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Testing the repellent efficacy of a newly stabilised formula of d-pulegone on wild kea to assess potential for use during aerial poisoning operations

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Abstract: The Nationally Endangered kea (*Nestor notabilis*) is one of five endemic New Zealand bird species for which non-target mortality from consumption of 1080 (sodium fluoroacetate) pellet baits, used to control invasive mammals, has been recorded. Kea by-kill varies among operations, but reducing predators can deliver population-level benefits that outweigh the risks. Inclusion of bird-specific repellents within the bait matrix is possible, provided that target species (possum (*Trichosurus vulpecula*) and ship rat (*Rattus rattus*)) kills remain high. The primary repellent d-pulegone (0.17% wt wt⁻¹) has previously shown potential as a kea repellent with high pest kill efficacy. However, d-pulegone use was precluded by instability in the bait matrix, with a very high rate of degradation causing its concentration to fall below the operational target concentration after manufacture. Recent work has improved the stability and formula of d-pulegone. We used (1) choice trials in which d-pulegone concentrations of 0, 6, 10, and 50% were presented in non-toxic cereal pellets to wild kea at Arthur's Pass village, and (2) non-choice trials presenting d-pulegone and non-repellent baits to free-ranging wild kea in the alpine zone in mountains surrounding Arthur's Pass. Overall we found some evidence that d-pulegone-treated baits had a repellent effect to kea; total bait consumption declined with 50% d-pulegone concentration in the choice trials and decreased with 6% and 10% d-pulegone in the alpine trials. Obvious adverse reactions to baits were rarely observed ($n < 5$). Individual bait consumption quantity was low, especially where repellent was present, suggesting that the inclusion of d-pulegone within 1080 cereal pellets has the potential to reduce non-target risk to kea if used in aerial poisoning operations. We therefore recommend pen trials to test the palatability of these lower concentrations on target mammal species (possums, rats) as a next step.

Keywords: 1080; bait palatability; *Nestor notabilis*; non-target risk; primary repellent

Introduction

The toxin 1080 (sodium fluoroacetate) has been used widely in New Zealand since the 1960s for landscape scale control of possums (*Trichosurus vulpecula*) and rats (*Rattus rattus*) as they pose significant threats to native biota (Green 2004). Landscape-scale use of 1080 is for the benefit of native biodiversity, as well as effectively controlling the spread of bovine tuberculosis (TB). The toxin is often 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). Unfortunately, along with a high level of

efficacy against target pests comes a non-target risk (Crowell et al. 2016). It has generally been calculated, for those species vulnerable to some level of non-target bykill, that the benefits of mammalian pest control outweigh the risks to non-target species (Spurr 1991). Benefits occur when the immediate loss of non-target individuals (via 1080 poisoning) at the time of a control operation is offset by the subsequent recovery of the population after removal of pest species.

The Nationally Endangered kea (*Nestor notabilis*) is a large (c. 1 kg) parrot, endemic to the South Island of New Zealand, and a taonga species to Ngāi Tahu and Ngā Iwi o Te Taihū (Robertson et al. 2017). Kea forage for a wide variety of foods, including berries, leaves, roots, tubers, seeds, and invertebrates (O'Donnell and Dilks 1994; Brejaart et al. 1998; Young et al.

2012; Greer et al. 2015). Kea can be curious and investigative of cereal baits which can lead to death by 1080 poisoning if sufficient bait is consumed (Orr-Walker & Roberts 2012; Kemp et al. 2019). Where kea have been killed by 1080 poisoning, the subsequent increase in annual survival rates and productivity of the local kea population through reduced predator pressure has been demonstrated to outweigh these losses in some situations (Kemp et al. 2018; Kemp et al. 2022). However, the risk to kea of non-target mortality varies across the landscape, with 1080 operations closest to areas where kea congregate and feed on human foods ("scrounge sites"; Kemp et al. 2018) having significantly higher mortality rates (Kemp et al. 2018). Kea at these sites are particularly investigative and younger birds readily investigate novel objects for edibility and exploration (Diamond & Bond 1991; Reid 2008). How neophilia and boldness persist into adulthood with regard to environment and experiences as a juvenile is poorly understood, but some influence can be expected. Neophilia and a predominance of ground-dwelling behaviours make kea likely to encounter and approach 1080 pellets, and some kea ingest a lethal dose. Identifying risk factors that increase the likelihood of kea mortality during 1080 operations is a subject of ongoing investigation (Kemp et al. 2019; Cieraad 2024).

Risk mitigation strategies are used in attempts to deter birds from consuming 1080 baits, such as adding green dye (Hartley et al. 1999, 2000; Weser & Ross 2013) and cinnamon lure (Hickling 1997; Cowan & Crowell 2017), applying only a single prefeed, using the less-preferred RS5 bait matrix (c.f. Wanganui #7; Blyth 2011) and having a maximum sowing rate of 2 kg ha⁻¹ in kea habitat (Department of Conservation 2020), although it is uncertain whether these strategies are of benefit to kea specifically. Other efforts to reduce the risk of 1080 poisoning to non-target species include the testing of various bird repellents. Repellents are substances or sensory cues that act directly on animals to modify their behaviour to prevent them from interacting with a treated object, area, or food (Day et al. 2003). In the context of feeding behaviour, repellents should directly reduce the consumption of a treated food, either partially or completely, but are not lethal at the concentrations used (Mason & Clark 1997). Repellents are utilised globally, usually to deter a range of bird species from ingesting agriculturally important crops (Spurr 2002; Avery 2003; Day et al. 2003; Werner et al. 2009) and have either primary or secondary modes of action (Rogers 1978). Primary repellents invoke instantaneous rejection by having unpleasant taste, smell, or irritant properties. Secondary repellents act via an illness-induced learned avoidance and require some ingestion of treated food before learning can occur (Spurr 2002). The physiological response needs to occur a short time after ingestion so that the learned aversion is associated with the repellent-treated item. An ideal repellent, or combination of repellents, should be specific to an animal group, e.g. birds, or preferably species: in this case, kea. For pest control operations in New Zealand using 1080, repellent specificity is required to avoid repelling the target pest species, primarily rats and possums (Spurr & Porter 1998; Orr-Walker et al. 2009; Cowan et al. 2016a, b; Crowell et al. 2016).

The New Zealand Department of Conservation (DOC) has committed to collaborative research projects to develop, register, and implement one or more effective bird repellent/s to reduce kea mortality from 1080 (Cowan et al. 2016a; Crowell et al. 2016). Crowell et al. (2016) defined a set of criteria for an effective bird repellent as: (1) wild kea consume very little (if any) repellent-treated toxic bait, (2) possum and rat kills

continue to be high when repellent is used, (3) the addition of repellent does not increase the welfare impact on poisoned possums and rats, (4) repellents are effective for at least 12 weeks after bait manufacture to allow for the storage of baits prior to aerial operations, and (5) the additional cost of the repellent is affordable. A range of repellents have been reviewed for their potential, particularly to address points 1 and 2 above, and a variety have been tested for their deterrent effects on kea, with several showing promise, particularly anthraquinone and d-pulegone (Orr-Walker et al. 2009; Cowan et al. 2016a, b; Crowell et al. 2015, 2016; van Klink and Crowell 2015; Nichols et al. 2020).

The secondary repellent anthraquinone showed promising results in studies on captive kea, with a learned aversion to 2.7% anthraquinone-treated non-toxic, green dyed 1080 bait mimics lasting nearly two years after last exposure to repellent bait, and nearly a year of repeated non repellent pre feeds to get back to baseline consumption (Nichols et al. 2020; McLean et al. 2022). However, when tested on wild kea, results showed that aversion training with those same bait mimics prior to aerial 1080 operations did not result in lower-than-expected non-target mortality (Young et al. 2025). Young et al. (2025) observed very few adverse responses to baits, and low quantities of baits were consumed, well below what was eaten by kea in captivity to learn an aversion. Anthraquinone at 2.7% was, therefore, not recommended for future use on wild kea. A risk of kea potentially obtaining sub-repellent doses and becoming cued on to green baits was also suggested and it was proposed that a primary repellent, or combination of primary and secondary repellents, is preferable to a secondary repellent acting alone.

Primary repellents require little or no learning to be effective, as animals should immediately reject foods treated with the repellent because of unpalatable cues presented by the substance, either visual, olfactory, gustatory, or chemesthetic (irritant) (Clark 1998). The compound d-pulegone is extracted from plants in the genus *Mentha* (mint family) and has a strong minty odour, similar to peppermint and camphor (Baser et al. 1998; Joshi 2013). This compound is used as a primary repellent and has previously shown promise as a potential repellent for kea (see Orr-Walker et al. 2012; Cowan et al. 2015; van Klink & Crowell 2015; Crowell et al. 2016). During trials with captive kea, Orr-Walker et al. (2012) found that kea ingested fewer cereal-based pellets when they contained a combination of both d-pulegone (0.17%) and the secondary repellent anthraquinone (0.1%). However, continued use of d-pulegone was required to maintain the aversion response. Based on this result, Orr-Walker et al. (2012) concluded that the use of d-pulegone repellent in both prefeed and 1080 toxin-laced pellets could substantially reduce kea mortality through aerially applied pest control operations.

Thus, two subsequent field trials were carried out, one measuring efficiency against target pests with and without 0.17% d-pulegone, and one measuring kea survival. Results from pest efficacy trials near Haast where repellent was (treatment area) and was not (control area) added to bait blocks suggested that possums in particular are not significantly repelled by 0.17% d-pulegone-laced baits, with rat and possum tracking indices being satisfactorily reduced in both blocks (Crowell et al. 2015). During the kea survival trial, d-pulegone (0.17%) was incorporated into prefeed and then toxin-laced baits during an aerial pest control operation at Otira, central Westland. Monitoring of radio-tagged kea revealed that 14.7% of kea exposed to 1080 died during this aerial operation, raising

doubt about the efficacy of d-pulegone as a primary repellent for kea (van Klink & Crowell 2015). It was later discovered that d-pulegone in that form was unstable in the bait matrix, losing efficacy over short time frames (van Klink & Crowell 2015; Crowell et al. 2016). The volatility of d-pulegone was an issue because much of it was lost during bait manufacture and further loss occurred during storage (see Crowell et al. 2016).

