A comparison of lure types and monitoring methods in wētāpunga

(*Deinacrida heteracantha*)

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General Abstract

Novel predators are one of the largest drivers behind insect population declines and extinctions. This is particularly true for New Zealand insect species as the lack of a mammalian predator archetype throughout their evolutionary history has resulted in many large-bodied, flightless, and nocturnal species. New Zealand wētāpunga populations have suffered large population declines due to novel predators and are now restricted to off-shore, pest-free islands. Currently lacking are reliable and non-lethal methods available to monitor wētāpunga and other large bodied wētā populations.

In my thesis, I review the direct and indirect impacts of novel predators on native species and how variation in prey naivety results in behavioural trade-offs, for example between antipredator behaviours and foraging. The data chapters in my thesis test two aspects of wētāpunga monitoring: lure attractiveness and the effectiveness of three field monitoring methods. My research aims to inform the effective use of monitoring methods for wētāpunga. In chapter 3, I compared the attractiveness of peanut butter and banana lures to captively bred wētāpunga at the Auckland Zoo breeding facility. There was no difference in the number of approaches or latency to approach a lure between the peanut butter and banana treatments. In chapter 4, I compared three field monitoring methods, baited tracking tunnels, baited arboreal tunnels and visual surveys, over two nights on Ōtata Island, The Noises. Due to heavy rain and wind, both the tracking tunnels and arboreal tunnels became waterlogged and no evidence of wētāpunga presence was recorded using these two methods. However, I observed 16 wētāpunga and 15 tree wētā during visual surveys, demonstrating that visual surveys are more reliable for monitoring wētāpunga in difficult weather conditions. The results of my research suggest that non-lethal food based lures can be effective for monitoring native insects. Monitoring programmes should consider the environment, season and behaviour of target species when selecting a monitoring method.

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Chapter 1: General Introduction

Anthropogenic impacts are driving extinction rates through the growing pressures of invasive species introductions, pollution, climate change and habitat loss (Ceballos et al., 2020). Extinction rates of vertebrate species are high enough to widely support the claim of the world's sixth mass extinction (Geyle et al., 2021). However, understanding how invertebrates are impacted by anthropogenic disturbance is more difficult (Geyle et al., 2021). Invertebrates make up 73% of described fauna, yet only a small proportion of taxa have been described (Leandro & Jay-Robert, 2019; Régnier et al., 2015). In contrast, the conservation status of birds and large mammals can generally be accurately assessed due to a strong understanding of their ecology and behaviour (Régnier et al., 2015). The developing methods by which extinction and population declines have been measured in invertebrates raises other concerns about how scientists are monitoring the populations of poorly understood taxa such as terrestrial invertebrates. Major concerns regarding insect monitoring methods include the lack of standardised methods that effectively track insect activity and abundance in a non-destructive way (Hansen et al., 2020). The conservation of terrestrial invertebrates is critical as their decline and extinctions have profound knock-on effects that negatively impact ecosystem processes and services (Ceballos et al., 2017).

In New Zealand, invasive species have become one of the largest threats to native and endemic biodiversity (Murphy et al., 2019). Since European settlement, a total of 34 mammalian species have been introduced to New Zealand (Barker, 2016). These introduced species have caused detrimental impacts throughout all areas of ecosystems services and functions and are one of the largest drivers of native population declines and extinctions (Innes et al., 2019). The high impact of invasive species is largely due to New Zealand species evolving without any large mammalian predators (Murphy et al., 2019). Since the arrival of predatory mammals, such as the Pacific rat/kiore (*Rattus exulans*), New Zealand has seen 59 bird species become extinct and an estimated 80% classified as threatened or at risk (Murphy et al., 2019). The conservation of New Zealand's native species has focused on the management and eradication of invasive species since at least the

1980s, and in 2016 the government announced its Predator-free New Zealand by 2050 programme (Carter et al., 2016; Pech & Maitland, 2016). PFNZ 2050 is a programme aiming to eradicate three species of rats (*Rattus* spp.), three species of mustelids (*Mustela* spp.), and brushtail possums (*Trichosurus vulpecula*) from New Zealand by 2050 (Murphy et al., 2019). This approach is ambitious and requires technology that is yet to be developed (Peltzer et al., 2019). Invasive species management and eradication from 10% of New Zealand's offshore islands has positively impacted taxa such as birds, lizards, and insects (Innes et al., 2019). While these efforts are significant, we are lacking fundamental baseline research for taxa such as insects (Lamont et al., 2017). There are 18,000 formally described arthropod species in New Zealand yet estimates predict the diversity to be almost double that number (Lamont et al., 2017). The lack of research dedicated to insects is likely due to their importance being overshadowed by charismatic taxa such as birds, and the difficulty in monitoring often small and cryptic species (Lamont et al., 2017; New, 2022). Research on insect populations increasingly demonstrates that they are critical indicators of environmental health (New, 2022).

New Zealand is home to over 70 species of endemic wētā (Orthoptera: Anostostomatidae) made up of five distinct groups; giant wētā (*Deinacrida* spp.), tusked wētā (*Motuweta isolata*), ground wētā (*Hemiandrus* spp.), tree wētā (*Hemideina* spp.) and cave wētā (Rhaphiophoridae) (Strauß & Howard, 2022). These giant, flightless insects typically inhabit subalpine environments and temperate forests across the country (Strauß & Howard, 2022). The introduction of mammalian predators, habitat loss and habitat modification has resulted in population declines of many wētā species (Gibbs, 1998; Green et al., 2011; Watts & Thornburrow, 2011). Sixteen species are considered 'at risk', with many of these species dependent on pest-free islands for their survival (Watts & Thornburrow, 2009). Continued conservation management of wētā species is needed to prevent extinction. However, many gaps remain in our understanding of their basic natural history, including population demographics, habitat use and behaviour. Filling these gaps is critical for effective conservation management. While there have been successful translocations and captive breeding programmes for species such as the tusked wētā and wētāpunga (*Deinacrida heteracantha*), consistent issues remain surrounding the use of effective monitoring methods to survey populations. There are several methods used to monitor wētā; tracking tunnels, arboreal tracking tunnels, visual surveys, frass dropping monitoring and artificial refuges (Bowie et al., 2014; Sweetapple & Barron, 2016; Watts et al., 2008). These methods are useful to obtain some data, but often provide inconsistent results when used across different seasons, weather conditions and short timeframes. Effective monitoring methods need to be developed to generate baseline knowledge of each species and better manage at risk populations.

1.1 Aims of this thesis

The aim of my thesis was to investigate the monitoring methods used for surveying wētāpunga and to improve their effectiveness in monitoring wild populations of wētāpunga.

In Chapter 2, I review the current body of literature on the direct and indirect impacts of novel predators on native species. The literature review discusses how novel predators can have direct impacts on prey through predation, and indirect impacts that arise through trade-offs in foraging and increased antipredator behaviours. This chapter was originally written at the beginning on my studies when I had planned to investigate Auckland tree wētā *(Hemideina thoracica)* behaviour and habitat-use in response to differing degrees of predator exposure. Unfortunately, I was not able to complete this research due to a very poor tree wētā season.

Chapter 3 compares the attractiveness of different lures in captive bred wētāpunga. Laboratory trials were carried out by presenting wētāpunga with either freshly cut banana or peanut butter. I compared the number of approaches to each lure to determine how attractive they were to wētāpunga. The objective of these trials was to investigate whether there was another lure that was more attractive to wētāpunga than peanut butter, which has historically been used.

Chapter 4 compares the use of three different monitoring methods in the field: baited tracking tunnels, baited arboreal tracking tunnels, and visual surveys. I compared the results from each method over two nights on Ōtata Island, The Noises. The objectives of this study were to identify which method is most effective, and how conditions such as the weather can influence monitoring results. I aimed to use the results of this study to broaden general understanding of each of the methods when monitoring wētāpunga, and how they can be applied more effectively.

Finally, in Chapter 5, I synthesise the main findings for both the lure study and the study comparing monitoring methods. I discuss how the findings from these studies contribute to monitoring method practices, the limitations of the study and directions for future research.

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Chapter 2: A review of direct and indirect impacts of novel predators on prey behaviour

Understanding how invasive species impact ecosystems is critical for the conservation of native and endemic wildlife (Jeschke et al., 2014). Globally, introduced or invasive species have been the cause of habitat destruction and modification, competition for resources and ecosystem processes, and ultimately the predation of native species. These impacts have resulted in population declines and species extinction (Berchtold & Côté, 2020). Individuals at risk from invasive predators face trade-offs in foraging, survival and reproduction that may differ from those they have evolved to cope with (Huang et al., 2017). Risk assessment is critical for almost every process or decision that is to be made across an individual's lifetime (Saxon-Mills et al., 2018). Predator recognition is a large part of how individuals avoid risk. Recognition is developed throughout co-evolutionary periods of exposure to predators that result in adaptive behaviours or physiological adaptations that mitigate specific predation types (Saxon-Mills et al., 2018). However, when a new predator is introduced to an ecosystem, native species may be particularly vulnerable to predation if individuals cannot recognise the novel predation cues and respond effectively (Polo-Cavia & Gomez-Mestre, 2014).

The introduction of novel predators to native ecosystems has led to important and growing understanding of how novel predators can shift the behaviour of native species, both directly and indirectly (West et al., 2018). Invasive species tend to target prey that lack the evolutionary adaptations or the plasticity to evade new predators and are the current leading cause of decline for threatened species globally (Berchtold & Côté, 2020; West et al., 2018). Native species face the challenge of not only recognising the level of risk posed by the novel predator, but also the possibility of disruptions to other ecological processes (Saul & Jeschke, 2015). For example, invasive species can cause habitat destruction and modification, and altered competition for food and resources (Carthey & Banks, 2014). Here, I review the current body of research on the direct and indirect consequences of novel predators on the behaviour of native species.

