

## RESEARCH

## Aversion training wild kea with anthraquinone repellent in non-toxic baits prior to 1080 operations does not improve survival outcomes

Laura M. Young<sup>1\*</sup> , Amy L. Whitehead<sup>2</sup> , Lana M. Handley<sup>3</sup> , Ivor J. Yockney<sup>4</sup>, Mark B. Watson<sup>5</sup>, Matthew Hickson<sup>6</sup>, Jeffrey W. Benson<sup>7</sup>, Ivana D. Giacon<sup>7</sup> and Kerry A. Weston<sup>8</sup> 

<sup>1</sup>Department of Conservation, 22 Gee Street, Renwick, Marlborough 7204, New Zealand

<sup>2</sup>Manaaki Whenua Landcare Research, Gerald Street, Lincoln, New Zealand

<sup>3</sup>Department of Conservation, 69 Cron Street, Franz Josef/Waiau 7856, New Zealand

<sup>4</sup>Wildlife Surveillance Ltd., Weedons, Christchurch, New Zealand

<sup>5</sup>Wyndon Aviation Ltd., Maddisons Road, Weedons, Christchurch, New Zealand

<sup>6</sup>Department of Conservation, 32 River Road, Rangiora 7400, New Zealand

<sup>7</sup>OSPRI, Level 9, 15 Willeston Street, PO Box 3412, Wellington 6140, New Zealand

<sup>8</sup>Department of Conservation, Grand Central, 161 Cashel Street, Christchurch 8011, New Zealand

\*Author for correspondence (Email: [lyoung@doc.govt.nz](mailto:lyoung@doc.govt.nz))

Published online: 28 May 2025

**Abstract:** In New Zealand, the Nationally Endangered kea (*Nestor notabilis*) is a large endemic parrot susceptible to non-target mortality from 1080 (sodium fluoroacetate) which is used to control introduced mammals that threaten native biodiversity and livestock. Across all 1080 operations monitored since 2008, mean kea mortality is estimated to be 13%. Public concern around kea by-kill remains high and, consequently, significant effort is directed towards mitigating 1080 risk. Anthraquinone has previously shown potential as a suitable kea repellent, with captive kea learning and retaining an aversion to non-toxic baits containing 2.7% anthraquinone for at least ten months after repeated exposure. We tested whether wild kea could be aversion trained using these repellent baits prior to two large aerial 1080 operations during spring 2022 in central Westland (Otira-Taipo) and Arthur's Pass (Arthur's Pass West) and if this reduced kea mortality. Kea bait interactions and consumption were scored using trail camera video footage from 23 alpine sites where aversion training took place during the four-month period prior to 1080 baiting. Of the 40 radio-tagged kea present within the treatment area during one or both operations, 11 died from 1080 poisoning (7 of 24, or 29%, at Otira-Taipo and 4 of 18, or 22%, at Arthur's Pass West). Aversion training with anthraquinone was therefore unsuccessful at reducing mortality to below the average. While rates of interaction with repellent baits were high overall, the mean quantity of baits consumed by 33 banded individuals was just 0.09 of a bait, well below the amount eaten by kea in the captive trials, and likely below the quantity required to create a lasting aversion. Very few adverse responses to baits were observed. A more desirable repellent for wild kea would induce an immediate and unequivocal negative effect upon first interaction with baits to create an immediate association. We recommend that no further attempts to aversion train wild kea prior to 1080 operations should be undertaken until such a repellent is developed or methodology is developed to mitigate sub-repellent doses. If wild kea do not consume enough repellent bait to induce an emetic response adequate to ingrain a strong aversion prior to a 1080 operation, it is possible that aversion training could increase the risk during toxic operations, because repeated exposure without ill-effect may unnecessarily cue birds onto baits.

**Keywords:** mortality, *Nestor notabilis*, non-target impacts, secondary repellent

### Introduction

Since the 1960s in New Zealand there has been widespread application of 1080 baits containing sodium fluoroacetate for landscape-scale control of possums (*Trichosurus vulpecula*) and rats (*Rattus rattus*), which pose a significant threat to native biota (Green 2004). The toxin is aerially delivered, generally in the form of a cereal based pellet, and is highly effective in reducing these target pests (Elliott & Kemp 2016)

and other carnivores such as stoats (*Mustela erminea*) through secondary poisoning (Murphy et al. 1999; Brown et al. 2015). Landscape-scale use of 1080 is for the benefit of native biodiversity as well as effectively controlling the spread of bovine tuberculosis (TB) (Parliamentary Commissioner for the Environment 2013). Unfortunately, along with a high level of efficacy against target pests comes a non-target risk to several native bird species that is becoming increasingly unacceptable (Crowell et al. 2015). Kea (*Nestor notabilis*) are a Nationally

Endangered large (ca. 1 kg) mountain parrot, endemic to the South Island of New Zealand and are a taonga species to Ngāi Tahu and Ngā Iwi o Te Taihū (Robertson et al. 2017; Weston et al. 2023). Kea are omnivorous, primarily forage on the ground (O'Donnell & Dilks 1994; Brejaart 1998; Young et al. 2012; Greer et al. 2015), and readily investigate novel objects for edibility (Reid 2008), often retaining neophilia into adulthood (Diamond & Bond 1991). These characteristics mean that many kea encounter and consume 1080 baits directly, leading to death by 1080 poisoning (Orr-Walker & Roberts 2009; Kemp et al. 2019).

Where kea have been killed by 1080 poisoning, the subsequent increase in annual survival and productivity of the local kea population through reduced predation can outweigh these losses (Kemp et al. 2018, 2022). Monitored kea nests within a 1080 treated area in South Westland were almost seven times more likely to have chicks that survived to fledging than those outside the treatment zone (Kemp et al. 2018). Kea of all ages are also susceptible to carnivore predation both in nests and when foraging or roosting (Kemp et al. 2022). During mast-seeding years in beech and podocarp dominated forests (both primary kea habitat), seed becomes abundant by autumn; rodents then respond positively to the increased food resource and are numerous by the following spring. Due to the increase in rodent prey, stoat numbers increase, and by the summer post-seedfall, a stoat irruption occurs which can lead to catastrophic reductions in kea survival and reproduction (Kemp et al. 2019; Kemp et al. 2022). When landscape-scale aerial 1080 operations occur in post mast-seedfall years, high rates of stoat predation that would otherwise occur are prevented (due to the presence of moderate to high rodent numbers which act as effective vectors for stoat secondary poisoning). Less well understood is whether the benefits of 1080 baiting are lower for kea when applied during non-mast years, given that stoat numbers can remain high when there are lower numbers of rodents in the system (Elliot & Kemp 2016).

Kea are considered to be at greater risk of 1080 poisoning at scrounge-affected sites within a 20 km radius of human-occupied areas, where they are likely to encounter novel foods (Kemp et al. 2019; Department of Conservation 2020). Kea mortality varies widely from zero to 50% across 1080 operations (Veltman & Westbrooke 2011; Kemp et al. 2019; Cieraad 2024), but is highest at scrounge-affected sites (mean = 22.5%, 95% CI = 15.2–32.1%) (Kemp et al. 2019; Kemp et al. unpubl. data). Therefore, when 1080 operations are carried out, particularly in higher risk sites, agencies must comply with the compulsory performance standards outlined in the Code of Practice for Aerial 1080 Use in Kea Habitat (COP) (Department of Conservation 2020). Several risk mitigation standards are already in place, including the timing of 1080 operations, the incorporation of primary bird repellents such as green dye (Hartley et al. 1999, 2000; Weser & Ross 2013), and cinnamon lure (Hickling 1997; Cowan & Crowell 2017), a single prefeed, the use of the less-preferred RS5 bait type matrix (c.f. Wanganui #7 bait; Blyth 2011) and a maximum sowing rate of 2 kg ha<sup>-1</sup> in kea habitat (COP, Department of Conservation 2020). However, some operations falling outside of the COP stipulations (e.g. 1080 use outside of mast seeding years or at higher risk sites) require exemptions from the Department of Conservation.

Repellents are used globally, usually to deter a range of bird species from ingesting agriculturally important seeds and/or baits (Avery et al. 1997; Avery 2003; Day et al. 2003; Spurr 2002; Werner et al. 2009). These may act as a primary repellent

due to their unpleasant taste, smell, or irritant properties, or as a secondary repellent by causing a mild but unpleasant physiological response that occurs a short time after ingestion (Spurr 2002). An ideal repellent should be specific to the species (or group) in question, in this case kea. For pest control operations in New Zealand, this is constrained by the need to not repel the target species, primarily rats and possums (Spurr & Porter 1998; Orr-Walker et al. 2012; Crowell et al. 2015; Cowan et al. 2016a). A range of potential repellents have been tested for their deterrent effects on kea, with several showing promise, including anthraquinone, d-pulegone, tannic acid, ortho-aminoacetophenone, and garlic oil (Cowan et al. 2016b; Crowell et al. 2016). Anthraquinone is principally a taste-based (c.f. odour-based) secondary repellent (Poché 1998) commonly used for crop protection (Werner et al. 2011, 2015). A bird has to consume and suffer ill-effects of the repellent, experience gastrointestinal discomfort and/or an emetic (i.e. vomiting) response to learn, or condition, an aversion. Captive kea trials using anthraquinone in cereal baits have shown promising results (Orr-Walker et al. 2012; Reardon 2014; Nichols et al. 2020; McLean et al. 2022). Nichols et al. (2020) undertook trials on captive kea to determine whether consumption of non-toxic bait that mimicked the visual, textural, and olfactory nature of 1080 baits (6 g, green-dyed, cinnamon-laced), hereafter bait mimics, containing 2.7% anthraquinone could lead to an aversion strong enough to avoid a hypothetical lethal dose (LD50: a lethal dose that kills 50% of a sample population) of 1080. They demonstrated that anthraquinone was a potent repellent for captive kea, as all subjects ceased to interact with non-repellent baits following conditioning. McLean et al. (2022) then determined that this aversion persisted in those same captive kea for over ten months after the last exposure to repellent baits. Both studies deemed this a highly promising tool for conservation managers to reduce kea mortality through 1080 operations.

Unfortunately, anthraquinone cannot be applied directly to baits within a 1080 treatment area because it has a repellent effect on target species, i.e. rats and possums (Cowan et al. 2016a; Ogilvie et al. 2000; Clapperton et al. 2015; Nugent et al. 2019). Therefore, the repellent baits must be made available to kea either outside of the treatment area, or within dispensers which prevent rat and possum access. Aversion training with anthraquinone-treated baits should take place in the months preceding the 1080 operation for it to be effective. It is crucial that kea will avoid eating non-repellent bait after eating repellent bait, and that this behaviour continues over repeated interactions and especially through the risk period of the toxin operation (Nichols et al. 2020; McLean et al. 2022). Individual kea must consume enough repellent-laced bait initially to induce a negative response and create a learned association so they can avoid future toxic baits which are otherwise identical.

One approach to reduce kea 1080 by-kill involved laying piles of anthraquinone (1.5%) bait mimics at a number of strategically placed alpine sites (> 1500 m asl) in the vicinity of the 1080 treatment area in the months leading up to South Westland aerial 1080 operations (Nichols & Bell 2019; Nichols et al. 2020). A fresh Himalayan tahr (*Hemitragus jemlahicus*) carcass was placed alongside the bait mimics to 1) initially lure or attract kea to the sites and thus maximise exposure to repellent baits; and 2) test whether carcasses could be used as a distraction tool to divert kea attention from cereal baits. Kea showed a clear preference for carcasses (protein and/or fat) over cereal baits (Nichols & Bell 2019), suggesting

that carcasses could serve as a useful distraction tool for kea during 1080 operations, also potentially satiating them and possibly preventing ingestion of 1080 baits during pest control operations. Kea surveys (<https://survey.keadatabase.nz>) and anecdotal reports indicated healthy kea numbers in the general area post-1080. Whether that was a result of the carcass and/or repellent bait risk mitigation approach, due to the near-elimination of key predators, or a combination of both, is unclear. Similar studies were carried out in the nearby Wanganui-Whataroa catchment (South Westland) prior to aerial 1080 operations and demonstrated that kea visitation to these alpine risk-mitigation sites was high (Weston et al. 2022; Yockney et al. 2022). Unfortunately however, it was not possible to determine whether the method improved outcomes for kea during those operations because radio-monitoring and mark-recapture measures of survival were not carried out (Weston et al. 2022; Yockney et al. 2022). None of these studies (Nichols & Bell 2019; Weston et al. 2022; Yockney et al. 2022) investigated whether anthraquinone baits conditioned an aversion in kea prior to the 1080 operation without the potentially confounding effects of the carcasses as attraction, distraction, and/or satiation tools. Nor did they establish whether there was any measurable benefit to kea survival through the 1080 operations that followed.

Captive trials have indicated that a learned aversion to repellent baits is feasible (Nichols et al. 2020; McLean et al.

2022). Here we attempt to build on these findings by field testing whether wild kea can develop an aversion to cereal bait and whether this can reduce mortality rates during 1080 operations. We aimed to: (1) understand whether exposure to and consumption of anthraquinone-treated 1080 bait mimics prior to 1080 operations can create a learned aversion in kea, (2) understand whether this translates to a reduction in mortality during a subsequent 1080 operation, and (3) assess whether aversion training of wild kea can be carried out on a landscape scale to mitigate risk to kea during 1080 operations.