Recent work by bait manufacturer Orillion has led to a new version of the repellent where d-pulegone has been stabilised through an encapsulation process and is able to be added as a surface coating to premade baits (William McCook, Chief Executive, Orillion, pers. comm). Given the results of past trials, and the newly stabilised d-pulegone formula, it is timely to re-test the repellent efficacy of d-pulegone-laced 1080 baits (as per van Klink & Crowell 2015; Crowell et al. 2016). In this study, we focus on the primary criterion outlined in Crowell et al. (2016), understanding whether “wild kea consume very little (if any) repellent-treated [toxic] bait” (Crowell et al. 2016), though we test this using non-toxic 1080 bait mimics. Understanding the concentration of d-pulegone required to repel kea is essential to assess whether d-pulegone could be a useful addition to cereal pellets to deter kea during 1080 operations.

We investigate whether wild kea can be deterred by a newly stabilised d-pulegone formula applied to non-toxic, green dyed RS5 cereal pellets (i.e. 1080 bait mimics). We aim to evaluate the effectiveness of different d-pulegone concentrations in reducing bait consumption by kea, using (1) choice trials with kea at a scrounge site in Arthur’s Pass Village and (2) non-choice trials with free-ranging wild kea at alpine sites in the mountains surrounding Arthur’s Pass. Our goal is to identify which concentrations are suitable for further investigation in operational contexts. We measure consumption and a range of behavioural responses towards the bait.

Methods

Baits

Due to the unavailability of the previously trialled 0.17% (by weight), non-encapsulated d-pulegone interspersed in a cereal bait matrix (the original formula), comparing the effectiveness of this with that of the new formula was not an option. Therefore, the concentration of the new formula required to repel kea, compared to that of the original formula, requires further investigation. Experimentation with a range of potential concentrations was conducted prior to undertaking the trials (see pilot trials section below).

All baits used in these trials were manufactured by Orillion (Animal Control Products Ltd., Whanganui, New Zealand), the principle commercial supplier to the Department of Conservation. The baits were a non-toxic (i.e. not containing 1080) version identical to those deployed in aerial poison operations in the study area, i.e. cylindrically-shaped RS5 (Pronature™ Dry Forest) cereal formula, 6 g weight with cinnamon lure, green-dyed 1080 bait mimics (hereafter baits). For all repellent trials referred to in this study, we used the new repellent formula, i.e. encapsulated d-pulegone in liquid form, surface coated on the above baits. The manufacturing requirements to stabilise the new d-pulegone formula and any detailed information around the repellent properties, including stability, concentration testing, and weathering related degradation are unknown due to the commercially sensitive nature of the repellent manufacture. However, note that we

acknowledge this as a vital component of understanding the repellents’ performance, the investigation of which is planned as the next phase of this research programme, alongside target species efficacy trials.

d-pulegone concentrations - pilot investigations and choice trials

We undertook this work within Arthur’s Pass Village (42°94’12” S, 171°56’27” E) where 20–30 banded kea were often present at any one time. Over 90% of kea observed in the area at the time of the study were banded, therefore observations of individuals and their interactions with repellent trials, and any repeat observations, can be accounted for.

We carried out pilot investigations to gain a broad understanding of kea responses to the repellents at low concentrations prior to selecting the final concentrations to test in the trials. Fresh baits surface coated with 2% d-pulegone were placed alongside non-repellent, otherwise identical control baits on the ground, freely available to any kea present in the area. Kea interactions with the baits were observed in person, from a distance using binoculars for an initial two-hour session. During this observation period, there was no obvious difference in interest or types of interactions between the two bait types, with ample interest in, and some consumption of both. It was also clear that baits needed to be tethered to a hard, immovable surface so that kea wouldn’t remove them and interact with them elsewhere, preventing interactions from being recorded. Therefore, we repeated the observations again with 2% d-pulegone vs. control bait comparison, followed by a 4% vs. control bait comparison, this time also trialling the concept of baits tethered to boards. We did this by carefully drilling holes through the middle of each bait before nailing them onto a one-metre-long wooden plank of 4 × 2 inches. From observation, again, there was no obvious difference in interest or interaction with different bait types, suggesting that the 4% concentration was also likely inadequate to achieve deterrence to kea. It also suggested that this method of securing baits to a board and placing the two bait types on boards alongside each other, one metre apart, was a valuable way to carry out the choice trials. This allowed for maximum interaction time at baits while still allowing bait consumption to take place in view of observers and/or cameras.

Because d-pulegone is a primary repellent targeting the chemosensory system (unpalatable taste, odour, and/or irritation; Mason & Clark 2000) if successfully repellent to kea, we predicted responses such as avoiding physically touching the bait, attempting to smell (or nare) the bait, less willingness to approach, or rejecting baits soon after picking them up in the bill. We also expected no or very low consumption of baits if the d-pulegone was repellent to kea. These pilot observations aided us in understanding the range of potential kea responses to baits, determining what behavioural responses to score, and how to capture consumption and other interactions with the baits for the choice trials and alpine trials.

Choice trials testing kea responses to 0%, 6%, 10% and 50% d-pulegone baits

Due to the apparent lack of difference between the control bait and 2% and 4% d-pulegone baits in the pilot trials, we proceeded with the choice trials using fresh baits with higher concentrations (6%, 10%, and 50%) alongside control bait. Trials took place between 1–16 December 2021 on a site centrally located within Arthur’s Pass village. Each trial

session was established for a minimum of 1.5 hours, with most sessions occurring throughout either sunrise or sunset when kea are most active. Two wooden boards with attached baits were placed approximately two metres apart on a flat, lawned surface, and a trail camera (Browning Dark Ops BTC-6 Pro XD) was mounted near the end of each to record kea behaviour (set to take 10 s videos with a 3 s delay) (Supplementary Material Appendix S1). An observer was also nearby (using binoculars) recording interactions on paper and video camera (phone) to use as supplementary evidence. Some sessions took place overnight between the evening and morning sessions with no observer, however these mostly became overrun with possum interactions. Trials only took place in fine weather, as bait weathering tests had not yet been conducted and kea activity declined in wet weather. Kea who frequented these trials in the village have learnt to scrounge food from humans or human-related objects such as rubbish bins. To minimise this association of humans with the bait, boards were laid out in the minutes prior to peak activity (while kea were not yet on site to witness), and gloves were worn while handling bait (to minimise human scent on it). No lures were used to attract kea to this site as it was a known area of regular congregation.

To test various concentrations of d-pulegone to determine whether a practicable formula could be found to limit or prevent kea from interacting with and/or consuming bait, a series of tests were carried out involving (1) choice trials with various paired combinations (of 0% vs. 6%, 10%, or 50% d-pulegone baits), (2) 0% d-pulegone bait only, and (3) 50% d-pulegone bait only. Sessions for (2) and (3) took place at the beginning and end of the choice trials, respectively (see below).

Sessions were intended to be conducted at regular intervals with several days between each choice trial session, sequentially introducing baits with higher concentration formulas over time: i.e. starting with 0% vs. 6%, then 0% vs. 10%, then 0% vs. 50% d-pulegone. However, sessions and trial dates were unable to occur as planned, mostly due to significant and unanticipated human interference (kea were being hand-fed nearby and thus unable to participate in the trials due to the distraction of food), possum interference, and weather conditions. Therefore, we were left with the following arrangement of dates and bait comparison sessions.

Prior to the first official choice session of this trial, only baits with (2) the 0% d-pulegone (control) concentration were used on both boards to establish a baseline for comparison with the higher concentrations in subsequent sessions. These data were not officially scored as for all the sessions thereafter; only the presence or absence of particular behavioural responses and interactions with baits were recorded. These responses were used to inform the final methods for scoring the choice trial data. In this preliminary session, all ten kea that were present and close to the bait boards interacted with the baits, and none showed adverse responses towards the baits. We used this trial to develop the final scoring protocol for the subsequent sessions (Fig 1).

In the following eleven sessions (1), paired comparisons were established with control baits vs. either 6%, 10%, or 50% d-pulegone. The final five sessions (3) contained only 50% concentration baits. The high concentration 50% d-pulegone was trialled as an upper-end extreme and we predicted it would serve as a reference for adverse reactions, serving the opposite purpose to the control baits. At each new session, the position of each board was randomised to prevent kea cueing onto boards containing a particular concentration of bait. In total, 16 sessions were conducted: 0% vs. 6% ($n = 5$),

0% vs. 10% ($n = 5$), 0% vs. 50% ($n = 1$), and 50% only ($n = 5$) d-pulegone concentrations (Fig. 1). If lower concentrations demonstrated little or no apparent repellent effects to kea, then the final testing using the extremely high concentration was to understand whether the substance actually has any striking negative effects at all as a repellent or should be ruled out completely. An additional reason for the five 50% d-pulegone-only sessions at the end of the trials (3) was to use the strong concentration of the repellent to deter most of the kea (due to different individuals being present between different sessions) from developing an affinity for these baits and attempt to create a negative association at the conclusion of the trials.

We recorded and scored kea behavioural responses to baits, along with interactions and consumption (Table 1) for individually identifiable birds (both banded and unbanded) where possible. Following each session, bait boards were collected, as well as any bait fragments that may have been moved from the board onto the ground. New bait was attached to boards one hour before each session, and the bait was otherwise stored in an airtight plastic bag in a cool, dark location to retain freshness.

Alpine (non-choice) trials testing wild kea responses to 0, 6, and 10% d-pulegone baits

In this non-choice trial, we investigated consumption, interactions, and responses of wild kea to baits surface-coated with 6% or 10% d-pulegone concentration at a range of alpine sites in the mountains surrounding Arthur's Pass. The purpose of this trial was to identify whether similar responses to d-pulegone repellent baits were evident in free-ranging wild kea (i.e. those not scrounging from humans on a regular basis). 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. These trials were carried out at 18 sites, (most 1500–1750 m a.s.l.) within high alpine vegetation communities dominated by short-statured snow grasses, alpine herbs, and/or bare rock and gravel (Appendix S2).

