst the full moon sat distinctly brighter than all three (Figure 6.4). Very little was found in the literature regarding how moon phase impacts illumination levels as studies on light levels studies have tended to focus on urban light pollution (Abdullahi, Roslan, & Kamarudin, 2016; Birriel, Wheatley, & McMichael, 2010; Davies, Bennie, Inger, & Gaston, 2013; Gil et al., 2015; Katz & Levin, 2016; Kyba et al., 2011; Rich & Longcore, 2006). The results of this study, however, show that the meter is able to detect variations in illumination between moon phases regardless of cloud cover, rain and canopy cover.

A final observation was that the variables dropped out of the model, time and cloud cover, had little impact on illumination levels. Additionally, throughout a night it appears light levels tend to stay reasonably constant until near sunrise when light levels begin to increase. It is worth noting, that this could be due to human error when removing the daylight data as the times for sunrise and sunset were reasonably coarse so it is possible that a brighter reading was unaccounted for.

In conclusion, this study has demonstrated that the Sky Quality Meter can indeed detect illumination differences between moon phases and between canopy covers, suggesting that the tool can measure on the ground illumination in a biologically significant way. This finding highlights the importance of moon phase and canopy cover when considering the impact of illumination on nocturnal animals. It also displays the strong relationship between moon phase and illumination. Research on animal behaviour often focusses more on the impact of moon phase than that of illumination; sometimes due to a lack of understanding, but more often because the equipment has not been available within the research period. The SQM allows moon phase and illumination to be untangled and applied to data separately. The challenge now is to apply this new understanding of how a SQM can be used in New Zealand's dark conditions and apply this data to the wanderings of nocturnal mammals.

Chapter 7

Research question 3: Assessing nocturnal mammalian pest activity based on big data sets and updated methodologies

7.1 Introduction

Nocturnal mammalian pests impact New Zealand's ecology and economy. Possums (*Trichosurus vulpecula*), rats (*Rattus* spp.), mice (*Mus* musclus), stoats (*Mustela erminea*) and cats (*felis catus*) either compete with fauna, prey on them or both (King, 2005). This has caused a great number of, in particular, bird species to decline with some populations disappearing altogether. Monitoring and controlling these pests is expensive, but protecting the unique flora and fauna of our islands is priceless. By cultivating a greater understanding of nocturnal mammalian pests we can increase the efficiency and effectiveness of monitoring and control.

One area of knowledge in which we are lacking is how these pest's behaviours are influenced by moon phase and illumination levels. Over the past twenty years three studies have been conducted in New Zealand to study the impact of these abiotic variables on possum (*T. vulpecula*) behaviour. The studies did not expand to other nocturnal mammalian pests. Lennon (1998) theorised that possums were lunar phobic, yet ten years after his study Dutton (2008) found the animal displayed lunar philic tendencies. Alternately, Parisi (2011) postulated that the possums are, in fact, lunar neutral (See chapter 2). Clearly there are some factors at work preventing us from understanding brushtail possums. One might be that all three of the studies had difficulty in collecting illumination data, the technology available was not sensitive enough and could not be used to measure illumination in a biologically significant way. Meaning that illumination as an explanatory variable essentially had to be removed from the equation. Thus, to date we have no clear understanding of how moon phase and illumination impact possums and other nocturnal mammalian pests.

It's important that we understand how these factors impact the pests because, as a country, we rely on our spectacular scenery to attract tourists (of which pests are slowly destroying) and the exports of our dairy/beef farmers (to which possums are able to spread bovine Tb to). Our government has even set the lofty goal of a pest free NZ by 2050. If we can pin down how rats, stoats, mice and possums react to lunar phase and/or illumination then we can streamline pest control and monitoring by targeting the pests when they are most active.

To achieve this, the Blue Mountains and Hawkes Bay data sets (see chapter 5) helped garner a greater understanding of pest activity around the phases of the moon; we discovered that there is some relationship occurring but the lack of accurate on the ground illumination data meant that not enough light could be shed on the picture. To combat this a relatively new piece of illumination measuring equipment was trialled (Sky Quality meter/SQM). This was found to successfully measure the changes in illumination between moon phases and canopy cover. Conditions on the full moon and under an open canopy were significantly lighter than the other phases and a closed canopy respectively.

The next step was to combine these two new pieces of knowledge. To do so, presence/absence activity data was collected using Waxtags™ and camera traps, while SQM's measured the levels of illumination on the ground, at three locations on Banks Peninsula. This data was analysed to discover any changes in activity levels in the nocturnal pests. This was the first time biologically applicable illumination data was successfully collected and used to discover any impact on NZ's nocturnal mammalian pest's activity. Here, we show that moon phase impacts possums, rats and mice (using the Waxtag™ data) significantly, and the camera trap data showed illuminations significant impact on a wider variety of pests.

7.2 Methods

Having acquired a greater understanding of how illumination is impacted by other abiotic factors the Sky Quality Meter (SQM) was then applied to field trials. The SQM was used in conjunction with camera traps (see below) and Waxtags™ to assess any changes in activity levels of nocturnal mammalian pests between four moon phases (full, new, first quarter, and last quarter). Stoats, cats, rats, mice and possums were the focus but other nocturnal mammals were recorded (see chapter 7.3.2). Other variables considered were canopy cover (percentage cover, and open or closed), habitat type (tussock/grassland, pine plantation or lowland podocarp-broadleaf forest) cloud cover, temperature, rainfall, wind speed and wind direction. Weather variables were retrieved from Metservice, cloud cover (0, 2, 4, 7, 8, 9 Octas) was recorded at the Christchurch International Airport, and all other weather variables stated were recorded at Le Bons Bay (–43.746S 173.122E, elevation: 236 m above sea level).

7.2.1 Study sites

Figure 7.1 **Field sites on Banks Peninsula, Canterbury, New Zealand. Waipuna Saddle and the Port Levy plantation are both within the Port Levy saddle area. Okuti Valley is the third field site. (Map data Google, 2015)**

The three study sites (Figure 7.1), Port Levy Plantation (643600.55 m E, 5158486.66 m S (UTM)), Okuti Valley reserve (647443.74 m E, 5150398.84 m S (UTM)) and Waipuna saddle (644892.62 m E, 5158289.64 m S (UTM)), are located in Banks Peninsula, New Zealand. Parisi (2011) and (Dutton, 2008) used Port Levy Plantation and Okuti Valley in their studies but were unable to include illumination levels and only focused on the new and full moon. The habitat varies between the sites, allowing the impact of vegetation and habitat on pest activity to be considered. Waipuna Saddle (Figure 7.2 and 7.4) consists of grasslands, tussock, exotic pine forest, tōtara (*Podocarpus tōtara*) forests, and some regenerating native bush. The pine plantation (Figure 7.3 and 7.4) is dominated by *Pinus radiata,* but the understory has some ferns, native fuchsia (*Fuchsia excorticata*), tōtora and mosses. Bordering one side of the pine plantation are tussock grasses, the other a dirt road. Okuti Valley (Figure 7.5) is a forested reserve made up of lowland podocarp-broadleaf's such as kahikatea (*Dacrycarpus dacrydioides*), tōtara, māhoe (*Melicytus ramiflorus*), kotukutuku (*Dacrycarpus dacryioides)*, kānuka (*Kunzea ericoides*), ponga (*Cyathea dealbata*), mamaku (*Cyathea medullaris*), nikau (*Rhopalostylis sapida*), pate (*Schefflera digitate)* and puahou (*Pseudopanax arboreus*). Many relatively common birds, such as the songthrush (*Turdus philomelos)* and blackbird (*Turdus merula*), are present in the reserve along with less common natives, including;

Ruru/morepork owl (*Ninox novaeseelandiae*), tui (*Prosthemadera novaeseelandiae*), korimako/bellbird (*Anthornis melanura*), piwakawaka/fantail (*Rhipidura fuliginosa*) .

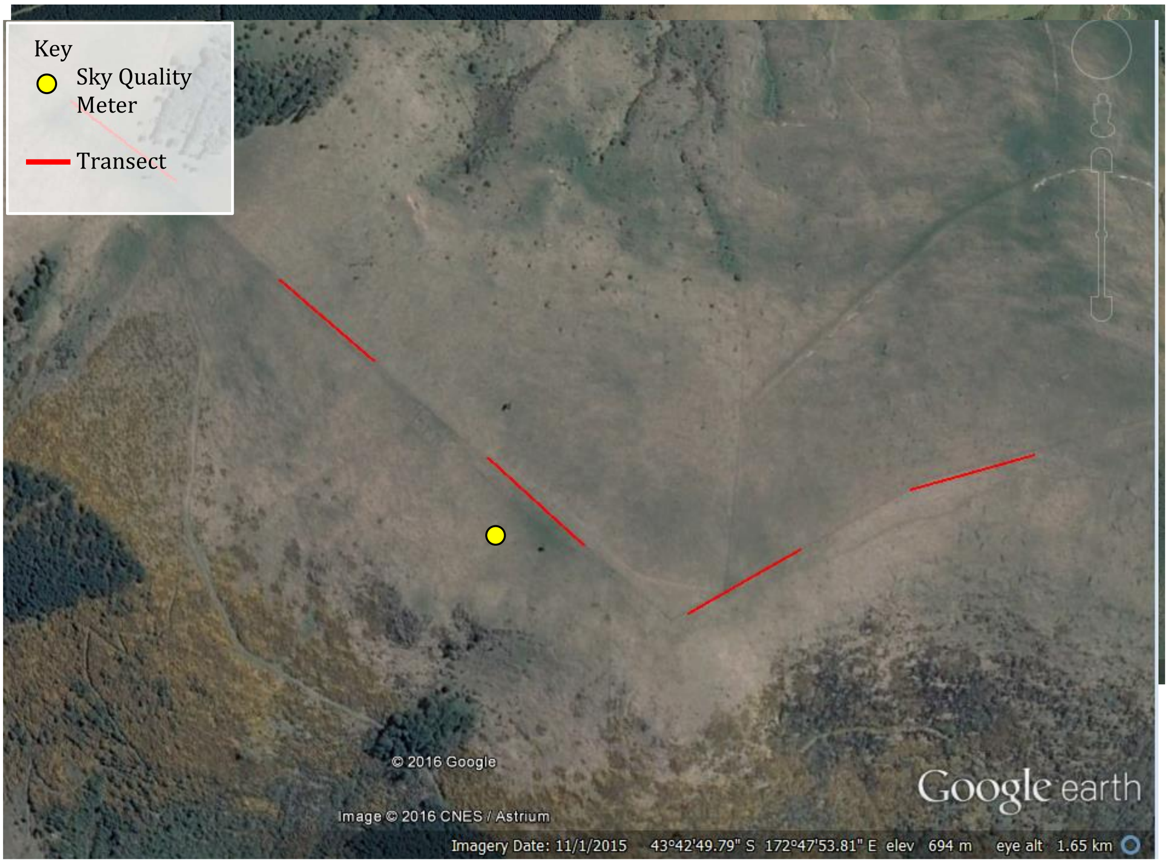


Figure 7.3 **Waxtag and camera trap transects on Waipuna Saddle, Banks Peninsula**

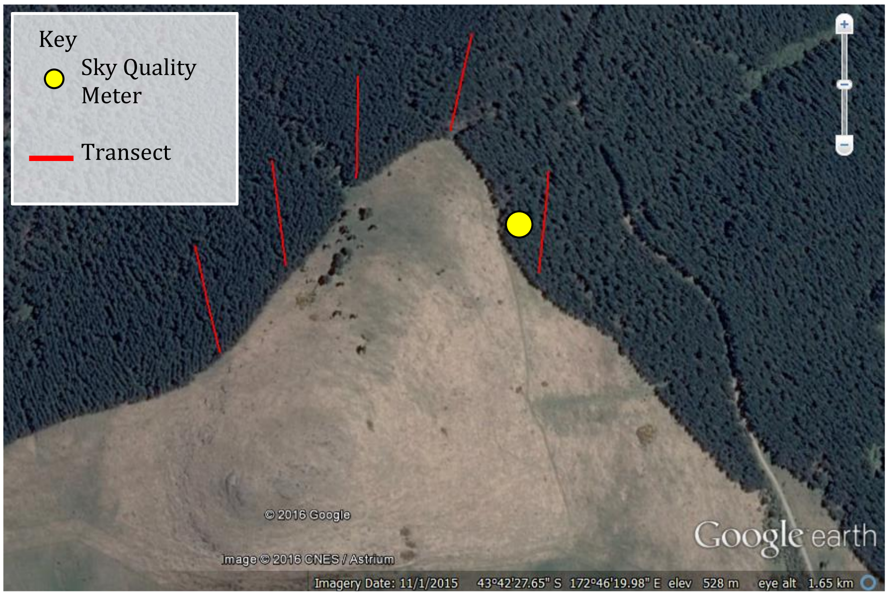


Figure 7.2 **Waxtag and camera trap transects in the Port Levy Plantation, Banks Peninsula.**

Figure 7.5 Waxtag and camera trap transects at Okuti Valley Reserve

7.2.2 Sampling protocol

The three sites were sampled during autumn/winter from May–June 2016 on Banks Peninsula, New Zealand. Each site was sampled four times, under each moon phase, 12 nights were sampled at each site. Camera traps and Waxtags™ recorded levels of pest activity and SQM's recorded illumination levels.