## Methods

### Site description: 1080 treatment areas

This research took place over an expansive (69 739 ha) area of the central Southern Alps and central Westland of the South Island, New Zealand. The Otira-Taipo aerial 1080 operation was an OSPRI (a non-profit organisation responsible for managing TB and other livestock disease in farmland) possum-focussed operation for TB management with a treatment area of 26 722 ha. Arthur's Pass West (43 017 ha) was a standard Department of Conservation possum and ship rat control operation to protect endangered birds such as great-spotted kiwi (*Apteryx haastii*) (Fig. 1). The central and western parts of the treatment blocks are dominated by podocarp-broadleaf

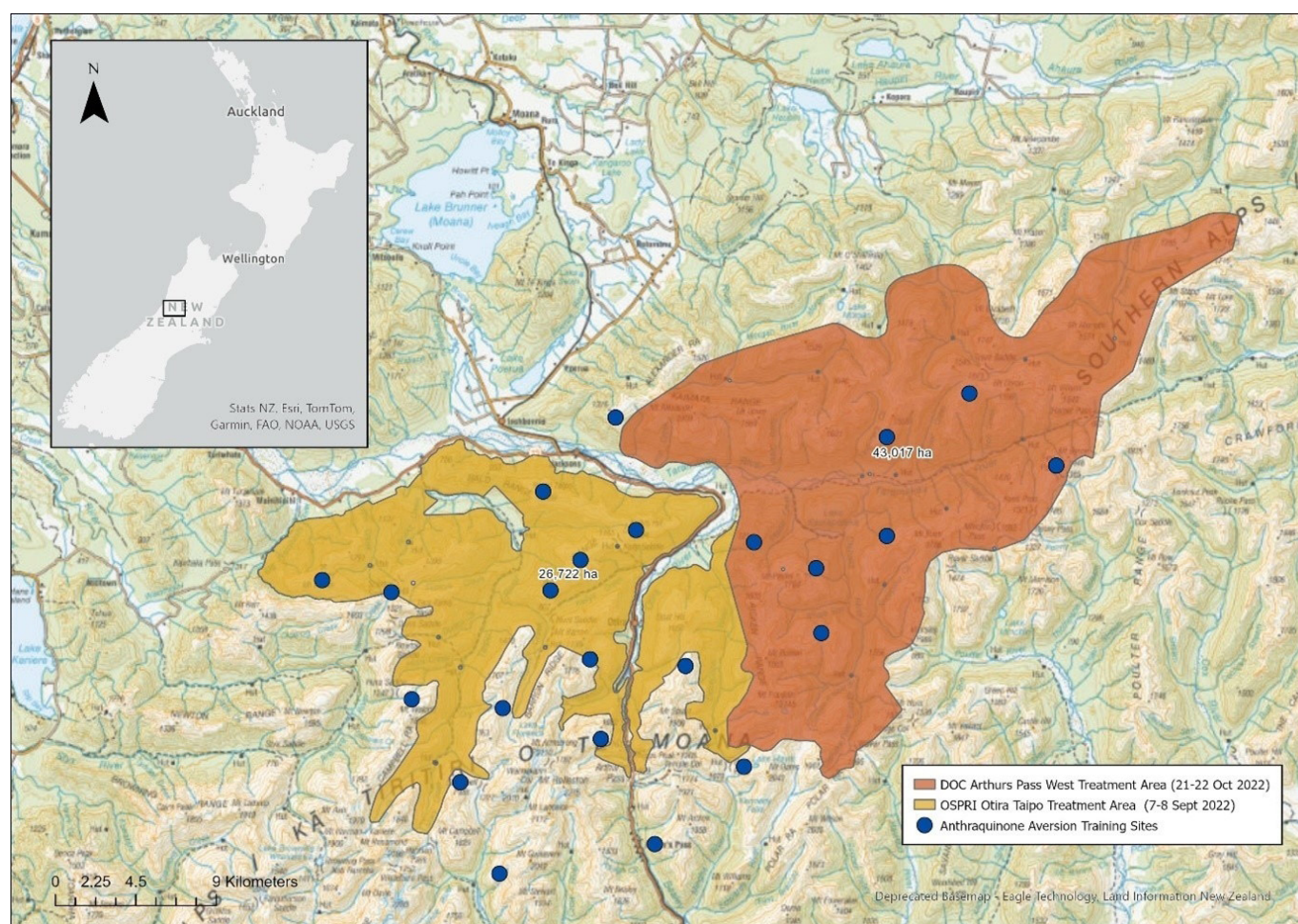


**Fig. 1.** The 23 alpine sites used for anthraquinone repellent aversion trials located at practical and strategic locations > 1500 m a.s.l. within and around the two 1080 treatment areas.

forest, while towards the east, mixed beech-hardwood forest dominates. There is a belt of subalpine shrubland at c. 1100–1400 m, which mainly consists of woody daisies (e.g. *Olearia*, *Brachyglottis* spp.) and *Dracophyllum* spp. The subalpine belt transitions into higher alpine vegetation communities with snow tussocks (*Chionochloa* spp.), alpine herbs, and grasses to ca. 1700 m, and above that is mainly bare rock and scree.

For the Otira-Taipo operation, prefeed (the non-dyed, non-toxic, but otherwise identical version of the 1080 bait that is delivered weeks prior to toxic bait to train target species to eat baits) was sown on August 27<sup>th</sup> 2022 (1 kg ha<sup>-1</sup>, 6 g baits). Toxic 1080 bait (0.15% sodium fluoroacetate) was sown 11 days later on September 7<sup>th</sup> 2022 (2 kg ha<sup>-1</sup>, 12 g baits). For Arthur's Pass West, prefeed was sown on October 14<sup>th</sup> 2022 (1.5 kg ha<sup>-1</sup>, 6 g baits) with toxic bait sown seven days later on October 21<sup>st</sup> 2022 (1.5 kg ha<sup>-1</sup>, 6 g baits). Three fine nights was considered the minimum period necessary to enable pest species to forage and consume a bait, as determined in previous field trials in a similar area (van Klink & Crowell 2015). Bait disintegration and loss of toxicity is expected to occur after 100 ml rainfall accumulation (Poutu et al. 2021), and this occurred after about 20 days for Otira-Taipo and six days for Arthur's Pass West.

### Kea monitoring: tagging and radio tracking

Kea were present across the study area, although numbers varied depending on specific location. Prior to the repellent trial, 90 wild kea were captured in alpine areas above the treeline during mid-January 2022 and fitted with leg bands, very high frequency (VHF) radio transmitters, and radio frequency identification (RFID) tags. The entire study area was well represented by the tagged kea sample, which included a range of male and female kea from all age classes. Kea were caught using hand nooses, noose lines, or mats, and were attracted to catching areas using amplified kea calls played through a FOXPRO (Patriot) speaker (Foxpro Inc. Lewistown PA, USA). All kea were marked with a unique combination of one metal V-band and two coloured plastic alpha-numeric Interrex bands (INTERREX, Poland) to allow individual identification. Radio transmitters ("Long-life Juvenile" model, Kiwitrack Ltd., NZ) were attached to all kea caught using flying-bird harnesses, which have a weak link to ensure the eventual shedding of the transmitter, in case birds could not be recaptured (Karl & Clout 1987). The radio transmitters had an inbuilt mortality "time since death" measurement function, which is triggered after 24 h of inactivity, and were specified to have an average battery life of 3.5 years. RFID tags were inserted into the radio-transmitter units or plastic bands and these enabled kea that visited sites to be detected using the RFID readers.

Aerial radio-tracking flights took place approximately monthly (dictated by weather) from early February 2022 in a fixed wing (Cessna 185) aircraft with directional Telonics RA2A Yagi aerials (Telonics, AZ) mounted on each wing strut coupled to a tracking receiver unit (Sirtrack Ultra) for manual tracking. Tracking radio-tagged kea regularly enabled us to determine accurate kea locations in the months leading up to the aerial operations. The aerial tracking search area spanned > 100 000 ha due to large movements of some birds and the extent of kea ranges around the greater study area. Extra radiotracking flights took place immediately pre- and post-aerial 1080 operations to confirm which kea were in the treatment area and likely to be exposed to toxic bait at the time of sowing. Aerial radio-tracking continued throughout the greater risk period when kea had the opportunity to be exposed

to 1080 baits (i.e. until baits on the ground were deemed to be non-toxic after 100 mm rainfall accumulation). Geographic location for aerial telemetry observations was estimated based on signal strength and direction, with the accuracy of these fixes being enough to allocate the kea's location in or outside the boundaries of the 1080 operations.

For each of the 1080 operations, kea survival was measured and defined as the proportion of radio-tagged birds confirmed to be in the baited area that survived through the entire risk period. The sample considered "at risk" in the Otira-Taipo aerial operation was defined as only those radio-tagged birds present inside the boundary of the treatment area during one or more radiotracking flights, which took place on the 6<sup>th</sup>, 14<sup>th</sup>, and 17<sup>th</sup> of September 2022 (the final post-risk period flight was on 7<sup>th</sup> October 2022). For Arthur's Pass West, the radio-tagged kea designated to be "at risk" were those inside the treatment boundary on the day of toxic bait application (21<sup>st</sup> October 2022) and up until the final tracking flight post-risk period (11<sup>th</sup> November 2022).

Radio-transmitters that had switched to mortality mode after aerial 1080 deployment were followed up at the first available opportunity using a helicopter (MD520N) with an externally mounted 3-element Yagi tracking aerial and/or on foot using experienced personnel to track the signal using a Sirtrack Ultra VHF receiver and a hand-held folding Yagi antenna. If a dead kea was found, it was sent for necropsy by wildlife veterinarians at Massey University, Palmerston North. Samples of breast muscle tissue were sent to Manaaki Whenua Landcare Research (MWLR) toxicology laboratory (Lincoln) to be tested for the presence and concentration of sodium fluoroacetate. Kea found dead during radiotracking flights outside of the 1080 operation risk period were also followed up at the first available opportunity and underwent the aforementioned testing as well as forensic testing for evidence of predator DNA at Ecogene, MWLR (Auckland).

### Alpine anthraquinone aversion training trial sites

All baits used in the repellent trials were manufactured by Orillion Ltd. (Whanganui, New Zealand), a commercial supplier to OSPRI and the Department of Conservation. The baits (i.e. bait mimics) were a non-toxic (not containing 1080) version identical to those deployed in the aerial poison operations; RS5 cereal formula (i.e. Pronature™ Dry Forest), 6 g weight with 0.15% cinnamon lure, green-dyed, cylindrical in shape, with anthraquinone 2.7% nominal concentration by weight (CAS84-65-1). Nichols et al. (2020) found that green dye appears to effectively mask anthraquinone's natural colour, up to a concentration of 2.7%, thus allowing all baits to appear identical to 1080 baits. Because this bait formula and repellent concentration was successful in causing ill-effects in captive kea, we did not alter the bait specifications in these field trials. Additionally, because this study necessitated conforming to the bait specifications and requirements of standard 1080 operational delivery, it was not within the scope of this study to trial different bait colours or types (though this would be a useful topic worthy of further investigation given the research on UV feeding cues as repellents by Werner et al. 2014). All prefeed and toxic RS5 baits used for the Otira-Taipo and Arthur's Pass West operations were also supplied by Orillion.

From May 2022, at least five months prior to the 1080 operations, alpine aversion training trials took place at 23 sites with representative coverage across the treatment area (Fig.1). Where possible, sites were established above 1500 m a.s.l. to minimise visitation by target mammal species. Each

site contained a 500 g pile of bait mimics containing 2.7% anthraquinone (Fig. 2). Audio lures, which attract kea over large distances (Young et al. 2024), were situated at each site to attract as many kea as possible. These were automated to play five minutes of intermittent loud kea contact calls at 6 a.m., midday, and 6 p.m. daily. Audio lures were placed at least 3 m behind the bait pile with the speaker facing away so that any kea present when the calls played would not be intimidated by the sound. At each site, two metal Waratah™ standards were installed: one 1.5–2 m away and one 3–4 m away from bait piles (to capture a range of close and wider field activity). Two motion-triggered trail cameras were attached to each Waratah™ (one on top and one lower down) to record all kea visits and interactions with repellent baits. The cameras were Bushnell Core DS 30MP and Browning Dark Ops BTC-6 Pro XD. Each of the four cameras was programmed with different settings, with two recording video (10 s duration with a 3 s delay) and two capturing still images. One camera taking still images was set at high resolution and one set at low resolution as a trade-off for image quality and battery life. Trial sites were established on either bare rock or short-statured mat vegetation to avoid movement by taller tussocks and vegetation causing false triggering of the cameras (Fig. 2). An RFID reader was placed at the sites, housed within a wooden kea-proof box, and

baits were laid directly in front of and atop the box, in front of the cameras, to concentrate kea activity into one area. If RFID-tagged kea stood on or within ca. 30 cm of the box (i.e. while interacting with baits), the reader would electronically record and store the kea's tag number, time, and date, and these data would be downloaded at each site visit.

Baits were deployed at each site every 2–4 weeks ("rounds", Table 1) prior to the aerial operations. Timing was dictated by the need to operate in fine weather, as well as ensuring at least three fine nights after each fresh baiting to allow adequate time for kea visits to baits before potential repellent and bait degradation. When baits were replenished during each round, old baits were removed, camera batteries and memory cards were replaced, and audio lure and RFID reader batteries were checked and replaced as required. Baits, batteries, and memory cards were also replenished in two more rounds over a two-month period following the toxic operations to record any colour-banded individuals visiting. An additional site was also established on a rocky bluff 200 m above Arthur's Pass township in order to gain extra information on the responses of current scrounge-affected kea to repellent baits, under the assumption that those individuals would be most at risk should they fly into an adjacent 1080-baited area at the time of toxic baiting.