Repellent baits were deployed at the alpine sites during three rounds over a five-week period from early March to early April 2022. Where possible, sites were established above 1500 m altitude to minimise visitation and exposure to green-dyed (non-toxic) baits by target mammal species, particularly possums and rats. At each site, a 500 g pile of green-dyed standard non-toxic RS5 cereal bait mimics

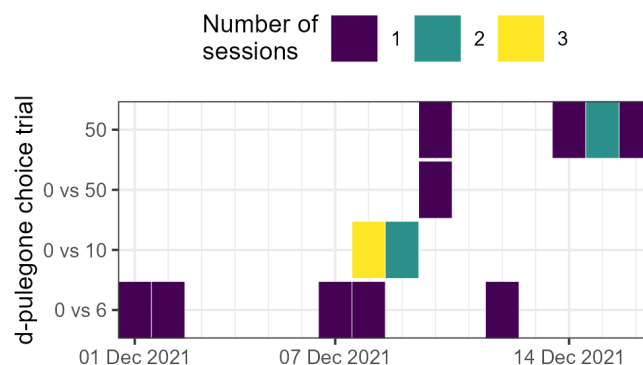


Figure 1. Dates of each choice trial and session, with colours denoting the number of sessions of each trial on a given day. The % concentration of d-pulegone compared in each trial is shown on the y-axis.

Table 1. Behavioural responses of kea to the presence of bait in each of the d-pulegone repellent trials. X indicates which responses were recorded within each trial, while shading indicates those responses that had sufficient data for subsequent analyses.

Variable	Choice trials	Alpine trials	Control trial
(a) Presence of behaviours (TRUE/FALSE)			
Present in area but not approaching bait	X	X	X
Bait interaction	X	X	X
Smell/nare touching bait	X	X	
Picking up bait in beak	X	X	
Picking up bait in foot	X	X	
Beak rubbing	X	X	X
Bait residue on beak			X
Tossing bait	X	X	X
Biting bait	X	X	X
Consuming bait	X	X	X
Shaking head	X	X	X
Fluffing/shaking feathers	X	X	X
Gagging	X	X	X
Vomiting			X
Sneezing	X		
Moving choice board around	X		
(b) Duration of behaviours (seconds)			
Time within body length of bait	X	X	
Time touching nare to bait	X	X	
Time interacting with bait		X	X
Time tossing bait	X	X	
Time chewing or biting bait	X	X	X
Time consuming bait	X	X	X
Time beak rubbing	X	X	
(c) Numeric bait interactions			
Number of bait interactions	X	X	X
Number of baits tossed	X	X	X
Number of baits eaten (1–5 score)	X	X	X

containing cinnamon lure and surface coated with either 6% or 10% d-pulegone repellent was placed on the ground. Half of the sites, selected at random in each of the rounds, received the 6% repellent baits and the other half received 10% repellent baits. Audio lures were situated at each site to attract kea. 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 erected on 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 were programmed with different settings, with two recording video (10 s duration with a 1 s delay) and two capturing still images. One of each set was programmed to high resolution to allow for the need to trade off image quality while maximising 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. A radio frequency identification (RFID) reader was placed at

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

Each site was replenished three times, approximately every 1–2 weeks. The timing of bait replenishment was dictated by the need to operate in fine weather, as well as ensuring at least three fine nights after each fresh bait deployment to allow adequate time for kea visits before the degradation of the repellent and bait. At each site revisit, the repellent baits were replenished, old baits were removed, camera batteries and SD cards were replaced, and audio lure and RFID reader batteries were checked and replaced as required.

Control trial

It was not feasible to conduct the alpine trials as a choice experiment (using 0% repellent in control baits) because two large-scale 1080 operations were scheduled for the surrounding areas within the following year. The Otira-Taipo aerial 1080 operation (September 2022) was an OSPRI possum-focussed operation for TB management with a treatment area of 26 722 ha. The Arthur's Pass West operation (October 2022)

was a standard Department of Conservation pest control operation to protect endangered birds such as great-spotted kiwi (*Apteryx haastii*) across a treatment area of 43 017 ha. Due to the potential risk of pre-feeding kea and cueing them on to non-toxic baits prior to these operations, we did not use control baits (without repellent applied) for this trial. Instead, we conducted a separate trial starting eight months after the Arthur's Pass West 1080 operation. During this trial, we collected three rounds of data at similar alpine sites during late June and early September 2023 using green-dyed, RS5, cinnamon-laced, non-repellent baits to obtain baseline data for comparison with the repellent alpine dataset.

Data scoring and analysis

Video camera data were analysed to score kea interactions with, and consumption of, the baits, while higher-resolution still images and RFID reader data were used to determine presence and unique IDs of banded kea. For the alpine trial, unidentified or unbanded individual kea that were observed on continuous footage, and confirmed to be the same individual throughout, were given a unique ID number. Most analyses presented below only include uniquely identified individual birds. The date and time stamps across the range of data collection methods were then used to match up confirmed individuals with their bait interactions and responses.

Bait consumption by each individual within one session 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 from individual kea were classified into three behavioural responses: the presence/absence of a given behaviour, the duration of a given behaviour, and the number of times a behaviour was observed (Table 1). A composite behavioural response category (bait interaction) was also generated to record any observed interaction with bait. An additional five behaviours (pick up bait in foot, bite, fluffing or shaking, gagging, sneezing, moving board around) were recorded but excluded from analyses as they were observed in less than 5% of interactions. The duration of time that individual kea spent performing four behaviours was also recorded (time spent within a body length of bait, bite or chew, beak rub, bait toss).

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% of a bait). All birds of unknown identity were pooled together to give an estimate of the potential amount of bait consumed across all rounds by those individuals.

Poisson mixed models were used to assess whether the d-pulegone concentration influenced the number of times that identified kea interacted with bait, the duration of these bait interactions, and the total amount of bait consumed. Models were developed separately for the choice and alpine trials, with round included as a random effect to account for potential differences in the order and combination of repellent concentration deployment. For the choice trials, we utilised all available data, including the data from rounds where only bait with 50% d-pulegone was available. While these rounds were not true choice trials, as no other bait was available for birds to interact with, preliminary results suggested that including this data did not influence the strength or direction of the model coefficients. Therefore, we chose to include these

data to maximise the sample size.

Logistic mixed models were used to determine whether the behavioural responses of kea varied by the concentration of repellent. The response of individual kea for a given behaviour was converted to the proportion of TRUE interactions (i.e. the number of times they were observed performing that behaviour divided by the number of times they were observed to be present), with the number of observations also included in each model as a weight. Models were developed separately for the choice and alpine trials, with round included as a random effect.

All data analysis was conducted using R 4.3.0 (R Core Team 2023). Models were fitted using the “lme4” package (Bates et al. 2015), with the mean ($\pm$ 95% confidence intervals) model predictions for each d-pulegone concentration calculated using the “ggeffects” package (Lüdtke 2018).

Results

Choice trials: bait interactions

Thirty-one identified banded birds took part in this trial (Fig. 2). Four individuals were present in every session and seven individuals were observed in only one trial. Between 21–30 individual banded kea interacted with each of the d-pulegone concentrations. The number of baits that individual kea interacted with was highly variable across all trials and d-pulegone concentrations (mean 21.0 ± 27.1 , range 1–140). There were only 16 instances (1.2%) where birds were observed in the presence of bait but did not interact with it (Fig. 2).

There was no relationship between the number of times banded kea interacted with bait and the d-pulegone concentration (Fig. 3a, Table 2). While the order in which birds were exposed to baits of different d-pulegone concentrations varied, there was no discernible impact of the order of exposure on the likelihood of kea interacting with the bait (Fig. 3b).

The concentration of d-pulegone was positively related to the proportion of times that banded kea were observed smelling bait, rubbing their beaks, picking bait up in their beaks, and tossing bait (Table 2). However, this effect was driven by a higher proportion of interactions at the 50% d-pulegone concentration, with no differences observed between the 0%, 6% and 10% concentrations (Fig. 4a). The d-pulegone concentration did not significantly affect the proportion of times that individuals shook their heads or consumed bait (Table 2).

Conversely, the duration of time that kea spent within a body length of bait was negatively correlated with d-pulegone concentration (Table 2), with 15 ± 0.26 seconds at 50% d-pulegone compared to 41 ± 0.27 seconds at 6% d-pulegone (Fig. 4b). No significant effects of d-pulegone concentration were observed on the duration of time that kea spent tossing or chewing bait or rubbing beaks after bait consumption.