Non-toxic fluorescent tags, Waxtags™ (Figure 7.6) are widely used across New Zealand to measure pest activity (National Possum Control Agencies, 2010). In this study they were used to calculate an index based abundance estimate which was extrapolated to measure pest activity levels. Activity levels are calculated based on bite marks from possums, rats or mice present in the wax (Figure 7.10). No lures were set so as to avoid saturation (where devices are flooded with subjects and give an unreliable estimate as to the actual activity levels) or contagion (where possums actively search for Waxtags™ inflating indices of abundance) (M. D. Thomas, Morgan, & Maddigan, 2007). At each site 25 wax tags were left for three nights around a moon phase, i.e. the night before a full moon, the night of a full moon and the night after. The tags were affixed to the base of a tree or fence pole approximately 30cm above the ground. The wax tags were spaced 20m apart along five transect lines spaced 100m apart (Figure 7.7). This method has been developed by the National Possum Control Agencies

(2010); it encourages independence between wax tags so the potential for a single pest reaching and biting a large number of the tags in the area is significantly reduced. GPS coordinates of each wax tag were also recorded. When retrieving the Waxtags™ line and tag number were noted on the plastic backing of each tag.

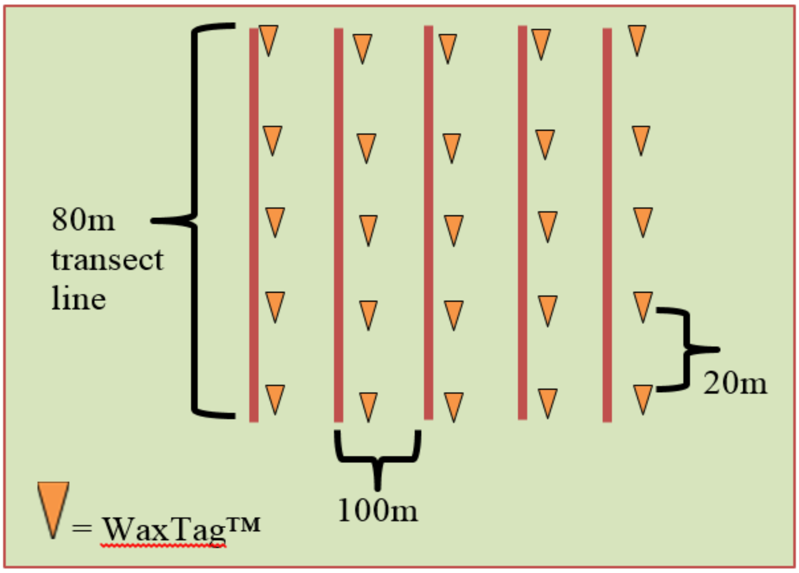


Figure 7.7 **Ideal Waxtag™ layout as described by the National Possum Control Agencies (2010)**

Camera traps (Figure 7.8) are well suited for densely vegetated areas with high rainfall and rugged topography and are widely used to collect data on animal presence and activity in challenging landscapes (Tobler, Carrillo-Percastegui, Pitman, Mares, & Powell, 2008) such as New Zealand' s forests (e.g. Okuti Valley) and the Port Levy pine plantation. Camera traps are most often used to create indices of population abundance and are particularly useful here as it is not necessary to identify individuals from the photographs in order to calculate abundance or activity (Bengsen, Leung, Lapidge, & Gordon, 2011). This method is cost effective and particularly good at collecting presence data (De Bondi, White, Stevens, & Cooke, 2010).

The cameras used were the LTL Acorn 5210A and the Bushnell Trophy cam. A camera was placed at random (by rolling a six sided die for every line) on each transect line (i.e. five cameras per site) and left active for the same duration as the wax tags (i.e. for 3 days on either side of the moon's phase). The cameras were attached 30cm above the ground to either a nearby tree or stake, and faced the wax tag. The camera traps collected count data, this being the number of animals seen in a night per camera. The cameras were programmed to take three photos with flash whenever the sensor was triggered. Rechargeable batteries (brands:

PowerEx, Eneloop and Powertech) were used in every camera and were fully charged after each sampling run (approximately 60% of the charge was exhausted in each battery after 3 days but this was different with each brand).

Figure 7.8 LTL Acorn camera traps were used to record animal activity

Other data recorded for both the wax tags and cameras were canopy cover (which impacts the level of ground illumination), habitat type, vegetation, geographic location and season. Canopy cover was recorded as a percentage (10, 20…100%). Estimated vegetation density (dense/moderate/sparse) and height (metres) were recorded. Habitat was described as RENB (regenerating exotic and native bush), PRP (*Pinus radiata* plantation), MPB (mixed podocarp-broadleaf) or TG (Tussock grassland). Weather variables (cloud cover, rain fall, temperature and wind speed) were acquired from Metservice (R. Hamilton, pers. comm., 26 January–July 29, 2016). Additionally, the impact of the field sites on data analysis was reduced by randomising the moon phase and site; helping prevent animals from learning and thus changing their behaviour.

Illumination was measured using a SQM-LU-DL, a USB enabled data-logging light meter (Unihedron, n.d.). Illumination levels were read throughout the night every five minutes over two months. The two SQM units were set up for each sampling run, one unit under canopy cover and the other with no foliage blocking its sensor (‘open’ canopy). The units were programmed to take a recording every five minutes and recorded illumination (mag/arcsec^2), temperature and battery pack voltage. The units were housed in a weather proof casing and attached to a stake so the unit was 60 cm above the ground to reduce interference from animals and insects.

7.2.3 Data analysis

Activity outcomes (presence/absence) were modelled using a generalized linear mixed model (GLMM) with a binomial distribution and a logit link function. For Waxtags™, camera ID and night were treated as repeated measures, for camera traps these were Site and Camera ID (Bengsen et al., 2014). In order to explain variations in activity the following fixed effects were entered into both the Waxtag™ and camera trap full models:

- Total rain between sunset and sunrise (retrieved from the Le Bons bay weather station, data provided by Metservice, NZ)
- Moon phase (full, first quarter, new, third quarter)
- Presence (0 or 1) – dependent variable
- Average hourly Illumination levels (mag/arcsec2)
- Cloud cover (included in only the Waxtag™ model)

Illumination data was retrieved every five minutes over each three day sampling period. For Waxtags™ these values were averaged over the three nights sampled, i.e. an average illumination for each moon phase was used. For camera traps illumination was averaged over each night. Weather data was retrieved from Metservice (R. Hamilton, pers. comm., 26 January–July 29, 2016). The cloud cover data was collected at Christchurch International Airport, all other weather data (rainfall, temperature, and wind speed and wind direction) was collected at the Le Bons Bay weather station.

To ensure model accuracy, collinearity was controlled before derivation of the full model. Collinearity was achieved by removing one variable from each pair of explanatory variables that were strongly correlated to each other. The fixed variables remaining were entered into the model. The least significant variables were dropped and the analysis re-run. The model with the most significant variables and with the lowest AIC (Akaike's Information Criterion) score was selected as the final model. After the final Waxtag™ model was selected the LS means function was used to extract the mean activity for each moon phase and give us the probability of detection of a pest. Once the final Camera trap model was selected the GLM outcomes were plotted using a marginal effects plot, adjusted for all predictors, using the sjp.glmer function.

All analyses were run using R i386 3.2.2 software (R Core Development Team 2010). For the GLMMs, the "lme4" package (Bates et al., 2015) was used, and for multiple comparisons the "multcomp" package (Hothorn et al., 2008) was used.

7.3 Results

In total, 73 pests were detected by Waxtags™ and by camera traps over all moon phases within the sampling period (6/5/16 – 22/7/16). Okuti valley reserve had the highest number of detections (n=43) (Figure 7.8).

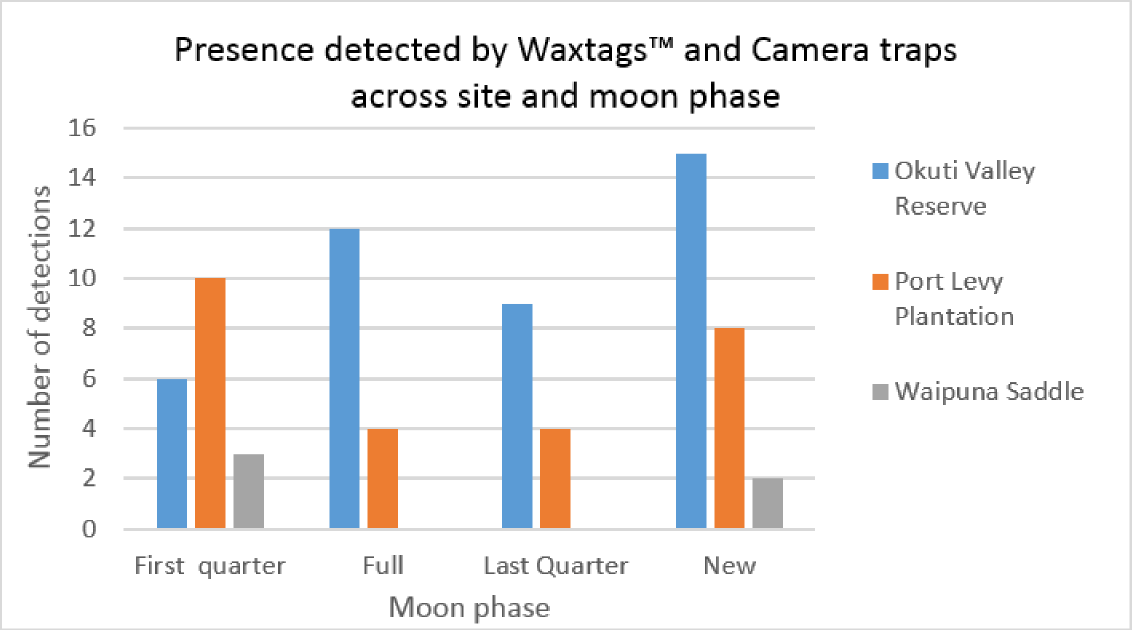


Figure 7.9 **Total pest presence detected by both Waxtags™ and camera traps during the sampling period (6/5/16 – 22/7/16)**

7.3.1 Waxtags™

Bites of rats (*Rattus* spp.), possums (*Trichosurus vulpecula*) and mice (*Mus musclus*) were identified (Figure 7.10) and any unclear markings were checked by James Ross, Lincoln University (who has experience in this area (Ogilvie, Paterson, Ross, & Thomas, 2006; Vargas et al., 2009)).

Canopy cover was not able to be considered as there were too few detections under open canopy (n=3), meaning the model was unable to converge when additional explanatory variables were added. Correlations between numeric variables were tested for; rain correlated with temperature (-0.6) and with wind (0.55) therefore temperature and wind were not run in the models (see appendix A.1.). Illumination and moon phase were run in separate models as moon phase was a significant predictor of average illumination levels. Day and site were run as random effects. The final explanatory fixed variables were moon phase and canopy cover.

Figure 7.10 **Waxtags™ collected from Okuti Valley Reserve and Port Levy Pine Plantation. From left to right: top row: Waxtags™ front and back. Bottom row: rat, possum, mouse.**

Moon phase

Rat, possum and mouse activity was spread over the four moon phases (Figure 7.11). The highest number of detections occurred over the new moon (n=16) and the lowest under a full moon (n=5). The mean pest presence per site differed greatly between the two forested sites and the open, tussock site. Okuti Valley Reserve ($\bar{x}$ = 0.22) and Port Levy Plantation ($\bar{x}$ = 0.13) had much higher rates of detection than the Waipuna Saddle ($\bar{x}$ = 0.03). Waipuna Saddle recorded only two detections when the moon was in its first quarter and a single detection on the new moon. While the site with the highest detection rate, Okuti Valley, experienced at least three detections on each moon phase, with nine detections on the new moon. The only time Port Levy had more detections than Okuti Valley was during the moon's first quarter (Figure 7.11).