**Fig. 2.** Example of alpine aversion training site. Back left to right shows audio caller and speaker enclosed in plastic casing (with information sign about the non-toxic baits and trial details), non-toxic repellent baits in foreground with RFID reader box, and four trail cameras in the distance mounted on metal waratah standards.

**Table 1.** Anthraquinone-treated bait aversion training rounds and dates for Otira-Taipo (OT) and Arthur's Pass West (APW). Start dates of each round represent fresh bait deployment, replacement of SD cards and camera and RFID reader batteries at each site. Most of round 6 and all of round 7 were post-1080 deployment.

| Round | Operation | Start date | End date   |
|-------|-----------|------------|------------|
| 1     | OT        | 26/05/2022 | 21/06/2022 |
| 2     | OT        | 21/06/2022 | 24/07/2022 |
| 3     | OT        | 24/07/2022 | 10/08/2022 |
| 4     | OT        | 10/08/2022 | 06/09/2022 |
| 5     | OT        | 06/09/2022 | 12/10/2022 |
| 6     | OT        | 12/10/2022 | 08/11/2022 |
| 7     | OT        | 07/11/2022 | 12/02/2023 |
| 1     | APW       | 24/07/2022 | 10/08/2022 |
| 2     | APW       | 10/08/2022 | 29/08/2022 |
| 3     | APW       | 29/08/2022 | 22/09/2022 |
| 4     | APW       | 22/09/2022 | 12/10/2022 |
| 5     | APW       | 12/10/2022 | 07/11/2022 |
| 6     | APW       | 07/11/2022 | 12/02/2023 |

### Bait weathering and degradation trials

To monitor any decline in concentration of anthraquinone in response to weathering, 3 kg of the trial baits were placed under a wire cage (to exclude birds, possums, mice, rats, etc. from interacting with baits), directly on the ground with full exposure to the weather. This was undertaken at Arthur's Pass village (900 m a.s.l.), and baits were placed on three different substrates: gravel, grass, and bare ground. At the end of days 3, 7, 14, 21, and 30, a 100 g sample was harvested from each surface, combined in a bag, and was labelled and stored in a chest freezer. At the end of day 30, samples were sent to MWLR toxicology lab (Lincoln) for anthraquinone concentration and moisture testing. Daily rainfall and temperature data were also recorded from the trial sites, noting when the 100 mm rainfall threshold was reached. These trials were undertaken during winter to capture similar conditions to those experienced at the alpine sites during a comparable time of year.

### Data analysis

Recorded videos were viewed to score kea interactions with the baits while higher-resolution still images and RFID reader data were used to determine the unique identification of banded kea. The date and time stamps across the range of data collection methods were then used to calibrate confirmed individuals with their bait interactions and responses. Bait consumption by each individual in one session (i.e. discrete time period from the start of activity on camera to the end where kea did not return for 30 min or more) was scored on a 1–5 scale: 1 = negligible (i.e. < 2% of a single bait); 2 = 2–25 %; 3 = 26–50%; 4 = 51–75%; 5 = 76–100% of one bait.

Behaviours and bait interactions by banded and unbanded kea were classified as: present in the area and approaching bait, bite, bait in mouth, bait residue on beak or in mouth, consumption, beak rub, head shake, bait toss, fluffing/shaking, gagging, and vomiting. Two composite behavioural response categories were also generated: bait interaction (any observed interaction with bait) and potential consumption (any

observations of bite, bait in mouth, bait residue on beak or in mouth, consumption) for inclusion in subsequent analyses. Five behaviours (bait residue on beak or in mouth, beak rub, fluffing/shaking, gagging, vomiting) were excluded from analyses as they were observed in less than 5% of interactions.

Before baits had been affected by any moisture to make them appear visibly softer and swollen on camera (including drizzle, rainfall, or snow), these were classified as “fresh”, while baits that were visibly moistened were classified as “weathered”. The potential amount of bait consumed by an individual bird was calculated by summing the total amount consumed across all interactions and rounds, assuming that an individual ate the maximum possible bait for a given score: e.g. a score of 1 = 0.02 (maximum consumption of 2% of a bait) compared to a score of 5 = 1 (maximum consumption of 100%, or one whole bait). All birds of unknown identity were pooled together to give an estimate of the total amount of bait consumed collectively across the whole trial. Most analyses presented below are for banded birds with confirmed identification.

We used a binomial generalised linear model (GLM) with a logistic link function to determine whether the behavioural responses of kea within the anthraquinone bait trials changed with exposure to the repellent (measured as round and days since baits deployed), by demographic factors (sex and age class: juveniles = 1–3 years, adults = 4+) or by bait condition (fresh or weathered). The response variable was the proportion of interactions, calculated as the number of times a behaviour was observed by an individual kea divided by the total number of observations of that individual. The total number of observations for each kea was also included as a weight in the model to account for variation in observation effort across individuals.

We used generalised linear mixed effects models (Gamma family with a log link) to assess differences in the time that kea interacted with bait or were observed consuming bait by round, demographics, or bait condition, with individual bird included as a random effect. Differences in bait consumption were assessed using generalised linear models (Gamma family with a log link), where the response was the total amount of bait consumed by an individual banded kea within each group. All data analysis was conducted using R 4.3.0 (R Core Team 2023). For all models, we used the “emmeans” package (Lenth 2023) to calculate the estimated marginal means ( $\pm$  95% confidence intervals) for the factors of interest.

## Results

### Kea bait interactions at alpine aversion training sites

Banded individuals contributed 23.9% of kea visits across both sites, with 68.5% being unbanded kea, and 7.6% having uncertain banding status and/or band identification. A total of 70 banded, identifiable kea were observed on cameras during the study period (Fig. 3). Of these, 52 individuals were present during the trials, while 40 banded individuals were known to be present during the 1080 operations due to their radio transmitters. Only 14 banded individuals were present in both the anthraquinone bait trials and the 1080 operations, with 10 of these individuals radio-tagged, and their survival through 1080 treatment thus able to be monitored (Tables 2 & 3). Within each of the treatment areas, 18–19 known banded kea were recorded. On average, individual kea were observed in  $2.0 \pm 0.89$  (mean  $\pm$  sd; range: 1–4) rounds of the trial.

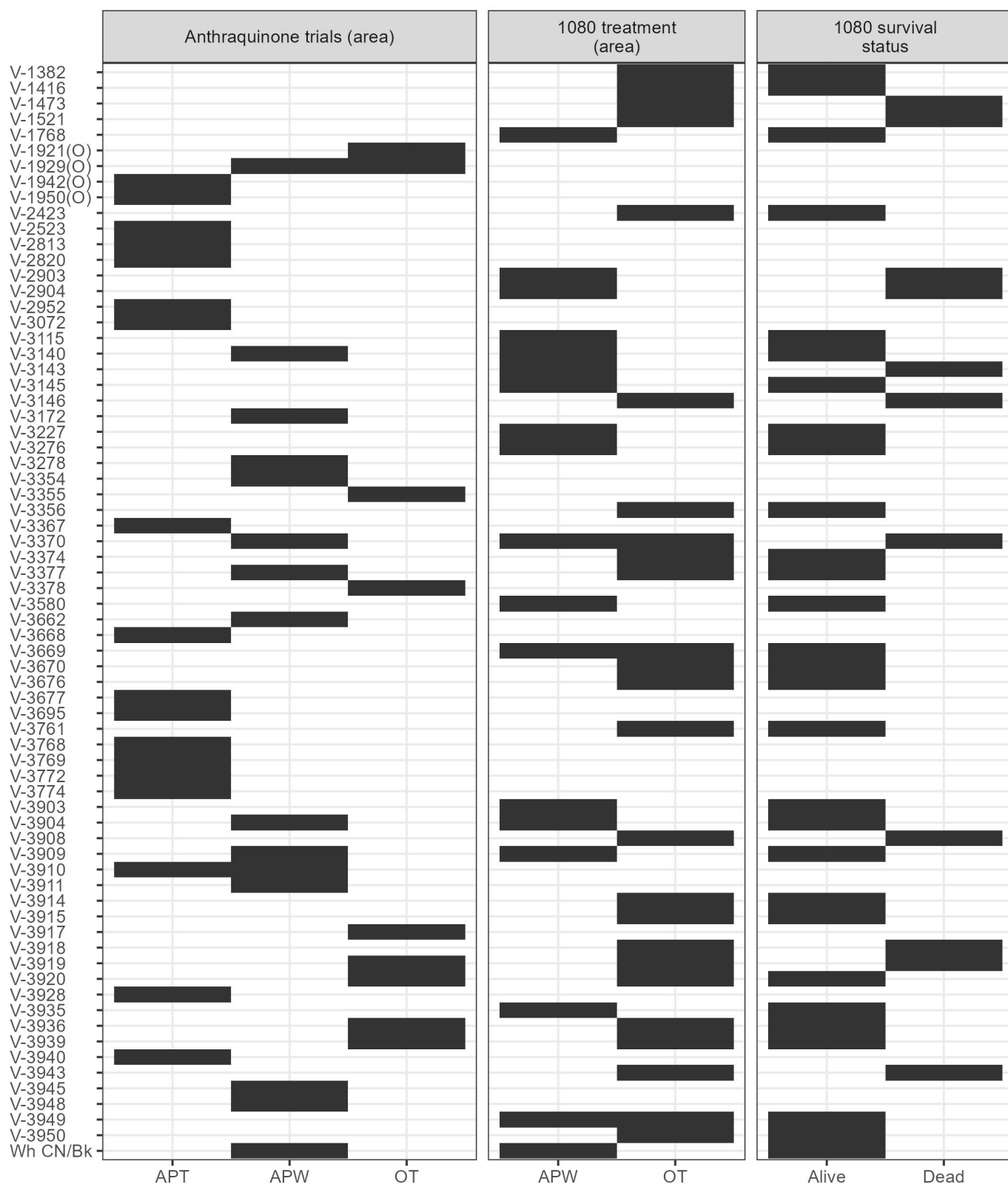


**Fig. 3.** The exposure of 40 individual kea to the anthraquinone trials prior to the 1080 operations (present on camera at repellent sites), their presence in one or both 1080 operations (monitored by radio tracking) and the status of each kea after the 1080 operations. The shaded blocks represent the presence of each identifiable kea (band ID on Y axis) in one or more of these categories. APT = Arthur's Pass Township, APW = Arthur's Pass West, OT = Otira-Taipo.

**Table 2.** Summary of tagged kea who died during the 1080 operations (OT = Otira-Taipo, APW = Arthur's Pass West).

| Kea ID    | Age class | Sex    | Date of mortality signal | Days since 1080 drop | Cause of death (operation) | In trial |
|-----------|-----------|--------|--------------------------|----------------------|----------------------------|----------|
| V-3918    | Adult     | Male   | 07/09/2022               | 0                    | 1080 (OT)                  |          |
| V-3146    | Adult     | Male   | 07/09/2022               | 0                    | 1080 (OT)                  |          |
| V-1473(O) | Adult     | Male   | 07/09/2022               | 0                    | 1080 (OT)                  |          |
| V-1521    | Adult     | Male   | 07/09/2022               | 0                    | 1080 (OT)                  |          |
| V-3919    | Juvenile  | Male   | 07/09/2022               | 0                    | 1080 (OT)                  | Yes      |
| V-3908    | Subadult  | Male   | 11/09/2022               | 4                    | 1080 secondary (OT)        |          |
| V-3943    | Juvenile  | Female | 15/09/2022               | 8                    | 1080 (OT)                  |          |
| V-3143    | Adult     | Male   | 22/10/2022               | 1                    | 1080 (APW)                 |          |
| V-3370    | Subadult  | Male   | 22/10/2022               | 1                    | 1080 (APW)                 | Yes      |
| V-2904    | Fledgling | Male   | 24/10/2022               | 3                    | 1080 (APW)                 |          |
| V-2903    | Adult     | Male   | 24/10/2022               | 3                    | 1080 (APW)                 |          |

**Table 3.** Status of the ten radio-tagged banded kea that were both present in the treatment area during the 1080 risk period and observed in the anthraquinone trials prior to the 1080 operations.

| Kea ID           | Age and sex     | Status after 1080 operation | Cause of death | Operation present in |
|------------------|-----------------|-----------------------------|----------------|----------------------|
| V-3370           | Adult male      | Dead                        | 1080 poisoning | OT, APW              |
| V-3919           | Juvenile male   | Dead                        | 1080 poisoning | OT                   |
| V-3904           | Juvenile male   | Alive                       | -              | APW                  |
| V-3909           | Juvenile male   | Alive                       | -              | APW                  |
| V-3140           | Adult male      | Alive                       | -              | APW                  |
| V-3936           | Juvenile female | Alive                       | -              | OT                   |
| White CN / Black | Juvenile male   | Alive                       | -              | APW                  |
| V-3939           | Juvenile male   | Alive                       | -              | OT                   |
| V-3920           | Juvenile female | Alive                       | -              | OT                   |
| V-3377           | Juvenile female | Alive                       | -              | APW                  |

The explanatory power of all the behavioural interaction models was generally very weak. For banded kea, no significant differences were observed for most behaviours between rounds (Fig. 4, Appendix S1 in Supplementary Material). Overall, the proportion of times individuals approached bait was high across the first six rounds, with significantly lower interaction rates in round seven, while bait consumption was significantly lower in round one than in rounds four and six (Fig. 4, Appendix S1). There was an apparent decrease in visitation (present in area, approaching bait) from day 1 to day 30 across all rounds, but there was no consistent pattern for the other behaviours (Fig. 5, Appendix S2). Adult females were significantly less likely to approach bait than other individuals and spent less time consuming bait (Fig. 6, Appendix S3). In contrast, adult males spent significantly more time consuming bait than juvenile males, although the actual difference in mean time was 1.1 seconds. Adult males were also significantly more likely to be observed with bait in their mouths than juvenile females. No significant differences were observed for the remainder of the behaviours with respect to sex or age class (Fig. 6, Appendix S3). Responses classified as “adverse reactions” to bait (beak rub, fluffing/shaking, gagging, vomiting) were excluded from final analyses because they were observed so few times. Only on one occasion did a single kea appear to gag after bait interaction, and no vomiting was witnessed across all observations, regardless of banding status.