2.1 Impacts: direct and indirect

The risks posed by novel predators to native species can be described broadly under three categories; (1) prey have no ability to recognise the new threat, (2) prey can recognise the threat but are unable to respond appropriately to evade predation, or (3) prey recognise the predation threat and respond appropriately (Carthey & Banks, 2014). While these categories are a useful framework predicting possible outcomes, prey behaviour often exists on a spectrum. The IUCN have stated that globally, novel predation accounts for 27% of terrestrial species under threat and 40% of critically endangered species (Duenas et al., 2021). While these figures comprise a high proportion relative to other threats impacting biodiversity, it is difficult to determine their accuracy. The IUCN red list only accounts for taxa that have been assessed, and therefore this may result in a systemic underestimation of taxa yet to be assessed, or those that are already extinct (Bellard et al., 2016). Native prey that can respond to novel predators are usually species that have evolved in ecosystems with a broad range of predators (Hooks & Padilla, 2014). However, if native prey are unable to immediately recognise the threat of novel predators and the predation pressure is strong, then it can prevent the development of novel anti-predator traits before the population goes extinct (Carthey & Banks, 2014). Generally, novel predators that have a similar archetype to that of predators that prey have coevolved with will not generate strong selection pressure to change prey behaviour (Berchtold & Côté, 2020). In contrast, truly novel predators will elicit much stronger selection on prey behaviour (Berchtold & Côté, 2020).

Indirect impacts of novel predators are more complex as prey are subject to multiple selection pressures, including predation risk from different species of predators, environmental variables and human activities (Pyšek et al., 2017). While effective responses by prey to novel predators can reduce the risk of direct consumption, novel predation can also result in non-consumptive effects that affect population dynamics, fitness and ecosystem dynamics as a whole (Raine et al., 2020). For example, prey behaviours such as shifting habitats or foraging behaviour to reduce exposure to a new predator can have multiple downstream effects (Coleman & Hill, 2014). Changes in foraging behaviour to avoid predation can have consequences on food webs such as native species switching from a generalist to a specialist diet, or prey switching (e.g. eating insects instead of fish) (Wainright et al., 2021). In some cases anti-predator behaviours can lead to prey being further exposed to predation from other predators. For example, New Zealand mudsnails introduced in North America escape predatory fish by burrowing into the substrate or hiding under rocks, but this anti-predator behaviour leaves the mudsnails vulnerable to predatory crayfish (Sih et al., 2010).

Indirect effects of novel predators can also include temporal changes in behavioural patterns, such as shifts in feeding rates due to the trade-off between predator avoidance and food intake (Palmer et al., 2022). A decrease in food intake or changes in nutrition can result in reduced growth rates, fecundity or at the extreme end, starvation (Palmer et al., 2022). For example, blackbirds (*Turdus merula)* reduced chick feeding rates after exposure to novel predators with no compensatory feeding after the threat was removed (Bonnington et al., 2013). Reduced feeding rates even over a short period can adversely influence chick condition, and over longer periods of time reduce clutch size (Bonnington et al., 2013). Trade-offs between avoiding predation and reproductive success shape how fitness, life-history traits and morphological traits are expressed within individuals and can change population dynamics entirely (West et al., 2018). Individuals faced with novel predators ultimately either change the way they interact with their environment (change refuge preferences, diet or resource allocation), move away from the threat or face being attacked and killed (Hudgens & Garcelon, 2011). For example, eastern fence lizards increased antipredator behaviours, such as fleeing, after the introduction of fire ants (*Solenopsis invicta*) (Thawley & Langkilde, 2017). The study noted that increased fleeing was also triggered by other, generalised native ants (Thawley & Langkilde, 2017), suggesting that the fence lizards could not distinguish fire ants from native ants as the tactile cues were potentially similar (Thawley &

Langkilde, 2017). The increase in anti-predator behaviour resulted in fence lizards having a higher rate of injuries, which increases mortality, and in the case of tail loss, a greater vulnerability to predators (Thawley & Langkilde, 2017).

The direct and indirect impacts of novel predators are not mutually exclusive, and interact with other environmental pressures (Duenas et al., 2021). For example, populations of endemic fish species in Lake Victoria, Africa, started to decline rapidly after the invasion of a brown tree snake (Pyšek et al., 2020). The snakes were consuming the fish rapidly, but fish predation was occurring simultaneously with an increase in intensive fishing practices and decline in water quality (Duenas et al., 2021). Interactions such as these are common where novel predators are introduced and pressures across trophic levels are magnified or changed and sometimes influenced by other pressures, such as human activity (Pyšek et al., 2020; Waser et al., 2015).

2.2 Plasticity

The ability of an individual to respond to an immediate novel threat is determined by its phenotypic plasticity (Berthon, 2015). Predators that exert strong selection pressure on prey may cause behavioural shifts that increase individual prey survival, assuming there is some degree of plasticity in prey responses. If these behavioural shifts confer a significant advantage over other, less plastic individuals, the response may become fixed at a population level and shift the evolutionary trajectory of a species. For example, the introduction of a ground-dwelling predator to small islands in the Caribbean caused anolis lizards to shift from the ground to trees (Zuk et al., 2014). The new predator initially resulted in increased selection for large females and males with longer legs, as they were able to run away faster (Zuk et al., 2014). However, ultimately, lizards that had shorter legs and moved to trees reversed the selection pressure, as the change in habitat was a more effective way to avoid predation than running (Zuk et al., 2014). This example highlights a behavioural response to a novel predator that resulted in selection for a physical trait that increased the effectiveness of the anti-predator behaviour. Morphological changes in response to predation are often connected to changes in behaviour (Berthon, 2015). For example, burrowing bettongs (*Bettongia lesueur*) exposed to feral cats (*Felis catus*) fled at twice the approach distance compared to naïve bettongs and also produced progeny with larger hind feet and larger heads (Moseby et al., 2022). The novel predator selected for phenotypic changes in behaviour and morphological traits to increase the effectiveness of a predisposed behaviour (Moseby et al., 2022).

Behavioural plasticity can be expressed within individuals and across populations as a whole (Snell-Rood, 2013). Behavioural plasticity is expressed through an individual's ability to detect and respond to a threat (Gazzola et al., 2021). Pressure from a novel predator that selects for an already existing behavioural type can result in stabilization of predation threats (Fleischer & Li, 2018). For example, in three-spined sticklebacks, predation rates influenced habitat choice across different populations that reflected individual behavioural types (Fleischer & Li, 2018). Vigilance and shyness were selected for when there were high rates of predation, whereas habitats with low rates of predation selected for bold individuals with more active lifestyles (Fleischer & Li, 2018). This example illustrates how predators and prey can coexist if the evolutionary adaption of the prey is faster than that of the predator (Fleischer & Li, 2018).

Understanding how species respond to novel predators through behavioural and morphological plasticity is critical for conservation. Predicting prey responses requires a knowledge of the level of predator naivety that species possess.

2.3 Islands vs continents

Native species that have been able to adapt to the presence of novel predators are predominantly found on continents, such as Africa, Eurasia and the Americas (Vanderwerf, 2012). Large continents can support diverse predator archetypes, which means that prey are more likely to evolve a range of anti-predator tactics (Saul & Jeschke, 2015). In contrast, islands often have higher rates of endemism and have a limited exchange of predator archetypes that have co-existed over several million years (Cox & Lima, 2006; Vanderwerf, 2012).

The impacts of novel predators are not limited to either adaption or extinction but exist across a spectrum of outcomes depending on a number of factors (Wood & Shepard, 2022). The odds of a species responding effectively to a novel predator are higher when they have coevolved with a variety of predator archetypes (Fleischer & Li, 2018). For example, a novel predator may possess a particular olfactory chemical that is similar to a known predator, an occurrence that is common across mammals that may be closely related (Moseby et al., 2016). Native species exposed to predators that are similar to known types are likely to already possess effective anti-predator traits, ultimately leading to less costly risk evasion than if the new predator is completely novel (Carthey & Banks, 2014). Ecosystems that contain a range of predator archetypes are more resilient when new predators are introduced, even after the predation pressure has been relaxed for a while (Heise-Pavlov, 2016). For example, tree-kangaroos in northern Queensland, Australia, still recognise and respond to odours from both terrestrial and arboreal predator archetypes since the extinction of their ancestral terrestrial predators (Heise-Pavlov, 2016). Tree-kangaroos displayed longer periods of anti-predator behaviour when odour cues from predators (python, Tasmanian devil and dog) were presented compared to control odours (water and lavender) (Heise-Pavlov, 2016). All the individuals within the trials had no previous experience with these predators, meaning that they possessed an innate antipredator response (Heise-Pavlov, 2016).

In contrast to continents, ecosystems on islands are isolated, have high rates of endemism, rich biodiversity and strong selection for flightlessness, nocturnal behaviour and gigantism (St Clair, 2011; Vanderwerf, 2012). Despite islands making up only 5% of the earth's surface, they support 20% of our biodiversity (Russell et al., 2015). The relative isolation of islands has resulted in fragile ecosystems and they account for 95% of bird, 90% of reptile and 70% of mammal extinctions, predominantly caused by invasive predators (Russell et al., 2015). Islands such as New

Zealand have a geographically smaller habitat, which limits resources, movement patterns and larger mammalian predator types (Anton et al., 2020; Towns, 2011). The smaller land area and population sizes on islands mean that they can generally only support fewer and less diverse predator populations than continental ecosystems. Without a predisposition to respond to a variety of predator types, prey species on islands often lack the innate responses vital to evade novel, introduced predators (Anton et al., 2020; Berchtold & Côté, 2020).

2.4 Gaps in the literature

Predation research to date is heavily focused on avifauna conservation and the use of birds as a biomarker for environmental health (Berto & Lopes, 2020). However, large-bodied invertebrates, reptiles and amphibians are at a higher risk of predation than birds from invasive species, particularly from rodents (St Clair, 2011).

The framework surrounding avifauna as indicator or keystone species has a solid foundation and tends to be widely supported by the general community (Ainsworth et al., 2018). This trend has enabled the responses of birds to novel predators to receive a large proportion of conservation focus (Ainsworth et al., 2018). While this research has been productive, it has created a gap in our understanding of other taxa (Lindenmayer & Westgate, 2020). In particular, there is a lack of effective monitoring frameworks for invertebrates. Invertebrates play essential roles in many ecosystem processes, so it is important that they are adequately represented in biodiversity monitoring programmes (Eisenhauer et al., 2019).

Insects, reptiles and amphibians are still lacking in empirical data that is needed to quantify the direct and indirect impacts of novel predators. It would be useful to further develop current tracking and monitoring methods to assess the population sizes and behaviour of small to medium sized invertebrates. Research into the general behaviour patterns and behavioural responses of invertebrates to novel predators would aid in developing management frameworks for future species invasions.