A number of generalized linear mixed models fit by maximum likelihood (Laplace Approximation), were run to assess which model fit the data best, with the "drop1" function determining which variable was the weakest modifier. The initial model (NULL) tested how fixed effects (site and day) impacted the number of detections (Table 7.1). The following

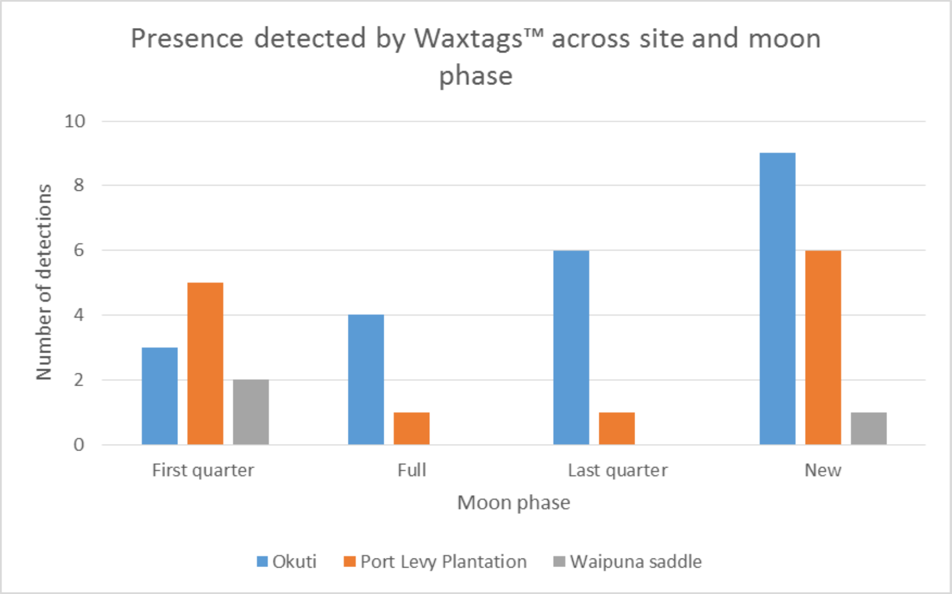


Figure 7.11 **The total number of pests detected by Waxtags™ on each moons phase and at each field site.**

model (MAM) included moon phase, maximum hourly illumination and total rain overnight (Table 7.1). Maximum hourly illumination was the first variable to be dropped (MAM1, Table 7.1), followed by the total rain overnight. The final model (MAM2, Table 7.1) included only moon phase as an explanatory variable. An ANOVA was run comparing the four models, the final model containing only moon phase was the most significant, but none of the models fully explained the data (Table 7.1).

The new and full phases were close to having significantly different activity levels (p= 0.0507, SE=0.5499, CI = 95%) (Figure 7.12) indicating that the pests might be influenced by moon phase to some extent and could, with further research and a greater sample size, be considered lunar phobic. The last quarter and full were the least significantly different (p=0.9263, SE=0.6140, CI = 95%) (Figure 7.12).

Table 7.1 **An ANOVA assessed the results from the GLM models for the Waxtag™ data set. Next to the model name are the variables included in the analysis. MAM2 was the most significant and is thus in bold.**

	Df	AIC	P-value
Null	3	221.76	N/A
MAM2 (moon phase)	**6**	**222.01**	**0.1243**
MAM1 (moon phase and illumination)	7	222.86	0.2836
MAM (moon phase, illumination and rain)	8	223.32	0.2142

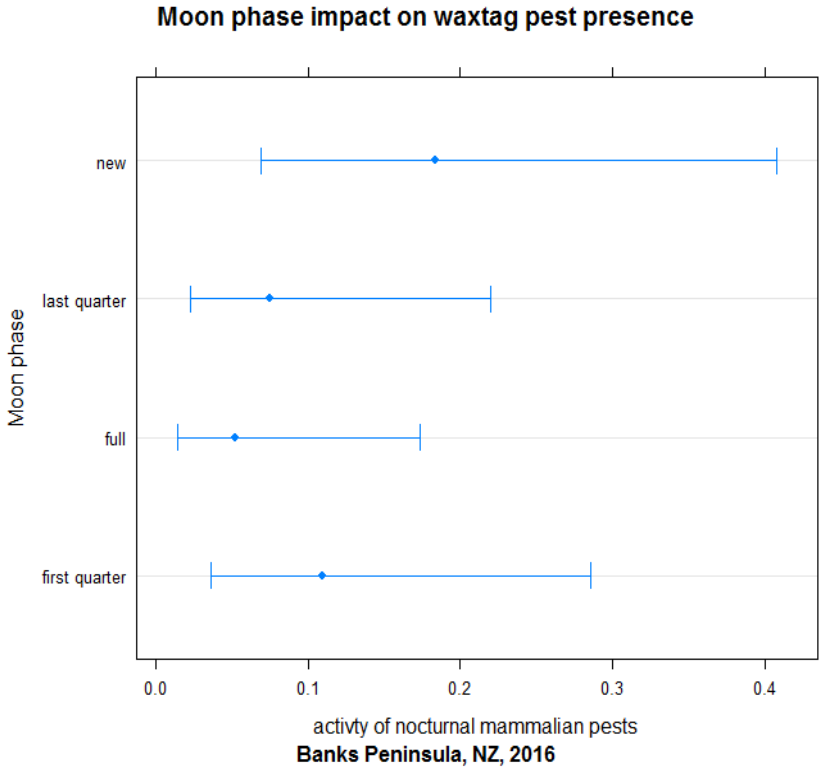


Figure 7.12 **A comparison of least-square means between pest presence and moon phase as predicted from the general linear model**

Illumination

The Sky Quality Meter measures values between -30 to +30 mag/arcsec^2, during the day average illumination will measure around 0. The higher the number the darker the conditions. Within this study, the levels of average illumination used were skewed to the right. This is because lighter daytime values were not relevant and so were removed. The values remaining were between 17 mag/arcsec^2 and 23 mag/arcsec^2 (Figure 7.13). However, Generalised Linear Mixed Models are capable of handling such non-normality.

Unexpectedly, the darkest value recorded was during the last quarter (24.54 mag/arcsec^2) but on average the new moon was darker (22.09 mag/arcsec^2), this unexpected last quarter value may be due to that nights heavy cloud cover (Figure 7.14). The full moon was the lightest night on average (19.82 mag/arcsec^2) and at maximum (22.74 mag/arcsec^2).

Overall, illumination levels on the first quarter, last quarter and new moon were darker than the full moon (Figure 7.15). There were instances where conditions were as dark on the full moon as the other phases, but this occurred under dense canopy cover. Similarly, the lightest (lowest) values for the other three phases were recorded when there was no canopy cover. Thus, we can see that under a closed canopy higher (darker) values are recorded under all moon phases, and the lower (lighter) values all occur when there is no canopy to block light.

This trend occurred when the Sky Quality Meter (SQM) was initially tested (see chapter 6). There was no median value for the full moon as the illumination levels for both closed canopy sites (Okuti Valley Reserve and the Pine Plantation) were recorded on the same night and by the same SQM, thus had the same illumination value (Figure 7.15).

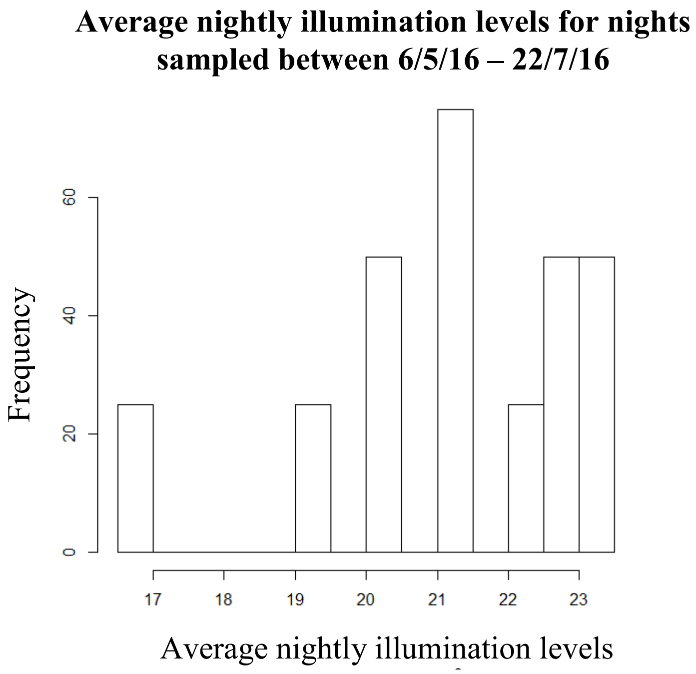


Figure 7.13 A histogram showing the spread of average hourly illumination in Banks Peninsula under open and closed canopies.

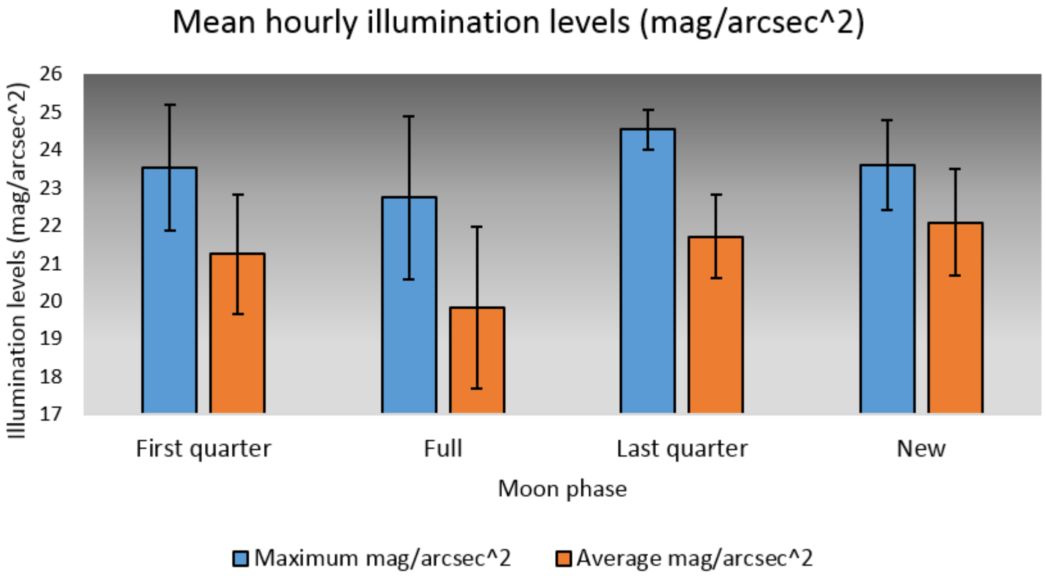


Figure 7.14 The difference in average and maximum illumination levels between the moon phases on Banks Peninsula between 6/5/16 – 22/7/16.

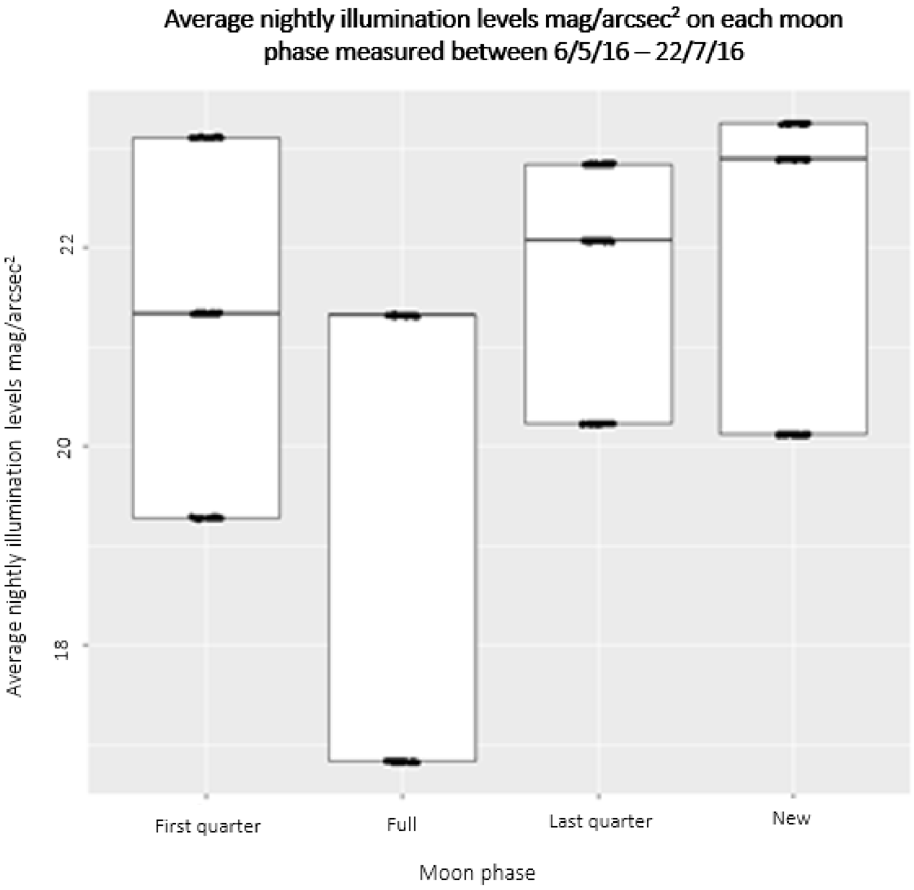


Figure 7.15 **The spread of average nightly illumination levels recorded on four moon phases at the three field sites on Banks Peninsula between 6/5/16 – 22/7/16.**

A number of generalized linear mixed models fit by maximum likelihood (GLMER) (Laplace Approximation), were run to assess which model fit the data best, with the drop1 function determining which variable was the weakest modifier. The initial model (NULL) tested how fixed effects (site and day) impacted the number of detections (AIC = 221.76) (Table 7.2). The following model (MAM, AIC = 218.11) included average hourly illumination, average cloud cover and the total rain overnight. Rain was the first variable to be dropped (MAM1, AIC = 218.11), followed by cloud cover. The final model (MAM2, AIC = 220) included only maximum hourly illumination as an explanatory variable (p=0.00946, SE=0.5466, CI = 95%). (Table 7.2).