Choice trials: bait consumption

All 31 banded kea were observed consuming bait on at least one occasion during the choice trials, with the total bait consumption per bird ranging from 0.02–6.92 (0.20 ± 0.03 ; mean $\pm$ SE) baits across the whole trial period, irrespective of the d-pulegone concentration (Table 3). Twenty-two banded individuals consumed bait on three or fewer days over the 15-day period of the choice trials, while one individual (V-2940) consumed bait on eight days (Fig. 5). Eleven banded individuals (35.5%) consumed more than the lower estimate of 1080 LD50 (0.3 baits) on at least one day when baits across

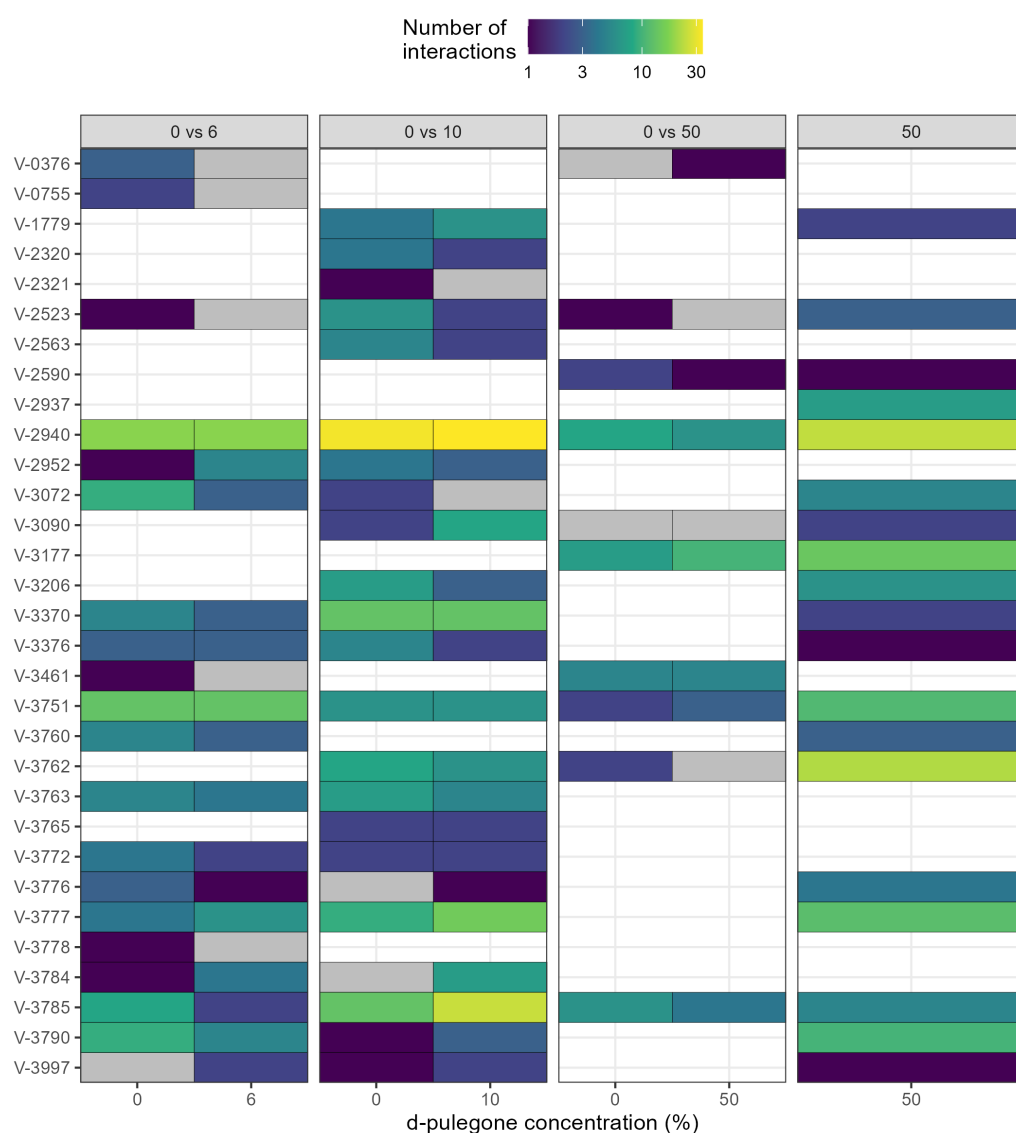


Figure 2. The interaction of 31 individual kea (identified by their metal V-band number) to d-pulegone trials with different concentrations of repellent. The shaded blocks indicate the number of times an individual interacted with bait of a given concentration in a given trial, with light grey blocks showing when a bird was present but did not interact with bait. Empty blocks occur when a bird was not observed in a trial.

Table 2. Model outputs for mixed effects models relating the concentration of d-pulegone repellent on cereal baits to observed behaviours of banded kea during the choice trials. Behaviours where there is a significant effect (at $\alpha = 0.05$) are indicated in bold. The mean ($\pm$ SE) beta value provides the estimated direction and strength of the relationship.

Behaviour	Response data type	Beta	z-score	p value
Bait interaction	Number of interactions	0.000 ± 0.004	0.066	0.947
Smell/touching nare to bait	Proportion of TRUE interactions	0.042 ± 0.017	2.430	0.015
Beak rubbing	Proportion of TRUE interactions	0.020 ± 0.006	3.378	0.001
Pick up bait in beak	Proportion of TRUE interactions	0.020 ± 0.007	2.759	0.006
Head shake	Proportion of TRUE interactions	-0.003 ± 0.013	-0.243	0.808
Bait toss	Proportion of TRUE interactions	0.045 ± 0.006	7.642	< 0.001
Consumption	Proportion of TRUE interactions	-0.020 ± 0.012	-1.698	0.090
Time spent within a body length of bait	Duration of behaviour (seconds)	-0.023 ± 0.001	-34.936	< 0.001
Bait toss	Duration of behaviour (seconds)	0.006 ± 0.013	0.455	0.649
Beak rubbing	Duration of behaviour (seconds)	0.001 ± 0.005	0.182	0.855
Bite/chew	Duration of behaviour (seconds)	-0.013 ± 0.007	-1.732	0.083
Baits tossed	Number of baits tossed	0.004 ± 0.005	0.798	0.425
Bait consumption per interaction	Number of baits consumed	-0.034 ± 0.002	-12.628	< 0.001
Total bait consumption	Number of baits consumed	-0.032 ± 0.003	-10.286	< 0.001

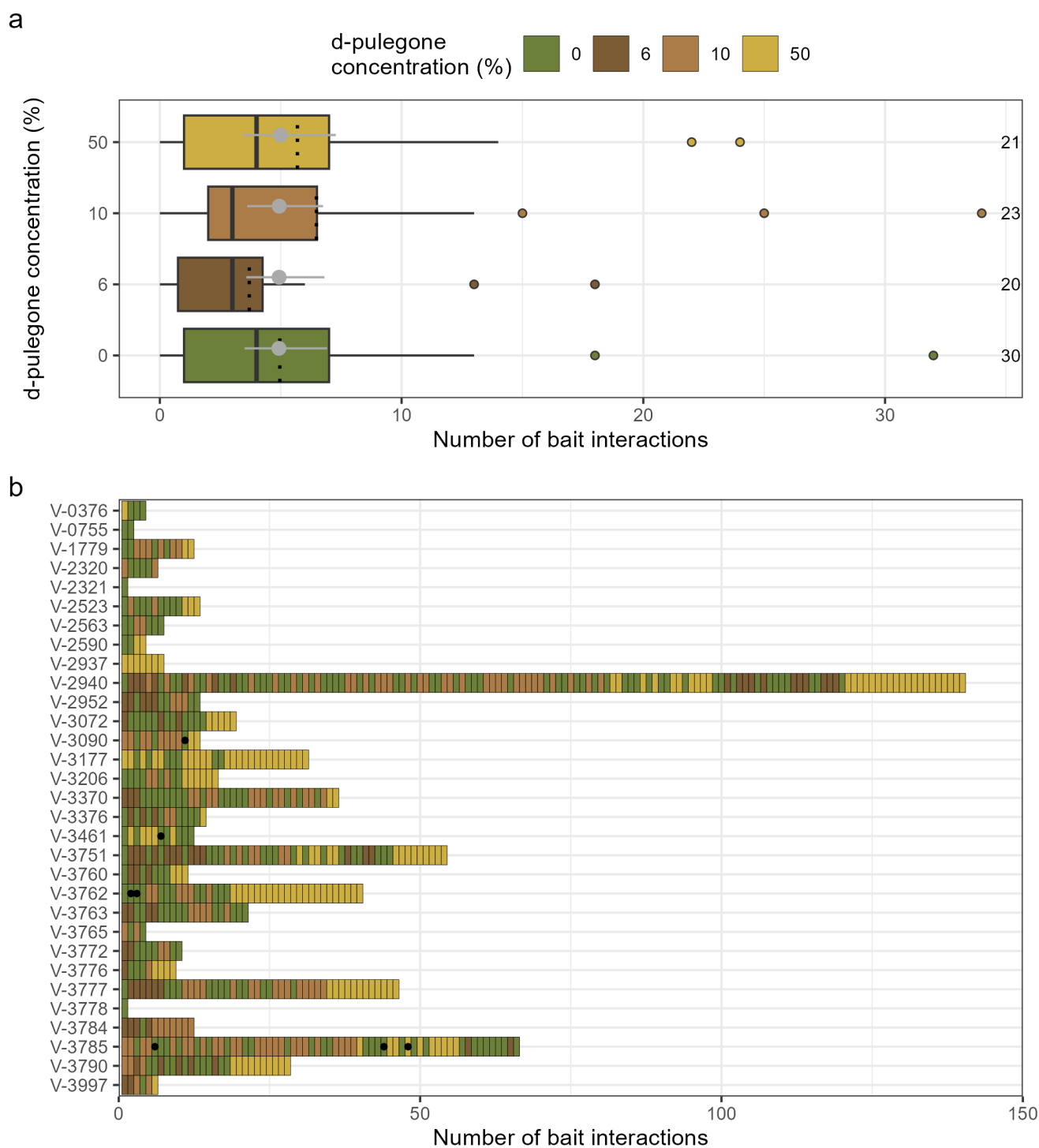


Figure 3. The number of times banded kea were in the presence of bait by (a) d-pulegone concentration across all trials and (b) the order of exposure to baits with different d-pulegone concentrations for individual banded kea (identified by their metal V-band number). Numbers to the right of each boxplot (in a) indicate the number of banded kea in each class (across all choice trials). Black dots (in b) indicate occasions when an individual was in the presence of bait but did not interact with it. Box-and-whisker plots provide a graphical representation of the data, where the box indicates the interquartile range (IQR), the central solid and dashed lines represent the median and mean, respectively, and whiskers depict the maximum value up to 1.5 times the IQR. Outliers beyond 1.5 times the IQR are indicated as points.