The interactions of kea varied significantly by bait condition for all behaviours assessed, with individuals significantly more likely to interact with fresh bait (Fig. 7a, Appendix S4). Female kea were significantly more likely to spend more time consuming fresh bait than weathered bait, while the opposite pattern was observed for male kea (Fig. 7b, Appendix S4). However, the mean duration of consumption was only several seconds long overall. There was no evidence that male and female kea interacted differently with fresh bait, although female kea were significantly less likely to approach weathered bait than male kea and spent significantly less time consuming weathered bait (Fig. 7a, Appendix S4).

#### Kea survival outcomes during the aerial 1080 operations

Forty radio-tagged kea were observed during the risk period of the two 1080 operations, with eleven deaths recorded (Fig. 3, Table 2). All but two of these individuals were present during the risk period of just one of the operations, with the remaining two present in both. Of these, one kea survived both operations and the other died during its second exposure. The deaths of ten individuals were attributed to primary 1080 poisoning. The remaining individual likely died from secondary 1080 poisoning via consumption of a possum killed by 1080 (Table 2, Appendix S5). The majority of poisoned individuals (55%) were adult males, while 36% and 9% were male and female juveniles, respectively (Table 2). Sixty-four percent of

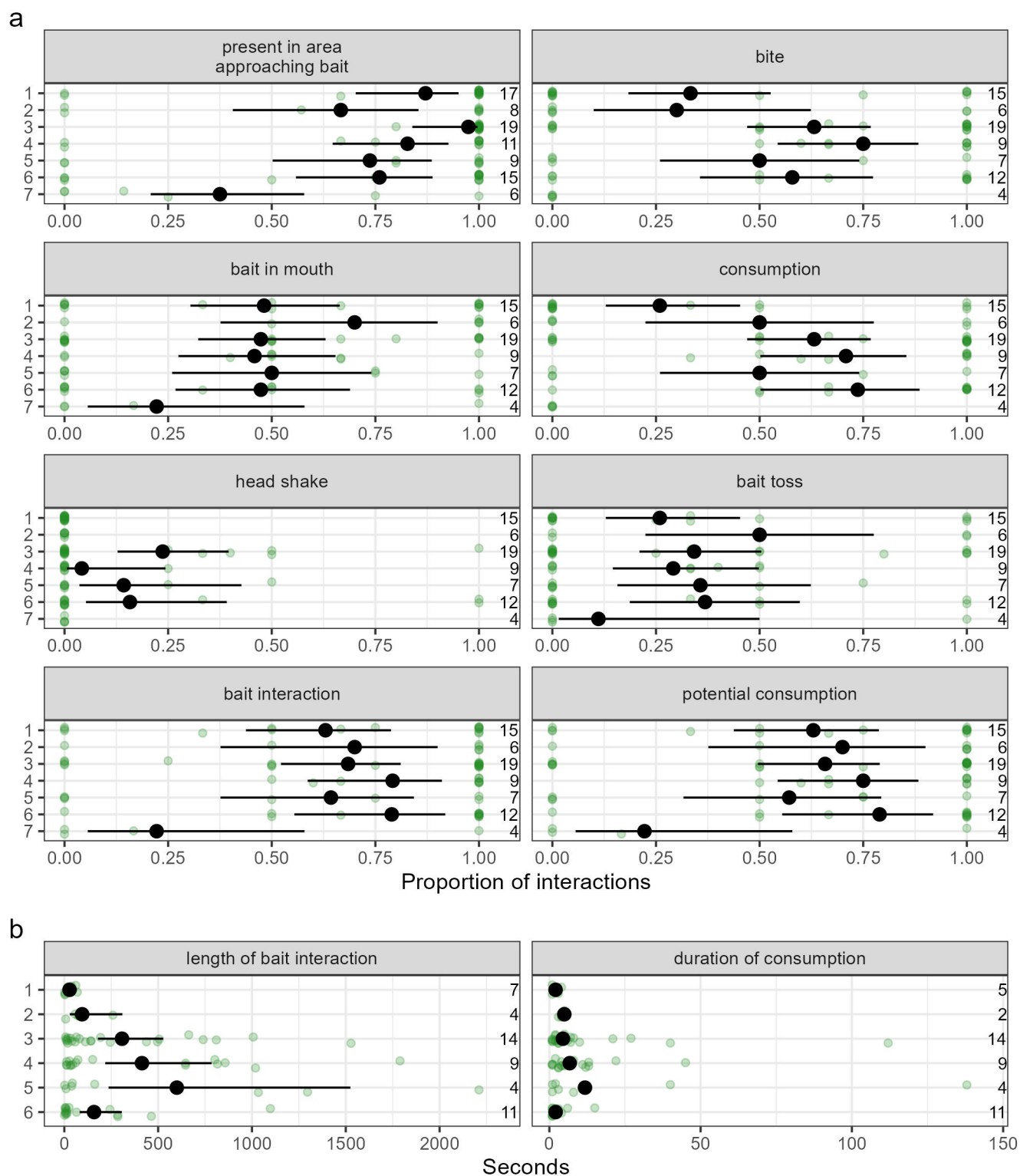


**Figure 4.** Interactions of banded kea with anthraquinone-treated bait by round (with round 1 starting in May/June and round 6 and 7 post-1080), with: a) the proportion of interactions observed for individual kea for each behaviour and b) the length of time interactions were observed. Black points and error bars represent the estimated marginal mean ( $\pm$  95% confidence intervals) for each factor, with the raw data shown as green points. Numbers to the right of each panel indicate the number of banded kea in each round (across all sites). Pairwise comparisons are shown in Appendix S1.

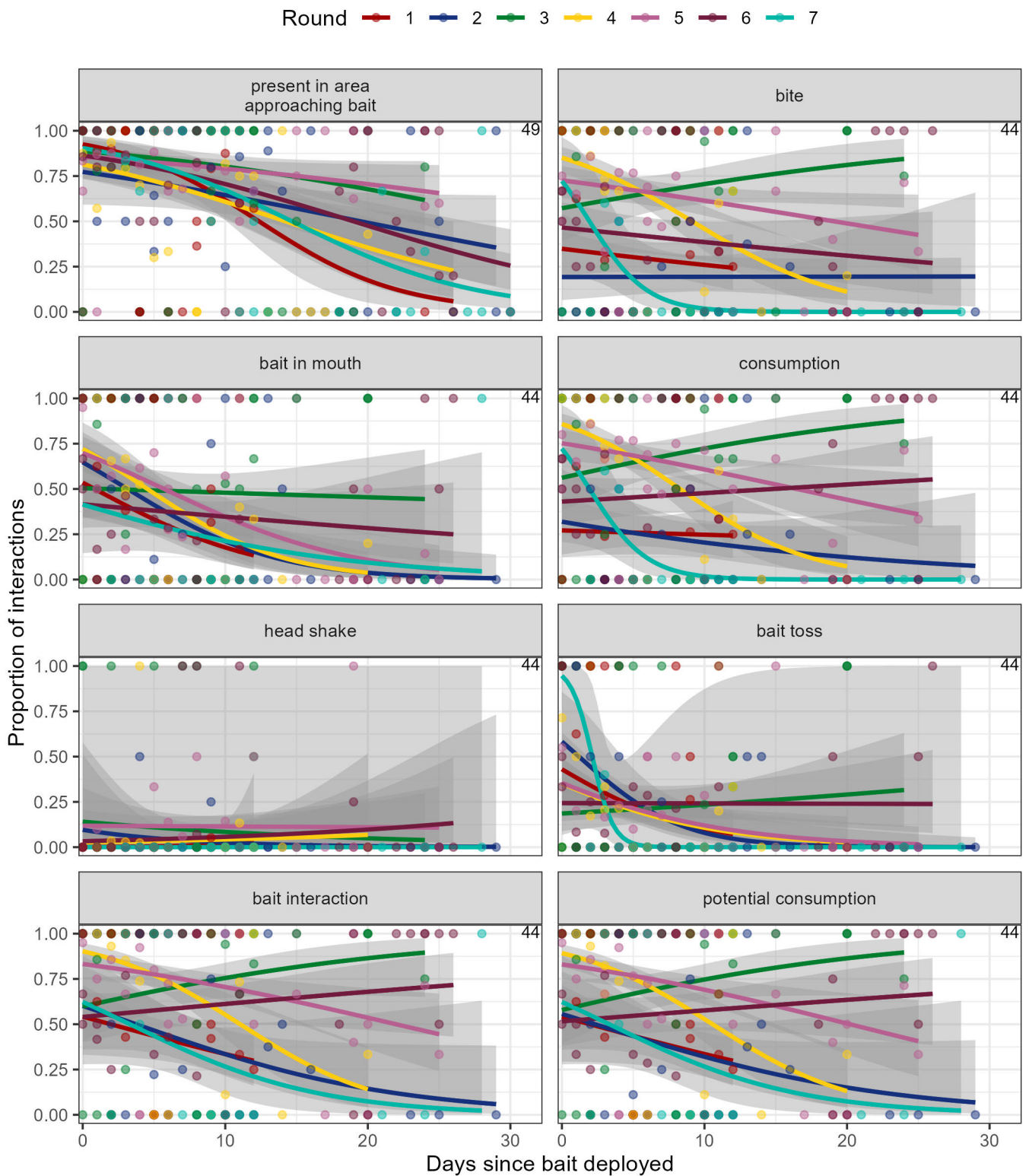
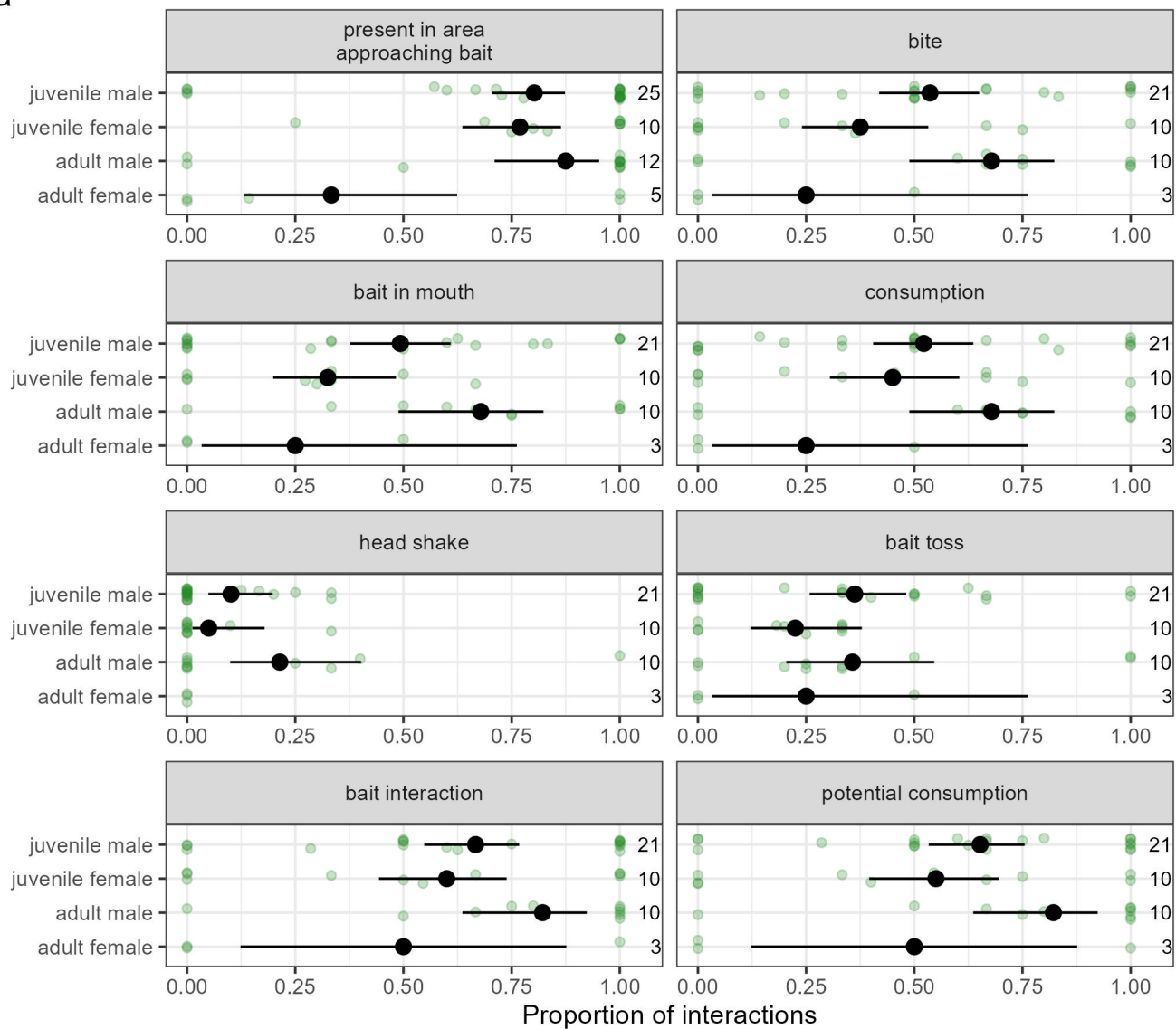