Table 7.2 An ANOVA assessed the results from the GLM models for the camera trap data set. Next to the model name are the variables included in the analysis. MAM2 was the most significant and is thus in bold.

	Df	AIC	P-value
Null	3	221.76	
MAM2 (average illumination)	**4**	**220**	**0.00946**
MAM1 (average illumination and cloud cover)	10	218.11	0.0309
MAM (rain , average illumination and cloud cover)	10	218.11	0.0261

7.3.2 Camera traps

A wide range of animals were detected by the camera traps. Including korimako/bellbird (*Anthornis melanura*), ruru/morepork owl (*Ninox novaeseelandiae*), silvereye (*Zosterops lateralis*), cows (*Bos taurus*), rifleman (*Acanthisitta chloris*), songthrush (*Turdus philomelos*) and blackbird (*Turdus merula*). The species included in this analysis were stoats, rats, possums, hedgehogs, mice, hare and cats (Table 7.3, Figure 7.16). All are exotic pests and all have an impact on native flora and fauna (Atkinson & Towns, 2005; Cowan, 2005; Gillies & Fitzgerald, 2005; Innes, 2005a, 2005b; C. Jones & Sanders, 2005; King & Murphy, 2005; G.L. Norbury & Flux, 2005; G. L. Norbury & Reddiex, 2005; Ruscoe & Murphy, 2005). Additionally, detection rates were too low for each species to run singly (Table 7.3).

Table 7.3 Camera trap detections for each nocturnal mammalian pest at each site. Okuti and Port Levy Plantation had closed canopies, Waipuna Saddle is an open grassland.

Camera trap detections between sites and pests				
	Okuti Valley Reserve	Port Levy Pine Plantation	Waipuna Saddle	**Total**
Stoat (*Mustela erminea*)	1	1	0	**1**
Rat (*Rattus spp.*)	5	5	4	**5**
Possum (*Trichosurus vulpecula)*	11	14	11	**14**
Mouse (*Mus musclus)*	2	2	2	**2**
Hedgehog (*Erinaceus europaeus occidentalis*)	6	6	1	**6**
Hare (*Lepus europaeus occidentalis*)	1	4	4	**4**
Cat (*Felis catus)*	3	3	3	**3**
Total	**29**	**35**	**25**	**35**

Canopy cover (open/closed) was not able to be considered as there were too few detections under open canopy (n=2) meaning the model was unable to converge when additional explanatory variables were added. It is still important to note that canopy cover does have some role in pest animal activity, as only 1.36% of detections occurred under an open canopy (Table 7.4).

Table 7.4 Detections under canopy cover for all sites sampled.

Detections recorded under open and closed canopy cover		
	Closed	**Open**
Absence	92	55
Presence	33	2
Probability of detection	22.45	1.36

Additionally, all illumination measures (average, max and min) correlated with canopy cover (%) by over 0.78 (R). Total rain overnight correlated with average wind speed (R =-0.5) and average temperature (R = -0.5). Wind speed and temperature also correlated (R = 0.72) (see appendix A.2.). Therefore temperature, wind and canopy cover (%) were not run in the models.

Moon phase and illumination are hard to separate as moon phase, of course impacts illumination. The full moon reflects the most light and so had the lowest mag/arcsec^2 (22.58), whilst the new moon was much darker (by one full magnitude) (Table 7.5). Unexpectedly, the lowest level of illumination was recorded during a last quarter (24.34 mag/arcsec^2).

Table 7.5 Means and Standard Deviations of maximum illumination levels within a night

	Maximum illumination within a night	
Moon phase	**Mean**	**Standard Deviation**
First quarter	23.43	1.68
Full	22.58	2.19
Last quarter	24.34	0.77
New	23.59	1.19

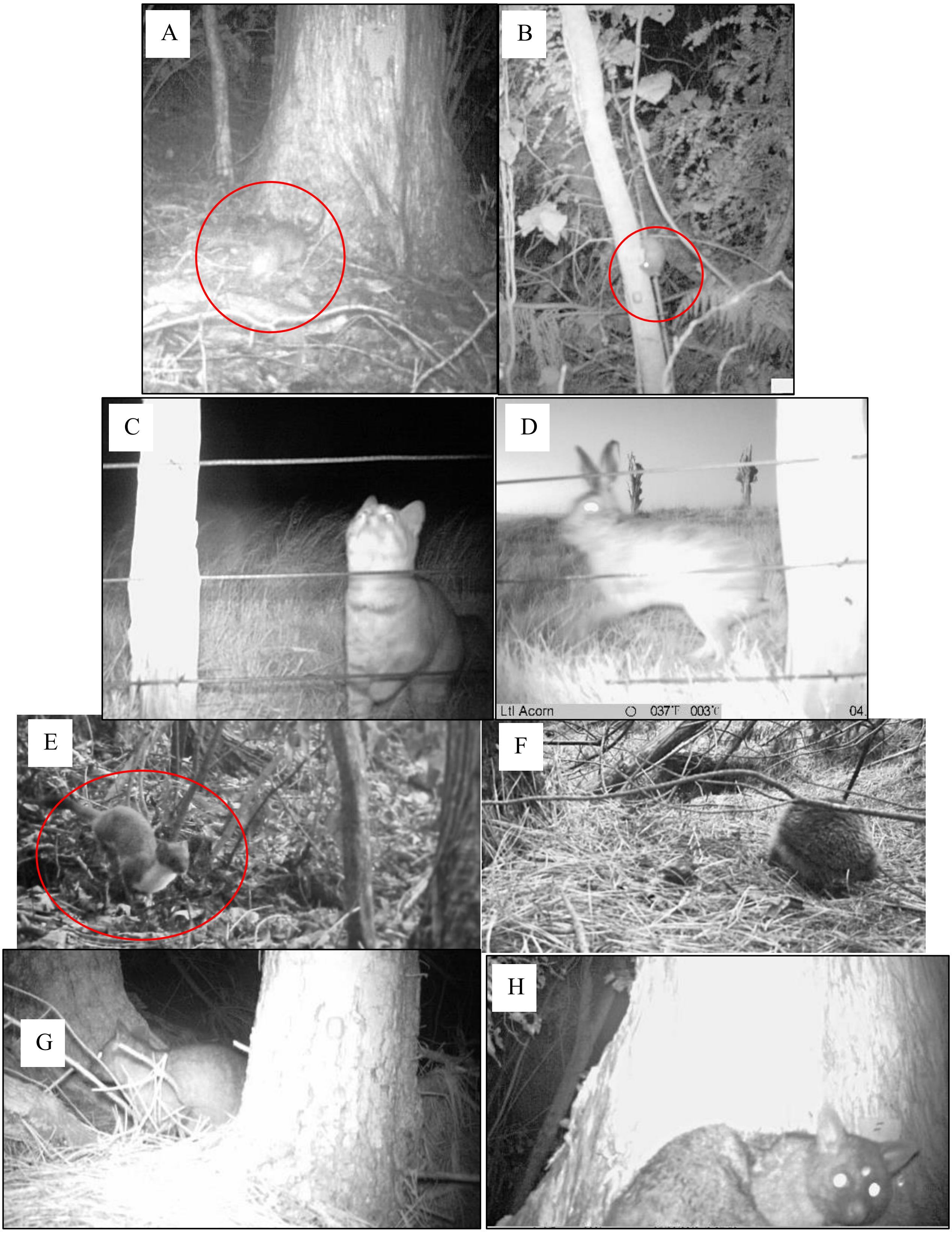


Figure 7.16 **Camera trap detections. A: Rat (Okuti Valley Reserve (OVR)). B: Mouse (OVR). C: Cat (Waipuna Saddle (WS)). D: Hare (WP). E: Stoat (OVR). F: Hedgehog (Port Levy Pine Plantation (PLP)). G: Possum (PLP). H: Possum (OVR). A, B, D, E, G and H: New moon. C and F: first quarter.**

To test whether moon phase was a significant predictor of illumination a GLM (generalised linear model) was run comparing average hourly maximum illumination to moon phase (AIC = 683.59). The new moon was not a significant predictor of maximum illumination levels (p-value = 0.64049, SE= 0.3306). However, full, first and last quarter were significant (respectively p values = < 2e-16, 0.0094, 0.0053, SE= 0.2271, 0.3229, 0.3212). Therefore, illumination and moon phase were run in separate models as moon phase was a significant predictor of maximum illumination levels.

Moon phase

The highest number of detections occurred under the full moon (n=11), with the lowest detection rate on the new moon (n=6) and the first and last quarter had the same number of detections (n=9) (Table 7.6). As occurred for the Waxtags™ the site with the greatest detection rate was Okuti Valley, followed by the pine plantation and finally Waipuna Saddle with a grand two detections. Overall 35 animals were detected within the sampling period (6/5/16 – 22/7/16). Moon phase is a good predictor but we were interested to know whether illumination would have higher predictive power. The value of camera traps is that we know exactly when the pest encountered the device, whereas Waxtags™ can only indicate activity within the three nights sampled. This means a more exact illumination measure can be used here and the result is significant.

Table 7.6 Detections from camera traps on each moon phase and at each site between 6/5/16 – 22/7/16.

Total camera trap site detections under each moon phase					
	First quarter	Full	Last Quarter	New	Total
Okuti Valley Reserve	3	8	3	6	**20**
Port Levy Plantation	5	3	3	2	**13**
Waipuna Saddle	1	0	0	1	**2**
Total	**9**	**11**	**6**	**9**	**35**

Illumination

Within this study, the levels of average illumination used were skewed to the right. This is because the lighter values, during the day, were not relevant and so were removed. Meaning the values remaining were clustered between 16 mag/arcsec^2 and 24 mag/arcsec^2 for average illumination (Figure 7.17-A), 7 mag/arcsec^2 and 13 mag/arcsec^2 for minimum illumination (Figure 7.17-B) and 19 mag/arcsec^2 and 25 mag/arcsec^2 for maximum illumination (Figure 7.18-C). Minimum illumination data was not used, in part, because it was bimodial. Maximum illumination was used because it was considered more biologically relevant than mean levels, e.g. a bright moment where clouds reveal a bright full moon may cause animals to run for cover. Generalised Linear Mixed Models are capable of handling the non-normality exhibited in the maximum illumination data, thus it was decided that neither the data not the analysis need be changed.

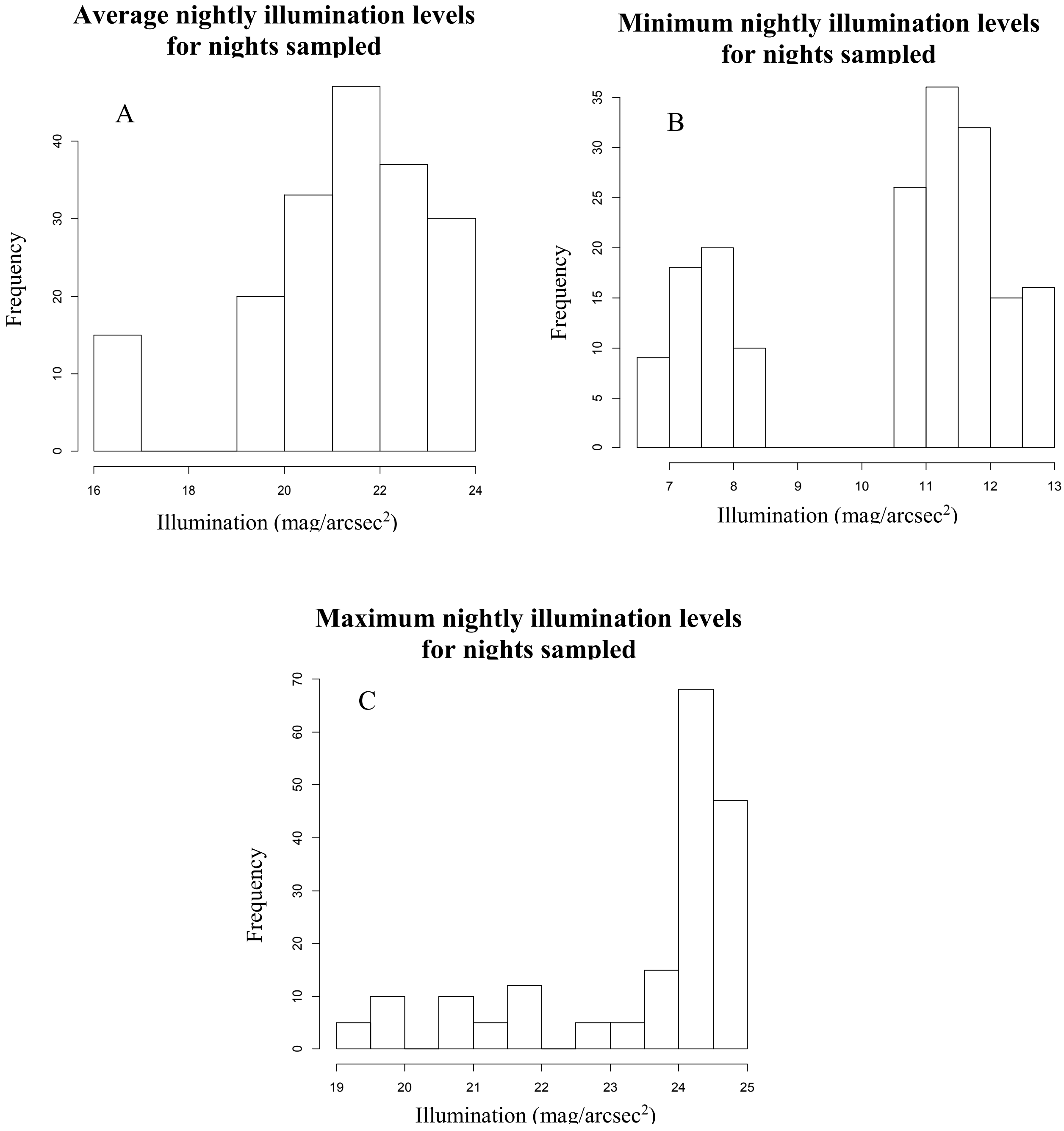


Figure 7.17 Hourly illumination per sample night between 6/5/16 – 22/7/16. A: Average illumination, B: Minimum illumination, C: Maximum illumination.