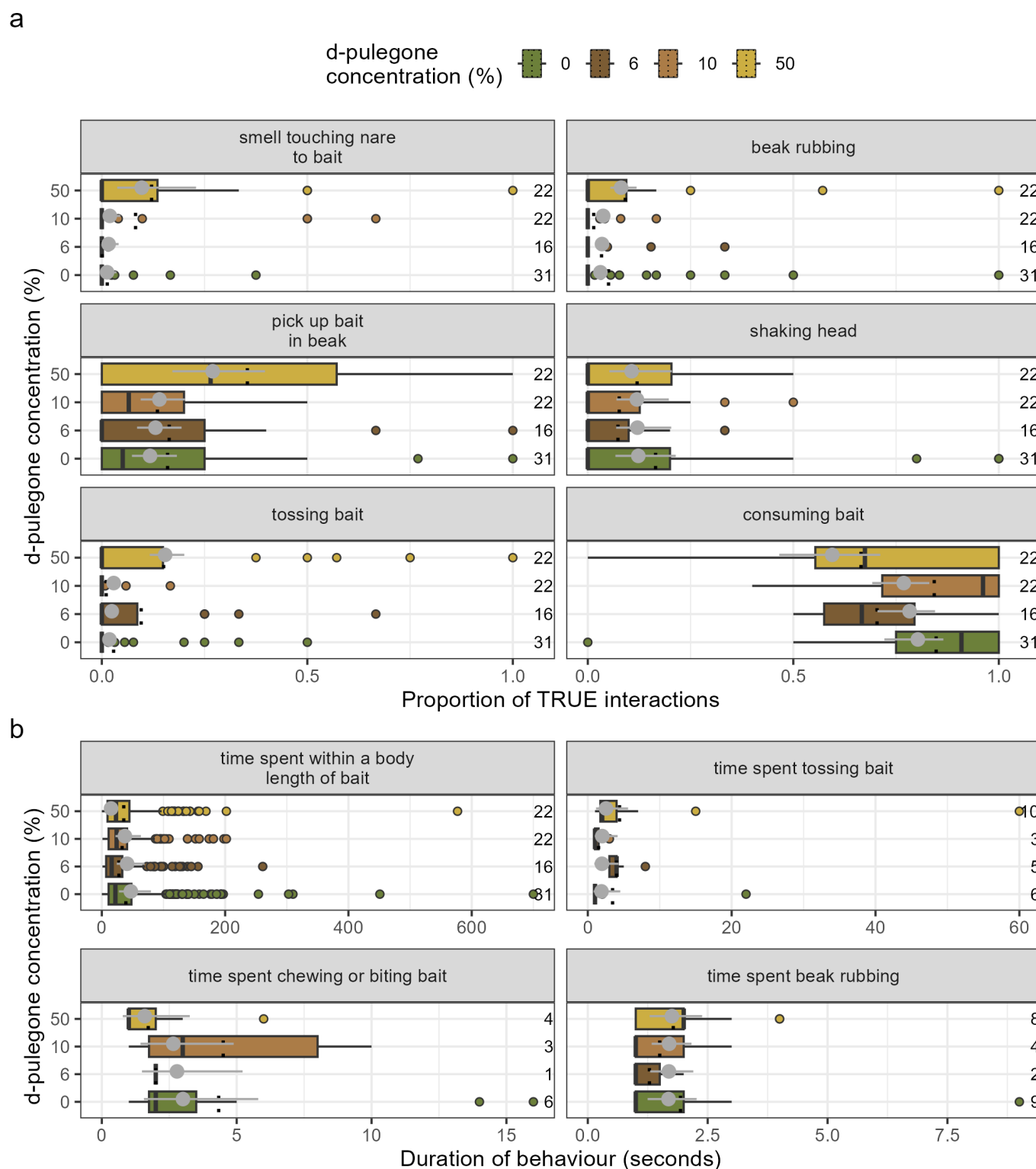


Figure 4. Interactions of banded kea with d-pulegone treated bait by concentration across the choice trials, with (a) the proportion of TRUE interactions observed for individual kea for each behaviour and (b) the length of time interactions were observed. Numbers to the right of each boxplot indicate the number of identified kea in each class (across all trials). Grey points and error bars represent the mean predictions ($\pm$ 95% confidence intervals) from mixed effects models where overlapping error bars indicate no significant difference between treatments.

Table 3. The estimated total amount of d-pulegone treated bait eaten by individuals across all choice trials. Consumption data for all birds of unknown identity are grouped together in the top row. Columns (L to R) reflect the number of times a banded kea was observed interacting with and consuming bait, the percentage of bait interactions where bait was consumed, the total number of baits consumed across all rounds, and the number of consumed baits across each of the four concentrations of d-pulegone. Shading indicates where, over the whole two-week trial period for a given d-pulegone concentration, individuals consumed greater than the lower threshold (0.3 baits) of the potential LD50 for a 900 g kea, based on the consumption of 1.8–4.7 g of bait with 0.15% 1080 loading (Orr-Walker et al. 2012).

Kea ID	Bait interactions (count)	Bait consumption events (count)	Bait interactions when consumption occurred (%)	Baits consumed (count)				
				Total	0% DP	6% DP	10% DP	50% DP
Unknown	623	418	67.1	11.83	6.28	1.79	2.14	1.62
V-2940	140	114	81.4	6.92	4.28	0.51	1.71	0.42
V-3785	63	51	81.0	3.11	1.84	0.02	0.86	0.39
V-3751	54	45	83.3	2.05	1.30	0.45	0.12	0.18
V-3790	28	20	71.4	1.09	0.64	0.33	0.06	0.06
V-3072	19	16	84.2	1.01	0.64	0.27	0.00	0.10
V-3777	46	36	78.3	0.95	0.43	0.06	0.26	0.20
V-3370	36	32	88.9	0.87	0.55	0.04	0.24	0.04
V-3762	38	27	71.1	0.77	0.35	0.00	0.12	0.30
V-3763	21	15	71.4	0.76	0.43	0.29	0.04	0.00
V-3760	11	9	81.8	0.64	0.33	0.27	0.00	0.04
V-3376	14	10	71.4	0.43	0.37	0.04	0.02	0.00
V-2952	13	10	76.9	0.43	0.10	0.29	0.04	0.00
V-3177	31	17	54.8	0.34	0.12	0.00	0.00	0.22
V-3206	16	13	81.2	0.26	0.12	0.00	0.06	0.08
V-1779	12	12	100.0	0.24	0.08	0.00	0.12	0.04
V-3461	11	10	90.9	0.20	0.12	0.00	0.00	0.08
V-3784	12	10	83.3	0.20	0.02	0.04	0.14	0.00
V-2523	13	10	76.9	0.20	0.12	0.00	0.04	0.04
V-3772	10	9	90.0	0.18	0.10	0.04	0.04	0.00
V-3090	12	8	66.7	0.16	0.00	0.00	0.14	0.02
V-2937	7	7	100.0	0.14	0.00	0.00	0.00	0.14
V-2563	7	7	100.0	0.14	0.10	0.00	0.04	0.00
V-3997	6	4	66.7	0.08	0.02	0.02	0.02	0.02
V-2320	6	4	66.7	0.08	0.04	0.00	0.04	0.00
V-3776	9	4	44.4	0.08	0.04	0.02	0.02	0.00
V-2590	4	4	100.0	0.08	0.04	0.00	0.00	0.04
V-3765	4	3	75.0	0.06	0.04	0.00	0.02	0.00
V-0755	2	2	100.0	0.04	0.04	0.00	0.00	0.00
V-0376	4	2	50.0	0.04	0.04	0.00	0.00	0.00
V-3778	1	1	100.0	0.02	0.02	0.00	0.00	0.00
V-2321	1	1	100.0	0.02	0.02	0.00	0.00	0.00

all available d-pulegone concentrations were pooled (Table 4). This behaviour occurred more frequently when d-pulegone was absent (0%) but did occur at all concentrations for at least one banded individual. Thirty-five percent of banded individuals consumed more than the lower estimate of 1080 LD50 (0.3 baits) across all the choice trials when d-pulegone repellent was not present. This was reduced to three individuals (9.7%) in each of the choice trials where d-pulegone repellent was present (Table 3).

Both the amount of bait consumed per interaction and the total amount of bait consumed by kea across all the trial sessions declined with increasing concentrations of d-pulegone (Fig. 6, Table 2). This effect was likely driven by lower consumption rates at the 50% concentration, with limited differences in consumption between the other treatments.

Alpine and control trials: bait interactions

Sixteen banded birds and an additional 38 uniquely identified birds (within sessions) were observed during the alpine trials (Fig. 7). Of these, 36 birds were exposed to 6% d-pulegone, while 17 birds were exposed to 10% d-pulegone. Only five banded individuals were present in more than one of the alpine trials, with just two banded kea exposed to both d-pulegone concentrations. Eighteen banded individuals and an additional 174 uniquely identified individuals were observed during the control trial. Only two banded individuals were present in both the alpine and control trials (V-3916, V-3920; Fig. 7). Overall, there were 196 instances (20.1%) where birds were observed in the presence of bait but did not interact with it. The proportion of observations where kea did not interact with bait declined significantly with increasing d-pulegone