**Figure 5.** Interactions of banded kea with anthraquinone-treated bait by days since bait deployment for each behaviour in each round of the trial. Numbers in the top right corner of each panel represent the minimum number of individual kea (across all rounds), where unidentified individuals were pooled together. Coloured lines represent the model predictions ( $\pm$  standard error) from a binomial GLM. For a more detailed breakdown, see Appendix S2 in Supplementary Material.

a



b

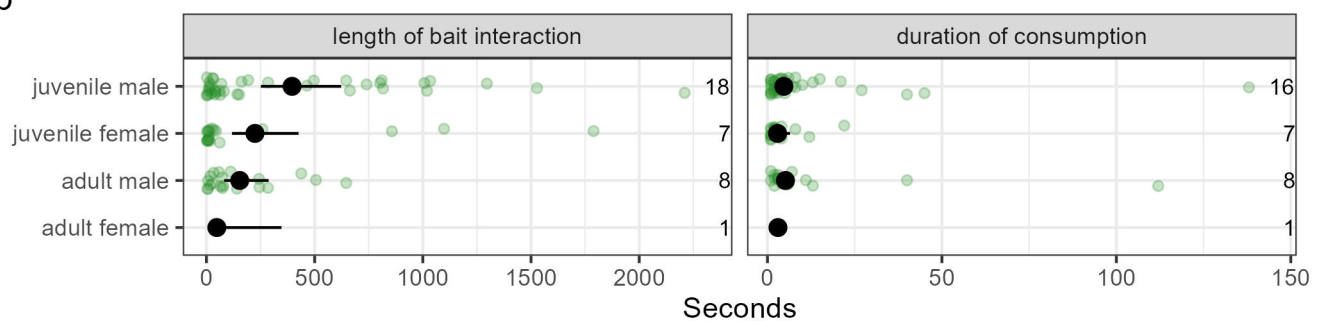
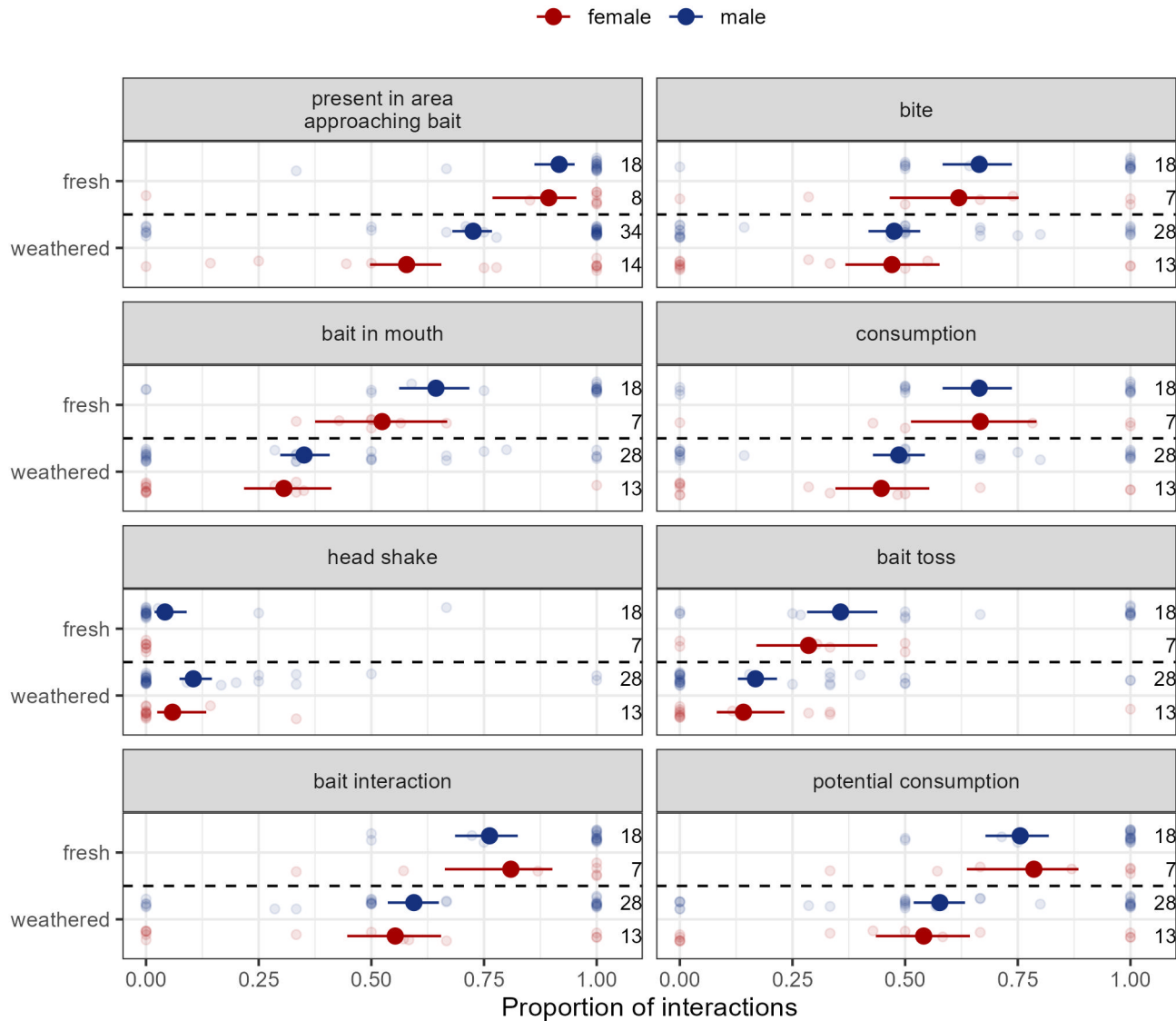


**Figure 6.** Interactions of banded kea with anthraquinone-treated bait by sex and age class, with a) the proportion of interactions observed for individual kea for each behaviour and b) the length of time interactions were observed. Black points and error bars represent the estimated marginal mean ( $\pm$  95% confidence intervals) with the raw data shown as green points. Numbers to the right of each panel indicate the number of banded kea in each group (across all rounds and sites). *Pairwise comparisons are provided in Appendix S3.*

a



b

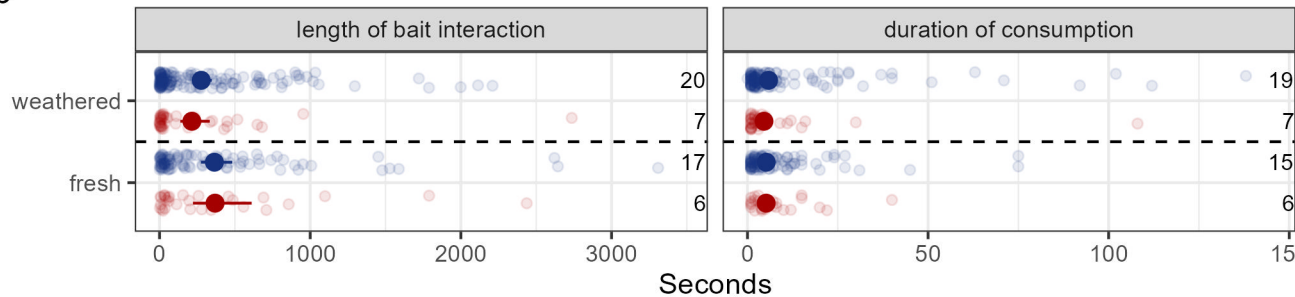


**Figure 7.** Interactions of kea with fresh and weathered anthraquinone-treated bait grouped by sex. Coloured points and error bars represent the estimated marginal mean ( $\pm$  95% confidence intervals) with the raw data shown as points. Numbers to the right of each panel indicate the number of banded kea in each group (across all rounds and sites). *Pairwise comparisons are provided in Appendix S4.*

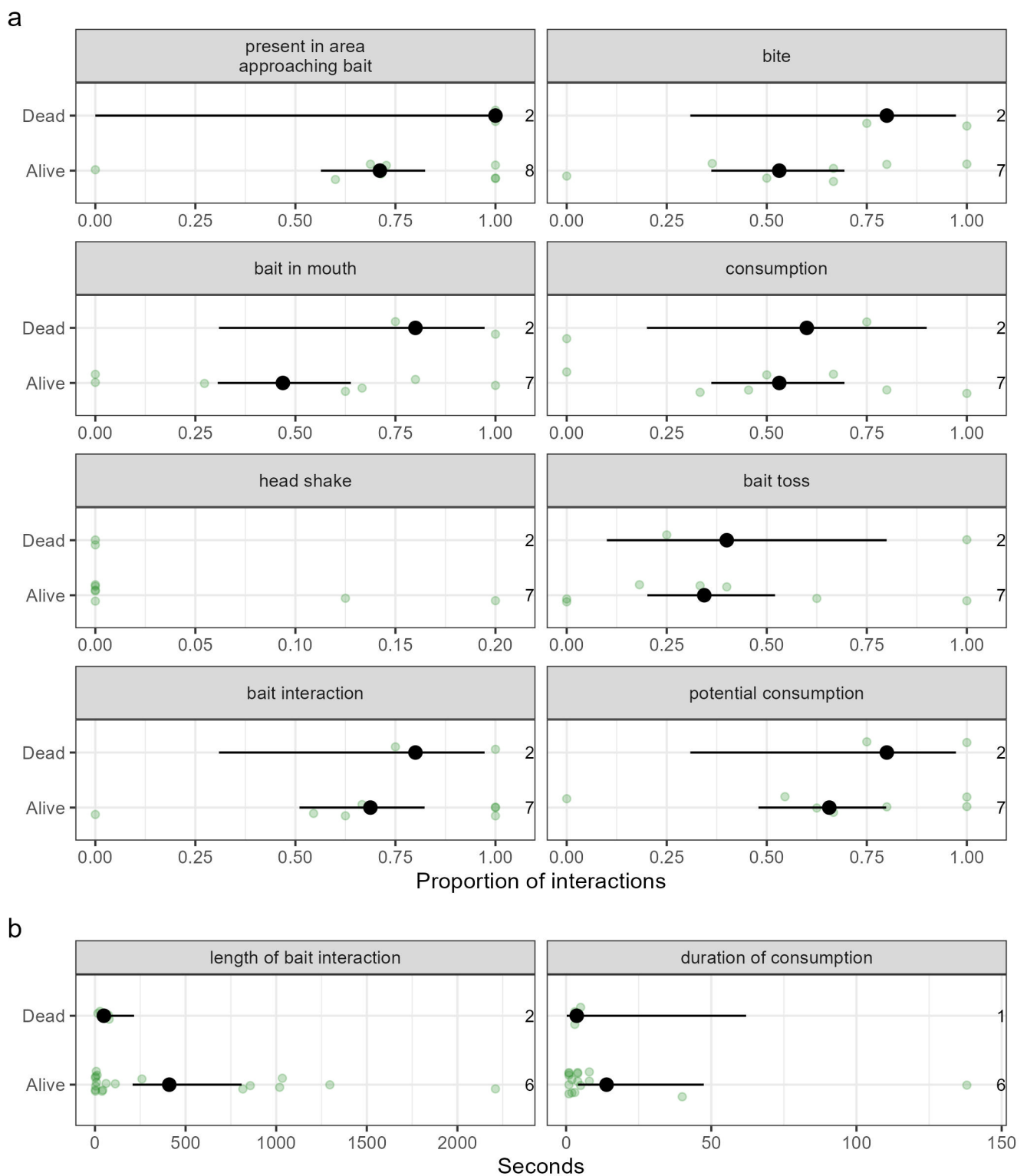


**Figure 8.** Interactions with anthraquinone-treated bait by individual kea that were subsequently exposed to the 1080 operations. Black points and error bars represent the estimated marginal mean ( $\pm$  95% confidence intervals) with the raw data shown as points. Numbers to the right of each panel indicate the number of banded kea in each group (across all rounds and sites). *Pairwise comparisons are provided in Appendix S6.*

individuals died within one day of 1080 deployment, while the only female death that occurred was eight days after baiting via primary poisoning (Table 2). Fourteen banded kea were observed during both the anthraquinone trials and the 1080 operations (Fig. 3), although only ten of those individuals were exposed to the anthraquinone-treated baits prior to the 1080 operations (Table 3). Of these ten individuals, two died due to 1080 poisoning but only one (V-3370) was observed consuming anthraquinone-treated baits during the trial (Appendix S6), while the other only interacted with it. We detected no statistically significant differences in the interaction responses associated with anthraquinone-treated baits between birds with different survival outcomes for the 1080 operations (Fig. 8a, Appendix S7). However, individual kea that survived 1080 operations spent significantly longer interacting with baits, although there was no significant difference in amount or duration of their consumption (Fig. 8b, Appendix S7).

Anthraquinone concentration and weathering trials

Laboratory testing showed that, in bait weathering trials, anthraquinone concentration on day one averaged 3.03% by weight, but from day three the concentration had dropped to around half the nominal concentration, averaging just 1.65% at day 30 (min 1.56%, max 1.70%; Appendix S8). This concentration did not further decrease between days 3 and 30.

Weather information collected specifically over the duration of this trial showed that rainfall exceeded 100 mm on day 3.

