



Can acoustic deterrents reduce Red Fox *Vulpes vulpes* take of shorebird eggs on sandy beaches?

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Can acoustic deterrents reduce Red Fox *Vulpes vulpes* take of
shorebird eggs on sandy beaches?



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Submitted in partial fulfilment of the degree of Bachelor of Environmental
Science (Honours)

April 2023

Statement of responsibility

This Thesis is submitted in accordance with the regulations of Deakin University in partial fulfilment of the requirements of the degree of Bachelor of Environmental Science (Honours). I, Finn Saurine, hereby certify that the information presented in this thesis is the result of my own research, except where otherwise acknowledged or referenced, and that none of the material has been presented for any degree at another university or institution.

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This project involved the use of animal subjects and the project was conducted in accordance with the regulations of the Deakin University Animal Welfare Committee under Approval No. 'B16/2020'. In Victoria the study was carried out under Wildlife Act 1975 and National Parks Act 1975 Permit No. '10009536' and in accordance with Parks Victoria Access Agreement: 'Scent deterrents as a way of changing Fox activity around shorebird nests on Victorian sandy beaches'. In South Australia the study was conducted in accordance with regulations of Department of Environment and Water under Wildlife Ethics Permit No. '16-2022 Eliminating Fox depredation on coastal birds via audio and scent repellents' and Department of Environment and Water's Scientific Research Permit No. 'U27201-1'.

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Abstract

Invasive species have caused widespread devastation to ecosystems and biodiversity worldwide, with lethal control techniques often failing to adequately control the impacts of species such as the Red Fox *Vulpes vulpes*. For example, Red Foxes are a key driver of low reproductive success in beach-nesting shorebirds such as the Hooded Plover *Thinornis cucullatus cucullatus*, which inhabits areas in which lethal fox control is curtailed by free-roaming pets and nearby urban dwellings. The need for new techniques to mitigate fox take of Hooded Plover eggs is critical to arresting population declines. This study tested the efficacy of an ultrasonic deterrent to alter fox behaviour, reduce visitation of foxes to nest areas, and ultimately improve survival of clutches. An initial test of the device on mock clutches demonstrated some promising results (improved clutch survival), so testing was conducted on real Hooded Plover clutches. The ultrasonic deterrent evoked responses from foxes but not domestic Dogs *Canis familiaris*. Assemblages of species visiting the vicinity of clutches differed between clutches between treatment and control sites, such that foxes tended to visit control clutches more frequently than those with the acoustic deterrent. However, the acoustic device did not confer any benefit in terms of improved clutch survival. This study underlines the importance of testing new conservation techniques on real clutches and suggests that additional aversive stimuli are required to deter fox take of plover eggs. Combined with methods which reduce corvid (raven) take of eggs, the ultrasonic device may still have a role to play in integrated management of foxes on beaches.

Keywords: Artificial clutches, aversion, avoidance, Hooded Plover, ultrasonic deterrent, threatened species conservation

Field of Research Code: 4104

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This thesis was written and formatted to the structure and rules of the journal *Bird Conservation International*.

List of abbreviations

CTA – conditioned taste aversion

FOV – field of view

PUFD – portable ultrasonic fox deterrent

Introduction

Invasive predators are major threats to ecosystems worldwide and are key drivers of species population declines and extinctions (Doherty *et al.* 2016, Stobo-Wilson *et al.* 2022). Native prey species often lack the required evolutionary adaptations to cope with the broad-scale invasion and establishment of novel predators (Woinarski *et al.* 2015, Brzeziński *et al.* 2020). Therefore, to conserve native species, management actions to mitigate or eliminate impacts of invasive predators occur worldwide. These include lethal control of pest predators (Parkes *et al.* 2006, Dexter and Murray 2009), non-lethal approaches to reducing their populations such as inhibiting reproduction (Teem *et al.* 2020, Birand *et al.* 2022) or through inducing behaviour change in predators such as using repellents or inducing conditioned aversion (Shivik 2004, Maguire *et al.* 2009, Macdonald and Baker 2004).

Different predator management techniques vary in their success depending on the predator requiring control and local ecosystems (Treves *et al.* 2016), however in many cases impacts are largely intractable, or not suppressed sufficiently to mitigate key threats to sensitive prey populations (Hare *et al.* 2019). Additionally, changing societal expectations in conservation management sees the controversial, yet undeniably increasing, support for non-lethal methods of pest species management (Hayward *et al.* 2015, Wallach *et al.* 2018, Zander *et al.* 2021). This is especially prominent where non-target harvest occurs, and particularly where such bycatch threatens people's free-roaming pets (Jackson *et al.* 2010, Mallick *et al.* 2016). There is an urgent need to develop, apply and test effective mitigation techniques to reduce extinction due to over- or hyper-predation (Lurgi *et al.* 2018). One broad set of mitigations - deterring predators from sensitive prey using stimuli such as strobe lights, guarding animals, odour repellents or acoustic deterrents – may hold promise

with respect to discouraging predators away from a small, localised, sensitive areas while avoiding lethal bycatch and meeting society's changing expectations regarding animal welfare (Shivik *et al.* 2003, Mapari *et al.* 2022). At a minimum, these approaches may delay declines and extinctions among native species while other more effective approaches are developed (Saunders and Mcleod 2007, McManus *et al.* 2015).

The introduced Red Fox *Vulpes vulpes* has caused widespread devastation to native species in Australia (Abbot *et al.* 2014, Doherty *et al.* 2016, Woinarski *et al.* 2019) thanks to its intense predatory activities supplementing its broad diet (White *et al.* 2006, Fleming *et al.* 2021). Unsurprisingly, substantial efforts at fox control occur in Australia, > \$40 million being spent each year (Bomford and Hart 2002), and these efforts are dominated by lethal baiting control programs (Saunders and Mcleod 2007). Baiting programs are often ineffective when of small-scale and short duration (Gentle *et al.* 2007, Newsome *et al.* 2014), and while long-term landscape-scale baiting has realised suppression of fox populations and prompted recovery of some native animals, it requires ongoing resources and cannot eliminate foxes (Saunders *et al.* 1995, Gentle *et al.* 2007, Dexter and Murray 2009). Even within landscapes subject to large-scale ongoing fox control, foxes persist in "pockets" that are especially difficult to bait (Gentle *et al.* 2007, Newsome *et al.* 2014). One example of areas in which foxes often persist despite control is coastlines – habitats within which foxes are especially active and in which they compromise the viability of threatened beach-dwelling fauna such as beach-nesting birds (Brown *et al.* 2015, Schlacher *et al.* 2015). Fox control in coastal ecosystems is especially challenging because dune and beach areas are generally linear habitats, backed by urban or agricultural landscapes (Gilby *et al.* 2023) – the former presents a challenge in laying baits for fox control and because foxes sometimes cache food, they can transport lethal baits into urban areas posing a risk to humans and pets (Jackson *et al.* 2007,

Gil-Fernández *et al.* 2021). Agricultural landscapes present a challenge for sustained control due to recolonisation of foxes from adjacent uncontrolled areas (Newsome *et al.* 2014). Native fauna which are obligate beach-dwellers, which breed on the ground (i.e. where Foxes primarily forage), and which are threatened, represent key challenges in relation to mitigating the impacts of fox depredation.

In south-eastern Australia, the Hooded Plover *Thinornis cucullatus cucullatus* is a medium-sized, threatened, endemic, obligate beach-and dune-breeding shorebird (Marchant and Higgins 1993). The long-term viability of Hooded Plover populations is thought to be compromised primarily from suppressed reproductive success (low survival of eggs and chicks) which is driven by a range of threats (Dowling and Weston 1999, Maguire *et al.* 2014). One of the most prominent threats is that posed by foxes to eggs – foxes are responsible for up to 30% of clutch failures equating to 23% of all clutches laid (Weston 2000, Mead 2012, Maguire *et al.* 2014). Active, ongoing management of breeding Hooded Plovers addresses a range of threats, including foxes (Maguire *et al.* 2014). While baiting and soft jaw trapping has and does occur on beaches specifically to protect Hooded Plover eggs and chicks, foxes and egg take by foxes persist even in the most heavily baited/trapped areas. (G. Maguire and M. A. Weston pers. comms). Therefore, further solutions are required.

In search of alternative methods to suppress the predatory impacts of foxes on Hooded Plover clutches, conditioned taste aversion (CTA) has been tested in which quail eggs were injected with a aversive agent (undetectable but inducing immediate, temporary illness) to elicit a learned response from foxes to avoid eggs as a food source (Maguire *et al.* 2009, Cribbin 2012). Early results from small-scale trials were promising in reducing fox take of eggs (Maguire *et al.* 2009) but broad-scale testing revealed no improvement in egg

survival, as predators other than foxes took most clutches (Cribbin 2012). Given that CTA has not been found to represent a viable non-lethal option for reducing fox take of Hooded Plover eggs on the beaches of south-eastern Australia, further methods are still required.

A non-lethal and currently untested alternative approach to reduce fox take of eggs is the use of acoustic sound deterrents to alter predator behaviour i.e. using aversive sounds to ward predators away from specific locations (Saunders and McLeod 2007). Loud acoustic deterrents such as gas exploders and firecrackers have been deployed to frighten Red Foxes and Coyotes *Canis latrans* away from livestock in North America with varying success (Pfeifer and Goos 1982, Linhart *et al.* 1984, Shivik 2004). However, if applied to Victorian beaches, loud audible deterrents would likely disrupt the incubation of plover eggs (Weston and Elgar 2007, Maguire 2008) and compromise amenity of beaches to the beach-going public (Pesonen and Komppula 2010). Acoustic deterrents which use ultrasonic noise (> 20 kHz), are likely inaudible to plovers (most bird species hear 1 - 4 kHz and no species is sensitive to the ultrasonic range; Beason 2004) and people (who can hear 0.03 – 17.6 kHz and not within the ultrasonic range; Heffner and Heffner 2007), yet audible to foxes (which hear frequencies of 0.9 - 34 kHz; Meek *et al.* 2014). As such, ultrasonic deterrents could offer a viable alternative to altering fox behaviour around shorebird clutches, without unduly disturbing incubating plovers or people. The recent emergence of a range of remotely triggered, battery operated, lightweight and cost-effective ultrasonic acoustic deterrents for Foxes (portable ultrasonic fox deterrents, PUFDs; Bunnings n.d., Concept Research n.d.), also means broad-scale deployment on plover clutches, which are already managed in various ways (e.g. symbolic fencing, provision of shelters for chicks; Maguire 2008), is practical.