Generalized linear mixed model fit by maximum likelihood (Laplace Approximation), binomial: A number of GLM's were run to assess which model fit the data best, with the drop1 function determining which variable was the weakest modifier. The initial model (NULL) tested how fixed effects (camera and night) impacted the number of detections (AIC = 174.5). The following model (MAM) included moon phase, maximum hourly illumination and the total rain overnight. Rain was the first variable to be dropped (MAM1), followed by moon phase. The final model (MAM2, AIC = 168) included only maximum hourly illumination as an explanatory variable (p-value = 0.01636, SE = 0.2365). An ANOVA was run comparing the four models, the final model containing only maximum hourly illumination (MAM2, p-value = 0.035, AIC = 167.97) was significant (Table 7.7).

Table 7.7 Results of the ANOVA run comparing the four models.

	Df	AIC	P-value
Null	3	174.47	N/A
MAM2 (maximum hourly illumination)	4	167.97	**0.0035**
MAM1 (moon phase and maximum hourly illumination)	7	171.53	0.4863
MAM (moon phase, maximum hourly illumination and rain)	8	173.52	0.9619

A marginal effects plot adjusted for all predictors showed that as maximum hourly illumination levels (mag/arcsec^2) over all sites decreased there is a higher probability of detecting a pest (Figure 7.18). The key result from this graph is that the majority of detections occurred under conditions darker than 23 mag/arsec^2. In the darkest illumination conditions recorded during this study, 25 mag/arcsec^2, the probability of detection was 25%; whilst during lighter conditions, 20 mag/arcsec^2, this probability is closer to a 3% chance. The graphs line of best fit follows the data well, however the line was expected to level off into an S-shaped curve; this difference may be due to insufficient data or there could be no conditions too dark for the animals.

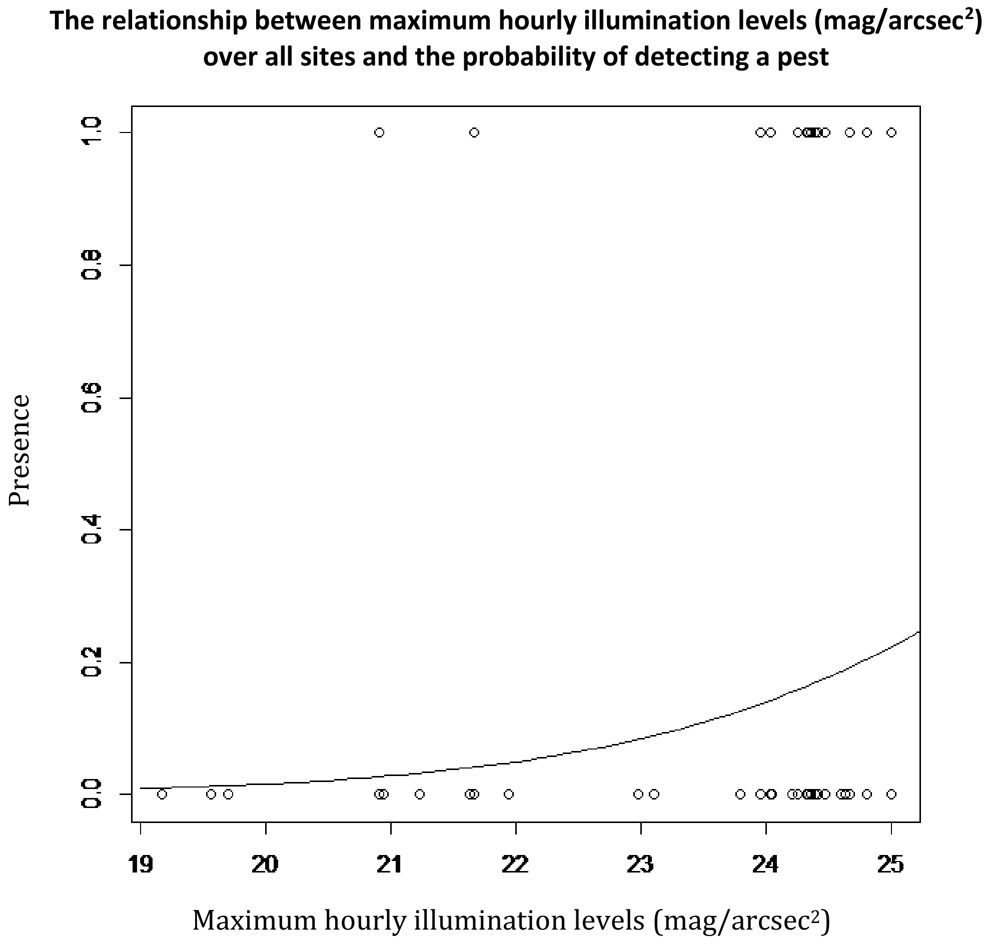


Figure 7.18 The function of the relationship between maximum hourly illumination levels (mag/arcsec^2) and actual camera trap pest detections.

7.4 Discussion

Moon phase and illumination are driving factors of nocturnal mammalian activity. In this section we delve into the results from both the Waxtag™ and camera trap data where moon phase and illumination are seen to impact the activity levels of our nocturnal mammalian pests. Following this, I will also consider the impacts of vegetation, canopy cover and site.

7.4.1 Waxtags™:

Moon phase:

The Waxtag™ data showed an increase in pest activity around the new moon, with the lowest number of detections on the full moon. This indicates that there may be some relationship between the pests (rats, possums and mice) and moon phase, suggesting that these pests could be lunar phobic or at least lunar influenced. The GLMM for moon phase ($p=0.1243$) was not in itself statistically significant but it explained the variation in the data set to a greater degree than illumination levels or rain. A contributing factor to this result may have been the large variety within moon phase as an explanatory variable. The results from the 'lsmeans' test show a close to significant difference in detection rate between the full and new moon (p= 0.0507, SE=0.5499, CI = 95%) (Figure 7.12). This may not be statistically significant but it is biologically significant. A higher number of pests were detected on the new moon, consequently possums, rats and mice may shy away from the full moon like many lunar phobic animals.

Vegetation*:*

There is some evidence that vegetation may impact pest activity, the field sites experienced differing levels of activity with the highest number detections in Okuti Valley, and Waipuna saddle measuring the least. The two sites have vastly different vegetation types; Okuti Valley has dense canopy in some areas from the broadleaf trees ranging between 5-15 metres high whilst Waipuna Saddle consisted largely of tussock measuring 30cm in height. This lack of cover may reduce the area in which the pests range. However, we were unable to apply this to our own analysis as we had no data of population sizes in these areas.

Illumination:

Maximum illumination levels were found to significantly impact pest activity levels (p=0.00946, SE=0.5466, CI = 95%). In higher illumination levels there were fewer pest detected, meaning that on brighter nights pests may have been less active. This supports the theory of lunar phobia in the moon phase analysis but also in previous studies (Dutton, 2008; Parisi, 2011). It could be, however, that their perceived preference for darker areas could be entangled with a preference for denser habitats with greater canopy cover. We must consider that under dense canopy illumination levels do still vary and the pests were seen to be most active in darker times of the night under dense canopy cover – therefore showing that illumination may have a greater impact than canopy cover, as seen by the camera trap data.

7.4.2 Camera traps:

A number of pests were recorded by the camera trap survey, including some predator and some prey species. All were included because they are all pests and detection rates were not high enough for single species analysis. Stoats and cats in particular had comparatively low levels of detection, however they are known to be difficult to monitor and control (King, McDonald, Martin, & Dennis, 2009).

Moon phase:

Contrary to the other results in this study the highest number of detections, by the cameras, occurred on the full moon and were the lowest on the new moon. Indicating that the pests recorded lean towards being lunar philic. This is consistent with the findings by Parisi (2011) but disagrees with the findings of both Lennon (1998) and Dutton (2008). This result is unexpected as it is generally assumed that prey species will be lunar phobic, largely as an anti-predator response. Considering that in Australia possums are devoured by birds-of-prey and by foxes, and that in other countries rats, mice, hares and hedgehogs (which were included in this analysis) are common prey items; the assumption would be that they, as prey, would be lunar phobic. However, moon phase was a significantly weaker predictor of pest activity than illumination.

Illumination:

The most interesting finding was that maximum hourly illumination was found to have a significant impact on pest detection rates (p-value = 0.01636, SE = 0.2365). This variable had a greater impact than moon phase or total rain overnight. It is clear that as conditions become darker the probability of detecting a pest increases (Figure 7.18).

Maximum illumination levels were considered more biologically relevant than average or minimum levels. For example if we consider our own behaviour on a cloudy day; when the sun suddenly comes out behind a cloud many people will look up and take note of this abrupt change. Similarly for nocturnal animals, the moon appearing from behind a cloud, increasing illumination levels, is likely to cause some change in their behaviour. Additionally, there were zero detections when conditions were lighter than 21.3mag/arcsec^2, indicating that illumination does impact pest activity levels to some degree. Paterson et al. (1995) found possums to be most active from 11pm-2am, which tends to be the darkest time of a night (See chapter 2). Yet only three out of our 16 detections were within this time frame. However, with a small sample size, caution must be applied, as the findings might not be representative of the population.

7.4.3 Comparison to literature:

Several reports have shown that possums have some relationship with moon phase, whilst there are little to none on the other pests considered within this study. The first study in New Zealand that considered the impact of moon phase on possum activity was researched by Lennon (1998). My results are consistent with data obtained by Lennon (1998), who found that on darker nights possum activity increased. My results further support Lennon's most interesting result; being that possums increase their activity levels (bait consumption) by up to 30% in forested areas on a new moon. This outcome is contrary to that of Dutton (2008) and Parisi (2011) who found activity levels increased during the full moon. Additionally, Parisi (2011) showed that possums are more active in open, scrubland areas. This differs from the findings presented here.

This inconsistency may be due to the fact that these three studies, as well as our research, all stated that greater sample sizes were needed with longer sampling periods. However, we were able to increase the accuracy of assessment within this study; by using the SQM we were able to apply accurate illumination data to the data collected. Allowing illumination to be considered, for the first time, as a reliable explanatory variable of nocturnal mammalian pest activity in New Zealand.

7.4.4 Impact of habitat:

We must consider that two of the three sites tested had dense canopy cover (60-90% cover) meaning there were greater opportunities for a pest to be detected under closed canopy than open; and we did experience low levels of detection under an open canopy. This may be due to vegetative differences, such as food quality and abundance, or predator avoidance strategies. Consequently, it could be less about opportunity for detections but more about pest preferences. Previous studies have shown that possums have no strong preference between open and closed canopies, they are found in both open pasture and dense forests (Cowan, 2005). In Australia, brushtail possums are not known to flee for ground cover when threatened (e.g. by a bird-of-prey) but rather shelter under dense canopy with the aim to remain hidden from avian predators (Pickett et al., 2005). Indeed, tall grasses and shrubs may hide the predator of a possum, rat or rabbit (Pickett et al., 2005). Which may explain why more of these pests were detected under closed canopies.

The density of forest canopy dictates on the ground illumination levels (see chapter 6.3), which means that in pasture and tussock grasslands moon phase may play a greater role for the pests. Unfortunately, low levels of detection under open canopy meant canopy cover could not be included in the GLMM as it prevented the model from converging. Also, canopy cover correlated highly with illumination levels, unsurprisingly, as foliage will block light reaching the ground (see chapter 6.3). These points further cemented the decision to leave canopy cover out of the analyses. Although exclusion of canopy cover did not seem to impact the results found, these results should be interpreted with caution as the impacts of canopy cover, moon phase and illumination can be difficult to separate.