2.5 New Zealand

New Zealand's endemic and native fauna has evolved in isolation from the threats of mammalian predators and so few species possess anti-predator behaviours in response to terrestrial mammals such as rats, mice, possums and stoats (Barker, 2016). Mammalian predators were introduced to New Zealand around 1300 and since then have been the cause of an estimated 26.6 million chick and egg losses each year for native bird species, 40% of all avifauna extinctions since the arrival of rats, and the consumption of approximately 7.67 million tons of vegetation annually by possums alone (Gibbs, 2009; Goldson et al., 2015; Russell et al., 2015).

For millions of years, the only terrestrial mammals present in New Zealand were two species of native bat (Goldson et al., 2015). The presence of mainly avian predators, and the absence of mammalian predators such as rats and possums, has resulted in many endemic species evolving anti-predator behaviours such as remaining motionless, hiding near or in substrates, and nocturnal activity (Gibbs, 2010; Muralidhar et al., 2019). The lack of mammalian predators has also allowed the development of traits such as flightlessness, gigantism and often strong odour cues (Gibbs, 2010; Muralidhar et al., 2019). The combination of these behavioural and physical traits makes many New Zealand species particularly susceptible to introduced mammals. For example, the kākāpō's (*Strigops habrotilus*) 'freeze response' to threats, ground-nesting behaviour, flightlessness, a strong odour and loud, recognisable mating calls have made it particularly vulnerable to invasive mammalian predators (Carthey & Blumstein, 2018). Kākāpō are currently restricted to only three pest-free offshore islands.

There is a growing understanding of how taxa such as invertebrates, reptiles and amphibians are likely to be sensitive to novel predators (Anton et al., 2020). For example, tuatara (*Sphenodon* *punctatus*) are vulnerable to rats that prey on eggs and hatchlings (Towns, 2011). Understanding the direct impacts of novel predators on tuatara was critical to the success of translocation programmes for the species (Towns, 2011). Unexpectedly, tuatara increased body condition after the eradication of rats (Towns, 2011). Further, fledgling success in burrowing seabirds also increased after the eradication of rats (Towns, 2011), highlighting the advantageous, indirect effects of conservation work that is aimed at indicator species. Indicator taxa are incredibly important for conservation (Watts et al., 2017). Many invertebrates are excellent candidates for indicators as they are widespread, easily accessible in many environments, and represent an extensive proportion of biodiversity and ecological functions (Watts et al., 2017). Invertebrates exhibit high levels of endism, particularly in New Zealand (St Clair, 2011). This often reflects their roles in ecosystem function, such as detritivores, primary consumers, competitors, mutualists, pollinators and disease vectors (Samways et al., 2020). We also know that invertebrates are particularly vulnerable to predation by invasive predators such as rodents, as a significant proportion of many rodent diets is insects (Samways et al., 2020).

Beetles have often been used as bioindicators for New Zealand ecosystems, however, there is now a growing body of evidence that supports the use of tree wētā (*Hemideina* spp.) as bioindicators (Hutcheson et al., 1999; Watts et al., 2011, 2017). Tree wētā are currently listed as an indicator for the New Zealand Inventory and Monitoring Framework developed by the New Zealand Department of Conservation (Watts et al., 2017). Tree wētā are widespread across New Zealand, arboreal, flightless, large bodied, relatively long-lived and are excellent indicators for monitoring the effects of pest control, especially small mammals such as rats (Watts et al., 2017). Other wētā species have seen population declines and many wētā species are currently confined to pest-free offshore islands (St Clair, 2011). For example, tusked wētā (*Motuweta isolata*) disappeared on Mercury Island after the arrival of rats (Gibbs, 2009). After rodents were eradicated, tusked wētā were then successfully reintroduced through a translocation programme (Gibbs, 2009).

This confirmed that rats were the likely cause for the population decline, rather than an unsuitable ecological environment (Gibbs, 2009). Another study surveyed the activity of Wellington tree wētā (*Hemideina crassidens*) over a four year period during the removal of the Polynesian rat kiore (*Rattus exulans*) (Rufaut and Gibbs, 2003). After the removal of kiore, tree wētā activity and the proportion of adults in the population increased, illustrating how invasive species impact native populations not only through direct predation effects, but also behaviour (Rufaut and Gibbs, 2003). Similar reductions in activity patterns when predators such as rats were present were identified in another study of Wellington tree wētā (Kelly, 2022). Further, male aggression was lower in areas of high predation, which could potentially lead to reduced mating success and further predator avoidance (Kelly, 2022).

New Zealand has committed to invasive mammalian eradication, pest-free islands and fenced mainland sanctuaries for over 50 years now (Russell & Broome, 2016). Invasive species eradication and management has been capitalised on by captive breeding programmes, reintroduction programmes, and hundreds of translocations (Goldson et al., 2015). While the total eradication of invasive species is a distant and complex goal, the country is aiming for a 'Predator-Free New Zealand' by 2050 (PFNZ 2050). The direct and indirect effects of invasive species on endemic and native species and their ecosystems are still yet to be fully understood. However, conservation efforts thus far have been paramount to the survival of many endemic species (Towns, 2011). The New Zealand government has already invested NZ$28million to kickstart the eradication of rats, possums and mustelids (Norbury, 2020). Whether or not the PFNZ 2050 goals are achievable are the focus of debate as, first, the technology and processes needed to eradicate the target predator species are currently insufficient (Murphy et al., 2019). Second, the social and ethical challenges with respect to community approval and the integration of Māori partnerships have not been adequately addressed (Peltzer et al., 2019). Third, the ecological implications of removing apex predators from highly modified systems can have complex and unpredictable results

(Peltzer et al., 2019). For example, while the removal of cats and mustelids in Alexandra resulted in the recovery of some native lizard species and reduction of mice, it also allowed rabbit populations to increase rapidly, with detrimental impacts on agriculture, soil quality and an increase in vectors for disease (Peltzer et al., 2019). This highlights the ecological implications of removing an entire species from an ecosystem. PFNZ 2050 is still a long way off, and reaching this goal is questionable given the resources currently available. By focusing our research efforts on understanding the behavioural plasticity of native species in response to novel predators, we can better understand how to support conservation efforts that are happening now.

In apparent opposition to PFNZ 2050 goals, introduced species support many economic activities, recreational values and areas of primary production, such as urban cats, pigs, deer and salmonoid fish (Lyver et al., 2019). Some of these introduced species are legally protected to support recreation and tourism (Lyver et al., 2019). Further, PFNZ 2050 does not take into account the value of some non-native species as integral parts of Māori communities or their significance within indigenous tradition (Palmer et al., 2021). The PFNZ 2050 policy overlooks Māori systems of law and morality that are grounded in philosophies that protect whakapapa, and its fundamental connection between humans and the natural world (Palmer et al., 2021). The policy initiatives also have the capacity to impose responsibility and financial cost directly onto Māori land owners (Peltzer et al., 2019). The costs of implementing and maintaining pest control are problematic because Māori own large and marginal lands that would be particularly difficult and expensive to target. This passes an ecological debt from government to Māori, potentially leading to treaty grievances and claims (Peltzer et al., 2019). The use of introduced species as natural resources by Māori also differs from western views (Palmer et al., 2021). For example, possum fur is often woven into wool for yarn and is considered a valuable resource in rural communities with low employment rates and low income (Peltzer et al., 2019). Conversely, trapping and killing of possums is taught in city schools as a ‘war’ against introduced species (Morris, 2020). The contrasting value of possums as a sink or source between western societies and Māori communities is not accounted for in the PFNZ 2050 goals. Demonising some introduced species and not others grossly overlooks the interconnected ecological and social impacts of complete eradication. While PF2050 is clear in its goal of total eradication, it is not clear on why this goal is important outside of examples of species extinction. Investigating how native species respond to low or controlled levels of novel predators could provide an avenue for species to respond to the predation pressure and reduce naivety over time (Moseby et al., 2022). Understanding how native species respond to different densities of novel predators temporally and spatially will provided critical insight for conservation efforts (Ferrari et al., 2015).

A re-evaluation of PFNZ 2050 goals should include a framework supported by a multifaceted approach that includes existing technologies and a strong integration between science, government, community values, Māori and Te Tiriti. The framework should outline the motivation for a predator-free New Zealand that highlights how the removal of invasive species supports the restoration of biodiversity, reduces the spread of diseases and pathogens, and restores ecosystem functions and processes. This would allow for a more nuanced approach to conserving New Zealand's biodiversity. Predator eradication plans could be developed on a case-by-case system where the consideration of positive and negative impacts is incorporated into its actions. This is where the value of understanding community level responses to introduced species lies. Conservation of New Zealand's threatened species can be achieved through a flexible and lower risk approach than PFNZ 2050 that supports a broader swathe of the country's biodiversity, indigenous, social and economic values.

2.6 Conclusions

The direct and indirect consequences of novel predators on the behaviour of native species has resulted in population declines and extinctions of many species (Saul & Jeschke, 2015).

Understanding how novel predators influence a spectrum of trade-offs in foraging, survival and reproduction will ultimately create a framework for effective conservation of native fauna. The degrees of prey naivety toward a new predator are dependent on predator archetypes, current resident predators, habitat quality and the phenotypic plasticity of prey (Gazzola et al., 2021). The current body of literature exploring these concepts provides a robust framework for future research surrounding novel predators and prey naivety. Novel predators should be understood from a multifaceted lens that considers both the consumptive and non-consumptive effects on prey. The body of research currently available heavily focuses on terrestrial vertebrates and fish as examples. Future research should investigate the impacts of novel predators on less studied taxa such as insects that are essential to ecosystem function. Identifying the impacts of novel predators from a bottom-up perspective would be highly valuable in understanding where to focus future conservation efforts.

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Chapter 3: Comparing the attractiveness of banana and peanut butter lures for monitoring wētāpunga (*Deinacrida heteracantha*) populations

3.1 Abstract

Non-lethal monitoring of insects for conservation purposes requires an effective lure. The use of food-based lures for monitoring is limited as they tend to attract non-target species in addition to the target species. Wētāpunga (*Deinacrida heteracantha*) are routinely monitored using tracking tunnels baited with peanut butter. While peanut butter is attractive to wētāpunga, it is also commonly used to monitor several other species such as rats and mice, which are known predators of wētā. To investigate if there is a lure that is more attractive than peanut butter, I compared the attractiveness of peanut butter and banana lures to captively bred wētāpunga at the Auckland Zoo breeding facility. Wētāpunga were tested within their home enclosures and presented with a banana or peanut butter lure in a petri dish, in random order, together with an empty, control petri dish. Thirty juvenile enclosures (each containing two to twenty individuals) and three individually housed adults were tested. I assessed the attractiveness of each lure by comparing how many approaches each lure received, and latency to approach a lure. There was no significant difference in the number of approaches between the peanut butter and banana treatments or latency to approach a lure. Therefore, both peanut butter and banana may be equally effective lures for wētāpunga monitoring.