Use of ultrasonic acoustic deterrents have historically low use and success (Pfeifer and Goos 1982, Linhart *et al.* 1984, Shivik 2004), and use on Foxes has been restricted to protecting livestock over a large pasture area with limited success (Koehler *et al.* 1990), not a small area such as a Hooded Plover nest. However, commercially available PUFDs are designed to deter foxes from small areas, such as lawns and chicken coups (Bunnings n.d., Concept Research n.d.), circumstances which apply to Hooded Plover nests. I know of no research on the use of PUFDs for protecting wildlife from foxes, and none is available regarding their potential efficacy in protecting ground-nests from foxes in coastal environments. Studies have been conducted using similar devices for domestic Cats *Felis catus* and Dingoes *Canis familiaris dingo* with some success shown for cats but not Dingoes (Nelson *et al.* 2006, Edgar *et al.* 2007, Crawford *et al.* 2018). Here, I investigate the efficacy of using a portable ultrasonic acoustic fox deterrent to improve Hooded Plover clutch success.

Aims and predictions

I investigate the potential for a commercially available PUFD to reduce egg take rates by Red Foxes for the beach-nesting Hooded Plover, across southern Australian sandy beaches. Given the Hooded Plover is a threatened species, and risks exist with any new management approach (e.g. disruption of incubation by a PUFD), I adopted a staged, cautionary approach (*sensu* Maguire *et al.* 2009) whereby I tested for efficacy of PUFDs on “mock clutches” (quail eggs; “phase 1”) before testing PUFDs on real Hooded Plover clutches (“phase 2”). This study conducted both phases.

If PUFDs successfully reduce Fox take of Hooded Plover clutches, I predict that:

- 1) foxes will react to a PUFDF by leaving the area around a clutch (the “immediate aversion response” hypothesis). Effective triggering of the PUFDF and some level of fox aversion to a triggering PUFDF are pre-requisites to PUFDF success;
- 2) that PUFDFs will alter the assemblage of “visitors” (non-plover species) detected near clutches, specifically by reducing the number of fox visits (the “fox avoidance” hypothesis). Foxes are highly intelligent and may learn to avoid areas with active PUFDFs (González *et al.* 2021), such that they are detected less frequently where PUFDFs operate. As such, it is possible that I may detect few direct interactions between PUFDFs and foxes, yet effective aversion may still have been achieved; and/or,
- 3) that fox take of eggs will be reduced by PUFDFs, consequently improving egg survival, the ultimate measure of PUFDF success with respect to plover conservation. Eggs represent a food reward to a fox, individual foxes are likely to experience different energy states and needs (Houtman and Dill 1998), and aversive stimuli might vary in their effect on individuals through site (e.g. acoustic attenuation, absorption etc.; Kalauni and Pawar 2019) or recipient-based traits (e.g. “personality”; Start and Gilbert 2017). It is therefore possible that foxes may respond to triggering PUFDFs, and/or avoid areas with PUFDFs, yet still take eggs.

This study does not make any conclusions regarding the specific brand of PUFDF I use.

I note that I use the PUFDF in ways it was not intended to be used by the general consumer, and caution against any extension of results to the general utility of the device in other contexts.

Methods

Treatments

The acoustic deterrent device selected was 'FOXWatch™', developed by Concept Research (United Kingdom) and commercially available worldwide (Concept Research n.d.). It was judged to be practical in terms of cost, weight and portability for application in plover management. FOXWatch is marketed to be operable in most weather conditions and offer a battery life of 2-3 months with a single 9-volt battery (Concept Research n.d.). FOXWatch™ (Figure 1) is a small brown device 16.5 cm high x 8 cm wide x 5 deep cm and emits a "sweeping" ultrasonic sound of 20 – 24 kHz when triggered by its motion and heat sensor which illuminates red when emitting its sound (Concept Research n.d.). To describe and validate the sound profile of the device, I tested this using an Anabat Swift™ bat detector and found FOXWatch™ to emit a frequency of 30 – 36 kHz (Figure 2), higher than the frequency stated in the device manual (Concept Research n.d.). FOXWatch™ can be purchased from a variety of online stores and different frequency ranges are listed on different websites with ranges of 20 – 24 kHz, 32 – 36 kHz and 40 – 45 kHz (Concept Research n.d., Electric Fence Online n.d., Fox Repellent Expert n.d.). However, the range of frequencies listed above and recorded from my study devices are within the accepted upper limit of fox hearing capacity. Foxes have optimal hearing 10 - 14 kHz (Meek *et al.* 2014) and the upper limits of the hearing range 34 - 65 kHz (Peterson *et al.* 1969; Isley and Gysel 1975).



Figure 1. FOXWatch™ acoustic device (left) and control device (right).

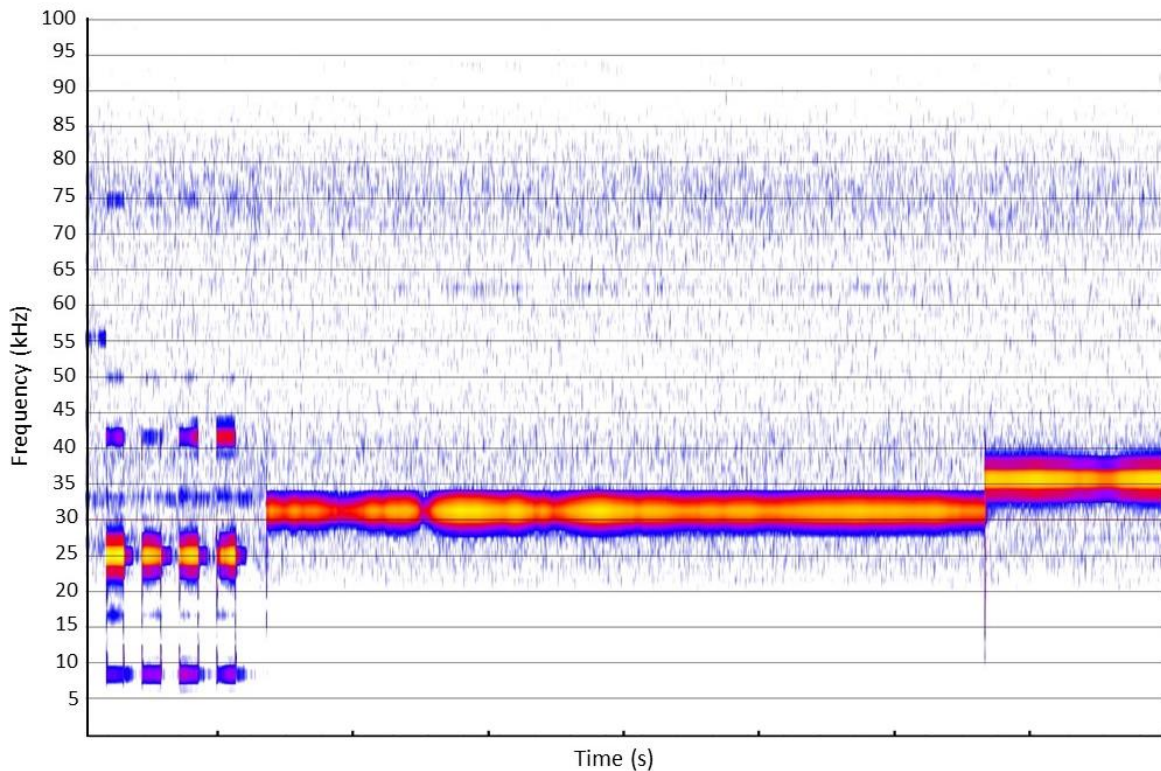


Figure 2. Sonagram of FOXWatch™ emitted frequency recorded at 6 m from the device to mirror deployment distances used in this study (see below). The small pulses at the start of the test are the startup noise’s frequency and the large solid sound wave is the sound emitted from FOXWatch™ when triggered.

The FOXWatch™ motion sensor has a detection range of ≤ 12 m and the sound emitted from the device has a range of ≤ 12 m projected outwards in a conical shape (Concept Research n.d.). I tested this detection distance by measuring the triggering distances as I approached the device from different angles and distances in an open area. I found its motion sensor had a detection angle of $\sim 100^\circ$, a detection range of ≤ 12 m. The ultrasonic sound frequency of FOXWatch™ is marketed to be inaudible to non-target species such as birds and humans (Concept Research n.d.), and despite many triggers, no personnel involved in this study ever heard the ultrasonic noise. The above features meant it holds

promise at repelling foxes from the clutches of Hooded Plovers while avoiding disturbance of incubating Hooded Plovers.

To test the effectiveness of FOXWatch™ a control was required, which mimicked the visual stimulus of a FOXWatch™ device but did not emit the ultrasonic deterrent. A control device was created out of a shampoo bottle of similar dimensions and spray-painted mission brown with its lid glued to the front to mimic the reflective sensor of FOXWatch™ (Figure 1). Control devices were cleaned and aired thoroughly to remove any odours. They were mounted in the same manner as real devices, on a stake, at ~15 cm.

“Treatment” sites (those with an operating FOXWatch™) and “control” sites (those with a control device) were selected in a systematic random fashion (see below).

[A staged approach to testing effectiveness](#)

This study used a staged approach to test FOXWatch™, with initial tests on ‘mock clutches’ to be vigilant for any unanticipated negative effects, before testing on real clutches (*sensu* Maguire *et al.* 2009, Stojanovic *et al.* 2009). More specifically:

1. Phase 1 ‘Mock clutch trial’ involved testing the FOXWatch™ device on artificial clutches containing two quail eggs which are similar in size and colouration to Hooded Plover eggs, offering equivalent attractants to foxes without risking real Hooded Plover clutches or disturbance to Hooded Plovers (*sensu* Stojanovic *et al.* 2009). The objective of this phase was to establish whether FOXWatch™ was efficacious and to be alerted to any unanticipated responses that could pose a risk to real Hooded Plover clutches (Maguire *et al.* 2009).
2. Phase 2 ‘Real Hooded Plover clutch trial’ involved testing the device on real Hooded Plover clutches, to determine the efficacy when used as a management tool on real

clutches, and to ensure the device did not compromise parental care of the eggs of Hooded Plovers by disrupting incubation (i.e. disturbing incubating adults).