The three field sites experienced vastly different pest detections. Only five pests were detected at Waipuna Saddle whilst Port Levy had 26 detections and Okuti Valley Reserve totalled at 42 detections. There are several possible explanations for this result, one being the difference in habitat between the sites (see chapter 7.2.1). Waipuna Saddle had sparse, low lying vegetation and sampled areas were at least 50m from the nearest forest edge, while Port Levy and Okuti Valley are both densely forested, with a medium to high, and often dense, canopy. Lennon (1998) found that possums were distinctly more active further away from the bush edge. Thus, it is important to bear in mind the possible bias in these responses.

There may also have been an impact from the markedly different habitats between Okuti Valley and Port Levy pine plantation. Possums are well known to travel within native forest (Cowan, 2005; Jolly, 1976; Porphyre et al., 2013) but evidence is less well known as to their taste for pine forests. Jolly (1976) suggest this habitat may be explored during winter when food is short but implies that otherwise it holds no interest for the animal. This agrees with Warburton (1978), who suggests that possums damage young *Pinus radiata* stands in winter (the season in which this studies data were collected) and spring, by eating pollen cones. Other research details that they browse the main shoots and strip bark, killing up to half the trees at some sites (Department of Conservation, n.d.-e). Possum impacts on pine plantations are serious enough that particular methods to assess the animal's impact on the canopy exist (Payton & Frampton, 2003). Consequently, while there was a difference in detection rates between the plantation and the regenerating forest in Okuti Valley, it is unlikely that these habitat differences impacted detection rates to any great degree.

7.4.5 Points of consideration:

A source of uncertainty within this study is that individual possums, and potentially other pests, may have developed a wariness of Waxtags™. Possibly due to a sub-lethal dose of cyanide causing the animal to become shy of new objects, however M. D. Thomas et al. (2007) found this to be an uncommon occurrence. Unfortunately our lack of knowledge around pest populations in the study areas meant we could not test for this effect.

Figure 7.19 Pidgeonwood fruit found desiccated on the forest floor (Hedycarya arborea).

Figure 7.20 Left: The A24 rat and stoat trap by Goodnature (n.d.). Right: A tracking tunnel, seemingly not in use (no lure or paper inside).Both were likely installed by the Little River Trap library.

A note of caution is due in interpreting these results because during monitoring in the Okuti Valley reserve we noticed that pidgeonwood (*Hedycarya arborea*) was in fruit. The ground was littered with empty skins of the orange fruit (Figure 7.19), which could have been the work of possums (A. E. Fitzgerald, 1976). Also, there was some monitoring and trapping within the reserve conducted by locals (Little River-Wairewa Community Trust, n.d.) (Figure 7.20). We were unable to contact the group arranging this so there is no information as to how active or maintained the traps or monitoring stations were. Finally, at the Waipuna Saddle site the Department of Conservation was carrying out weed control during data collection, gorse was the only target and the plants were sprayed with poison by two workers over the course of two weeks. This unexpected occurrence may have dissuaded some pests to venture towards the cameras and Waxtags™ but we cannot say for certain.

7.5 Conclusion

The Waxtag™ data showed possums, rats and mice activity is impacted by illumination levels more so than moon phase. The pests were found to be more active during the full moon to a small extent but illumination data showed the pests to have significantly higher activity levels on darker nights. The camera data showed a similar trend. Where nocturnal mammalian pests (Figure 7.13) are impacted by illumination to a greater extent than moon phase. The model studying moon phase discovered a small preference by the pests for a full moon night, however the highly significant illumination data showed that darker nights were most preferred.

The small disparities between data set results may be due to the finer data that could collected with the camera traps. Time and date stamps on the photos allowed more specific illumination and weather (rain and cloud cover) data to be attached to the pest detections. The camera trap data used nightly average maximum illumination levels but the Waxtag™ data had to be averaged over the three days they were set out for. If it had been feasible to set a camera at every Waxtag™, allowing the time and date of the bite to be recorded, the Waxtag™ data may have shown a clearer trend concerning illumination levels.

Overall, the darker the conditions the greater the number of pests detected, and on the new moon (when conditions tend to be darker, see chapter 6) pest detections were also higher. This suggests that pests may be lunar phobic but also that the pests are impacted by illumination levels, and these illumination levels may play a more significant part in pest activity levels. In this section, it has been explained using current data that moon phase and illumination impact pest activity levels. The chapter that follows moves on to discuss the overall effect of these variables and how new equipment has aided the quest for answers.

Chapter 8

Overall discussion

8.1 Summary of the thesis

This thesis aimed to assess the impact of moon phase and illumination on several introduced nocturnal mammalian pests in New Zealand, with the objective that this understanding would increase the efficiency and effectiveness of pest control and monitoring. Camera data from the Blue Mountains (Otago) and Hawkes Bay were analysed, but moon phase was not able to explain the variation in the data set. Two factors which have been shown to impact nocturnal mammals were not included in these data sets; being canopy cover (Leaver & Daly, 2003) and illumination (Rich & Longcore, 2006) (see chapter 2). A highly sensitive illumination meter, a Sky Quality Meter (SQM) used by astronomers, was assessed for its usefulness in this ecological setting (see chapter 6). The successful trials of the SQM meant we could apply this technique to more data collection on Banks Peninsula (Canterbury) (see chapter 7). The results of this study suggest that illumination does have an effect on animal activity, as does lunar cycle to a lesser extent. Illumination has at least as much of an impact as rainy weather.

It is not often that illumination is specifically considered in ecology without the influence of urban light pollution, and with equipment that can take fine and highly accurate measurements. Several studies have attempted to collect illumination data but were either unable to accurately measure changes in light levels (Dutton, 2008; Gilbert & Boutin, 1991; Lennon, 1998; Parisi, 2011) or focused instead exclusively on moon phase (Lima Sabato et al., 2006; Penteriani et al., 2010; Penteriani et al., 2011). Additionally, the research that has considered the impact of illumination largely focusses on urban light pollution (Abdullahi et al., 2016; Birriel et al., 2010; Davies et al., 2013; Gil et al., 2015; Goyret & Yuan, 2015; Katz & Levin, 2016; Kyba et al., 2011; Rich & Longcore, 2006). In these studies, light levels were higher and thus more easily measured. Conditions in rural New Zealand can become very dark, especially on Banks Peninsula where there are few settlements and thus little light pollution and many light meters are unable to measure at such low light levels. For example, when attempting to measure illumination levels using an OL-754 spectrometer (Optronics Laboratories Inc.) Johnsen et al. (2006) were surprised when it was not sensitive enough to measure light from a new moon. Considering the challenges most studies face when measuring illumination it is unsurprising that we still have little knowledge as to how nocturnal mammalian pests change their levels of activity in response to illumination.

8.2 Measuring illumination in a biologically significant way

To address the lack of effective tools for measuring illumination in ecological studies the SQM's were tested in Banks Peninsula's dark conditions to assess whether the device could measure light levels in a biologically significant way. These devices were used because they are a low cost light meter and are widely used by astronomers to measure sky quality (essentially the number of visible stars) (den Outer et al., 2011).

Two SQM's were set up on two sites on Banks Peninsula, one under canopy cover and the other in the open. This tool has allowed illumination levels and moon phase to be measured separately from each other (as moon phase is a significant predictor of illumination), meaning we can assess which factor impacts nocturnal animals more.

The SQM successfully measured the differences in illumination between moon phases and also under different canopy covers. Canopy cover was found to have a greater impact on illumination than moon phase. This provides evidence to support the conclusion that canopy cover is an important factor to include when you consider how illumination impacts an animal's behaviour. If canopy cover had been included in the Blue Mountains and Hawkes Bay data we may have been able to extrapolate some of the on-the-ground illumination levels. It is possible, therefore, that if a light meter is not available or cannot measure light well enough then canopy cover could help to infer conditions. Cloud cover was not shown to impact illumination levels, but this might be because the only available data was collected by Metservice at the Christchurch International Airport (over 40km away from the field sites). It could be that cloud cover was different at the field sites than the measurements taken at the airport, due to the distance between the field sites and the airport.

One interesting finding is that average hourly illumination levels on the new, first quarter and last quarter were very similar. This is interesting because the assumption we make when call an animal lunar phobic is that it will be least active on the full moon and most active on the new. Whereas, it seems instead that they are merely least active on the full and equally active on the other phases because conditions are overall darker outside the small window of the full moon. Another important finding was that illumination does not vary significantly during a night, thus when considering this variable in relation to animal behaviour we can focus on the broader conditions instead of a time consuming hour to hour study.

An aim of this study was to investigate whether a SQM could be used in the ecological setting of assessing whether illumination impacts the activity levels of nocturnal mammalian pests.

The SQM has shown it is able to measure illumination in a biologically significant way and thus can be applied to analysis of animal behaviours.

8.3 Factors that influence pest behaviour

What follows is an account of how moon phase, illumination, vegetation and rainy weather impact nocturnal mammalian pest activity levels in the Blue Mountains (Otago), Hawkes Bay and on Banks Peninsula (Canterbury).

8.3.1 Moon phase and illumination

This study found that both moon phase and illumination impacted pest activity levels, but to different extents. Visually inspecting the Blue Mountains data set found that moon phase did not greatly influence activity levels of rats (*Rattus* spp.), mice (*Mus musclus*) and stoats (*Mustela erminea*), suggesting they may be lunar neutral. This result is contrary to the result described by Navarro-Castilla and Barja (2014) who found that wood mice (*Apodemus sylvaticus*) significantly reduced their foraging activity on the full moon (as an anti-predator response). Additionally several studies have shown that rodents reduce activity on full moon (Daly et al., 1992; Leaver & Daly, 2003; Wolfe & Summerlin, 1989). By comparing these studies, it becomes evident that there must be other factors at work here.

Possums (*Trichosurus vulpecula*) in the Blue Mountains were not significantly affected by moon phase although they were slightly more active on the full moon and less active on the last quarter. This result differed from previous research on NZ's possums. Lennon (1998) found the possums increased their activity levels on the new moon, while Dutton (2008) and Parisi (2011) showed their activity levels increasing on the full moon. There was insufficient Waxtag™ data from Banks Peninsula to statistically analyse the activity of different species, so a collective analysis was completed instead and found that the activity of possums, rats and mice were significantly higher on the new moon than the full moon ($P = 0.05$). Meaning that at the very least possums (and rats and mice) are lunar influenced but could be considered lunar phobic.

In Hawkes Bay a visual inspection of the data indicated that feral cats (*Felis catus*) were more active on the moon's last quarter and less so on the new moon. This is interesting because we found that illumination levels between the new, first quarter and last quarter were very similar (see chapter 6). Thus, for cats, illumination would most likely not be the driving factor for this behaviour. This leaves two reasonable possibilities; these cats are responding to the phase of the moon, which seems unlikely, or there is another variable impacting on the cat's behaviour such as canopy cover, prey densities, or prey behaviour. In the Blue Mountains study possums were slightly less active on the last quarter, and cats were more active. Cats are unlikely to prey on adult possums but this marsupial's behaviour could potentially be the last vestige of an anti-predator behaviour.

A note of caution is due in the Hawkes Bay study as some field sites had been treated with cat control halfway through the data set. It is possible that this changed the population densities of the cats. This may also have caused cats probability of detection to be lower than normal, seeming less active, post control when their populations were just smaller.

Regarding the Banks Peninsula data, illumination was a more significant predictor of pest activity than moon phase (see chapter 7). The Waxtag™ data showed that the activity levels of possums, rats and mice increased with lower illumination levels (P= 0.0095). The camera trap data revealed that all pests recorded (Table 7.3) increased their activity significantly on darker nights, but, unexpectedly, showed that out of the four moon phases they were most active on the full moon. However, illumination explained significantly more of the variation in the data than moon phase (P= 0.016). These findings suggest that on darker nights a pest is more likely to be active and it is highly unlikely that this behaviour is due to a lunar awareness.

To my knowledge there is no term for responding to illumination levels in this way (or the other influencing factors: see limitations), neither lunar influenced nor lunar phobic adequately describe this change in behaviour. Perhaps a better term might be (the somewhat gothic) dark lovers or nyctophiles. The fact that the Hawkes Bay and Blue Mountain studies were unable to fully explain the variation in the data sets but the Banks Peninsula data was able to show highly significant results demonstrates the importance of including illumination levels when considering nocturnal mammalian activity levels.

A potential explanation for the higher activity of possums, rats and mice on darker nights could be anti-predator behaviour. We know that nocturnal predators feed on these pests (see chapter 4) and a common response by prey is to reduce their activity when their predator is most deadly, such as on brighter nights when it is easier to spot prey. Whilst the pests included in this study have little in the way of predators in NZ we cannot state whether a century of liberation has wiped away anti-predator behaviours cultivated in populations over many centuries.

There are some studies that agree with the Banks Peninsula results. Lennon (1998) showed possums are more active on dark nights. Rodents have been known to reduce foraging activity when moonlight intensity is high (Kotler et al., 2010; Rich & Longcore, 2004). Also, Griffin et al. (2005) found that snowshoe hare (*Lepus americanus Erxleben)* activity decreased significantly on snowy full moon nights; however, other researchers disagree. As mentioned in the literature review, a number of studies have shown possums (Cowan & Clout, 2000; Dutton, 2008; Parisi, 2011) and rodents (Johnson & De Leon, 2015) to be more active during the full moon. Although it is important to note that none of these studies were able to fully consider the confounding role of illumination.