3.2 Introduction

The ability to accurately monitor populations is essential to measure the success of conservation efforts (Witmer, 2005). However, monitoring populations can be a difficult task when timeframes and resources are limited, the species behaviour is poorly understood, or monitoring methods are yet to be developed. Monitoring insect populations is particularly difficult as they are highly diverse, small in body size and we often lack basic information about their distribution and ecology (van Klink et al., 2022). Insects are critical to many ecological processes such as plant and flower pollination, nutrient cycling and act as primary consumers in grassland biomes (Muzafar Riyaz et al., 2022). Despite more than 80% of all animal species being insects, only 8% have been assessed under the IUCN Red list criteria (Chowdhury et al., 2023). The true decline in species globally is yet to be understood and urgently requires solutions for accurate population monitoring (Noskov et al., 2021; van Klink et al., 2022)

A common issue with insect monitoring methods is that many methods lack transferability across species (Noskov et al., 2021). Pitfall traps are routinely used for ground-dwelling insect species. However, pitfall traps are non-specific, often lethal, and biased towards ground-dwelling species, which makes them inappropriate for rare and endangered species (Knapp et al., 2020). Other methods such as visual surveys, tracking tunnels and camera traps have value, but require longer timeframes and heavily rely on observer expertise for accurate data (O'Connor et al., 2019). Scientists are currently exploring how modifying traditional monitoring methods can provide more specific and accurate information about population size. For example, Fite et al. (2020) found that seasonal changes, particularly wind speed, influence the number of moths attracted to different types of traps and pheromone lures. Understanding ecological conditions in conjunction with lure preferences are key when deciding which monitoring method to use (Fite et al., 2020).

In New Zealand, insect conservation has piggybacked on the country's large focus on eradicating invasive mammals (Watts et al., 2011). The eradication of invasive mammals has allowed scientists to monitor some insect populations through methods such as small mammal tracking tunnels (Watts et al., 2011). Tracking tunnels as a monitoring method have been a pillar in monitoring wētā (Orthoptera: Anostostomatidae) as they are non-lethal, allowing observations of endangered species like wētāpunga (*Deinacrida heteracantha*) (Green et al., 2011). The use of tracking tunnels for wētā was first described in 1977 (King & Edgar, 1977). Since then, research has confirmed that tunnels baited with peanut butter are more attractive to wētā than non-baited tunnels (Watts et al., 2013; Watts et al., 2008, 2011). Peanut butter has been the only documented lure used for wētā monitoring, and no other lures have been trialled (Watts et al., 2008, 2011). Another study suggested that placing the tracking tunnels in trees would be more effective in monitoring arboreal wētā species, however, there has been little research since then to compare their effectiveness (Watts et al., 2008). Visual surveys are the only other commonly used method to monitor wētā (Hodge, 2020) and are often used in conjunction with tracking tunnels (Watts et al., 2008). This is because tracking tunnels currently have low rates of detection and do not give any information about population dynamics (Watts et al., 2011). However, visual survey methods are labour intensive. For this reason, improving the rates of detection in tracking tunnels would be very useful. To increase the effectiveness of tracking tunnels, identifying a lure type that is more attractive to wētā than peanut butter would be a large boost to the success of wētā monitoring and conservation efforts.

Wētāpunga are the largest of all the wētā species in New Zealand (Green et al., 2011). Like most other species they are nocturnal and flightless, leaving them particularly vulnerable to invasive species predation (Green et al., 2011). Since the 1900's, surveys of wētāpunga showed heavy population declines due to predation from rats and mice, which resulted in the species being classified as nationally endangered at one point (Green et al., 2011; Watts and Thornburrow, 2011). Wētāpunga were once widespread throughout Northland, Auckland and Great Barrier Island, however, the decline of wētāpunga resulted in a single population restricted to Little Barrier Island in the Hauraki Gulf, Auckland (Watts and Thornburrow, 2011). Conservation of the species was then aimed at rebuilding the population (Watts and Thornburrow, 2011). Several successful captive breeding programmes were implemented, and individuals were released onto several pest-free islands including Tiritiri Matangi (Griffiths et al., 2019). While this critical effort in wētāpunga conservation prevented the extinction of the species, wētāpunga are still listed as vulnerable and are confined to offshore, pest-free islands. Like all wētā species, wētāpunga monitoring is reliant on visual surveys and tracking tunnels. Improving the effectiveness of these methods will greatly support their conservation.

In this chapter, I tested whether peanut butter or banana is more attractive to captively bred wētāpunga. This study will be used to inform which lure is most effective for attracting wētāpunga to tracking tunnels in field monitoring programmes.

3.3 Methods

Study species and husbandry

The animals used for this experiment were provided by Auckland Zoo (Auckland, New Zealand), who have been managing a highly successful captive breeding programme for wētāpunga since 2012. Auckland Zoo houses juveniles in groups of up to 20 individuals in 30 × 30 × 40 cm enclosures until their 5th instar. Animals older than 5th instar are individually maintained in enclosures 90 × 50 × 50 cm. The zoo maintained 30 enclosures over the study period (June – August 2022), containing 2-20 juveniles (mean = 18.88, sd = 3.67) of mixed age and sex, and a further three enclosures individually housing three adults (one male and two females). Enclosures provided elevated refugia comprising clumps of dead *Cyathea dealbata* fronds held together by a cylinder of plastic netting and lengths of plastic hose for refuge. Young nymphs were sprayed with rainwater daily. Individually housed adults or subadults were provided with dry browse of *Kunzea* spp, clumps of dry *Cordyline australis* and/or *Rhopalostylis sapida* leaves, and dry *Cyathea* *dealbata* fronds. The two mature females were also provided with an egg field in a plastic ice cream container filled with soil. All individually housed adults were supplied with a water reservoir.

A shifted light cycle (12h L:12h D; lights off at 2:30pm) was incrementally introduced by one hour per day in the lab before the experiment to facilitate the experiments while still mimicking the natural activity patterns of wētāpunga. The wētāpunga were fed fish flakes and fresh browse on Monday, Wednesday, and Friday. Trials were completed on the days in-between feeding days to minimise interference of their regular feeding schedules and activities as food was removed from enclosures for the duration of the trials.

Trial procedure

To compare the effectiveness of each lure (fresh banana and Macro Organic smooth peanut butter) in juvenile wētāpunga, four enclosures were moved onto a shelf in the middle of the lab immediately before the trials to minimise interactions between neighbouring enclosures and draughts from the air-conditioning unit within the lab. Each enclosure underwent two trials (starting at either 2:30pm or 4:30pm) in which they were presented with peanut butter or banana in random order. Feeding trays and any residual fish flakes were removed from the enclosure before each trial. One lure (one tablespoon of freshly chopped banana or peanut butter) was placed in a petri dish with a perforated lid on one side of the enclosure, and an empty petri dish on the other side. Lure type and placement of petri dishes were randomly allocated. The lures were left in the enclosure and filmed for 90 minutes. To ensure minimal disruption to the animals, no people were present during the trials. Trials were filmed using an infrared video camera (Canon XA11 or Canon XA20). After the trial, both petri dishes were removed, and feeding trays returned to the enclosures. Petri dishes were washed with warm water and mild soap to ensure no residue was present. Two days later (after another feeding/maintenance cycle), the alternate lure was presented using the same experimental procedure. Overall, we tested 30 juvenile enclosures and three adults. There was no handling of any animals, and all animals remained in their enclosure for the duration of each trial.

A wētā was recorded as attracted to the lure or empty dish when it approached the petri dish using mouthparts, antennae, or legs to touch or feel the dish. The number of wētā from each enclosure that approached the lures was recorded, as well as the latency for the first wētā to arrive at a lure.

Limitations

Due to the conservation status of wētāpunga, this research was limited in the types of lures that could be tested to ensure that the study posed no risk to the animals. Peanut butter is routinely used for monitoring many wētā species in the wild (Watts et al., 2008). Banana was proposed as an alternative lure during conversations with zookeepers as they previously had observed wētāpunga to be attracted to banana. While banana may also attract non-target species, it may still improve the effectiveness of monitoring programmes if it is more attractive to wētāpunga than peanut butter. However, the effects of variation in diet for juvenile wētāpunga is unknown. As a result, I presented only odour cues as lures in our experiment. The use of odour cues to attract wētā should not limit the interpretation of my results as initial attraction to lures in tracking tunnels in the field is also based on odour cues. My experimental trials would ideally have presented lures to individual wētāpunga rather than in groups, however no handling of animals was allowed under our permit due to the vulnerable status of the species.

Data Analysis

All statistical analyses were conducted in R version 4.2.1 (R Core Team, 2022). Analyses concentrated on juvenile trials as the sample size for adults was low (n = 3). Lure attractiveness data were analysed with mixed-effects models using the package *lme4* and the ‘glmer’ function, with a

Poisson distribution (Bates et al., 2015). The response variable was the total number of approaches to the lure, with treatment and order included as fixed effects and enclosure ID as a random effect. All enclosures had 20 individuals except for four (with 2, 7, 9 and 13 individuals) so group size was not included as an effect. Lure position was removed from the analyses as a fixed effect as it did not influence lure visits ($p = 0.38$). Effect sizes (odds ratios) were calculated using exponentiated coefficients in the package *effectsize* (Ben-Shachar et al., 2021).

Latency of the first individual to reach the lure was compared using survival analysis in the *survival* package (Therneau, 2022; T. M. Therneau et al., 2000). I used a cox proportional hazards model with the 'coxph' function, including treatment and order as fixed effects and enclosure ID as a frailty term.

3.4 Results

Approaches to lure

There was no significant difference in the number of approaches to the lure between the peanut butter and banana treatments (peanut butter: 2.45 $\pm$ 2.04 visits; banana: 3.81 $\pm$ 2.54 visits; $z = -0.67$, $p = 0.50$; Fig. 3.1a; Table 3.1). There was an order effect ($z = 2.56$, $p = 0.01$), with enclosures receiving the second treatment (independent of lure type) having slightly more approaches to the lure than the first treatment. However, the number of approaches to the lure in the first and second treatments was similar (first treatment: 2.5 $\pm$ 1.58 visits; second treatment: 3.61 $\pm$ 2.85 visits; Fig. 3.1b).