Phase 1: Mock clutch trial

Mock clutches (small shallow hand dug scrapes in the sand mimicking real clutches, and containing two quail eggs after Stojanovic *et al.* 2009; Figure 3) were installed in an array (the configuration of equipment deployed at a site) across the Victorian Southern and Eastern Gippsland coast across 59 sites in a randomised systematic design (Figure 4). Most sites (where mock clutch and associated equipment were positioned; see below) were deployed during three periods spanning mid-September and October in 2022 to and left *in situ* for a minimum of 19 days until retrieval. The timing of deployments was within the main breeding season of Hooded Plovers. Sites were positioned at the base of dune systems to ensure low risk of tidal inundation, and to mimic the main nesting habitat used by Hooded Plovers (Dowling and Weston 1999). Sites were established along the coastline in a systematic random method (a randomly selected treatment level, treatment [FOXWatch™] or control [mock device], followed by alternating treatments for adjacent sites) with a minimum one kilometre between sites.

A trail camera was set up on a wooden stake with a plastic cover to improve weather resistance ~2 m from the mock clutch and set to take still images in three image bursts, high sensitivity, one second intervals, with time and date stamps on. The treatment or control device were set up on a wooden stake ~15 cm off the ground and ~5 m from the clutch and facing it. An additional trail camera (with a plastic cover) was also mounted to a wooden stake ~5 - 6 m from the quail eggs at an angle of ~30° from the axis between the acoustic deterrent and clutch, and was set to video mode. The video camera was designed to detect

visitors to the vicinity of the sites which were not captured on the still image camera closer to the mock clutch (FOXWatch™ may have repelled foxes from a broader area). The video camera was set to high sensitivity, large video size, one second interval, with time and date stamps turned on. All cameras were mounted on stakes ~ 15 cm above the sand. Exact configurations were occasionally adjusted to accommodate site-specific conditions such as slope and vegetation. Each site was set up parallel to the coastline (i.e. the device/clutch axis was parallel to the water line) to reduce the risk of tidal inundation and loss of equipment, and to mirror how management would apply to real clutches.

During set up of each site, three variables were recorded to enable later tests for equivalence between treatment and control sites:

1. distance from mock clutch to treatment/control device (cm), measured using a tape measure;
2. the presence of fox prints in the immediate vicinity, assessed by searching the surrounding area during approach and exit from the site and set up;
3. percentage of field of view (FOV) obstruction (e.g. from vegetation) between clutch and FOXWatch™ (measured as an ordinal scale from 0 - 4 (0 = no FOV obstruction, 1 = 1 - 20% obstruction, 2 = 21 - 40% obstruction, 3 = 41 - 60% obstruction, 4 = > 60% obstruction) or control device. While placement of sites sought to minimise visual obstructions between devices, clutches and cameras, inevitably some could not be avoided.

All equipment was checked for functionality during retrievals, because failure of FOXWatch™ could lead to skewed results. From the 29 treatment sites, all devices were still operational after a minimum 19-day deployment except one which received damage to its

sensor from a raven *Corvus spp.* after egg take and therefore the site was still included in analyses.

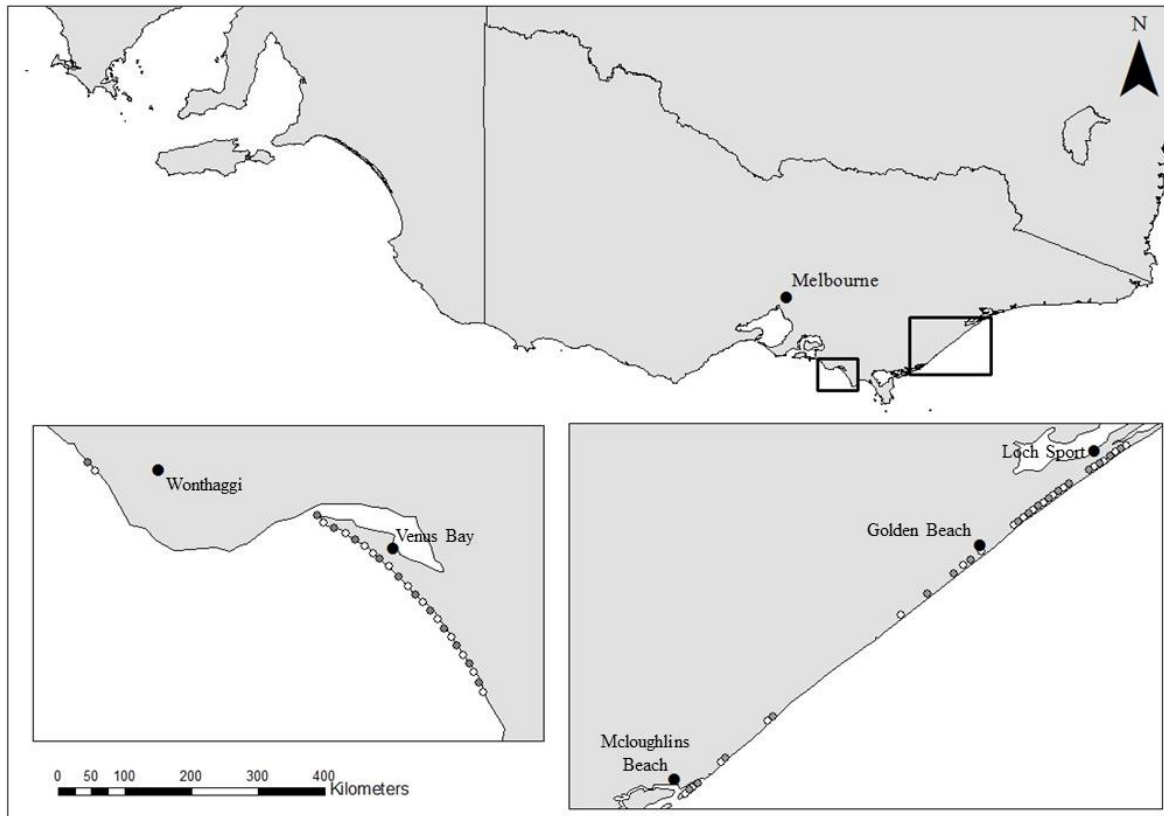


Figure 3. Mock clutch sites (phase 1). White diamonds represent control mock clutch sites and grey diamonds represent treatment mock clutch sites

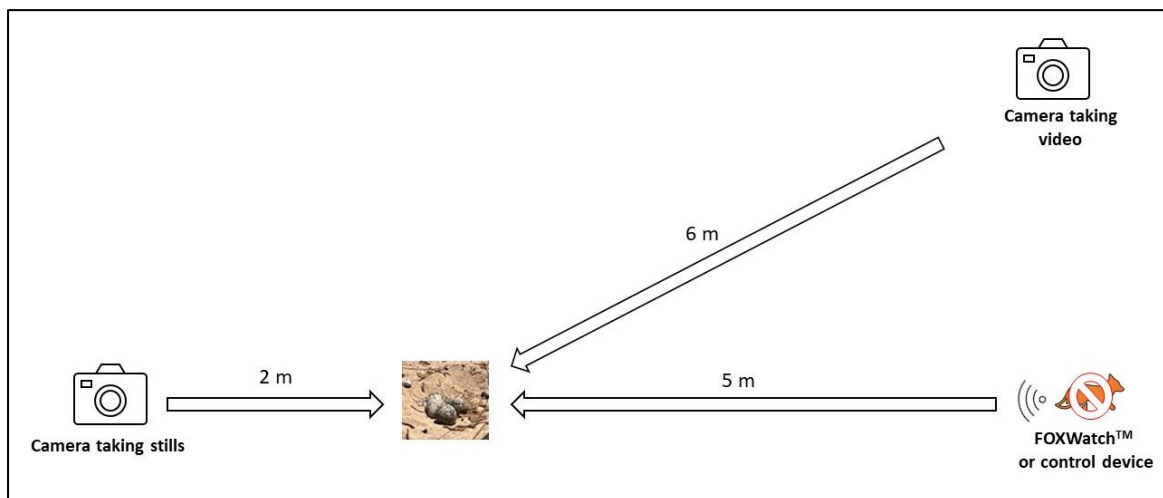


Figure 4. Configuration of equipment, eggs and clutches for both mock and real clutches.

Phase 2: Real Hooded Plover clutch trial

Thirty-five real Hooded Plover clutches across Victorian (Bass Coast, Bellarine Surf Coast and Mornington Peninsula) and South Australian sandy beaches (Adelaide region, Fleurieu and Yorke Peninsulas) were selected for phase 2 (Figure 5). South Australian sites were included in the study to boost the sample size, and to encompass a variety of coastal beach and dune forms not available from Victoria. The study areas also represented areas at which FOXWatch™ may be deployed for plover management, if found to be efficacious. Sites were deployed during the peak of the Hooded Plover breeding season, December to February 2022-23 (Baird and Dann 2003), and were left *in situ* until hatching occurred or eggs were lost. Sites were established in each study area using a systematic random design (Figure 5; a randomly selected treatment for the first clutch, treatment or control, followed by alternating treatments) with a minimum of one kilometre spacing between clutch sites adjacent to one another at one given time.