By using a SQM we were able to apply biologically relevant illumination data to the Banks Peninsula study, giving us a greater understanding as to how light levels impact these pests. Overall, the three data sets show that nocturnal mammalian pests are affected more by illumination than by moon phase. Therefore using a device such as the SQM to measure illumination levels is highly useful in such studies. We cannot rely on moon phase to reveal the behavioural trends of nocturnal animals as illumination must be taken into account.

8.3.2 Habitat

Vegetation was also a contributing factor to pest detections. Canopy cover has been known to influence pest behaviours around the full moon (Leaver & Daly, 2003). Within the Banks Peninsula study there were significantly fewer detections under open canopy during over the entire field study. This could be because canopy cover impacts illumination levels (see chapter 6), so the animals could be responding to this factor or another we did not consider (such as food availability or predator avoidance).

Additionally, the forested sites on Banks Peninsula detected significantly more pests than the pasture/tussock area. This finding is consistent with that of (R. E. Brockie, 1991) where open pasture land was less preferred by possums in comparison to swamp land with willows. Conversely, Parisi (2011) disagrees with this; she found possums to be most active in open scrubland. It is, however, difficult to determine the impact of vegetation and canopy cover without further information. As canopy cover reduces illumination level it might be used to explain some of the behaviour exhibited by the pests.

8.3.3 Weather variables

A number of weather variables were considered for all three data sets. Unsurprisingly, there were a high number of correlations between some of these weather variables. Temperature was affected by wind and rain, and cloud cover correlated with illumination.

One interesting finding was that rain impacted animal activity, all pests studied reduced their activity levels as rainfall increased, particularly over 15mm. In Hawkes Bay rainfall was shown to reduce cat activity levels, corroborating previous research findings that cats reduce activity during rain (Harper, 2007; Haspel & Calhoon, 1993). This trend in nocturnal mammals has been shown in a number of studies but there is sometimes contention over the impact on possums (see chapter 2, pg. 40).

Cats tend to be less active with higher rainfall as well as with decreasing temperatures, rain of course decreases temperature. Having access to rain data was important because it did help us explain some of the variation within the Hawkes Bay and Blue Mountains data sets. However, when we applied this to the Bank Peninsula study we found that rain had no obvious impact on pest activity and explained less of the variation in the data set than illumination levels did.

8.4 Contribution to conservation science

Across New Zealand, the mainland and most of the islands, we struggle to control pests. When once we welcomed many of them onto our land now we do our best to eradicate them and now we are striving for a Predator Free 2050. Every nocturnal mammal analysed in this research negatively impacts our natural environment; competing with our birds for resources, devouring our native animals (birds, lizards and insects alike), spreading disease, and destroying our forests. If we can’t control their populations New Zealand as we know will continue to change, and not for the better, which is why we have fought hard to understand these pests. We research their preferences for dens (Whyte et al., 2014), for traps (Sjoberg, 2013), for food (Miller & Webb, 2001) and apply it to control and monitoring methods. We know so much yet still struggle to control their populations, spending millions of dollars every year in an effort to do so. This is why we are interested in how moon phase and illumination may impact these pests. These factors may be the key to a small leap in efficiency allowing pests to be targeted more effectively. Bringing the dream of a pest free NZ that much closer, while simultaneously saving time and money.

My findings are ecologically relevant and will aid monitoring and control operations by helping optimize pest control resources. This research has shown that on brightly lit nights nocturnal mammalian pests do reduce their activity levels. Meaning that during the bright full moon, pest control and monitoring could be less effective and thus should be focussed on darker times of the month. And as we learned from the SQM, other parts of the lunar cycle were shown to be equally darker than the full moon. This implies that control and monitoring may experience better results throughout the new moon, first quarter and last quarter, and only the full moon need be avoided.

If control or monitoring operations must go ahead during a full moon, when illumination is high, then it would be better to focus on areas with dense canopy cover where conditions are darker. We also found further evidence that rain reduces activity levels, indicating that when pest control operations plan for clear weather to ensure bait is not destroyed by rain they are also avoiding times when pests are less active.

Finally, our study included data from the North Island (Hawkes Bay), the bottom (the Blue Mountains) and middle (Banks Peninsula) of the South Island. With this breadth of locations and vegetation types we can more assuredly say that the factors analysed show trends greater than a single population of pests and thus may be appropriate across the mainland.

Overall, it seems the actual level of illumination was a greater driver of pest activity than moon phase which had more impact than rainfall. These results suggest that by taking these variables into account we could increase the efficiency and effectiveness of pest control by targeting the animals when they are more likely to be active and thus encounter Waxtag™, tracking tunnel, trap and bait.

8.5 Limitations

The major limitation in previous studies was their inability to measure illumination accurately. Lennon (1998) presumed that the changes in light intensity due to moon phase would be the same under open and closed canopy but was unable to measure the difference between the two. Dutton (2008) used only moon phase as an indicator of illumination, and while the moon is a predictor of illumination there are a number of other variables which also impact illumination, such as canopy cover and rainfall. Parisi (2011) used a light meter that was not sensitive enough to detect the changes in light levels between moon phases, particularly when under a full canopy. A number of other researchers, as discussed in the literature review (see chapter 2), were unable to measure illumination data as finely, accurately, inexpensively and easily as the SQM's allowed (Digby et al., 2014; Dwyer et al., 2013; Hailman, 1984; Johnsen et al., 2006; Johnson & De Leon, 2015). Using SQM's within this study allowed us to separate the impact of moon phase and illumination, and determine that illumination has a greater impact than moon phase on the activities of nocturnal pests.

Secondly, many previous studies did not take canopy cover into account when using moon phase as an indicator of illumination. Canopy cover impacted illumination levels and was found to influence pest behaviour. If canopy density had been included in the Blue Mountains and Hawkes' Bay data sets we may have been able to estimate a coarse illumination measure.

Additionally, when studying New Zealand possum Lennon (1998), Dutton (2008) and (Parisi, 2011) did not consider the impact of nightly rainfall and cloud cover on illumination levels, we showed that both factors changed illumination levels. These authors considered the impact of rain on pest activity to a certain extent, but Lennon (1998) considered it from the point of the number of days since rain impacting activity, instead of the impact of the rain event itself. We included rain data from an accurate and reliable source (Metservice) and found it influenced pest behaviour.

By accounting for more environmental variables, analysing multiple data sets, and including illumination measurements from the SQM we were able to improve on previous research and demonstrate how illumination, weather and habitat can all affect nocturnal mammalian pests in NZ. Thus when considering the results of studies such as Lennon (1998), Dutton (2008) and (Parisi, 2011) we must take into account that they lacked some key data, most importantly the average illumination levels. In the future investigations into nocturnal mammalian activity rain and illumination should be considered as they help explain more of what is happening than just considering moon phase independently.

There are limitations of using big data sets obtained from other researchers. The Blue Mountains data set required a large amount of transformation before it could be analysed. Perhaps this time could have been better spent collecting data on Banks Peninsula. Also, neither the Blue Mountains nor the Hawkes Bay data sets included illumination or canopy cover information, two factors shown to be important from the Banks Peninsula study. While both data sets were large they still had relatively low rates of detection. This may be partly due to the nature of some of the pests in all of these data sets; stoats and cats are notoriously hard to monitor as they have large home ranges and small populations sizes. The large data sets contributed to the overall study but in future I would consider the amount of time needed to transform them, what information they were lacking and the potential output value.

Additionally, the Blue Mountain and Hawkes Bay studies used food lures to encourage animals to interact with their equipment, no lures (such as a flour blaze for the Waxtags™ (Figure 3.1)) were used in the Banks Peninsula study, and we must consider the possibility that the findings are not highly comparable as a result. The use of lures should be carefully considered, they were used in Banks Peninsula to avoid over saturation of results.

Although this study further developed the research on the nocturnal activities of mammalian pests in New Zealand, there were some limitations which could be addressed in future research. For example, some information was not available in the Blue Mountains and Hawkes Bay data sets, which was improved on by the Banks Peninsula study. However, some data was unable to be considered in the Banks Peninsula study purely due to time and resource constraints. For example, we had no information about actual pest population densities or of how suitable these habitats really are for the animals. This means that some sites may have had lower than normal numbers of animals or suggest previous undocumented control. We did not know whether food was available in sufficient amounts, or whether appropriate dens were available, and these factors may limit generalisation to other areas. If we had known the existing population sizes of the pests we may have been able to further determine the impact of the factors considered

Perhaps another option may have been to conduct the study at the large observation pen at the Johnson Memorial Laboratory (Lincoln University, NZ). Benefits would include a known population size and controlled canopy covers. These issues could have been overcome because this laboratory can release a determined number of animals into a 2 ha enclosure and they could be more intensively monitored using video surveillance. Using this approach, we could have been able to more accurately observe how moon phase and illumination impact the pests with control over other independent variables like their habitat.

In hindsight, we were unable to determine whether vegetation had an impact on the data sets. In the Banks Peninsula study canopy cover and vegetation type could not be run in the generalised linear mixed models due to data constraints. For example, canopy cover was not able to be included as too few animals were detected under open canopy to run the analyses. Therefore, any perceived preference for darker conditions could be instead a preference for closed canopies, as most of the Banks Peninsula detections were under canopy. These low detection rates do indicate that there was some effect impacting pest activity levels at the open canopied site (Waipuna Saddle) and that could be the dominant was tussock/grassland or it could be the lack of canopy cover. Future research should control for canopy cover during site selection to explore if this has a significant impact.

Additionally, the study did not evaluate all of the weather variables, due to high numbers of correlations (see appendix A). Studies have shown the impact of wind (Ward, 1978), humidity and temperature (Harper, 2007; Haspel & Calhoon, 1993) on pests, all variables we were unable to consider independently. Future research should include measures of these weather factors into their design.

In addition, it is important to consider unexpected human activity at the field sites. At Waipuna Saddle the Department of Conservation conducted weed control for a few weeks during the field study. It is not unreasonable to consider that this may have had an impact on the activity level of pests at this site. Also, at Okuti Valley there are local pest control and monitoring initiatives by the Little River Trap Library (Little River-Wairewa Community Trust). These are sprinkled throughout the reserve and most seem abandoned. Tracking tunnels with paper and ink missing, traps with no bait and filled with leaves, and A24 rat and stoat traps placed oddly high above the ground (Figure 7.20). This may impact on pest behaviour to novel objects such as Waxtags™ in our study.

Furthermore, it must be considered that the results in the Banks Peninsula study were during winter, when animals tend to change their activity. The implication being that our results are applicable to this time of year but could be totally different in other seasons when food is more available and conditions can be more favourable.

Finally, the camera trap data from Banks Peninsula grouped predators and prey species together due to low detection rates. This is partly due to the difference in detection rates between field sites but there were generally low detection rates as a whole.

Perhaps, the Banks Peninsula, Blue Mountains and Hawkes Bay data sets would have benefited from longer sampling periods on a greater number of sites over a number of seasons, this would help generate larger sample sizes and give us a more holistic view of nocturnal mammalian pest behaviour.

8.6 Further Research

Improving pest control and monitoring operations relies in increasing pest interactions with control or monitoring devices. Determining when these pests are most active and what influences activity means they can be targeted with greater success. It appears that illumination levels do influence pest activity but further study is needed to examine this in greater detail. It would be interesting to further collaborate with astronomers for best practice use of the SQM. Perhaps the light meter can be manipulated to be more biologically relevant, such as measuring low light levels in even greater detail so that we may focus on the illumination levels that nocturnal animals are exposed.

Future trials could also assess the impact of urban light pollution. A number of animal behaviour studies have considered this overseas and determined that urban light pollution can impact a number of animal's taxa and could change their physiology, behaviour and reproduction (Bliss-Ketchum, de Rivera, Turner, & Weisbaum, 2016; Isaksson, 2015; Newport, Shorthouse, & Manning, 2014; Statham & Statham, 1997). This aspect was unable to be considered within this thesis due to time and resource constraints. It has been noted however that in Christchurch's central park (Hagley) it is common to see at least one if not more than four possums within a half hour. It would be interesting to determine whether these urban possums behave differently to their cousins in the bush.

With regards to pest control and monitoring we should consider the possibility that there could be an interaction between food consumption and illumination levels. It could be argued that while pests are less active on brighter nights they could still consume more poison bait due to higher visibility. However, most of these pests have adapted to nocturnal life by having fantastic eyesight, hearing and sense of smell, thus there may be no interaction but if we are to be pest free by 2050 every angle needs to be considered. A future study could consider actual food consumption levels during different illumination levels, building on the earlier work by Lennon (1998).

Another possible area of future research would be to investigate how canopy cover impacts the pests. The open canopied site in the Bank Peninsula study had very few detections, this may be due to higher illumination levels but I reason that if this were the case we would have seen some increase in activity at this site during the new moon. As I was unable to consider vegetation and canopy cover within these studies it would be valuable to determine how these factors interact with illumination preferences for the pests. I would recommend a greater number of study sites and longer sampling seasons, as well as consideration of using controlled captive facilities such as the Johnson Memorial Laboratory.