Of all the juvenile wētāpunga trials, 41.9% (31/74) of trials contained at least one individual that was attracted to the lure (17 peanut butter, 14 banana). In comparison, in 83.3% (5/6) of adult wētāpunga trials the individual was attracted to the lure (3 peanut butter, 2 banana).

Table 3.1: GLMM and odds ratios comparing total number of approaches to the lures.

Parameter	***Estimate***	***z-value***	***P-value***	***Odds ratio (±95% CI)***
Intercept	-0.83	-2.15	0.03*	0.43 (0.20, 0.93)
Treatment	-0.15	-0.67	0.50	0.86 (0.55, 1.34)
Order	0.59	2.56	0.01*	1.80 (1.15, 2.82)

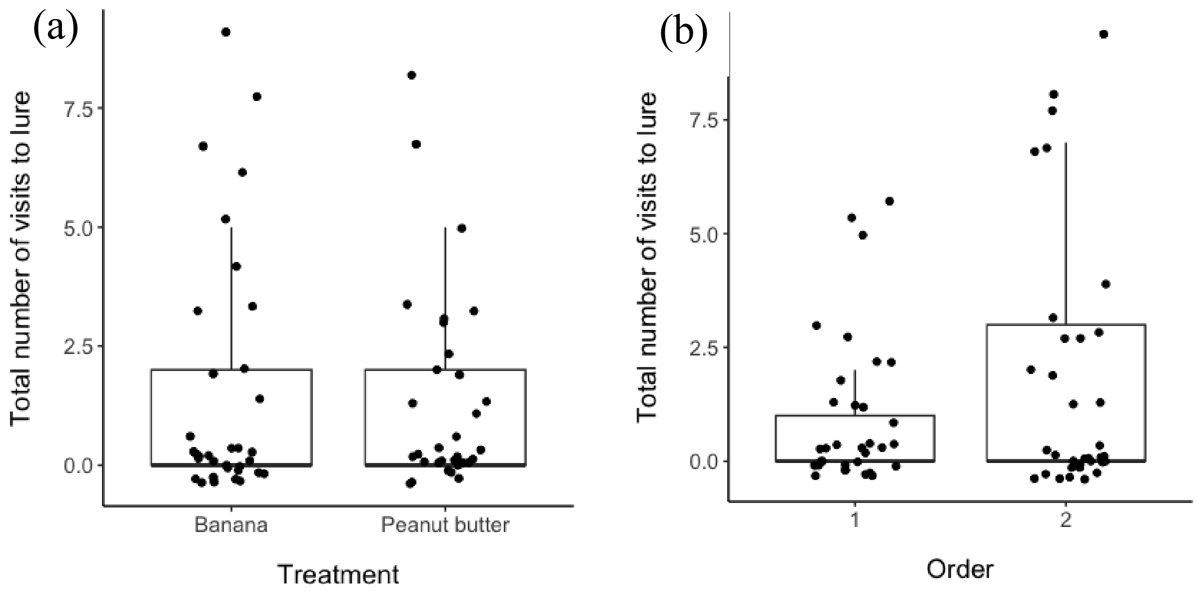
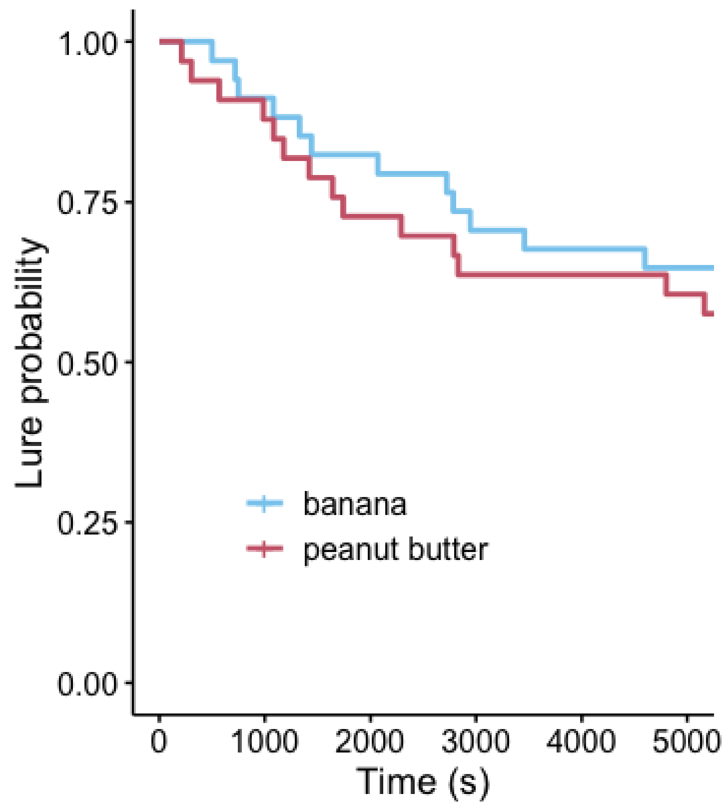


Figure 3.1: Total number of approaches to the lure dependent on (a) the type of lure, and (b) the trial order.

Latency to lure

There was no significant difference in the latency for the first individual to approach the peanut butter and banana lures (peanut butter: 2308 ± 2735 s; banana: 2487 ± 1594 s; z = 0.58, p = 0.56; Fig. 3.2a). Similarly, there was no significant difference in the latency to approach each lure depending on the order it was presented (first treatment: 2782 ± 2206 s; second treatment: 2467 ± 1818 s; z = 0.43, p = 0.67; Fig. 3.2b).

(a)



(b)

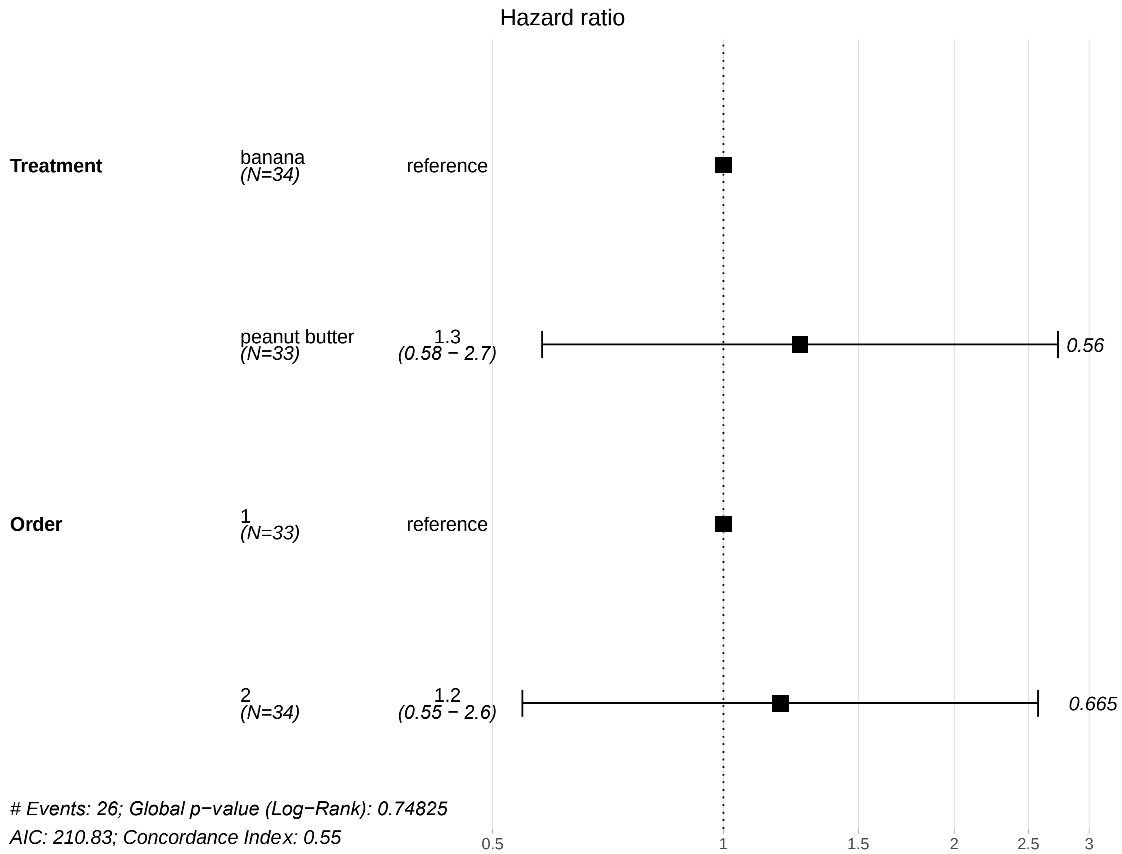


Figure 3.1: (a) Latency to approach each lure (peanut butter or banana), and (b): hazard ratios comparing treatments (peanut butter, banana) and trial order.

3.5 Discussion

Approaches to the lure

There was no difference in the number of approaches to peanut butter or banana lures in either the juvenile or adult wētāpunga trials. There was an order effect in the juvenile trials, in which the second lure presented received slightly more approaches than the first. However, given the small difference in means (banana: 1.5 approaches, peanut butter: 1.3 approaches), the difference is not likely to be biologically significant. Based on my results, it does not appear that one lure was more effective than the other. However, understanding how volatile peanut butter and banana are in the field may possibly result in one being more attractive as a lure in tracking tunnels to monitor wētāpunga.