Consumption of anthraquinone-treated bait

The estimated total amount of anthraquinone-treated bait consumed across the whole trial was 21.59 baits, with a mean individual bait consumption of 0.09 ( $\pm$  0.23 sd) baits eaten per bird. The maximum number of baits eaten by an identified individual bird across the whole trial was 1.29 baits, while 20 individuals never consumed any bait (Appendix S6). Although male kea were more likely to bite or be observed with bait in their mouths, there was no significant difference in the estimated number of baits consumed by individuals of different sex or age class, nor did this vary significantly by round or bait condition (Fig. 9, Appendix S9).

Scrounge kea bait interactions

Kea with known histories of scrounging food from Arthur’s Pass township were significantly more likely to approach baits than other kea ( $p < 0.001$ ); however, the two groups of birds did not differ in their other behavioural responses to baits, especially in their rates of bait biting and potential consumption behaviours (Fig. 10, Appendix S10). Average time spent on baits (length of interaction and duration of consumption) was

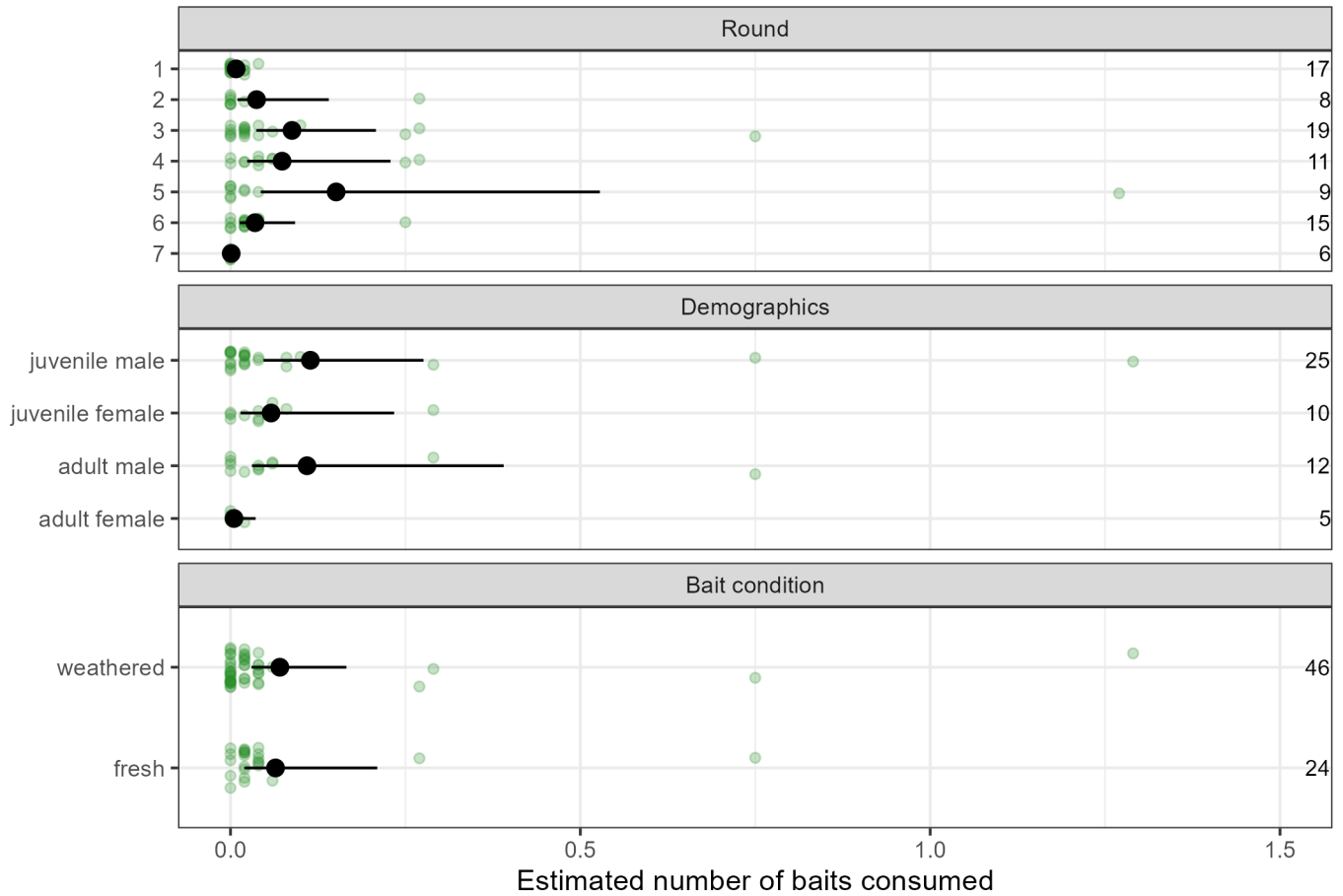
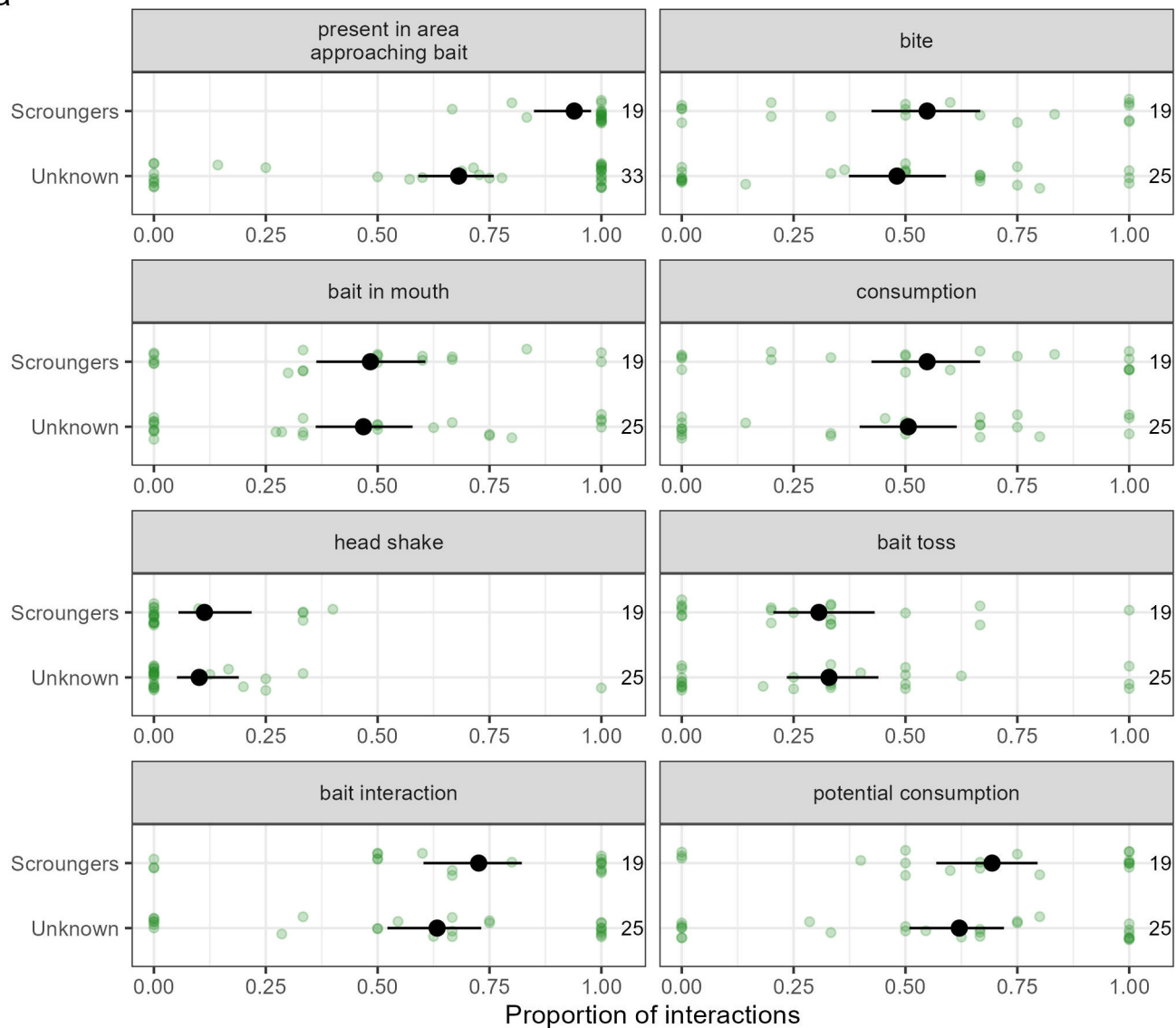


**Figure 9.** The estimated number of baits consumed by individually identified kea grouped by a) round, b) demographics and c) bait condition. Black points and error bars represent the estimated marginal mean ( $\pm$  95% confidence intervals) with the raw data shown as green points. Numbers to the right of each panel indicate the number of banded kea in each group. *Pairwise comparisons are provided in Appendix S9.*

a



b

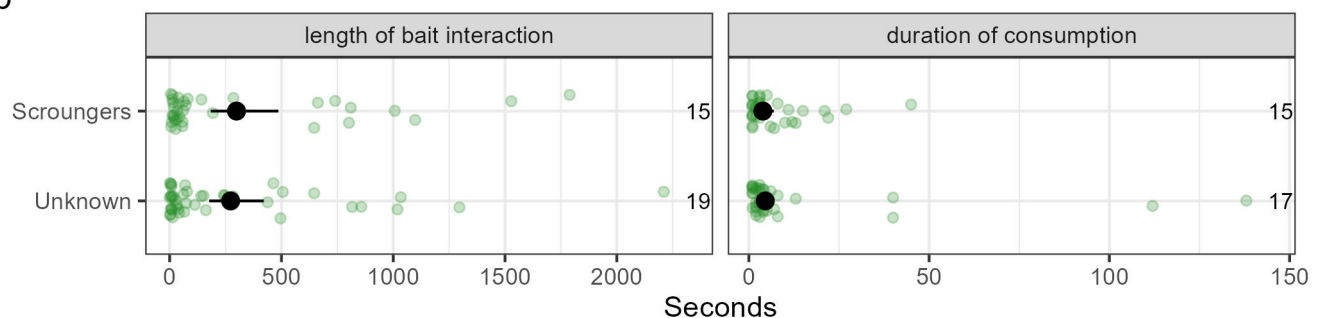


**Figure 10.** Interactions of kea with anthraquinone-treated bait grouped by scrounge status, with a) the proportion of interactions observed for individual kea for each behaviour and b) the length of time interactions were observed. Scroungers = individuals with a known history of feeding on human foods in Arthur's Pass township; Unknown = individuals with unknown scrounge histories. Black points and error bars represent the estimated marginal mean ( $\pm$  95% confidence intervals) with the raw data shown as green points. Numbers to the right of each panel indicate the number of banded kea in each group (across all rounds and sites). Pairwise comparisons are provided in Appendix S10.

also not significantly different between scroungers and kea of unknown scrounge histories.

Two individuals who in recent years were regularly seen consuming human foods in Arthur's Pass township (V-3172 and V-3910; <https://keadatabase.nz>) were captured on camera at O-T or APW aversion sites, and thus were grouped with the known scroungers. The only two kea in the entire study which exhibited adverse responses to repellent baits were known scroungers V-3772 and V-3769 (both young adult males) at the township site. These were obvious negative responses showing rapid head shaking combined with fluffing up, gaping, turning head on the side, and frantically tossing baits aside. Only one of these was actually gagging, though this behaviour was short-lived (1–2 s) and there was no vomiting observed in either, despite both remaining in front of the camera and returning to baits.

## Discussion

In this study we attempted to test whether aversion training wild kea with anthraquinone-treated non-toxic bait mimics could successfully be implemented at alpine sites across a mountainous landscape and whether this would translate to reduced mortality during two subsequent aerial 1080 operations. Banded kea visits comprised 23% of total kea visits. Interaction with baits was high, as were potential bait consumption rates (biting bait, bait in mouth, bait residue on beak or in mouth, or consumption). However, a critical finding was that actual bait consumption was very low, with scant evidence of clear, obvious negative reactions to baits observed across hundreds of kea bait interactions. The very small amount of bait consumed per individual overall suggests that insufficient anthraquinone bait was being eaten by wild kea to induce ill effects. As a consequence, wild kea are unlikely to develop a learned aversion to 1080 cereal baits. Even though there were potentially hundreds of different kea interacting with anthraquinone baits, the relatively high mortality rate observed within both 1080 operations suggests that, at a population level, aversion training with this repellent is unlikely to be an effective tool for mitigating risk to kea.

At the individual level, although low numbers of banded kea which had previously interacted with anthraquinone baits were present in one or both 1080 operations, there were no significant differences associated with any of the types of bait interactions between the birds that survived and those that died. However, the fact that the two radio-tagged kea that did interact with anthraquinone baits died is of concern. Notably, one of these birds had previously eaten a third of an anthraquinone-treated bait. It is possible that these two individuals are representative of kea with bolder or more neophilic personality traits who may be predisposed to consuming more cereal bait, either non-toxic or toxic. However, it may also indicate that feeding with anthraquinone-treated baits prior to 1080 deployment could unnecessarily cue birds onto toxic baits, thereby increasing risk during 1080 operations. If bait was increasingly repellent to the general population of kea over time, we should expect to see a decline in the overall rate of bait interactions and/or potential consumption over time across each successive bait replenishment round, and/or over the ca. 30-day period within rounds. However, no decrease was evident in the different behavioural interactions or potential consumption rates over time, within or across rounds. There was an apparent decrease in visitation from day 1 to 30 within rounds, though this is

likely a reflection of the fact that audio lure batteries would lose power during this time, and baits would weather and/or disintegrate or disappear over the 30-day duration, leading to lower kea visitation during the latter days of each trial round. Repeat visits were observed for known banded kea over time, so it can be assumed for unbanded kea there also must have been repeat visits by some of the same individuals over time. This suggests that even for repeat visitors to repellent bait sites, anthraquinone was ineffective in creating an aversion to the baits in most individuals.