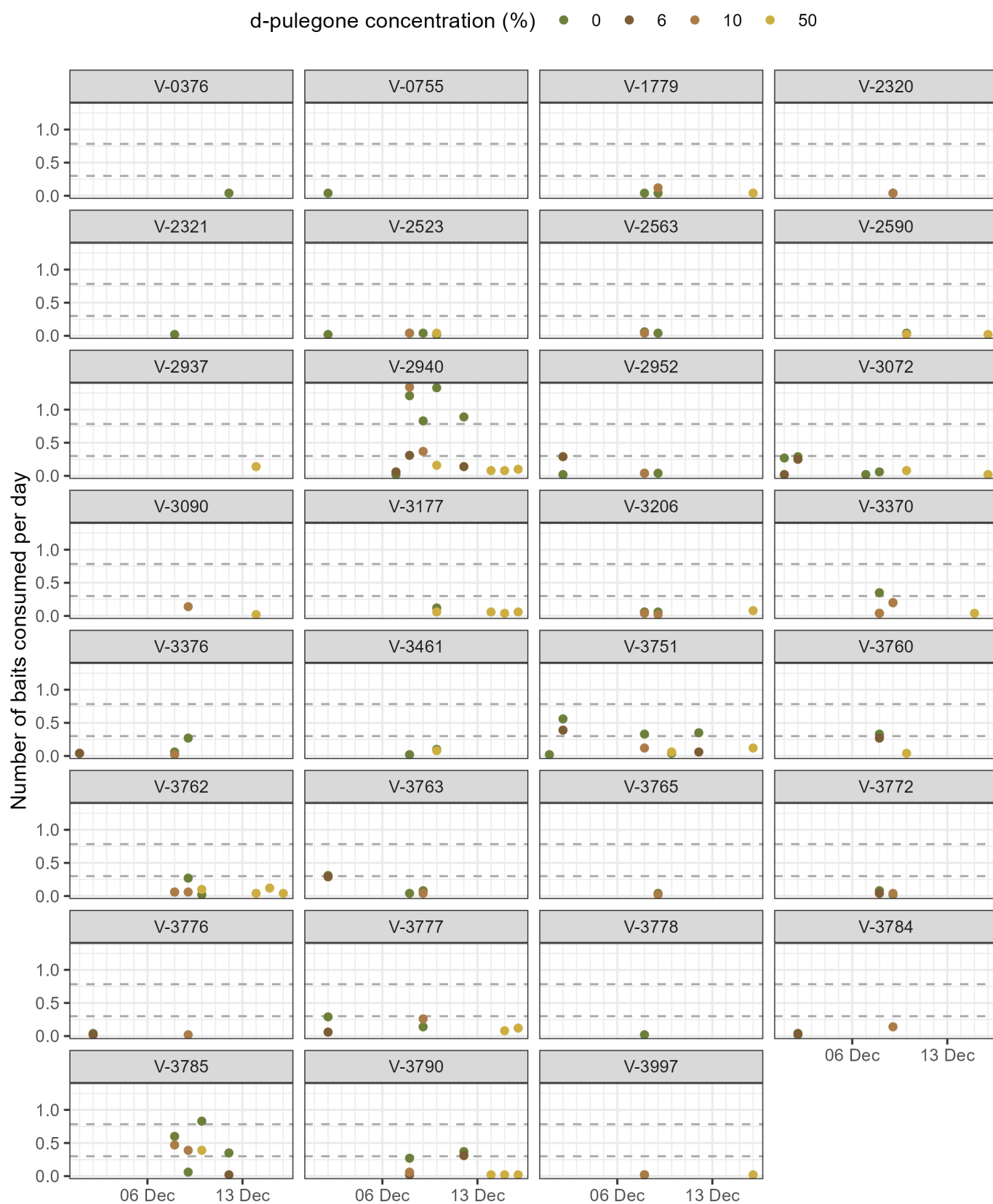


Figure 5. The estimated number of baits consumed per day by individually identified kea (each panel) grouped by d-pulegone concentration across the choice trials. Dashed lines show the number of baits that represent the lower and upper estimates of the potential LD50 for an average-sized 900 g kea, based on the consumption of 1.8–4.7 g of bait with 0.15% 1080 loading (Orr-Walker et al. 2012).

Table 4. Model outputs for mixed effects models relating the concentration of d-pulegone repellent on cereal baits to observed behaviours of identified kea during the alpine and control trials. Behaviours where there is a significant effect (at $\alpha = 0.05$) are indicated in bold. The mean ($\pm$ SE) beta value provides the estimated direction and strength of the relationship.

Behaviour	Response	Beta	z-score	p value
Bait interaction	Number of interactions	0.120 $\pm$ 0.015	7.981	< 0.001
Bait interaction	Proportion of TRUE interactions	0.093 $\pm$ 0.019	4.771	< 0.001
Bait toss	Proportion of TRUE interactions	0.034 $\pm$ 0.023	1.477	0.140
Bite	Proportion of TRUE interactions	-0.671 $\pm$ 0.048	-13.999	< 0.001
Consumption	Proportion of TRUE interactions	-0.138 $\pm$ 0.024	-5.817	< 0.001
Pick up bait in beak*	Proportion of TRUE interactions	0.101 $\pm$ 0.045	2.249	0.025
Smell/touching nare to bait*	Proportion of TRUE interactions	-0.066 $\pm$ 0.047	-1.411	0.158
Time spent within a body length of bait	Duration of behaviour (seconds)	-0.115 $\pm$ 0.004	-31.961	< 0.001
Time interacting with bait	Duration of behaviour (seconds)	-0.222 $\pm$ 0.001	-273.53	< 0.001
Time spent tossing bait*	Duration of behaviour (seconds)	-0.020 $\pm$ 0.017	-1.175	0.240
Number of baits tossed	Number of baits	0.026 $\pm$ 0.011	2.358	0.018
Bait consumption per exposure	Number of baits	-0.136 $\pm$ 0.006	-23.714	< 0.001
Total bait consumption	Number of baits	-0.060 $\pm$ 0.010	-5.755	< 0.001

* Model only includes data from the 6% and 10% d-pulegone alpine trials as this behaviour was not recorded in the control trial.

concentration (29.9% of observations at 0% concentration, 21.2% of observations at 6% concentration, and 12.7% of observations at 10% concentration) (Table 4).

Kea were significantly more likely to interact with bait containing higher concentrations of d-pulegone, both with respect to the total number of interactions and the proportion of TRUE interactions (Fig. 8a, Table 4). On average, individual identified kea interacted with bait on 2.48 ± 2.11 occasions across the alpine trials, compared with 1.00 ± 2.48 occasions in the control trial. While the order in which birds were exposed to baits with 6% and 10% d-pulegone concentrations varied, there was no discernible impact on the likelihood of birds interacting with the bait (Fig. 8b).

Individual kea were highly likely to interact with bait if they were exposed to it, with 78.3% of observations of kea in the presence of bait resulting in an interaction. Both the number and the proportion of TRUE interactions with bait were positively correlated with d-pulegone concentration (Figs. 8a & 9a, Table 4).

Kea were significantly more likely to pick bait up in their beaks with increasing d-pulegone concentration, although they were significantly less likely to bite or consume bait (Fig. 9a, Table 4). There was no significant difference in the proportion of time birds were observed smelling or tossing baits of different repellent concentrations.

The duration of time that kea spent within a body length of bait or interacting with bait was negatively correlated with d-pulegone concentration (Fig. 9b, Table 4). In contrast, the number of baits tossed by kea was significantly higher with increasing d-pulegone concentration. No significant effects of d-pulegone concentration were observed with regard to the duration of time that kea spent tossing bait.

Responses we classified as adverse reactions to bait (beak rubbing, head shaking, fluffing, shaking, gagging) were excluded from analyses because they were observed so few times in the alpine trial. For example, fluffing, shaking, and gagging behaviours were each only observed on six occasions across both the alpine and control trials.

Alpine and control trials: bait consumption

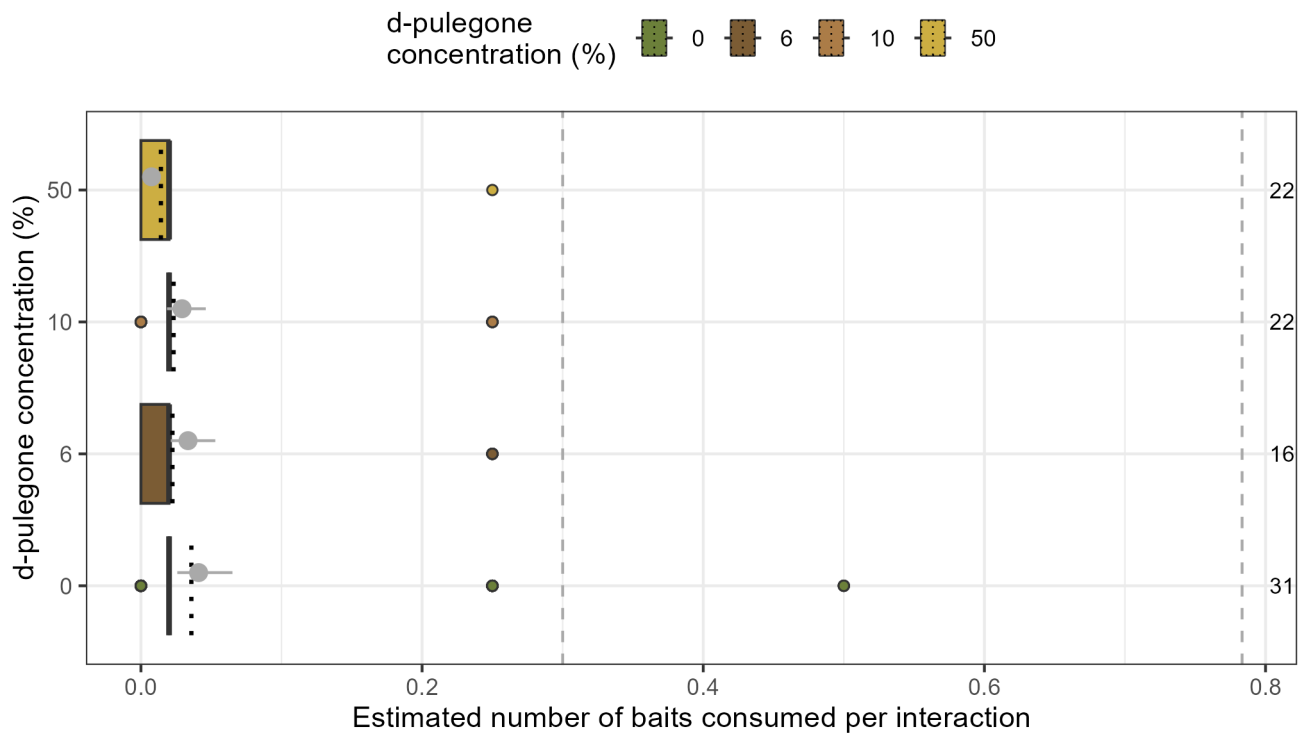
Overall, 49% of identified kea who interacted with bait were observed consuming it on at least one occasion during the alpine and control trials, with the total bait consumption per bird ranging from 0.00–0.52 (0.07 ± 0.03) baits, irrespective of the d-pulegone concentration (Fig. 10; Appendix S3). Fourteen banded individuals consumed bait on just one day over the period of the alpine and control trials (Fig. 10), while one individual (V-2940) consumed bait on eight days. Two banded individuals (V-2804, V-3920) consumed more than the lower estimate of 1080 LD50 (0.3 baits) on a single day when d-pulegone was absent (0%), but bait consumption was not observed in the banded population when d-pulegone was present at any concentration (though bait containing d-pulegone was still consumed by non-banded individuals). Bait consumption decreased with increasing d-pulegone concentration, both when considering mean bait consumption per exposure and total bait consumption across all alpine and control trials (Fig. 11, Table 4). Only one identified (non-banded) individual consumed more than the lower estimate of 1080 LD50 (0.3 baits) at the 10% d-pulegone concentration, while no birds consumed more than 0.3 baits at 6% d-pulegone concentration (Fig. 10). In comparison, three individuals in the control trial consumed more than the upper estimate of 1080 LD50 (0.8 baits) (Appendix S3).