It was interesting to note that 100% of approaches by wētāpunga were to the petri dish with the lure in it. No wētāpunga made its first approach to the empty petri dish, indicating that wētāpunga were attracted to the lures and not just the novel petri dish in their enclosure. Juvenile wētāpunga had a lower approach rate (41.9%) to the lures than the adults (83.3%). There is little information surrounding the movements patterns of juvenile wētāpunga, however, the lower approach rate could be because they are less active than adults. Research commonly acknowledges the challenges of monitoring juveniles as they are smaller, more cryptic and difficult to distinguish from background vegetation(Green et al., 2011; Watts et al., 2011; Watts et al., 2008). I noted while watching the trials that not all individuals were mobile within the arenas. It seemed that most juveniles stayed within the refugia for the duration of the trials. While only three adult wētāpunga were available for testing, they had a higher approach rate to the lures than juveniles. The one adult female wētāpunga that did not approach the lure at all was laying eggs for the duration of the trial. Adult wētāpunga may have been more bold in their activity patterns compared to juvenile wētāpunga as they have larger foraging requirements to fulfil, the drive to search for mates or in the case of females, find appropriate egg laying areas. As the adult wētāpunga in this experiment have had no predator experience, approaching a novel object is probably interpreted as having little risk, especially an object in close proximity, compared to an unknown object in the field that may be much further away. The lures being in close proximity meant that they were easy to detect and as the trials were controlled in the laboratory, there were no other stimuli present to distract from the lures. This may mean that approach rates in the field may be lower than I observed in this experiment as the proximity of the lures in the field will vary greatly and the number of other stimuli present in the environment will be unknown.

Latency to lure

There was a similar latency to the first approach for both peanut butter and banana lure types. This was consistent regardless of the order in which each lure was presented. The bulk of approaches for both lure types were made within the first 50 minutes of each trial. This suggests that these lures are effective in attracting wētāpunga, but not attractive enough that individuals repeatedly approach the lure for the entire duration of the trial. This could be due to volatiles from the lure dissipating within this time in the laboratory. Despite this, my results further support the use of either peanut butter or banana as lures for attracting wētāpunga in the field.

Limitations

This study was completed in a highly controlled laboratory environment. None of the wētāpunga had experience with predators, which could have allowed for bolder activity patterns than wild wētāpunga may exhibit. All wētāpunga were captive bred and were familiar with being handled by humans, again potentially desensitising them to novel stimuli such as the lures in their enclosures. Captive bred wētāpunga may be more likely to approach novel stimuli as they may have relaxed their antipredator responses (in adult wētāpunga) or in the case of juveniles, there is yet to be any known threats.

Further limitations surround the fact that the main proportion of the trials were conducted on juvenile wētāpunga. Further research is needed to understand how attractive both lure types are to adult wētāpunga compared to juvenile wētāpunga. The effectiveness of these lures in the field also needs to be compared as there are potentially other confounding factors that may influence their efficacy, such as breeding patterns, predator avoidance, weather conditions and foraging patterns.

3.6 Conclusions

My study did not find any difference in the attractiveness of peanut butter or banana lures to wētāpunga. It was difficult to assess how this study compares to other lure experiments as the research surrounding effective insect lures largely focuses on pheromone lures (both lethal and non-lethal). For example, a study on the pea leaf weevil (*Sitona lineatu)* compared the use of two pheromones in combination with four trap types (Reddy et al., 2018). This study's aim was to identify the most effective combination of monitoring method and pheromone lure type (Reddy et al., 2018). Studies like this are useful in exploring how placement, environmental conditions, and pheromone dose can impact the effectiveness of the lures, however the use of pheromones is specific to each species and implies an existing baseline level of attraction to begin with. There is little information describing how to monitor native and endemic insect species without the use of toxic baits or lethal trapping devices (Brodie et al., 2019). For many insects, pheromone lures are highly effective in attracting the target species (Zauli et al., 2016). However, there is no research yet to test whether pheromones would be useful as an effective lure for any species of wētā.

There are few food-based lures used to monitor insect species, potentially because they attract non-target species and tend to be more useful when surveying biodiversity, rather than a single species (Cha et al., 2015). For example, the use of wine and vinegar is often used to monitor spotted wing drosophila (*Drosophila suzukii*), however, the lures also attract large numbers of non-target species, some of which hold ecological value and require additional time to identify individuals (Cha et al., 2015; Landolt et al., 2012). The use of peanut butter lures when monitoring wētā in the field also attracts non-target species. The tracking tunnels in which peanut butter lures are used typically monitor small mammals such as rats and possums (King & Edgar, 1977). Similar to peanut butter, banana lures are likely to attract non-target species in addition to wētāpunga. Further research should investigate what lure types could target wētāpunga directly.

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Chapter 4: Comparing wētāpunga (*Deinacrida heteracantha*) monitoring methods on Ōtata Island, The Noises

4.1 Abstract

Effective monitoring methods are critical for population assessments and evaluating conversation efforts. Current monitoring methods often provide inaccurate assessments for cryptic and nocturnal species such as wētā. Several species of wētā are classified as vulnerable, including wētāpunga, *Deinacrida heteracantha* (Orthoptera: Anostostomatidae) and require accurate monitoring to understand population status. To support the conservation of wētāpunga I compared three monitoring methods to develop a best practice. I compared the results between baited tracking tunnels, baited arboreal tunnels and visual surveys over two nights on Ōtata Island, The Noises. Due to heavy rain and wind, both the tracking tunnels and arboreal tunnels became waterlogged and no evidence of wētāpunga presence was recorded using these two methods. However, I observed 16 wētāpunga and 15 tree wētā (*Hemideina thoracica*) using visual observations. My results show that visual surveys are more reliable for monitoring wētāpunga in temperamental weather conditions.

4.2 Introduction

Biodiversity is a crucial marker of the health of our ecosystems (Tilman et al., 2017). Globally, the decline of biodiversity is one of the biggest environmental problems (Ceballos et al., 2015). Anthropogenic threats such as deforestation, hunting, agriculture, urbanisation, the introduction of non-native species and the spread of pathogens have greatly elevated modern-day extinction rates (Tilman et al., 2017). Historically, conservation efforts have been aimed towards the management of single species, however, conservation is shifting towards multispecies planning that includes ecosystem restoration or enhancement (Casazza et al., 2016). Despite the shift, flagship species may still have a place in conservation programmes.

New Zealand's conservation efforts are largely directed from its Predator Free New Zealand by 2050 vision which focuses on the eradication of invasive species such as rats, possums, and mice (Vergara et al., 2021). The management of invasive pest species has centred on mitigating the decline of native bird species, which also has indirect benefits for many invertebrate taxa including insects (Vergara et al., 2021). Native insects are important for many ecological processes such as pollination, seed dispersal, and waste elimination (Harvey et al., 2020). Only 10% of the ~20,000 insects in New Zealand have currently been assessed under the New Zealand Threat Classification System (NZTCS) (Schori et al., 2020). The NZTCS is highly specific in its criteria, and it has become widely apparent that assessment tools for insect species are often not transferrable across species due to differences in ecology and behaviour. For example, the NZTCS does not account for differences in life history such as length of the juvenile phase, species that moult (inhibiting mark and recapture methods), and species that are highly cryptic and difficult to find within time constraints (Connolly & Ward, 2020; Schori et al., 2020).

New Zealand wētā (Orthoptera, Anostostomatidae) are flightless, nocturnal and are some of the largest insects in the world. Many species of wētā are 'at risk' or facing declines (Watts & Thornburrow, 2009). Although some species such as the Auckland tree wētā, *Hemideina thoracica* have persisted in urban environments and moderately tolerated invasive pests (Wehi et al., 2015), other wētā species have seen large declines and require significant management interventions (Watts et al., 2008; Watts & Thornburrow, 2009). Wētā conservation has been directly and indirectly supported by the management of invasive species, ecological restoration programmes and translocation programmes. There are a growing number of translocation programmes for endangered wētā species such as the Mercury Islands tusked wētā, *Motuweta isolata* (Orthoptera Anostostomatidae). However, the success of wētā translocations has been difficult to quantify as their ecology and behaviour of is often poorly studied. Despite difficulties in monitoring the success of the translocation of tusked wētā, the absence of rodents has played a critical part in the population's survival (Stringer et al., 2014).

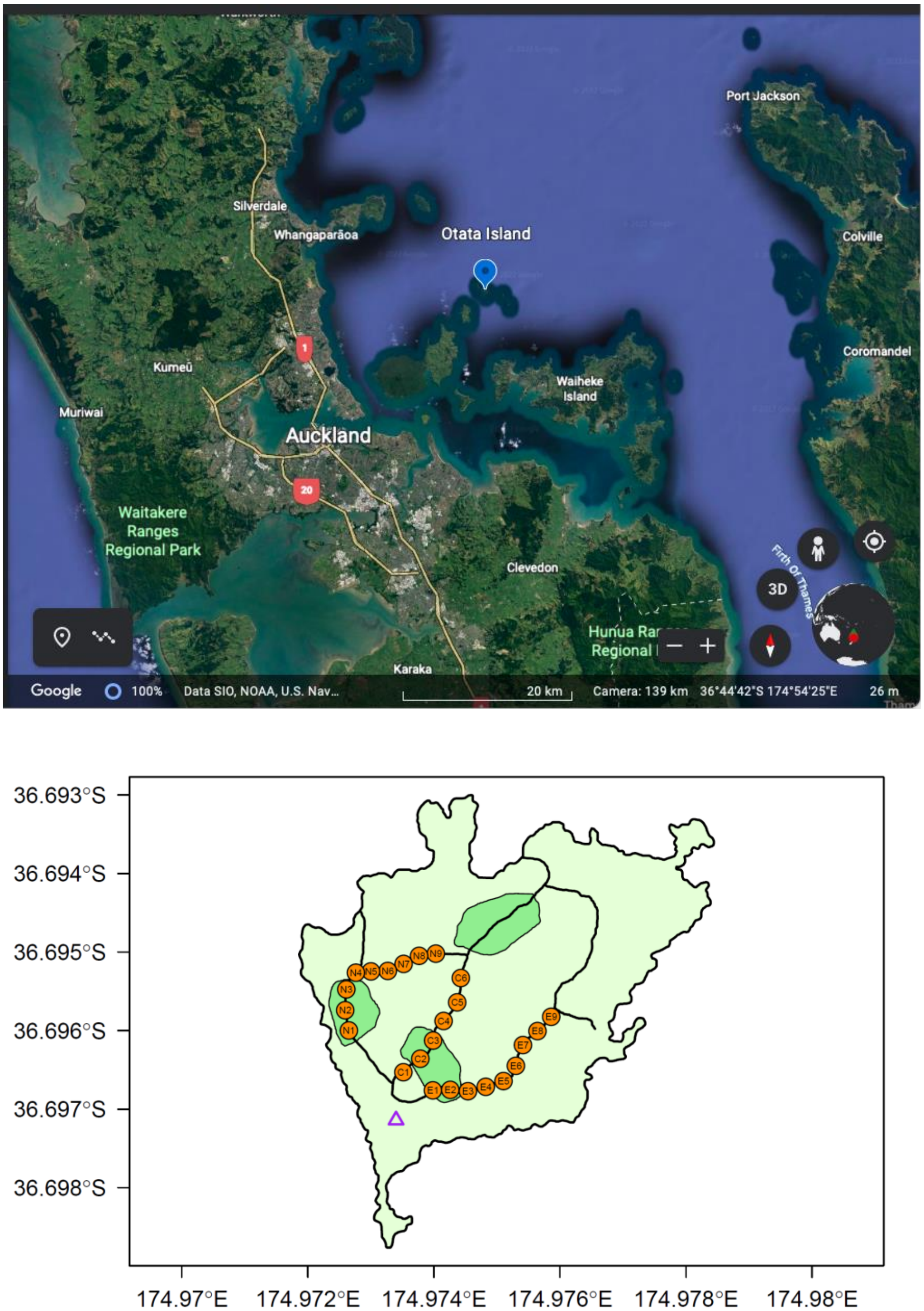
Another species that has received significant conservation focus is the wētāpunga *(Deinacrida heteracantha)*. Historically, wētāpunga were found across Northland, Auckland, and Great Barrier Island (Aotea). However, habitat degradation and predation from invasive mammalian species once limited the population to Little Barrier Island (Stringer et al., 2014). In 2009, the staff at Butterfly Creek, South Auckland, initiated a breeding programme for the very first time. The success of the breeding programme led to populations being translocated to Tiritiri Matangi and Motuora Island in 2011, both pest-free islands in the Hauraki Gulf Marine Park. In 2012, Auckland Zoo initiated their own captive breeding programme and released 150 individuals on Tiritiri Matangi to strengthen the growing population. The success of these efforts has since increased further, with wētāpunga populations now found on another group of pest-free islands, The Noises. While breeding programmes have been successful in preventing the extinction of wētāpunga, scientists now face the challenge of developing effective long-term methods for monitoring populations and understanding ecological behaviour. These issues are consistent across wētā species as a whole and are critical to understanding future challenges in their conservation.