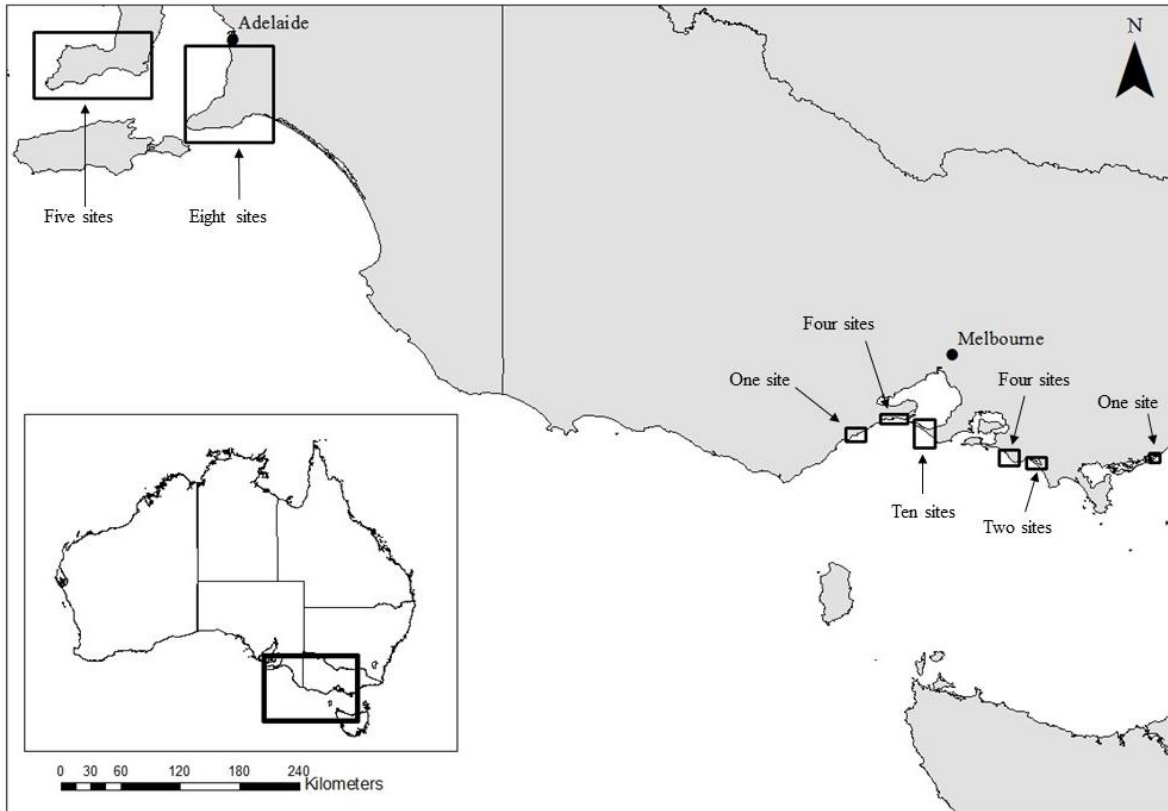


Figure 5. Real Hooded Plover clutch locations across South Australia and Victoria during phase 2 of the study.

To determine suitability for selection in the study, real eggs were floated (Liebezeit *et al.* 2007, Székely *et al.* 2008) to estimate the clutch age (days since clutch completion) prior to setting up equipment. Clutch age was determined by calculating lay date with the validated formula for Hooded Plover: $\text{lay date}_{(\text{Julian})} = -3.318 \times \text{max}(\text{float stage}) + 7.409$; where lay date is hatch date minus the average incubation period (28 days) (Mead 2012). Sites were only selected if clutches were at least 2 days since clutch completion and had an estimated minimum of one week left of incubation (Marchant and Higgins 1993). Clutches were prioritised such that I selected clutches that offered few obstructions and would be candidates for deployment under a management scenario.

Real clutches were fitted with the same configuration of devices and cameras as described for mock clutches. Exact configurations of each site were occasionally adjusted to accommodate site-specific conditions such as slope and vegetation. During site set up, distance from clutch to acoustic deterrent device, presence of fox prints in the immediate vicinity, obstruction to acoustic deterrent device were all recorded to test for biases in site selection between treatment and control sites. Again, procedures followed that already described for mock clutches. Clutch habitat was also recorded (beach, the seaward edge of dune to the water's edge [Dowling and Weston 1999, Meager *et al.* 2012]; or foredune, foremost vegetation on the sand dune, the slope between the beach and primary dune (Dowling and Weston 1999, Hesp *et al.* 2005).

Hooded Plover reaction to the setup of sites was also measured after site installation to investigate any possible negative effects to Hooded Plover behaviour following installation. While I always determined that adults returned to the clutch after deployment at all clutches, I used camera data to measure return time to clutch incubation (i.e. the interval between investigator departure and first camera detection of an incubating adult).

Once installed, sites were checked weekly to renew batteries (if required) and SD cards in trail cameras, check the FOXWatch™ battery and remove sand from the device speaker. Site checks continued until either clutch failure or hatching, at which point equipment was removed. All visits were logged in the BirdLife Australia MyBeachBird portal to alert local volunteers and land managers of study locations.

Equivalence between treatments

I monitored 59 mock clutch sites (30 control, 29 treatment) and 35 real Hooded Plover clutch sites (15 control, 20 treatment). At mock clutch sites, there was no difference

between treatment or control devices with respect to the distance each device was placed from the clutch ($F = 0.082$, $df = 1$, 48 , $p = 0.776$), the degree of obstruction between the device and mock clutch (Mann-Whitney, $U = 394.50$, $p = 0.500$; 0 - 3 FOV obstructions between clutch and device, median on scale 1) or the presence of fox prints around the site (contingency analysis, $\chi^2 = 1.565$, $df = 1$, $p = 0.211$). At real clutch sites, there was no difference between treatment and control devices with respect to the distance each device was placed to the clutch ($F = 0.018$, $df = 1$, 32 , $p = 0.895$) presence of fox prints around the site or the degree of obstructions (contingency analysis, $\chi^2 = 1.518$, $df = 2$, $p = 0.468$ and $\chi^2 = 1.791$, $df = 4$, $p = 0.774$ respectively). Despite randomisation, there was a difference in habitat between treatment levels, with 81.2% of control clutches in beach habitat and 57.9% of treatment clutches in primary foredune habitats ($\chi^2 = 7.868$, $df = 2$, $p = 0.020$). Importantly, presence of fox prints did not differ between habitats (contingency analysis, $\chi^2 = 0.297$, $df = 1$, $p = 0.586$) and thus I assume clutches were exposed to fox predation equally in either habitat.

Statistical methods

Data was downloaded from trail camera SD cards and coded. "Visits" to sites (any person or species other than those of the investigator near the clutch) were defined using a 15-minute rule, i.e. if the same species in the same numbers visited after > 15 min interval, a second event was recorded. If additional individuals visited the site or added to an existing group at the site within 15 minutes, this was deemed a new event. At the 15-minute mark of an event if visitors remained at the site, then a new event was recorded. During each event, the date, time start and end, species type and number of individuals detected were recorded in addition to the location of visitor (classified as "at clutch", "inside array" $\leq 3m$ from clutch,

outside array 3 - 5 m from clutch and “distant” where distance was estimated). FOXWatch™ triggers during each event (readily detectable by a red light on the sensor on the device) was recorded as was the reaction of the visitor to treatment or control devices (measured on a five-point ordinal scale: 0 = indeterminate, 1 = attraction [e.g. one image approaching the device], 2 = no response, 3 = vigilance to device [at least one image], 4 = escape, crouching, hiding or avoidance[at least one image]). Visitations where response was indeterminable (0) were removed from analyses. Egg status (*in situ* or “taken” i.e. eaten or removed) was assigned a measure of the degree of inference required for “taken” (ordinal scale 0 - 2, 0 = take fully captured in imagery, 1 = predator seen in vicinity around time of egg disappearance, 2 = eggs discovered missing with no camera evidence; after Weston *et al.* 2017).

Prior to analysis, I consolidated duplicate events i.e. those caught on both trail cameras. Additionally, events were filtered out from analysis which contained visitors < 20 m from the site which were deemed to be a ‘threat to the clutch’. Mock clutch deployments had slight variation in operating durations and I thus truncated data so that all mock clutches were exposed for 19 days to ensure equivalent exposure periods across all sites (Mayfield 1961).

Statistical analysis

Assemblage of visitors represented multivariate data, and was analysed by generating a zero-inflated Bray-Curtis resemblance matrix from square root transformed data (number of events per site). Assemblages were visualised using non-metric MDS (nMDS) overlaid with vectors indicating variables that exhibited a correlation ≥ 0.4 . This was repeated for all mock and real clutch sites, and then for a subset of mock and real clutch sites at which Fox

presence was recorded (either prints or imagery, at any point during deployment). An ANOSIM was used to test for differences between treatment and control for mock clutches (equivalent exposures for all clutches) whilst a PERMANOVA was used for real clutches because it allowed clutch age to be added as a covariate to control for the varying exposure durations between clutches. PERMDISP explored any differences in dispersions of multivariate assemblages. Canonical Analysis of Principal Coordinates (CAP) was used to explore any differences detected by PERMANOVA, but where a single CAP was resolved, I also present the nMDS to visual differences. The occurrence of foxes (the target of this study) and dogs (a potential bycatch of the study that has a similar hearing range to foxes REF) were examined separately using contingency analysis (with Yate's correction because $df = 1$).

The response of dogs and foxes to control and treatment sites were examined using a Mann-Whitney U test, based on my ordinal response scale, and only for fox and dog visitations within 5 m of mock and real clutches.

The survival of clutches for mock clutch trials (defined as eggs present at 19 days) was analysed using a chi-square test of days to take per treatment group. The survival of real clutches was analysed with a Cox Regression with age of clutch at discovery specified as a confounding factor. Cox regressions were run for all real clutch sites, and then for the subset of real clutch sites where fox presence was observed (prints or images). Assemblages of visitors to sites were analysed in PRIMER 7, all other analyses were conducted in SPSS 29.