Discussion

High bait interaction and consumption by wild kea in choice trials

The aim of the choice trials at Arthur's Pass village was to confirm whether the new formulation of surface-coated d-pulegone could repel kea, and to gain an understanding of which concentration(s) could warrant further investigation. The choice trial results revealed that kea in Arthur's Pass village showed a very high level of interest in the non-toxic

a



b

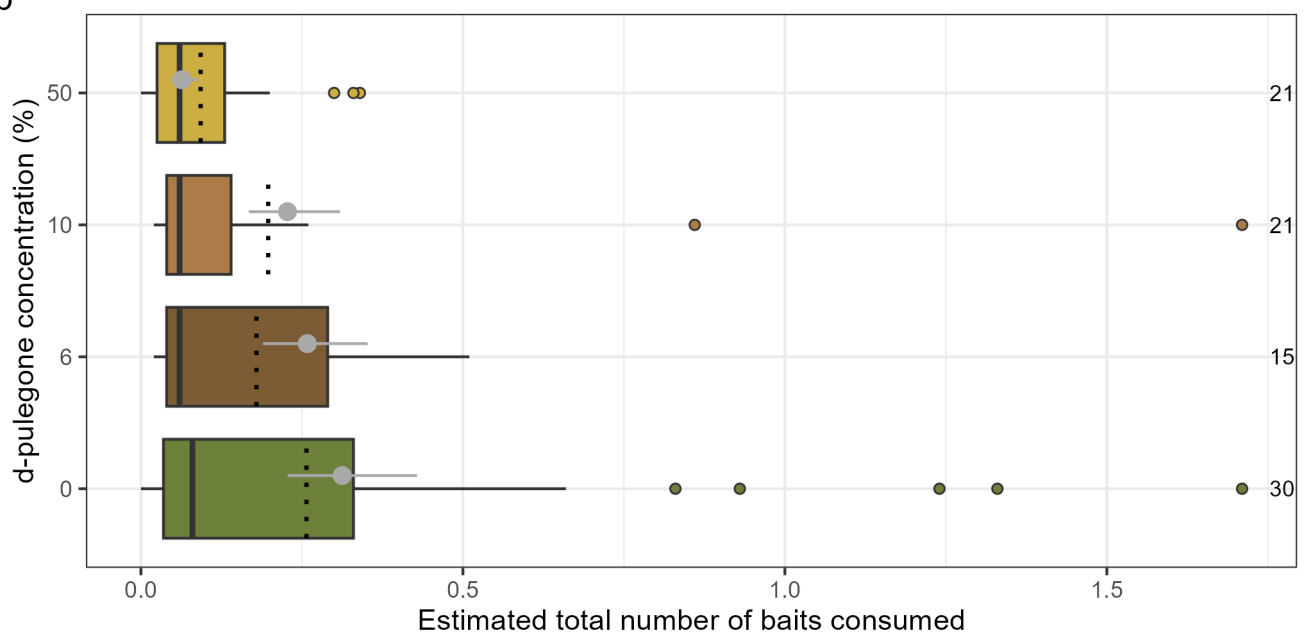


Figure 6. The estimated number of baits consumed by individually identified kea grouped by d-pulegone concentration (a) per interaction and (b) across all sessions in the alpine and control trials. Dashed lines show the number of baits that represent the lower and upper estimates of the potential LD50 for a 900 g kea, based on the consumption of 1.8–4.7 g of bait with 0.15% 1080 loading (Orr-Walker et al. 2012). Numbers to the right of each boxplot indicate the number of banded kea in each group. Grey points and error bars represent the adjusted predictions (± 95% confidence intervals) based on a Poisson mixed model where overlapping error bars indicate no significant difference between treatments.

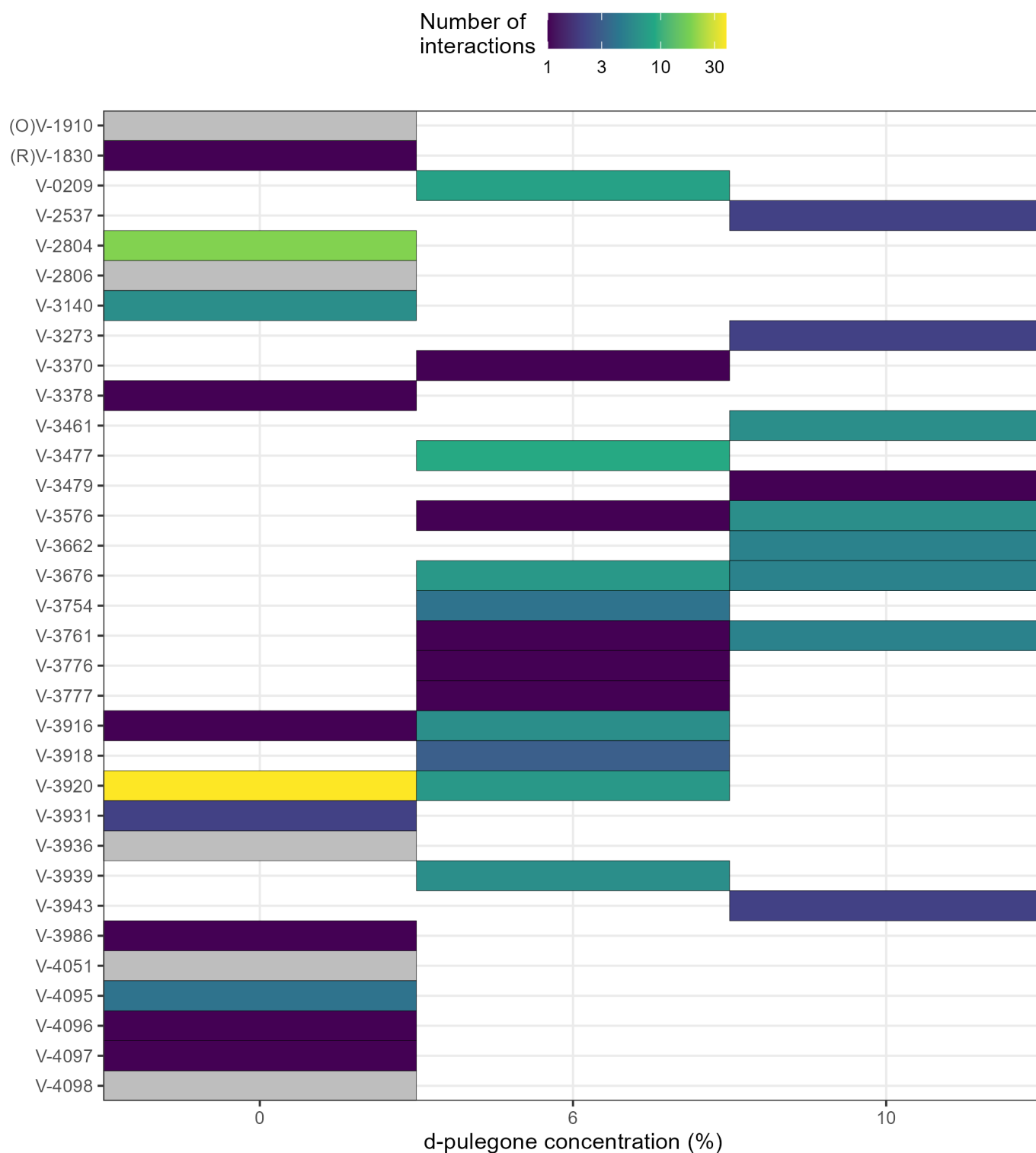


Figure 7. The exposure of 38 banded kea to the alpine (6% and 10%) and control (0%) trials with different concentrations of d-pulegone repellent. The shaded blocks (presented on a log₁₀ scale) indicate the number of times an individual interacted with bait of a given concentration in a given trial, with light grey blocks showing when a bird was present but did not interact with bait. Empty blocks occur when a bird was not observed in a trial.