With respect to study design it is always challenging to find true replicates within ecological studies, this could be addressed in future research by conducting density estimates before commencing trials. In addition, it is important to assess the benefit of using big data sets (that have been obtained by other researchers), those used in this study lacked data on canopy cover, vegetation types and illumination levels. If canopy cover had been included we may have been able to indicate illumination levels to a small extent. Also, I would recommend that wet nights be removed from data sets as they are a confounding factor for illumination levels.

Finally, data sets that can give this vein of research the most information would be from un-controlled areas for higher levels of interaction.

8.7 Thesis summary

The main goal of the current study was to determine how moon phase and illumination affect activity levels of nocturnal mammalian pests. These findings will doubtless be much scrutinised, but there are some immediately dependable conclusions. The main finding to emerge from this study is that illumination does impact nocturnal mammalian pests and appears to affect pest activity levels more than moon phase and rain.

The second major finding was that Sky Quality Meters (SQM) can detect differences in illumination under very dark conditions, between moon phases and under different canopy covers. Additionally, canopy cover appeared to affect illumination levels more than cloud cover. This research has several practical applications. Firstly, SQM's can be used in a biologically relevant way. Secondly, these findings have significant implications for pest control and monitoring by increasing efficiency and effectiveness by targeting the animals when they are more likely to be active.

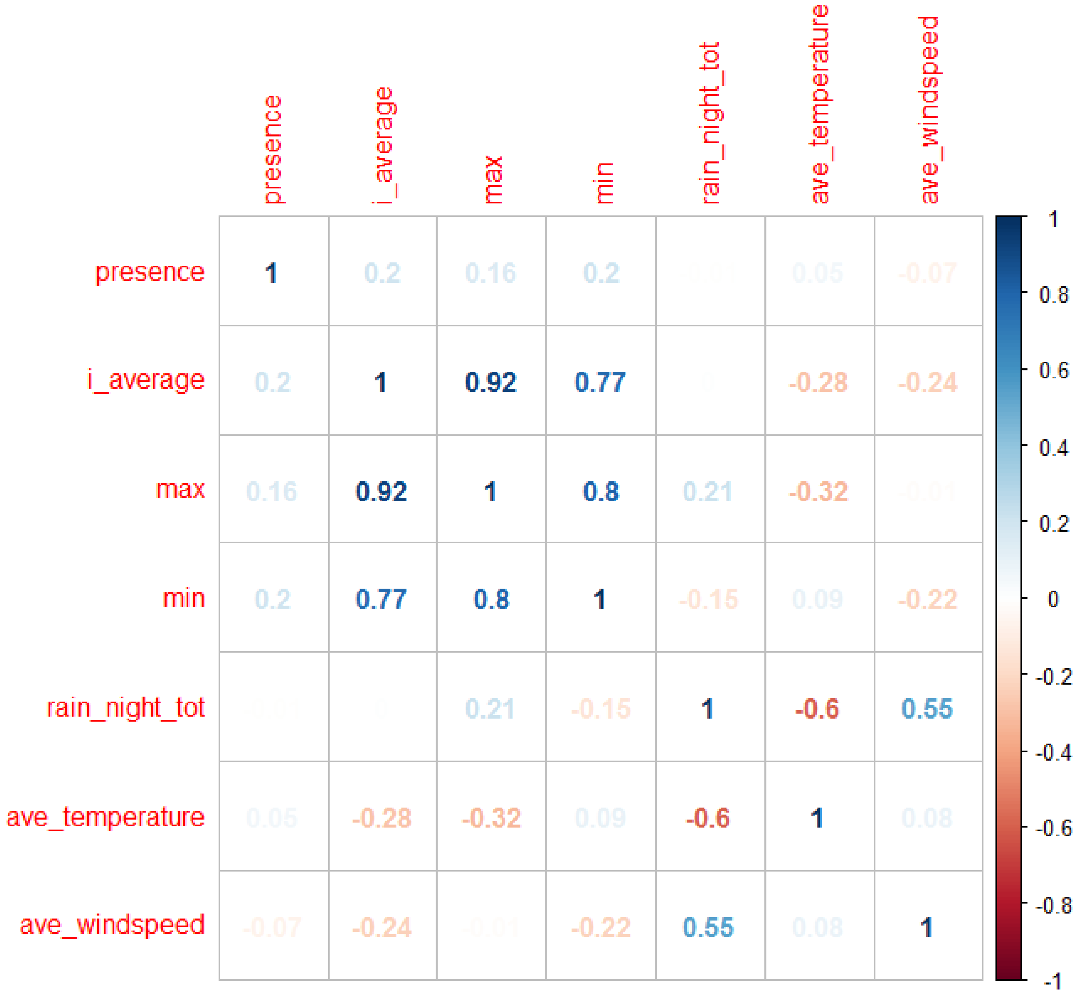
Finally, this study was limited by small sample sizes and time available for data collection. Secondly, the study was not able to evaluate the impact of vegetation type, wind and temperature and food availability. More research is needed to better understand the interaction of environmental factors and the pests. More study sites and longer sampling periods over multiple combined with the SQM would allow a greater understanding of how these pests respond to illumination levels.

Overall, this study strengthens the idea that illumination is an important predictor for New Zealand's nocturnal mammalian pests. My findings are ecologically relevant and will aid future research as well as monitoring and control operations by helping make the best use of resources.

Appendix A

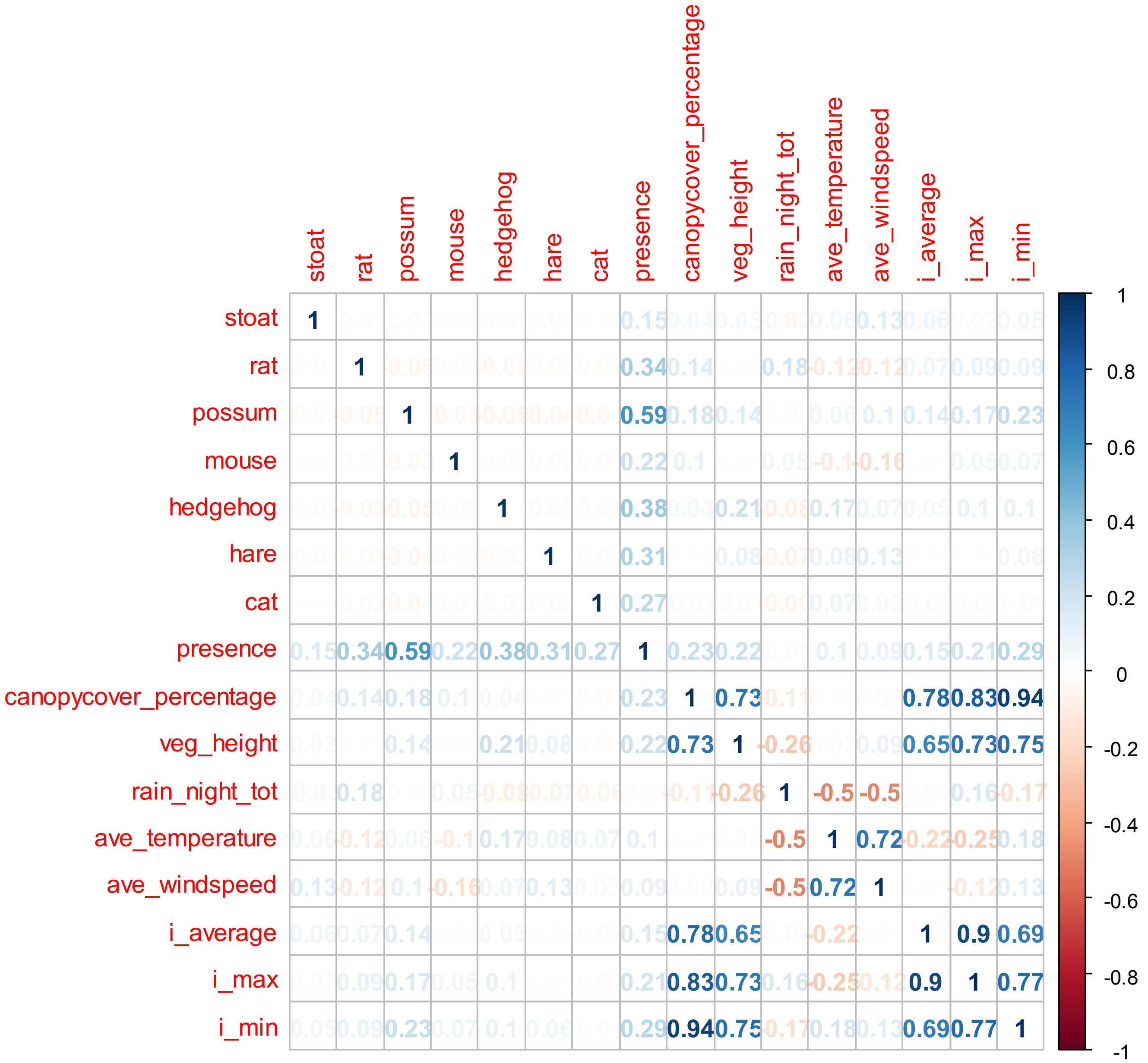
Correlations between numeric variables

A.1 Waxtag™ data correlation matrix, testing for collinearity (research question 3 (chapter 7))



	presence	i_average	max	min	rain_night_tot	ave_temperature	ave_windspeed
presence	1	0.2	0.16	0.2	-0.01	0.05	-0.07
i_average	0.2	1	0.92	0.77	0	-0.28	-0.24
max	0.16	0.92	1	0.8	0.21	-0.32	-0.01
min	0.2	0.77	0.8	1	-0.15	0.09	-0.22
rain_night_tot	-0.01	0	0.21	-0.15	1	-0.6	0.55
ave_temperature	0.05	-0.28	-0.32	0.09	-0.6	1	0.08
ave_windspeed	-0.07	-0.24	-0.01	-0.22	0.55	0.08	1

A.2 Camera trap data correlation matrix, testing for collinearity (research question 3 (chapter 7))



	stoat	rat	possum	mouse	hedgehog	hare	cat	presence	canopycover_percentage	veg_height	rain_night_tot	ave_temperature	ave_windspeed	i_average	i_max	i_min
stoat	1	-0.01	-0.02	0.01	-0.01	-0.01	-0.01	0.15	0.04	0.03	-0.03	0.06	0.13	0.06	0.02	0.05
rat	-0.01	1	-0.05	-0.02	-0.03	-0.03	-0.02	0.34	0.14	0.01	0.18	-0.12	-0.12	0.07	0.09	0.09
possum	-0.02	-0.05	1	-0.03	-0.05	-0.04	-0.04	0.59	0.18	0.14	-0.02	0.06	0.1	0.14	0.17	0.23
mouse	0.01	-0.02	-0.03	1	-0.02	-0.02	-0.01	0.22	0.1	-0.01	0.05	-0.1	-0.16	0.01	0.05	0.07
hedgehog	-0.01	-0.03	-0.05	-0.02	1	-0.03	-0.02	0.38	0.04	0.21	-0.08	0.17	0.07	0.05	0.1	0.1
hare	-0.01	-0.03	-0.04	-0.02	-0.03	1	-0.02	0.31	0.01	0.08	-0.07	0.08	0.13	0.01	0.01	0.06
cat	-0.01	-0.02	-0.04	-0.01	-0.02	-0.02	1	0.27	-0.01	-0.01	-0.06	0.07	0.03	-0.02	-0.02	-0.01
presence	0.15	0.34	0.59	0.22	0.38	0.31	0.27	1	0.23	0.22	-0.01	0.1	0.09	0.15	0.21	0.29
canopycover_percentage	0.04	0.14	0.18	0.1	0.04	0.01	-0.01	0.23	1	0.73	-0.11	-0.01	0.02	0.78	0.83	0.94
veg_height	0.03	0.01	0.14	-0.01	0.21	0.08	-0.01	0.22	0.73	1	-0.26	0.03	0.09	0.65	0.73	0.75
rain_night_tot	-0.03	0.18	-0.02	0.05	-0.08	-0.07	-0.06	-0.01	-0.11	-0.26	1	-0.5	-0.5	-0.03	0.16	-0.17
ave_temperature	0.06	-0.12	0.06	-0.1	0.17	0.08	0.07	0.1	-0.01	0.03	-0.5	1	0.72	-0.22	-0.25	0.18
ave_windspeed	0.13	-0.12	0.1	-0.16	0.07	0.13	0.03	0.09	0.02	0.09	-0.5	0.72	1	0.01	-0.12	0.13
i_average	0.06	0.07	0.14	0.01	0.05	0.01	-0.02	0.15	0.78	0.65	-0.03	-0.22	0.01	1	0.9	0.69
i_max	0.02	0.09	0.17	0.05	0.1	0.01	-0.02	0.21	0.83	0.73	0.16	-0.25	-0.12	0.9	1	0.77
i_min	0.05	0.09	0.23	0.07	0.1	0.06	-0.01	0.29	0.94	0.75	-0.17	0.18	0.13	0.69	0.77	1

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