Results

Fox and dog response at mock clutches

Two species are of particular interest with respect to their response at treatment and control sites: foxes and dogs. Foxes exhibited more intense responses at mock clutch sites with FOXWatch™ (treatments) compared to controls (intensity scale at treatment sites, 3 – 4, median = 4; control sites, 1 – 4, median = 2; U = 5.50, p = 0.004; N = 16; Figure 6). Dogs exhibited no significant increase in response intensity at treatment sites compared to controls (intensity at treatment sites, 2 – 4, median = 2; control sites, 2 only, median = 2; U = 8.00, p = 0.637; N = 11)

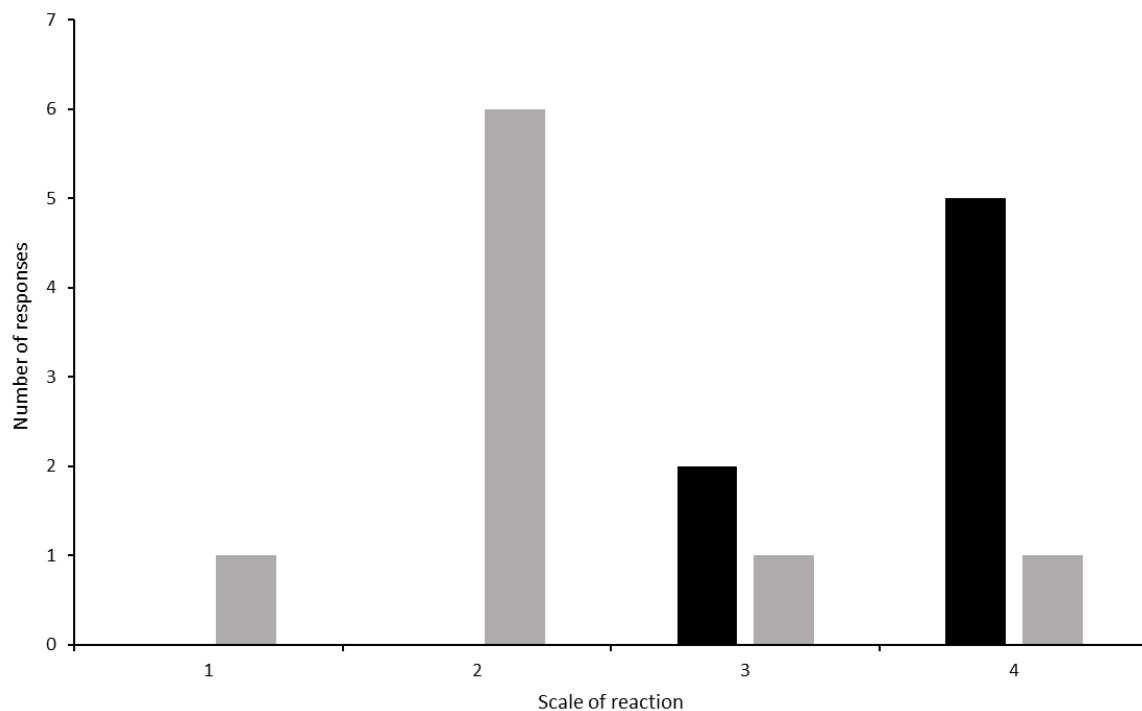


Figure 6. Number of fox responses to treatment and control devices at mock clutches. Grey bars represent reactions at control sites and black bars present reactions at treatment

(FOXWatch™) sites. Reaction intensity is measured on an ordinal scale where 1 = attraction to device, 2 = no reaction to device, 3 = vigilance to device and 4 = an escape/fear response.

Assemblage of predators at mock clutch sites

A wide variety of visitor species were observed across treatment and control sites including a Cat 1.7% of all sites, Dog 3.4%, Currawong *spp.* 13.6%, Deer *spp.* 10.2%, Human 8.5%, Human and dog 8.5%, Australian Magpie *Gymnorhina tibicen* 23.7%, Raven *spp.* 69.5%, Swamp Wallaby *Wallabia bicolor* , 1.7%, Wombat *spp.* 40.7% and Fox 22.0%. The assemblage of visitors at mock clutches (N = 59) was visualised using a non-metric Multi-Dimensional Scaling (nMDS) plot (Figure 7; stress = 0.19 for two dimensions). There was substantial overlap in assemblages of visitors between treatment and control sites (Figure 7). There was no difference in the assemblage of visitors between treatment and control sites (ANOSIM, $R = -0.021$, $p = 0.928$), nor was there a difference in multivariate dispersions (PERMDISP, $F = 0.740$, $df = 1, 57$, $p = 0.479$).

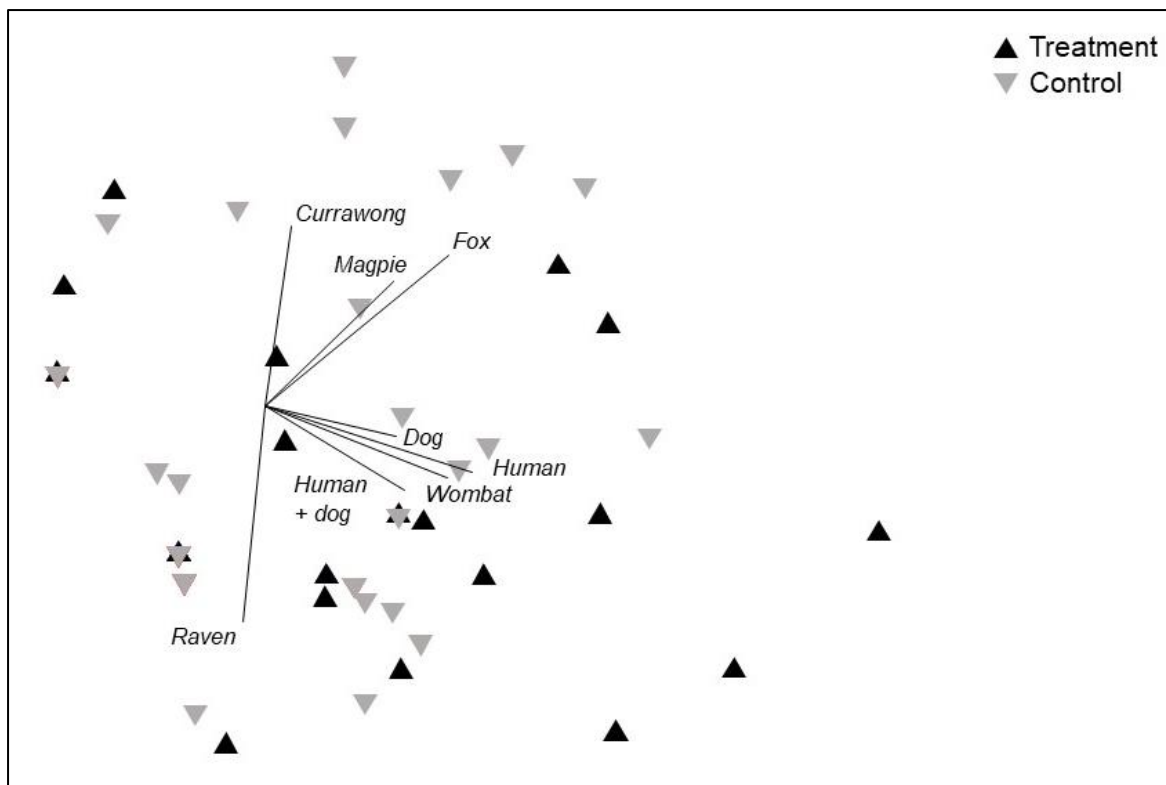


Figure 7. Non-metric Multi-Dimensional Scaling plot of the assemblage of visitors detected at all mock clutch sites. Vectors with a correlation of ≥ 0.4 are shown. Ravens and currawongs were only identified to genus level.

Foxes were not detected at all clutches (they were detected at 71.2% of mock clutches), and inclusion of visitors at clutches at which foxes did not occur may obscure any differences in assemblages of visitors between treatment and control sites. Therefore, the assemblage of visitors at mock clutches was also examined at a subset of clutches where fox presence was noted at some point during the deployment period (prints or images; $N = 42$). The nMDS again revealed substantial overlap in the assemblages of visitors at treatment and control mock clutches (Figure 8; stress = 0.16 across two dimensions) and these assemblages did not differ (ANOSIM, $R = -0.019$, $p = 0.636$; PERMDISP, $F = 0.029$ $df = 1, 40$, $p = 0.898$).

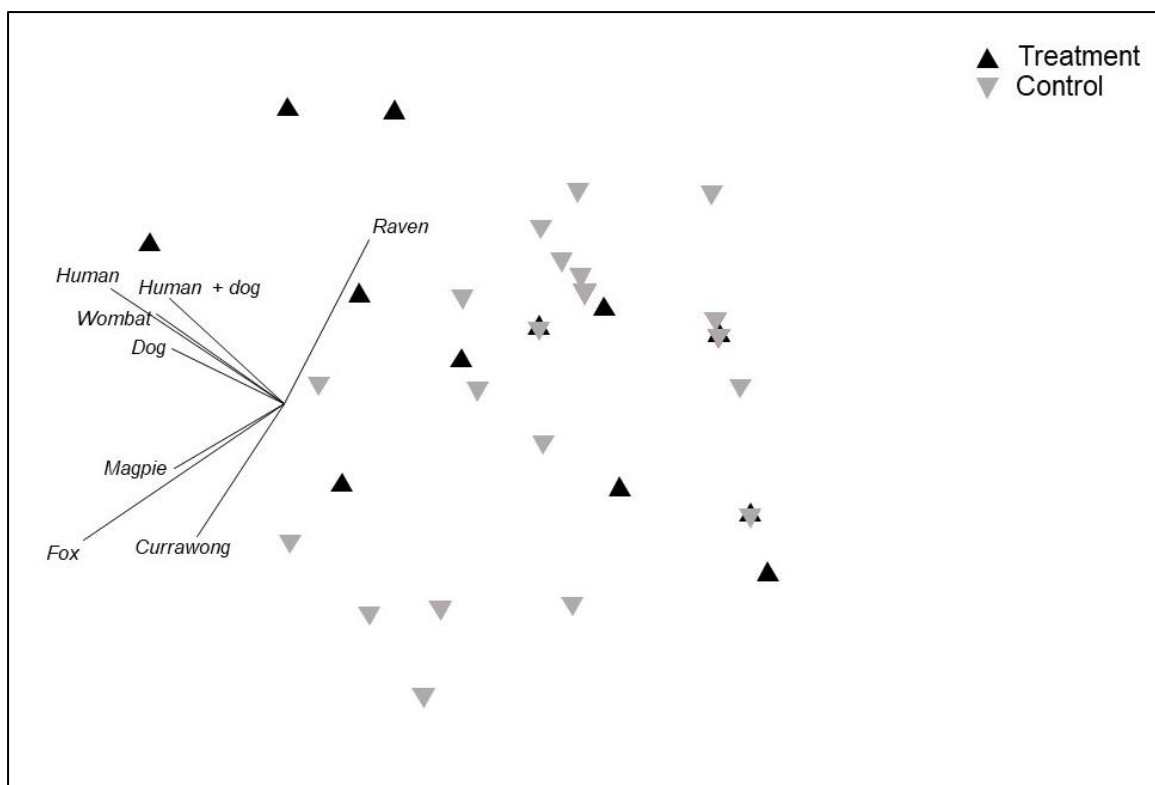


Figure 8. Non-metric Multi-Dimensional Scaling plot of the assemblage of visitors detected at mock clutches at which foxes were detected. Vectors with a correlation of ≥ 0.4 are shown. Ravens and currawongs were only identified to genus level.