It is possible that, like humans and other species, there is large variation in personalities and boldness in kea, which are likely to contribute to bait investigation decision making (see McLean et al. 2023a and references therein). If there was a widespread aversion effect of anthraquinone repellent baits, we would expect to have observed more adverse reactions by more kea. It is possible that some kea may have experienced adverse responses to baits, but that these were not exhibited in front of camera, and/or incorrectly interpreted or not recognised. The latter seems implausible given this behaviour was reported in other related studies, even from still images (Nichols and Bell 2019; Nichols et al. 2020). Information on timing, duration, and types of adverse responses to the repellent bait by kea specifically are not documented in the captive trials (Nichols et al. 2020; McLean et al. 2022) so it is unknown whether kea adverse reactions are immediate or can occur over a longer timeframe. This is a major limitation in any study of this nature; both captive and wild birds should be observed closely following exposure to anthraquinone-treated baits with a control comparison in order to address these knowledge gaps. The potential bias caused by human interpretation of animal behavioural responses to the repellent must also be carefully considered.

Females were significantly less likely to bite and have baits in their beaks than males, and adult females also generally approached the baits less than males. Interestingly, out of the ten primary poisoning (direct bait consumption) fatalities in this study, there was only one female (juvenile) kea death. Peculiarly, this death occurred eight days post-1080 deployment, whereas all other primary poisoning events occurred within the first few days. Our bait weathering trials showed that bait became softer, with moisture content increasing over time once on the ground, particularly in wet conditions such as on snow and damp ground or vegetation. It is possible that bill size and strength affects whether kea can eat 1080 baits, which may account for differences in consumption by sex and age. Kea exhibit pronounced sexual dimorphism in bill size, with females having significantly shorter and more slender bills than males. Based on these differences, we expected softened (weathered) cereal bait to be more palatable and accessible to female kea than the substantially harder fresh bait. However, there was no difference between male and female kea in their interactions with fresh or weathered baits during the anthraquinone aversion trials, so perhaps softer bait condition does not explain the delayed bait consumption preferences of the only female kea that died. McLean et al. (2023b) explored correlations between diet and bill size to determine whether diet is partitioned throughout age classes and sex. Their modelling showed that throughout their lifetime, female kea foraged at a consistent, relatively low, trophic level (i.e. plants) compared with male kea, where trophic level increased with age to become more protein-based. Adult males foraged at a high trophic level relative to females and younger kea of both sexes. Bill size is likely to make a

difference to which items can be eaten, with older males able to dig and extract discernibly tougher food items than females in their normal diet (Greer et al. 2015; McLean et al. 2023b).

During this study, we documented the first published case of secondary poisoning to kea; this subadult male ate a poisoned possum and died four days after 1080 deployment (Wildbase Pathology Report 61231; Ecogene Report S1337; see also Appendix S5). All other kea died as a result of primary poisoning, with 1080 bait present in the stomachs and/or crops of those individuals.

The risk to kea from poisoning during aerial 1080 operations is unevenly distributed; with one major risk factor being proximity of kea to locations where they have the opportunity to scrounge artificial food sources (Kemp et al. 2019; Department of Conservation 2020). The Otira-Taipo and Arthur's Pass West 1080 operations both fall within areas classified as "scrounge-adjacent" (within 20 km of a scrounge location; Department of Conservation 2020) so expected mortality rates during these 1080 operations were higher than the average. The hypothesised mechanism is that at scrounge sites where young kea are constantly exposed to calorically rewarding novel foods, bolder behaviours are rewarded and/or cautious behaviours are suppressed (Kemp et al. 2019). This results in an increased likelihood that a bird will sample new food types including bait. It is hypothesised that this scrounge effect is maintained throughout the birds' lives, meaning that the influence of any given scrounge site can remain in the population for some time after the source has been removed. Despite the deaths of some individuals during 1080 operations at higher-risk scrounge sites, when these operations successfully prevent stoat irruptions, the population level benefits are still likely to outweigh 1080-induced mortalities (Kemp et al. 2019; Department of Conservation 2020).

No prior studies have quantified approach to, interaction with, and consumption of baits, or bait mimics, in wild kea using video data. Following individuals within a high-risk, scrounge-adjacent aerial 1080 operation has enabled us to better understand the variation and risk profile of a range of known scrounge (or ex-scrounge) affected kea to test whether they are indeed more neophilic towards baits (and/or suppress innate neophobic behaviours). At scrounge-adjacent vs. remote sites, McLean et al. (2023a) documented time taken by kea to approach and contact a novel object (a blue plastic block) and found that adjacent kea contacted the object faster than remote kea, concluding that this enhanced neophilia exhibited by adjacent individuals may translate to a reduced life expectancy. While not possible in this study, clearly a similar study comparing scrounge-adjacent kea responses to baits with those of remote kea is needed. Here however, we could only explore a kea-bait response relationship with relative remoteness from a current scrounge site (Arthur's Pass township) by grouping kea into two categories: kea with known scrounge histories (all kea seen at Arthur's Pass township), and kea with unknown scrounge histories. Given that bait visitation, interaction, and potential consumption was uniformly high across all sites and all kea, including by some likely non-scroungers at relatively more remote locations, our study provides compelling evidence of a more uniform level of interest in, and interaction with, green cereal baits across all kea in the 1080 treatment area, regardless of distance to the scrounge centre. While highly unlikely, it may also be possible that all kea in the study area have previously had a scrounge history, and hence no difference in behaviours was observed. This information will contribute towards a useful

baseline for understanding, at the least, patterns or variation in how known scrounge and ex-scrounge-influenced kea respond to and interact with baits. While these outcomes may be a more conservative indication considering there is a repellent additive in the baits, furthering our knowledge of individuals' responses to baits contributes to improved management of risk.

We attempted to examine fine-scale movements of kea in the treatment area by tagging six kea with Lotek global positioning system (GPS)/VHF transmitters which record four-hourly location fixes. Unfortunately, due to technical failure of most of these units, movement data were not able to be obtained through this method. Fine-scale movement data of 15 scrounge kea GPS-tagged in Arthur's Pass township with Druid nano transmitters over this time period did, however, provide some enlightening and useful data on the movements of kea in and out of Arthur's Pass township. Some individuals moved in and out of the township frequently and made large forays across the treatment areas over a matter of days and weeks, while others remained in the Arthur's Pass township area for months at a time, not venturing further afield. We are trialing a variety of more modern GPS technology at the time of writing and anticipate having GPS unit options for kea in the near future that are fit for purpose that will help address questions of kea movement ecology in relation to management.

Contrary to our findings, generally where kea survival has been monitored through aerial 1080 operations using radio-transmitters, there is no significant difference in mortality rates between sexes (or with age class) despite equal representation in sample sizes of both sexes (Kemp et al. 2019, 2022b). It is uncertain whether there was any difference in our study in the likelihood of actual exposure to toxic baits between adult females and males. Seventeen of nineteen previously monitored aerial operations have occurred during kea breeding season (ca. July to December) (Kemp et al. 2019), as did both the 2022 Otira-Taipo and Arthur's Pass West operations. During this period, breeding females will be stationary on the nest while adult males forage away, returning to provision females and chicks in the nest cavity. This aspect of kea breeding ecology suggests a higher likelihood of adult males encountering toxic baits during 1080 operations carried out during kea nesting season. This may in turn negatively affect kea productivity if adult males obtain a lethal 1080 dose while provisioning nests, leading to nest abandonment and failure due to starvation of chicks. Recruitment failure would be witnessed in the general population as a lack of new fledglings seen during early the summer months following nesting. In our sample, the majority of the eleven deaths were adult ( $n = 6$ ) and subadult ( $n = 2$ ) males, all of which could potentially have been provisioning nests. A possible further risk is that if any breeding adult males consumed a sublethal 1080 dose, some could be transferred to females and/or chicks on the nest. Careful consideration should be given when planning the timing of aerial 1080 operations, and attention paid to population level recruitment in the years following these operations to assess whether increased mortality risk may be offset by the increased productivity through reduced predation (Veltman & Westbrooke 2011). A full cost-benefit analysis of outcomes at the level of kea population needs to be undertaken (Cieraad 2024). We predict that due to a reduction in predator numbers, successful recruitment of fledglings into the population should increase over time.

Several key strengths and limitations should be acknowledged to allow for improvement in any related future studies. First, automated audio calls worked extremely

well as attractant tools to lure kea to the bait piles. Their use is recommended in similar future studies because they are relatively cheap, transportable by helicopter, have a reasonable battery life, and are not subject to damage by kea. Most importantly, unlike carcasses, they do not introduce a confounding variable which involves a physical interaction to attract kea, distracting them from bait interaction once they are at site (see Nichols & Bell 2019; Weston et al. 2022; Yockney et al. 2022). A small portion (7.6%) of banded kea were not able to be identified via camera images or RFID readers for a range of reasons (including nighttime visitation, blurred images from moisture or snow, or flat RFID reader batteries). It is possible that some of these individuals may have also been present at anthraquinone bait sites, but it could not be confirmed. Likewise, it is possible that the radio-tagged kea designated as being inside the boundary during the 1080 risk period actually spent little time there, never encountered 1080 baits, chose not to interact with a toxic bait, or if they did, consumed a sub-lethal dose. There are many factors that cannot be accounted for when undertaking research on wild animals that could influence these outcomes and these are just a few examples. We also acknowledge the inability to undertake statistical analysis on individual survival due to the insufficient sample size of kea that both participated in anthraquinone aversion training and were exposed to aerial 1080 treatment. The ability to relate numerous individuals' experiences with anthraquinone baits directly with survival would have added significant value to this study. Nevertheless, our outcomes do indicate that population-level aversion training is unlikely to have had any population level benefits for kea. It is important to acknowledge these limitations and learn from them when planning future research. Any further studies of this nature should allow at least one year of lead in time, a large sample size, and cover a very large geographical area to ensure an adequate sample is obtained (and maintained) during the critical study period due to the highly mobile nature of kea.

Captive studies may be a good initial screening process to understand potential candidate repellents; however, we caution that results observed in captivity do not necessarily reflect responses observed in wild kea. Wild kea bait interactions were numerous, with high visitation to aversion training sites across the operational study area, suggesting this approach is logistically achievable at an operational scale. However, high implementation costs combined with little evidence of efficacy (an above-average mortality rate compared with similarly high-risk operations) suggests this method is of little added value for kea conservation in its current form. Video analysis revealed very low bait consumption by individuals, and < 1% of kea interactions showed obvious adverse responses to repellent baits. Anthraquinone-treated cereal bait appears to have not sufficiently repelled kea to create an aversion in the majority of individuals, likely due to insufficient bait consumption rather than bait exposure. This suggests that at a population-level, this was an ineffective risk mitigation tool. There is also a real risk of cueing kea on to baits if a repellent is not immediately effective, putting them at increased risk of 1080 poisoning. Based on this risk, we recommend that feeding wild kea with anthraquinone cereal baits prior to aerial 1080 operations is not undertaken. Monthly radio-monitoring to determine the fate of the remaining radio-tagged kea (including any ongoing losses to predation), should be continued to assess the net long-term benefits of predator control for kea in this area.

## Acknowledgements

We received input from Te Rūnanga o Ngāi Tahu and Zero Invasive Predators during the planning phases of this work. We thank all the hardy, passionate souls who helped with key field work and logistics including Jodanne Aitken, Paddy Dracophyllum, Lynda Harrap, Rose Lanman, Mark Brabyn, Grant Morriss, plus all the DOC staff, contractors and volunteers involved in the kea radio-tagging and survey work. Thanks to Stu Cockburn for designing and building the RFID readers. Thanks to Wyndon Aviation and Canterbury Aviation for safe and efficient flying work and aerial tracking. We hugely appreciate the generosity and support from landowners Ed and Michelle Evans and Ian Whitmore and Katie Milne for their ongoing cooperation and land access. We thank the DOC Animal Ethics Committee, particularly Craig Gillies, for important feedback during the early phases of designing this research and helpful DOC staff at Greymouth, Hokitika and North Canterbury districts for ongoing support and cooperation. Thanks to Ximena Nelson, Robert Holdaway, Lydia McLean, Ash Murphy, Margaret Stanley, and three anonymous referees for providing feedback on this manuscript.

## Additional information and declarations

**Author contributions:** LMY, KAW, MH, JWB and IJY designed the study, methods and sampling design. LMY, IJY, LMH and MBW designed and built field equipment and carried out the field work. LMH and LMY processed and scored the data. ALW analysed the data and IDG created maps and helped with logistics. LMY wrote the manuscript with significant input from ALW and input from KAW, LMH, MH, IJY and JWB.

**Funding:** This work was jointly conceived and funded by the Department of Conservation's National Predator Control Programme and OSPRI as part of an ongoing collaborative research programme to investigate and implement risk mitigation methods to protect kea during landscape-scale predator control operations.

**Data and code availability:** The data in this paper may be made available upon request to the corresponding author.

**Ethics:** All research undertaken was approved by, and undertaken in accordance with, the stipulations outlined by the Department of Conservation's Animal Ethics Committee (DOC-AEC409 and DOC-AEC403).