Current monitoring methods for wētā species include ground tracking tunnels that are traditionally used for small mammal tracking, arboreal tracking tunnels fixed into trees, and visual search surveys at night (Watts et al., 2008). While these methods have sufficed to date, they are labour intensive and rarely precise (Watts et al., 2008). In this chapter, I compare the three monitoring methods (ground tracking tunnels, arboreal tracking tunnels and visual searches) for wētāpunga. By identifying the strengths and weaknesses of each method, I hope to provide a robust framework that supports wētā monitoring programmes to select the ideal methods under different scenarios.

4.3 Methods

Initially, I planned several trips to Ōtata Island (Fig. 4.1a) so that the different monitoring methods for wētāpunga could be compared over time. However, due to poor weather, covid-19 restrictions, injuries to collaborators and other circumstances out of our control, only one trip was possible. On the 7th – 10th November 2022, ground tracking tunnels, arboreal tracking tunnels and visual surveys were trialled to compare the effectiveness of these three methods in monitoring the wētāpunga population. Each monitoring method was carried out across 24 sampling points along the eastern, northern, and central tracks on the island *(*Fig. 4.1b*)*.

(a)



(b)

Figure 4.1: a) Location of Ōtata Island, Auckland, New Zealand (Google Earth, 2023), and (b) map of Ōtata Island and sampling points. N1-N9, sampling points along the northern track of the island. C1-C6, sampling points along the central track of the island. E1-E9, sampling points along the eastern track of the island. Purple triangle shows location of the hut. Dark green areas indicate the original release sites.

Ground tracking tunnels

Traditional black ground tracking tunnels were used as a baseline method to compare against arboreal tracking tunnels. The tracking tunnels (500 mm × 100 mm × 100 mm) were made from a flat sheet of 3mm corflute plastic folded along crease lines to form a tunnel. The tracking tunnels had previously been used in the Fernhill Escarpment bush section on the Massey University Auckland campus. For biosecurity purposes the tunnels were cleaned with bleach and aired outside a week before the field trip. Tracking tunnels were placed and pegged with wire at the base of a tree or bush at each sampling point across the island. Tracking cards were inserted into the tunnels with a square of black ink and approximately two teaspoons of Homebrand smooth peanut butter in the centre of the tracking card *(Fig. 4.2)*. The tracking tunnels were left at the sampling points for the duration of the trip (two days, two nights) and the tracking cards were replaced each day to record activity each evening.

Figure 2.2: Tracking tunnel with tracking card at the base of a tree.

Arboreal tracking tunnels

Arboreal tracking tunnels were placed in trees at approximately 1-2 m high at each of the 24 sampling points. These tunnels were constructed out of white PVC pipe (250 mm long × 90 mm diameter). Each pipe was tied to a tree with twine *(Fig. 4.3)*. Like traditional tracking tunnels, they each had a tracking card with ink and peanut butter. Due to these tunnels being a different shape to traditional tracking tunnels, tracking cards were cut in half and sellotaped horizontally so they could be rolled into the PVC pipes, covering the entire inner surface area of the pipes. The tracking cards were also replaced daily to record wētāpunga activity from each evening.

Figure 4.3: Arboreal tracking tunnel in tree.

Visual surveys

Visual surveys were completed at dusk and dawn each day to compare observation rates against the tracking and arboreal tunnel methods. Visual surveys started at dusk when the birds reduced activity. This allowed time for wētāpunga to emerge from refugia. The visual surveys followed the transect lines but were not limited to the sampling points. This meant that if there was a tree or area that had thick bark, crevices, or woody vegetation (refugia), then it was surveyed if safe and easily accessible. Dawn searches were completed in the same manor, at least an hour before sunrise. For each wētā sighting we recorded date, time, location, species, temperature, height found, other species present and other wētā present.

<u>**4.4 Results**</u>

No wētā were detected from the 24 tracking tunnels and 24 arboreal tunnels. Initially my plan was to survey all three nights, however, an unlucky turn in the weather limited the tracking and arboreal tunnel surveys to two nights (November 7th and 8th). Unfortunately, heavy rain washed most of the ink and peanut butter out of the tunnels on these first two nights.

Visual surveys were also limited due to wild weather and only one dusk survey was able to be completed on November 7th. Despite light showers throughout the visual survey (8:32pm – 10:11pm), 16 wētāpunga were identified (two females and 14 males). All wētāpunga were found on mature pohutukawa trees with access to nearby refugia. Pohutukawa trees were mainly found on the northern track of the island and sheltered from the wind and rain. On the northern track, 13 wētāpunga and two tree wētā *(Hemideina thoracica)* were identified. On the eastern track, three wētāpunga and 13 tree wētā were identified. All wētāpunga were found on trees at heights between 0.5m and 3m, apart from one individual found at 6m. No wētāpunga were found on the ground. Most tree wētā were also found on pohutakawa trees apart from two individuals that were found on a mahoe, one individual on an *stelia* bush and one individual on a piece of dead wood on the ground. No other native New Zealand species were found apart from one Raukawa gecko *(Woodworthia maculate*) on a pohutakawa tree at 2m.

4.5 Discussion

I found that visual surveys were the most effective method of the three monitoring methods (tracking tunnels, arboreal tunnels, and visual surveys) for surveying wētāpunga under challenging weather conditions. The heavy wind and rain washed out the ink and peanut butter in both the tracking tunnels and arboreal tracking tunnels. This meant that tracking tunnels were unsuitable for monitoring in wet weather conditions.

Ground tracking tunnels

The use of tracking tunnels for monitoring wētāpunga is ineffective during periods of persistent and heavy rain. The rain caused the tracking cards to get wet, which made the ink run and potentially stopped footprints from being recorded on the paper. In some areas of the bush, the peanut butter had been washed out of the tunnel. The rain also disrupted the assemblage and replacement of tracking cards in tunnels, as it slowed the process down and amplified hazards in the bush, such as slips, falls, fallen trees across the tracks and strong winds near cliff edges.

Tracking tunnels are currently one of the most common methods for monitoring several species of wētā, including wētāpunga (Watts et al., 2013; Watts et al., 2008). Tracking tunnels are likely to be most effective across periods of little or no rain. Tracking tunnels seem to be most effective at detecting the presence of wētā when left out for over five days (Watts et al., 2011). While it is possible to distinguish between the footprints of different wētā species from tracking cards, tracking tunnels cannot be used to monitor for the presence of juveniles as they are too light to make prints (Watts et al., 2011). This should be considered carefully when deciding whether to use this method. Ideally, at least two people should be employed to assemble tracking tunnels and replace tracking cards safely and efficiently. While this study used Homebrand peanut butter, I am aware that other brands are often used, such as Pic's, which have a more viscous consistency and may provide a more robust adhesion in wet conditions.

The tracking tunnels used on Ōtata Island had been used several times previously. To follow biosecurity protocols, I cleaned the tracking tunnels with bleach the week before the field trip. Despite leaving the tunnels outside to air for a week, using Trigene might be a more suitable option as the bleach smell was still slightly apparent. The smell could have affected how likely wētāpunga were to enter the tracking tunnels.

Arboreal tracking tunnels

Arboreal tracking tunnels were also impacted by the rain and were not effective monitoring tools under wet and windy weather conditions. Like the ground tracking tunnel cards, the arboreal tracking cards got wet, and both the ink and peanut butter washed out of the tunnels. Further, some of the arboreal tunnels (n = 3) had fallen after the second evening when weather conditions became substantially worse. Under high winds, I suggest doubling down on twine to hold the tunnel in place.

Arboreal tracking tunnels are becoming more common as a monitoring method for arboreal wētā species (Watts et al., 2013; Watts et al., 2008). Arboreal tunnels require the same conditions, resources, and labour as tracking tunnels. Arboreal tunnels are most effective over longer studies that have access to consistent labour for tracking card replacement and periods of little or no rain (Gillies & Williams, 2013).

The tunnels used in this study were made of white PVC, which could potentially be a deterrent for wētāpunga, as traditional tracking tunnels, arboreal tunnels and natural refugia are typically black or dark brown (Watts et al., 2008). If weather and time had permitted, I would have placed the tunnels for a short period of time in the trees before the start of the monitoring period with no tracking cards or bait. This acclimatisation period could have removed any foreign smells that may have travelled with them (Gillies & Williams, 2013). Arboreal tracking tunnels have the potential to be useful as a survey method for arboreal wētā species, however this study was unable to compare their efficacy to ground tracking tunnels.