Fox visits caught on camera occurred at 20.7% of the 29 treatment and 23.3% of the 30 control sites (contingency analysis, $\chi^2 = 2.310$, $df = 1$, $p = 0.128$). The number of dog visits only occurred at 4 of 59 sites (3 were at treatment sites) and did not differ between control and treatment sites ($\chi^2 = 1.147$, $df = 1$, $p = 0.284$).

Clutch survival in mock clutches

The number of days between deployment and egg take of mock clutches was examined for all sites and then for a subset of sites where fox presence was observed (prints or images; Figure 9). Overall, 20.7% of mock clutches at treatment sites survived 19 days compared to only 3.4% at control sites (number survived, $\chi^2 = 4.248$, $df = 1$, $p = 0.039$; Figure 10). At mock

clutch sites where fox presence was observed, 27.8% of treatment clutches survived 19 days compared with 4.2% of control clutches (number survived, $\chi^2 = 4.683$, $df = 1$, $p = 0.030$; Figure 10).

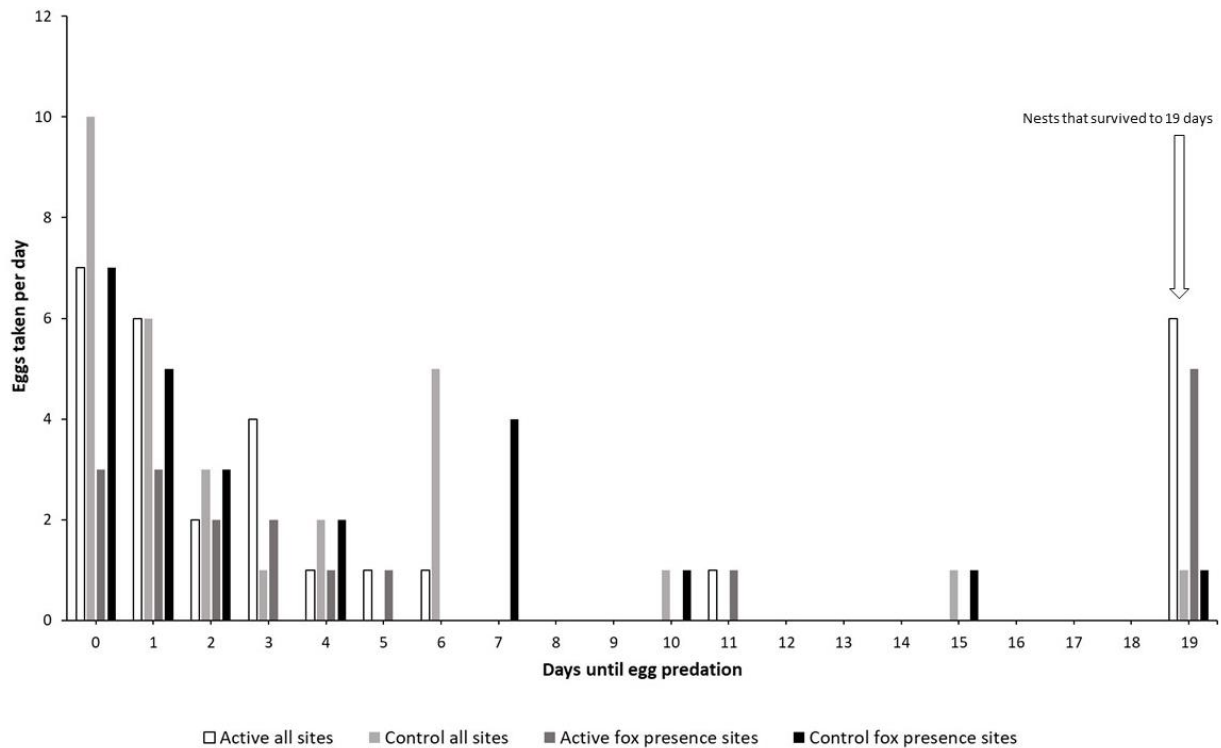


Figure 9. The number of days between deployment and egg loss at mock clutches fitted with treatments (FOXWatch™) and controls, for all mock clutches, and for only those clutches at which foxes were detected.

Real Hooded Plover clutches

Return times of Hooded Plovers to the clutch after deployment did not vary between treatment and control (GLM, $F = 0.212$, $df = 1$, 30 , $p = 0.649$). Clutch abandonment was not observed at any site after installation.

Fox and dog response at real Hooded Plover clutches

FOXWatch™ devices evoked more intense responses from foxes than control devices at real clutches ($N = 37$; $U = 67.00$, $p = 0.002$; Figure 10). No difference was found between intensity

of dog response at treatment and control sites ($U = 28.50$, $df = 1$, $p = 1.00$) which ranged 2 – 3 on the ordinal scale with a median of 2 (i.e. no response).

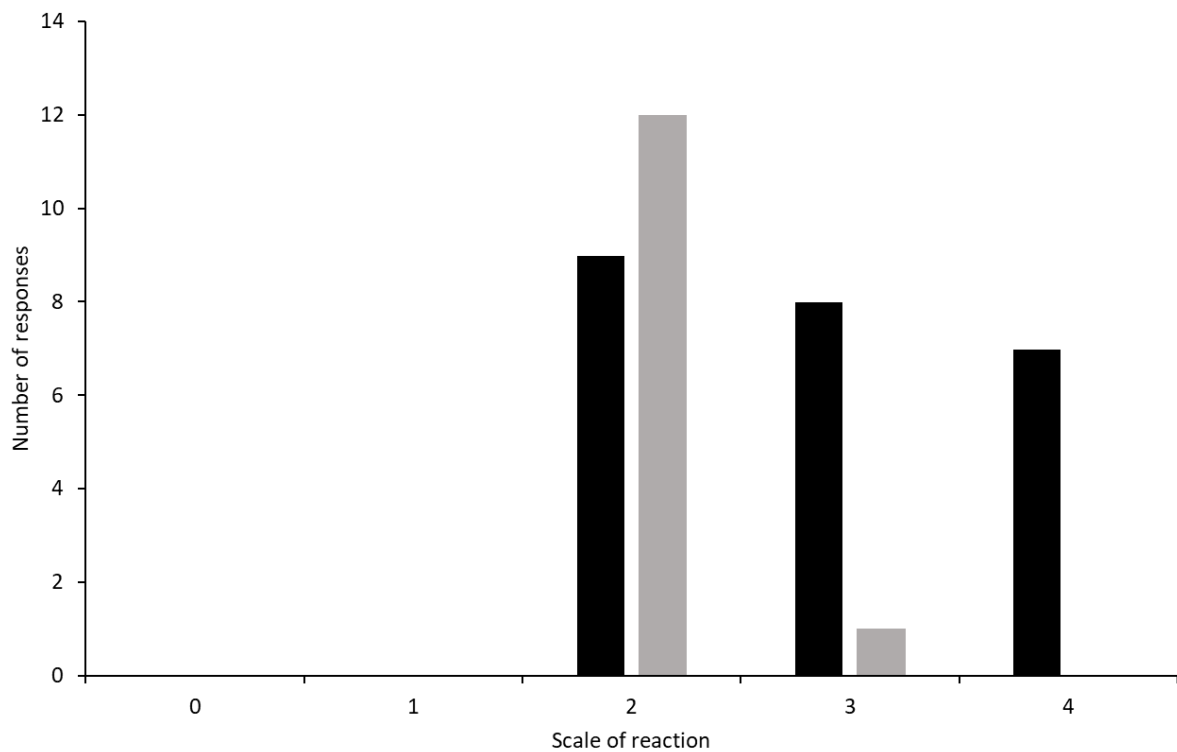


Figure 10. Number of fox responses of different intensities to FOXWatch™ and control devices at Hooded Plover clutches. Grey bars represent reaction at control sites and black bars represent reaction at FOXWatch™ sites. Response intensity is an ordinal scale whereby: 1 = attraction to device, 2 = no reaction to device, 3 = vigilance to device and 4 = an escape/fear response from foxes.

Assemblage of predators at Hooded Plover clutches

The assemblages of visitors at all Hooded Plover clutches ($N = 35$) differed between treatment and control sites (PERMANOVA, Pseudo-F = 3.409, $df = 1$, 31 $p = 0.008$; Figure 11, stress = 0.17 across two dimensions). The age of the clutch at deployment, the other term in the model, had no statistically significant effect on visitor assemblages (Pseudo-F = 1.966, $df = 1$, 31, $p = 0.096$). PERMDISP confirmed that the difference in the assemblage of visitors

between treatment and control sites did not pertain to different dispersions ($F = 3.262$, $df = 1, 32$, $p = 0.131$), instead it must relate to differences in location. The vectors on the nMDS suggest more dogs, humans and foxes occurred to the upper left of the plot (dominated by control sites) (Figure 11; stress 0.17 across two dimensions). Canonical Analysis of Principle Coordinates (CAP) analysis reveals clear differences in assemblages between clutch treatments (Figure 11) with an overlap between assemblages visiting control and treatment sites, but some visitor assemblages only occurring at treatment sites.