**Conflicts of interest:** The authors declare no conflicts of interest.

## References

- Avery ML 2003. Avian repellents. In: Plimmer, JR, Gammon, DW, Ragsdale, NN eds. *Encyclopedia of Agrochemicals*. Hoboken, New Jersey, USA, John Wiley. Pp. 122–128.
- Avery ML, Humphrey JS, Decker DG 1997. Feeding deterrence of anthraquinone, anthracene, and anthrone to rice-eating birds. *Journal of Wildlife Management* 61: 1359–1365.
- Blyth R 2011. Comparative bait preference in captive kea (*Nestor notabilis*). RMB Consultants Ltd. Report for the Animal Health Board, Wellington, New Zealand.
- Brejaart R 1988. Diet and feeding behaviour of the kea

- (*Nestor notabilis*). Unpublished dissertation, Lincoln University, Canterbury, New Zealand.
- Brown K, Elliott G, Innes J, Kemp J 2015. Ship rat, stoat and possum control on mainland New Zealand: an overview of techniques, successes and challenges. Wellington, Department of Conservation. 36 p.
- Cieraad E 2024. Risk factors for kea mortality during aerial 1080 operations. Department of Conservation Internal Report. 31 p.
- Clapperton BKT, Day D, Morgan DKJ, Huddart F, Cox N, Matthews LR 2015. Palatability and efficacy to possums and rats of pest control baits containing bird repellents. *New Zealand Journal of Zoology* 42: 104–118.
- Cowan P, Crowell M 2017. Visual and taste cues for minimising native bird interactions with toxic 1080 baits - a review of current practices. *New Zealand Journal of Ecology* 41: 178–185.
- Cowan P, Booth L, Crowell M 2016a. Repellents with potential to protect kea and other native birds from aerial poisoning for possum and rat control. *New Zealand Journal of Ecology* 40(1): 29–4.
- Cowan P, Brown S, Forrester G, Booth L, Crowell M 2016b. Bird-repellent effects on bait efficacy for control of invasive mammal pests. *Pest Management Science* 71: 1075–1081.
- Crowell M, Martini M, Moltchanova E 2015. Effect of the addition of bird repellents to aerially applied 1080 baits on rat and possum abundance. *New Zealand Journal of Ecology* 40: 48–59.
- Crowell M, Booth L, Cowan P, Fairweather A, Westbrooke I 2016. Stability of bird repellents used to protect kea (*Nestor notabilis*) during aerial 1080 cereal operations. *New Zealand Journal of Ecology* 40(1): 42–48.
- Day T, Matthews L, Waas J 2003. Repellents to deter New Zealand's North Island robin *Petroica australis longipes* from pest control baits. *Biological Conservation* 114: 309–316.
- Department of Conservation 2020. Aerial 1080 in kea habitat code of practice. Wellington, Department of Conservation. 25 p.
- Diamond J, Bond AB 1991. Social behaviour and the ontogeny of foraging in the kea (*Nestor notabilis*). *Ethology* 88: 128–144.
- Elliott G, Kemp J 2016. Large-scale pest control in New Zealand beech forests. *Ecological Management & Restoration* 17: 200–209.
- Green W 2004. The use of 1080 for pest control. A discussion document. Wellington, Animal Health Board and Department of Conservation. 64 p.
- Greer AL, Gajdon GK, Nelson XJ 2015. Intraspecific variation in the foraging ecology of kea, the world's only mountain-and rainforest-dwelling parrot. *New Zealand Journal of Ecology* 39: 254–261.
- Hartley L, O'Connor C, Waas J, Matthews L 1999. Colour preferences in North Island robins (*Petroica australis*): implications for deterring birds from poisonous baits. *New Zealand Journal of Ecology* 23(2): 255–259.
- Hartley LJR, Waas J, O'Connor C, Matthews LR 2000. Colour preferences and coloured bait consumption by weka *Gallirallus australis*, an endemic New Zealand rail. *Biological Conservation* 93: 255–263.
- Hickling GJ 1997. Effect of green dye and cinnamon oil on consumption of cereal pest baits by captive North Island kaka (*Nestor meridionalis*). *New Zealand Journal of Zoology* 24: 239–242.
- Karl BJ, Clout MN 1987. An improved radio transmitter harness with a weak link to prevent snagging. *Journal of Field Ornithology* 58(1): 73–77.
- Kemp J, Mosen CC, Elliot G, Hunter CM 2018. Effects of the aerial application of 1080 to control pest mammals on kea reproductive success. *New Zealand Journal of Ecology* 42: 158–168.
- Kemp J, Mosen CC, Elliot G, Hunter CM, van Klink P 2019. Kea survival during aerial poisoning for rat and possum control. *New Zealand Journal of Ecology* 43: 3351.
- Kemp JR, Young LM, Mosen C, Bolitho L, Orr-Walker T, Yockney IJ, Elliott G 2022. Irruptive dynamics of invasive carnivores and prey populations, and predator control, affect kea survivorship across the Southern Alps. *New Zealand Journal of Zoology*. 50(2): 279–304.
- Lenth R 2023. R package “emmeans: estimated marginal means, aka least-squares means”. Version 1.8.8. <https://CRAN.R-project.org/package=emmeans>.
- McLean L, Nichols M, Taylor A, Nelson XJ 2022. Memory retention of conditioned aversion training in New Zealand's alpine parrot, the kea. *The Journal of Wildlife Management* 86(5): e22221.
- McLean LRW, Goodman TF, Horton TW, Nelson XJ 2023a. Effects of proximity to humans on neophilia, foraging ecology and population structure of kea. *New Zealand Journal of Zoology* 51(2): 258–274.
- McLean L, Horton TW, Robertson BC, Robertson F, Greer A, Nelson XJ 2023b. Reproductive roles as likely drivers of sexual dimorphism in New Zealand's endangered mountain parrot, the Kea. *Ornithology* 140(4): ukad038.
- Murphy E, Robbins L, Young J, Dowding J 1999. Secondary poisoning of stoats after an aerial 1080 poison operation in Pureora Forest, New Zealand. *New Zealand Journal of Ecology* 23: 175–182.
- Nichols M, Bell P 2019. Technical Report #9: Tahr carcasses as an attractant over cereal bait for wild kea. Zero Invasive Predators (ZIP). <https://zip.org.nz/technical-reports-feed/2020/2/technical-report-9-tahr-carcasses-as-an-attractant-over-cereal-bait-for-wild-kea> (accessed 19th December 2024).
- Nichols M, Bell P, Mulgan N, Taylor A 2020. Conditioned aversion in kea to cereal bait: a captive study using anthraquinone. *Applied Animal Behaviour Science* 230:105077.
- Nugent G, Morriss G, Warburton B 2019. Can rapid-repeat ‘dual’ 1080 baiting overcome learned bait aversion and locally eliminate possums and rats? *New Zealand Journal of Ecology* 43(2): 3373.
- O'Donnell CF, Dilks PJ 1994. Foods and foraging of forest birds in temperate rainforest, South Westland, New Zealand. *New Zealand Journal of Ecology* 18: 87–107.
- Ogilvie S, Thomas M, Morriss G, Morgan D, Eason C 2000. Investigation of sodium monofluoroacetate (1080) bait shyness in wild brushtail possum (*Trichosurus vulpecula*) populations. *International Journal of Pest Management* 46: 77–80.
- Orr-Walker T, Roberts LG 2009. Population estimations of wild kea (*Nestor notabilis*). Queenstown, Kea Conservation Trust Internal Report. 6 p.
- Orr-Walker T, Adams NJ, Roberts LG, Kemp JR, Spurr EB 2012. Effectiveness of the bird repellents anthraquinone and d-pulegone on an endemic New Zealand parrot, the kea (*Nestor notabilis*). *Applied Animal Behaviour*

- Science 137: 80–85.
- Parliamentary Commissioner for the Environment 2013. <https://pce.parliament.nz/media/pwthbbah/evaluating-the-use-of-1080.pdf> (accessed 19th December 2024).
- Poché RM 1998. Development of a new bird repellent, Flight Control. Proceedings of the Vertebrate Pest Conference 18: 338–344.
- Poutu N, Fairweather AAC, Broome KG 2021. Sodium fluoroacetate pesticide information Review. Version 2021/3. Hamilton, Department of Conservation. 134 p.
- R Core Team 2023. R: A language and environment for statistical computing. Version 4.3.0. Vienna, Austria, R Foundation for statistical computing. <http://www.R-project.org/>.
- Reardon J 2014. Kea repellent development report July 2014. Wellington, Department of Conservation. 20 p.
- Reid C 2008. Exploration avoidance and an anthropogenic toxin (leadpb) in a wild parrot (kea: *Nestor notabilis*). Unpublished MSc Thesis, Victoria University of Wellington, Wellington, New Zealand.
- Robertson H, Baird K, Dowding JE, Elliott GP, Hitchmough RA, Miskelly CM, McArthur N, O'Donnell CFJ, Sagar PM, Scofield RP, Taylor GA 2017. Conservation status of New Zealand birds. New Zealand threat classification series no. 19. Wellington, Department of Conservation. 23 p.
- Spurr EB 2002. Bird control chemicals. In: Pimentel D ed. Encyclopedia of Pest Management. New York, USA, Marcel Dekker. Pp. 1–4.
- Spurr EB, Porter RER 1998. Cinnamamide as a bird repellent for baits used in mammalian pest control. Proceedings of the 11th Australian Vertebrate Pest Conference. Pp. 295–299.
- van Klink P, Crowell M 2015. Kea (*Nestor notabilis*) survivorship through a 1080 operation using cereal baits containing the bird repellent d-pulegone at Otira, central Westland. DOC research and development series 344. Wellington, Department of Conservation. 13 p.
- Veltman CJ, Westbrooke IM 2011. Forest bird mortality and baiting practices in New Zealand aerial 1080 operations from 1986 to 2009. New Zealand Journal of Ecology. 35: 21–29.
- Werner S, Carlson JC, Tupper SK, Santer MM, Linz GM 2009. Threshold concentrations of an anthraquinone-based repellent for Canada geese, red-winged blackbirds, and ring-necked pheasants. Applied Animal Behaviour Science. 121: 190–196.
- Werner SJ, Linz M, Carlson JC, Pettit SE, Tupper SK, Santer MM 2011. Anthraquinone-based bird repellent for sunflower crops. Applied Animal Behaviour Science 129: 162–169.
- Werner SJ, DeLiberto ST, Pettit SE, Mangan AM 2014. Synergistic effect of an ultraviolet cue for an avian repellent and protection of agricultural crops. Applied Animal Behaviour Science 159: 107–113.
- Werner SJ, DeLiberto ST, Mangan AM, Pettit SE, Ellis JW, Carlson JC 2015. Anthraquinone-based repellent for horned larks, great-tailed grackles, American crows and the protection of California's specialty crops. Crop Protection 72: 158–162.
- Weser C, Ross JG 2013. The effect of colour on bait consumption by kea (*Nestor notabilis*): implications for deterring birds from toxic baits. New Zealand Journal of Zoology 40(2): 137–144.
- Weston K, Lanman R, Krouse S 2022. Fox-Franz kea aerial 1080 risk mitigation trials. Department of Conservation internal report. 28 p.
- Weston K, Kemp J, McInnes K, Aley J, Orr-Walker T, Dearlove T, McAulay J, Young L. 2023. Kea (*Nestor notabilis*): a review of ecology, threats, and research gaps for conservation. Science for conservation series: 339. Wellington, Department of Conservation. 39 p.
- Yockney IJ, Young LM, Morriss G, Howard S 2022. Wanganui kea mitigation. Analysis and final milestone report to OSPRI. Manaaki Whenua Landcare Research. 6 p.
- Young LM, Kelly D, Nelson XJ 2012. Alpine flora may depend on declining frugivorous parrot for seed dispersal. Biological Conservation 147: 133–142.
- Young LM, Handley LM, Whitehead AL, Hickson M, Yockney IJ, Watson MB 2024. Wild kea responses to non-toxic baits with and without deer repellent – implications for management. New Zealand Journal of Zoology 51: 2424890.

Received: 10 September 2024; accepted: 6 January 2025  
Editorial board member: Margaret Stanley

## Supplementary Material

Additional supporting information may be found in the online version of this article.

**Appendix S1.** Pairwise comparisons of estimated mean differences between rounds for each response variable.

**Appendix S2.** Interactions of kea with anthraquinone-treated bait by days since bait deployment for each behaviour in each round of the trial.

**Appendix S3.** Pairwise comparisons of estimated mean differences between demographic classes of kea for each response variable.

**Appendix S4.** Pairwise comparisons of estimated mean differences between bait condition (fresh, weathered) and sex for each response variable.

**Appendix S5.** Photos from post-mortem analysis showing dissected stomach and crop contents from a subadult male kea (V-3908) confirmed to have died from secondary 1080 poisoning via consumption of a poisoned possum.

**Appendix S6.** The estimated amount of anthraquinone-treated bait eaten by individual birds across all rounds at Otira-Taipo and Arthur's Pass West sites.

**Appendix S7.** Pairwise comparisons of estimated mean differences between mortality status (dead/alive) for each response variable.

**Appendix S8.** Results from anthraquinone weathering trial showing concentration (percent weight) over a thirty-day period.

**Appendix S9.** Pairwise comparisons of estimated mean differences in the estimated amount of bait consumed by kea for each predictor.

**Appendix S10.** Pairwise comparisons of estimated mean differences between kea with differing scrounge status (scroungers, unknown) for each response variable.

The New Zealand Journal of Ecology provides online supporting information supplied by the authors where this may assist readers. Such materials are peer-reviewed and copy-edited but any issues relating to this information (other than missing files) should be addressed to the authors.