Visual surveys

I found 16 wētāpunga during one visual survey at dusk. This survey provided insight into several aspects of the Ōtata Island population. Most wētāpunga were found in the centre of the island where there are mature pohutakawa trees. The pohutakawa trees provided shelter from the wind and rain compared to the more exposed N and E tracks. Interestingly, the outer (N and E) tracks of the island had a large population of tree wētā. Tree wētā are tolerant to fluctuations in temperature and for this reason, could be more inclined to persist on the outer edges of the island than wētāpunga (Bulgarella et al., 2014).

The sex ratio of the wētāpunga observed was heavily skewed toward males. As male wētāpunga tend to be more active (Gwynne & Kelly, 2018), female wētāpunga could have been less conspicuous during visual searches due to the wind and rain. Completing several visual surveys over multiple nights may have provided a more detailed insight into the population sex ratio. I did not find any juvenile wētāpunga. Again, completing several surveys over multiple nights might have provided more information on where and how juveniles use the habitat.

Visual surveys are an excellent monitoring method if time is limited. Visual surveys also provide more flexibility, providing the ability to survey under a range of weather conditions: warm and dry conditions are ideal, but I found that visual surveys are still useful in a light drizzle. To gain an accurate understanding of the population several surveys would be more effective than just one. Unfortunately, there was no opportunity to compare dusk and dawn surveys, however, dusk surveys have been most commonly used in wētā monitoring programmes previously (Watts et al., 2013).

4.6 Conclusions

While I could not determine which monitoring method gave the most accurate survey of the Ōtata Island wētāpunga population, my study did highlight differences in the suitability of the three methods under adverse weather conditions and limited resource availability. To accurately assess the status of any wētā population it is critical to consider accessibility of the habitat and resources. Ultimately, the ideal monitoring methods are probably dependent on the aims of the monitoring study.

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Chapter 5: General Discussion

The aim of my research was to explore current monitoring methods for wētāpunga and how to make them more effective. Chapter 3 focused on laboratory-based trials comparing the effectiveness of food-based lures. The study compared the number of approaches to peanut butter against freshly cut banana. There were no significant difference in the number of approaches to each lure, highlighting that both peanut butter and banana were equally attractive as lures for wētāpunga. In chapter 4 I compared three types of monitoring methods used to survey wētāpunga in the field. Baited ground tracking tunnels, baited arboreal tunnels and visual surveys were trialled over two nights on Ōtata Island, the Noises. The trials were originally planned for three nights in clear weather, however due to weather, covid, and other unforeseen circumstances, the study was postponed several times and eventually cut short. However, I found that visual surveys were much more effective in conditions with poor weather. My thesis aims to strengthen currently used monitoring methods in the hope of supporting wētāpunga conservation.

5.1 Types of lures used for monitoring threatened invertebrates

I compared the effectiveness of peanut butter and banana as lures for wētāpunga and demonstrated that both lure types have a similar attractiveness. Understanding what lure types are effective for all wētā species is a critical component for the use of tracking tunnels in the field. I discussed with Ben Goodwin (Ectotherm keeper) and Don McFarlane (Team Leader Ectotherms) at Auckland Zoo their need for better information about the lures used in tracking tunnels for monitoring translocated wētāpunga populations. Since Auckland Zoo started the breeding programme in 2012, accurately monitoring translocated populations has been difficult. Several other lure types were considered, such as peanut oil, apple, and pureed fruit. However, I chose fresh banana as an appropriate candidate as it was widely available and is non-toxic to wētāpunga.

Research on non-lethal, food-based lures for native species is limited and has not been explored for wētāpunga specifically. The use of pheromones as lures for adult wētāpunga is undescribed, however tree wētā likely use pheromones for communication (Wehi et al., 2017). Another non-lethal monitoring method that has recently been explored is frass dropping monitoring. Frass sampling methods utilise litter trays along a transect that collect frass droppings. The frass is then identified and counted to estimate a relative abundance of the species in which the frass belongs to. One study has observed tree wētā frass droppings to measure abundance in tree wētā populations (Sweetapple & Barron, 2016). While the method is relatively effective and low cost, it requires further validation for accuracy (Sweetapple & Barron, 2016). For my study, exploring food-based lures was the most productive way to strengthen current methods in a way that is easily accessible and low cost for future monitoring. Despite my study not defining a more effective lure option, it did confirm that both peanut butter and banana could be used as lures in tracking tunnels for monitoring.

5.2 Monitoring methods for wētāpunga: ground tracking tunnels, arboreal tracking tunnels and visual surveys

In my study, visual surveys were the most effective method for monitoring wētāpunga. The use of both ground and arboreal tracking tunnels was ineffective due to the heavy rain and wind, and the limited number of nights the tunnels were left in the bush. I was not able to determine which method was more effective, however it did highlight important factors that influence the appropriateness of using each method in different conditions.

I aimed to provide greater insight into how each of the three monitoring methods can be used. Over the course of my thesis, several conversations with Auckland Zoo staff were had surrounding the challenges of monitoring wētāpunga. Auckland zoo staff explained that visual surveys were not always reliable for monitoring small populations after releasing captive bred individuals. They found that juveniles were very rarely observed, and sex ratios were difficult to determine. The use of tracking tunnels for arboreal wētā species is described in one study, however, during that study the ground tracking tunnels were more effective (Watts et al., 2008). Further research is recommended to investigate if seasonal changes influence the effectiveness of this method as the study was done when females were laying eggs and spending more time on the ground (Watts et al., 2008). Both forms of tracking tunnels also have issues surrounding identifying juveniles, as wētāpunga juvenile footprints are difficult to distinguish from other species due to the spacing of the tarsal pads being similar to tree wētā. This issue is avoidable if tree wētā are not present in the habitat. Furthermore, the method does rely on the activity patterns of each individual. The level of activity could be impacted by several factors such as weather conditions, seasons, foraging behaviours, mating behaviours or age (McIntyre, 2001; Wehi et al., 2013).

In my study, visual surveys were carried out in moderate winds and light rain. Visual survey efforts were influenced by the fact that the owner of the island had a knowledge of locations where the wētāpunga were usually found. This again reflected the experience of the researchers and general knowledge of the habitat being surveyed. Whilst I did have access to this support, the areas I surveyed were very typical of where wētāpunga are typically found in other regions. The use of visual surveys in this instance was most effective due to the limited timeframe and information about the population that was available. If monitoring in an unfamiliar habitat, a combination of methods may be most productive. For example, by using tracking tunnels to focus in on areas that may be suitable for visual surveys.

5.3 Limitations of the study

The largest limitation of my study was the very limited amount of time on Ōtata island. The original plan for the study outlined three to four trips over several months for three nights at a time. This schedule would have built a robust dataset detailing how each method preforms across different times of the year. Unfortunately, this was not possible and only one short trip was able to be made. The wind and rain presented safety hazards during the field trip and each of these monitoring methods should generally be avoided in these conditions. Clear weather and a longer timeframe could have provided further information about how widespread the population of wētāpunga are on the island as the tracking tunnels were placed across a broader area of the island compared to the localised area of the visual surveys. Further to this, a longer time frame could have been an opportunity to test the effectiveness of banana as a lure in the field. Testing banana as a lure in the field would have complimented the results of the laboratory trials and potentially identified if any non-target species are also attracted to banana.

Further limitations include the use of a captive bred population in a space-limited laboratory. Testing the use of banana as a lure should be explored further, particularly over larger distances. Trialling banana and peanut butter as lures in the field would give a more accurate comparison of their effectiveness. My study used a captive bred population that contained mostly juveniles. The results of the trials reflect the conditions of a small arena with no predators. The activity patterns may differ in the wild where other factors (such as predators and competitors) may limit how attractive banana is as a lure. Juveniles may have a lower foraging demand than adults and therefore may have lower activity levels, potentially preventing them from even encountering lures.

5.4 Suggestions for future research

Further studies are recommended to investigate the use of ground tracking tunnels, arboreal tracking tunnels and visual surveys. Understanding what conditions best suit each of these methods will help produce more accurate data. A study comparing these methods across different seasons would provide insight into which months of the year wētāpunga are most active, which sex is more active, and perhaps when the best time is to monitor juvenile populations. Watts et al. (2008) compared ground tracking tunnels and arboreal tracking tunnels in wētāpunga on Little Barrier Island over six nights in May 2007. While they concluded that ground tracking tunnels were more effective than arboreal tracking tunnels, this could have been due to the sexual activity of the animals as females were spending time on the ground to lay eggs (Watts et al., 2008). The study also concluded that tunnels baited with peanut butter were more effective than non-baited tunnels (Watts et al., 2008). However, their decision to use peanut butter was due to the fact that peanut butter had attracted tree wētā by proxy in small mammal tracking studies previously (Watts et al., 2008). A long-term study comparing peanut butter and banana as lures in the field would give a more accurate depiction of how truly attractive each lure is. Wētāpunga research is very limited, potentially due to the species' cryptic nature, previously being in decline and populations generally being confined to pest-free islands. In addition, obtaining permission to carry out more detailed or manipulative studies has proven very difficult. The bulk of research on wētāpunga investigates the changes in population numbers and habitat use after pest eradications, which relies on the accuracy of monitoring methods (Green et al., 2011; Watts & Thornburrow, 2009).

While my study focused on wētāpunga specifically, further studies could be extended across other arboreal species such as tree wētā. Tree wētā are widespread across urban areas of the North Island and South Island, making them an easily accessible subject (Bulgarella et al., 2014). The use of tracking tunnels and peanut butter as a lure is already general practice for both wētāpunga and tree wētā species (Green et al., 2011; Watts et al., 2011). Species such as tree wētā have managed to prevail in urban environments exposed to novel predators. Their success has been due to their smaller body size (tree wētā ~4 g, wētāpunga ~35 g), and tendency to spend less time on the ground compared to larger species like wētāpunga, making them less vulnerable to predation (Gibbs, 1998). Using tree wētā as study species would make it logistically easier to complete a study spanning over a year or several years to understand how seasons might influence results when using such monitoring methods. Findings from testing methods on more easily studied tree wētā would ideally be transferable to the more vulnerable wētāpunga.

Having a baseline knowledge of each species, their habitat and behaviour will aid in deciding what monitoring method to use and under what circumstances. Monitoring wētā populations accurately is critical for supporting conservation programmes and further development of monitoring methods will contribute greatly to their conservation.

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