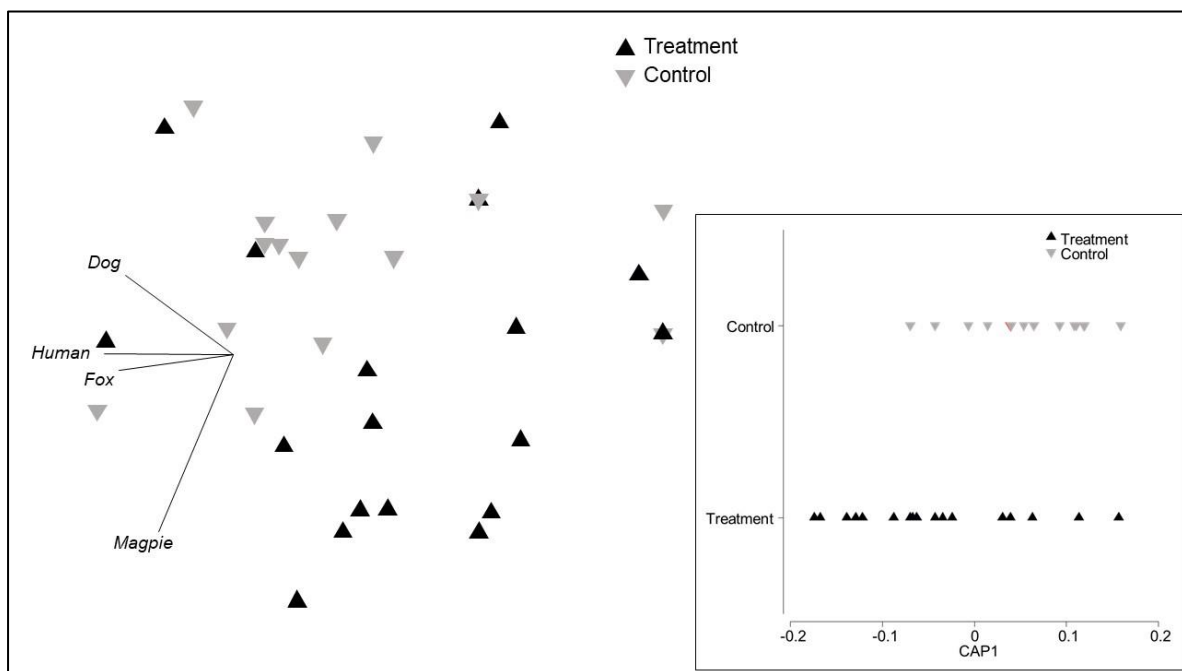


Figure 11. Non-metric Multi-Dimensional Scaling plot of the assemblage of visitors detected at real clutches (the inset shows the results of the CAP plot, which fitted only one CAP).

Vectors with a correlation of ≥ 0.4 are shown on the nMDS.

The assemblages of visitors at Hooded Plover clutches where fox presence was observed also differed between treatment and control sites (Figure 12, stress = 0.11 across two dimensions; PERMANOVA, treatment, Pseudo-F = 3.907, df = 1, 17, p = 0.006, age of the clutch at deployment, Pseudo-F = 1.890, df = 1, 17, p = 0.114). The differences in assemblage of visitors was not associated with different dispersions (PERMDISP, F = 3.675, df = 1, 18, p = 0.093). Canonical Analysis of Principle Coordinates (CAP) analysis reveals clear differences in assemblages between treatment and control clutches for sites with fox presence (prints or images; Figure 12). CAP revealed separation between assemblages of visitors at treatment and control sites, with some exceptions. The nMDS is also presented to display assemblages in multivariate space and revealed some separation between treatment and control assemblages, with foxes, dogs, magpies and humans tending to be more prominent where control sites dominated (Figure 12; stress 0.11 across two dimensions).

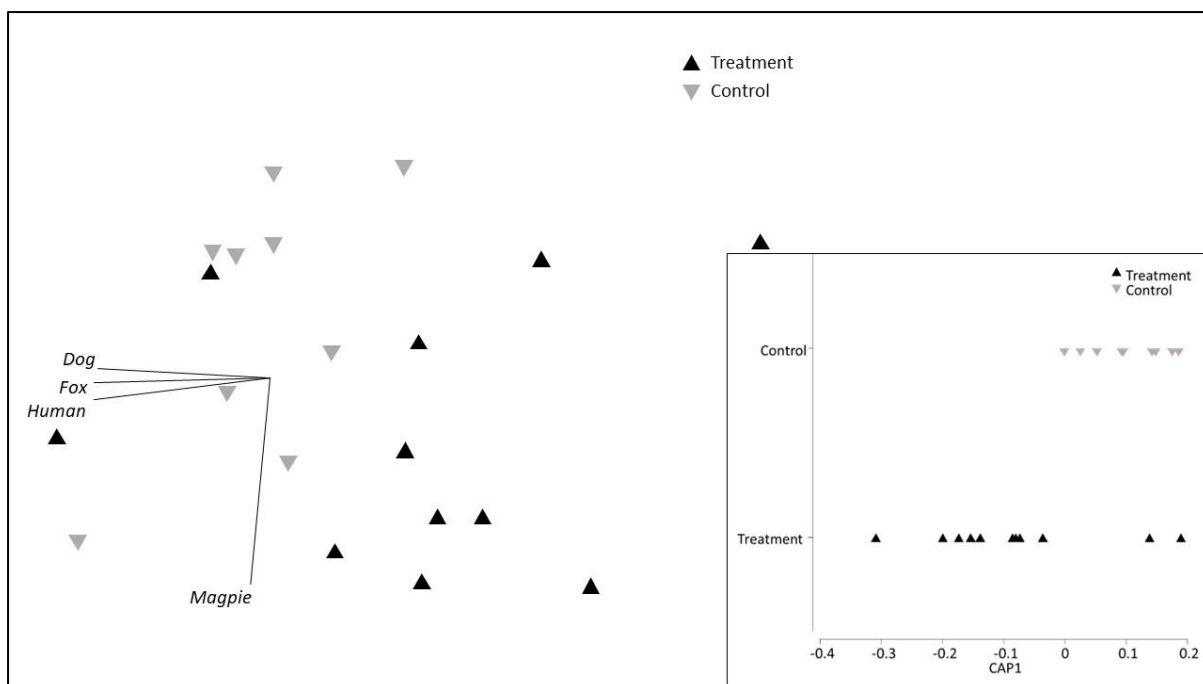


Figure 12. Non-metric Multi-Dimensional Scaling plot of the assemblage of visitors detected at real clutches where fox presence was observed (the inset shows the results of the CAP plot, which fitted only one CAP). Vectors with a correlation of ≥ 0.4 are shown.

Fox visits were captured on camera at 45.0% of treatment sites and 66.7% of control (contingency analysis, $\chi^2 = 1.62$, $df = 1$, $p = 0.20$). Dogs occurred at only 15.0% of treatment clutches but at 40.0% of control clutches ($\chi^2 = 5.87$, $df = 1$, $p = 0.02$).

Clutch survival

The survival of Hooded Plover clutches was analysed using a Cox regression with clutch age at discovery specified as a confounding factor (Figure 13). Clutch survival did not differ between treatment and control clutches (hazard ratio = 0.426, $p = 0.487$), however, older clutches at time of set up were more likely to hatch (hazard ratio = 1.119, $p = 0.001$). Hooded Plover clutch survival was also analysed for sites at which some fox presence was observed (prints or images; Figure 14). Again, treatment did not influence clutch survival (hazard ratio

= 0.464, $p = 0.547$) whilst older clutches had a greater chance of hatching (hazard ratio = 1.176, $p < 0.001$).

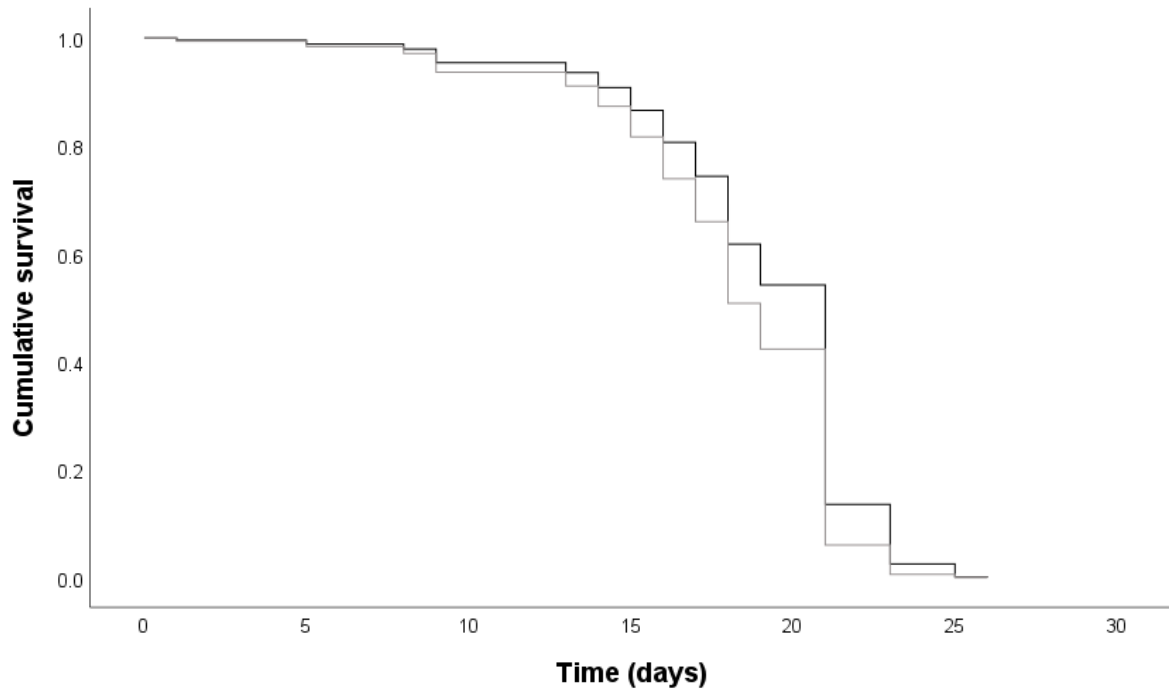


Figure 13. Clutch survival of Hooded Plover clutches (across time, in days). Grey line represents control sites and black line represents treatment sites.

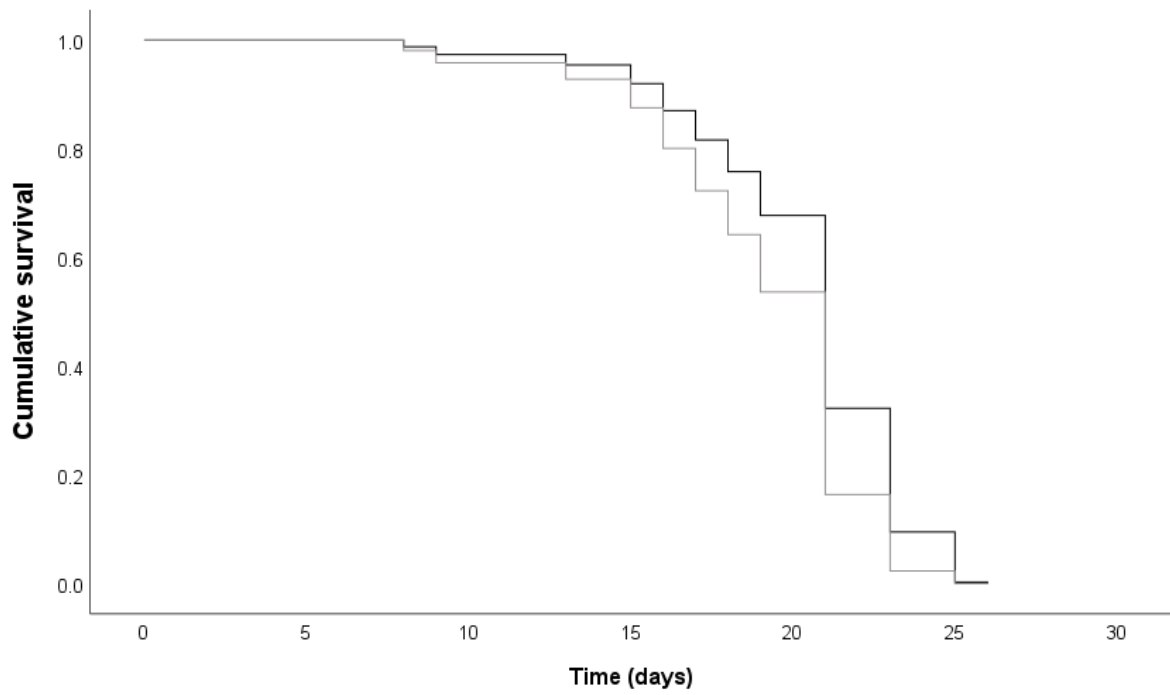


Figure 14. Clutch survival of Hooded Plover clutches (across time, in days) where fox presence was observed. Grey line represents control sites and black line represents treatment sites.

Discussion

Aversion responses

This study found the use of a Portable Ultrasonic Fox Deterrents (PUFDs) can produce an aversion response for foxes at mock and real Hooded Plover clutches. Aversion responses (i.e. escape) were seen consistently from fox visitations within 5 m of the clutch. Vigilance responses were also common, indicating detection of the ultrasonic sound, and this likely then initiated an escape which may not have been caught on camera. This result adds to the scant literature demonstrating that ultrasonic deterrents can produce an aversive response in Foxes (Koehler *et al.* 1990), limited trials thus far have largely targeted to other canid species such as Coyotes and Dingoes *Canis lupus dingo*, with limited or no response (Nelson *et al.* 2006, Edgar *et al.* 2007, Crawford *et al.* 2018). Repeat visitations to sites, and exposure to the ultrasonic sound, could lead to learning on the part of the Fox in the form of habituation (Blumstein 2016), which could see individual Foxes eventually overcome their aversion and take eggs. This response was observed at one site in South Australia, where visitation to a clutch was observed each day by foxes for seven days. An avoidance response was observed for the first six days until three juvenile Foxes, which had previously been repelled by FOXWatch™ during earlier visits, eventually ate the eggs.

No aversion was found for Dogs, a species which can also take Hooded Plover clutches, and for which aversion could also deliver conservation benefits (Dowling and Weston 1999, Weston and Elgar 2007). Alternatively, a response from Dogs could have generated concerns from the public about impacts on their pets and been a factor that could have led to land managers being unsupportive of use of the device on public land (G. Maguire pers. comms. Foxes and Dogs have overlapping hearing ranges (foxes, 0.9 - 65 kHz,

Peterson *et al.* 1969, Isley and Gysel 1975; dogs, 6 - 45 kHz, Peterson *et al.* 1969) thus dogs should be able to hear the output frequency of the chosen PUF (30 - 36 kHz). The non-reaction of Dogs to FOXWatch™ is consistent with PUF trials on a close relative to domestic Dogs, the Dingo (Edgar *et al.* 2007), suggesting it is not a failure to detect the sound, but the absence of a fearful response, that might explain the lack of response among Dogs recorded by this study.

Aversion through avoidance

Aversion through avoidance of PUFs were measured through comparisons of assemblages in species which visited treatment and control sites, and I found inconsistent results. For mock clutches, there were no differences in visitor assemblages across all study sites and sites with established fox occurrence. In contrast, at real Hooded Plover clutches visitor assemblages differed between treatment and control sites across all clutches and for those where fox presence was observed. On sandy beaches and dunes, mock and real clutches differ in the predator assemblages they attract, and this may be due to different predator cues such as the presence of an incubating adults and defensive behaviours (Weston *et al.* 2017). The use of mock clutches for preliminary testing of new conservation methods remains prudent (Maguire *et al.* 2009, Stojanovic *et al.* 2009) but results from mock clutches do not necessarily translate to real clutches, highlighting the importance of testing new methods on real clutches (Maguire *et al.* 2009, this study).

Given differences between mock and real clutches, it is prudent to focus on visitor assemblage differences on real clutches. Foxes, magpies, dogs and humans appeared more common at control sites (Figures 11 and Figure 12). These differences are unlikely to be driven by any capacity for magpies and humans to detect ultrasonic sound (Beason 2004).

Fox and Dog occurrence tended to be higher at control sites, which may suggest that the PUFDF was able to produce an avoidance response in foxes which can detect the ultrasonic sound, however, does not explain the pattern with Dogs, which we have shown not to respond to the device.

I also directly examined visitation rates of two key species, Fox and Dog. Fox visitation did not differ between treatment and control sites across both mock and real clutches, however domestic Dog visitation was higher at control sites for real clutches (but not mock clutches) – a result which could be interpreted as Dog avoidance of FOXWatch™. However, it is more likely that Dog visitation was influenced by habitat of sites with all 22 visits occurring at beach habitat clutches, spaces which are commonly shared with recreational users and would expect to see higher dog presence than primary foredune sites (Maguire *et al.* 2013, Rimmer *et al.* 2013). Additionally, these tests featured low sample sizes, and also did not control for exposure (i.e. the number of days for which cameras were deployed). Thus, these results need to be interpreted cautiously.

Clutch take rate and survival

PUFDF installation was associated with higher mock clutch survival across all sites and sites where fox presence was observed; real clutch survival was not correlated with PUFDF installation (across all sites and fox presence observed sites) but unsurprisingly, deployments later in incubation had an increased chance of hatching (Mayfield 1961). The aforementioned differences between mock and real clutches are therefore evident in clutch survival, again highlighting the need to validate any findings derived from mock clutches on real clutches.

Given that foxes are territorial, often revisit known food sources, and are intelligent (colloquially, “cunning”; Sonerud 1988, González *et al.* 2021), survival of clutches can be considered the outcome of the interplay between a possible food reward and the aversion impacted by any PUFd for the Fox. The higher survival of mock clutches with PUFd suggest the ultrasonic aversive stimulus outweighed the food reward of the eggs. However, for real clutches the PUFd seemed insufficient to overcome the food reward, suggesting perhaps that the reward was greater than for mock clutches. This could have resulted from larger clutch sizes in real clutches (mock clutch sites used two quail eggs whereas real clutches varied between two to three eggs, 50.0% of measured clutch sizes in the study exhibited a clutch size of three), additional cues due to extra visual and odour attractants such as the presence of adult, hence greater potential food reward (Hughes *et al.* 2010), longer deployment times allowing more time for fox learning, or perhaps even to palatability (Young *et al.* 2015).

The lack of an effect of the PUFd on real clutch survival could also have other explanations. “Complementary predation”, whereby two predators (in this case foxes and corvids) compete for prey (eggs), could see a system where there is an effective race between predators to consume prey (Casula *et al.* 2006). Thus, failure of foxes to consume a clutch means corvids have a higher chance of taking those eggs, with predator risk balancing between the two predators. My data were insufficient to clearly test these ideas. Finally, it could be that the PUFd did not deliver an aversive stimulus of sufficient repulsion to overcome the food reward. Differences in fox learning capacity, fearfulness, energy needs and states (Houtman and Dill 1998), may mean some or even many or all are willing to take risks to obtain food. Given the high learning capacity of foxes, it seems likely that ongoing

use of PUFDs could be associated with suppressed fox response and avoidance, possibly diminishing any utility of PUFDs further.

Future research

This study has shown that use of PUFDs in conservation management of Hooded Plovers exhibits promise in eliciting a response from foxes and altering visitor assemblages, although the aversive stimulus may not be sufficient to translate into improved clutch outcomes. It therefore seems likely that the aversion response does not outweigh the food reward of clutches. The food reward of a clutch cannot be altered and therefore the aversion must be strengthened which could be explored through different sounds in from the PUFD device or the addition of extra PUFD devices. Alternative methods such as conditioned taste aversion or the use of a visual aversion such as flashing lights have been trialled in the past with some success (Shivik 2004, Saunders and Mcleod 2007) and could help alter fox behaviour. An additional theory which requires further testing is complimentary predation by ravens occurring due to the potential removal of fox predation, creating additional opportunities for raven predation. Raven take of eggs solutions are a defined need in future research (Maguire *et al.* 2014, Ekanayake *et al.* 2015, Rees *et al.* 2015).

Conclusion

The use of PUFDs for reducing fox predation on Hooded Plover clutches showed promise during trials on 'mock clutches' but this did not translate to improved real clutch survival. PUFDs were shown to be able to elicit a fox response and alter visitor assemblages to real clutches but ultimately the food reward for foxes apparently outweighed the aversive stimuli offered by the PUFD. Enhanced PUFD stimuli may contribute to effective non-lethal fox

control methods available to reduce fox take of Hooded Plover clutches and arrest ongoing population declines in that species.

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