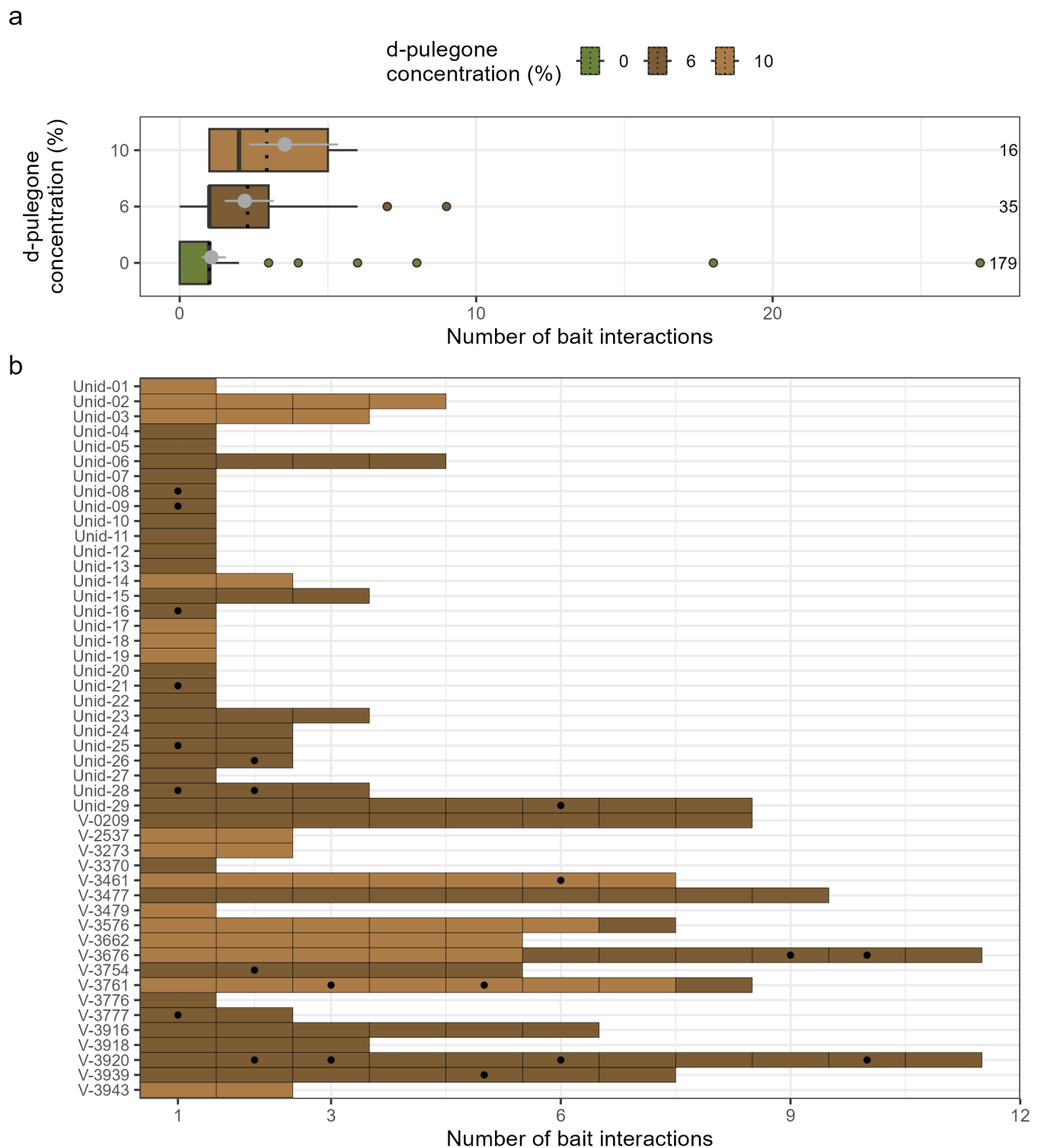
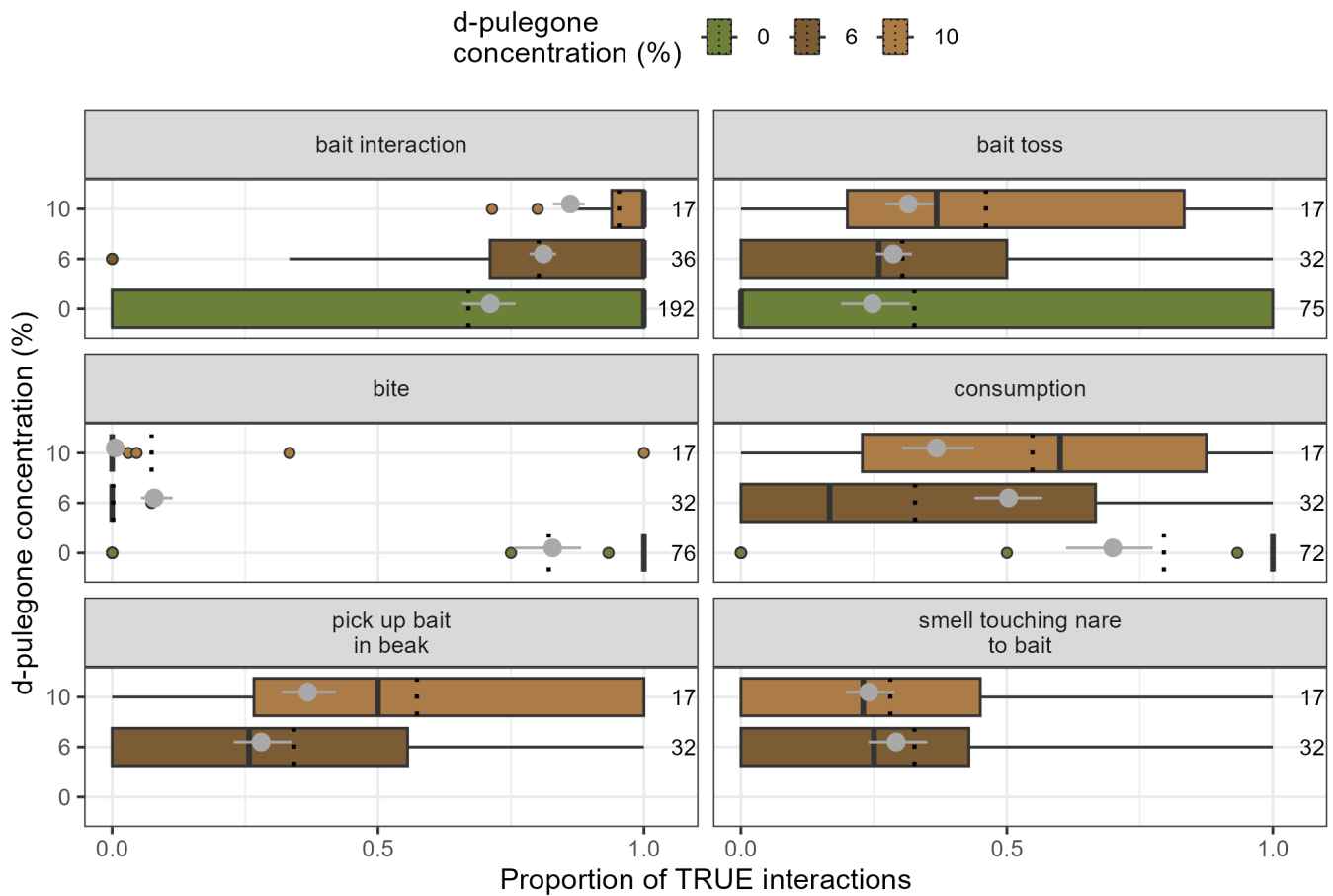


Figure 8. The number of times banded kea were in the presence of bait by (a) d-pulegone concentration across all alpine trials (including the control trial) and (b) the order of exposure to baits with different d-pulegone concentrations for individual identified kea within the d-pulegone alpine trial only. Numbers to the right of each boxplot (in a) indicate the number of identified kea in each class (across all rounds). Black dots (in b) indicate occasions when an individual was in the presence of bait but did not interact with it.

a



b

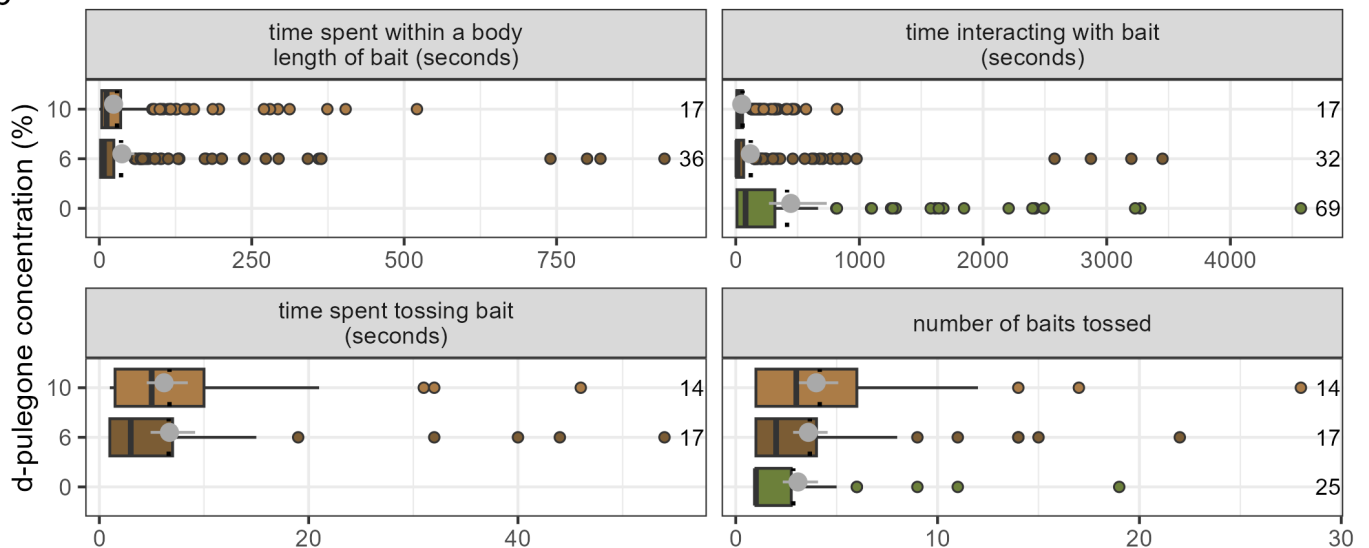


Figure 9. Interactions of identified kea with d-pulegone treated bait by concentration across the alpine and control trials, with (a) the proportion of TRUE interactions observed for individual kea for each behaviour and (b) the duration or number of times interactions were observed. Missing boxplots for 0% d-pulegone for some behaviours occur where these behaviours were not scored for the control trial. Numbers to the right of each boxplot indicate the number of identified kea in each group (across all alpine rounds). Grey points and error bars represent the mean predictions ($\pm$ 95% confidence intervals) based on mixed effects models where overlapping error bars indicate no significant difference between treatments.

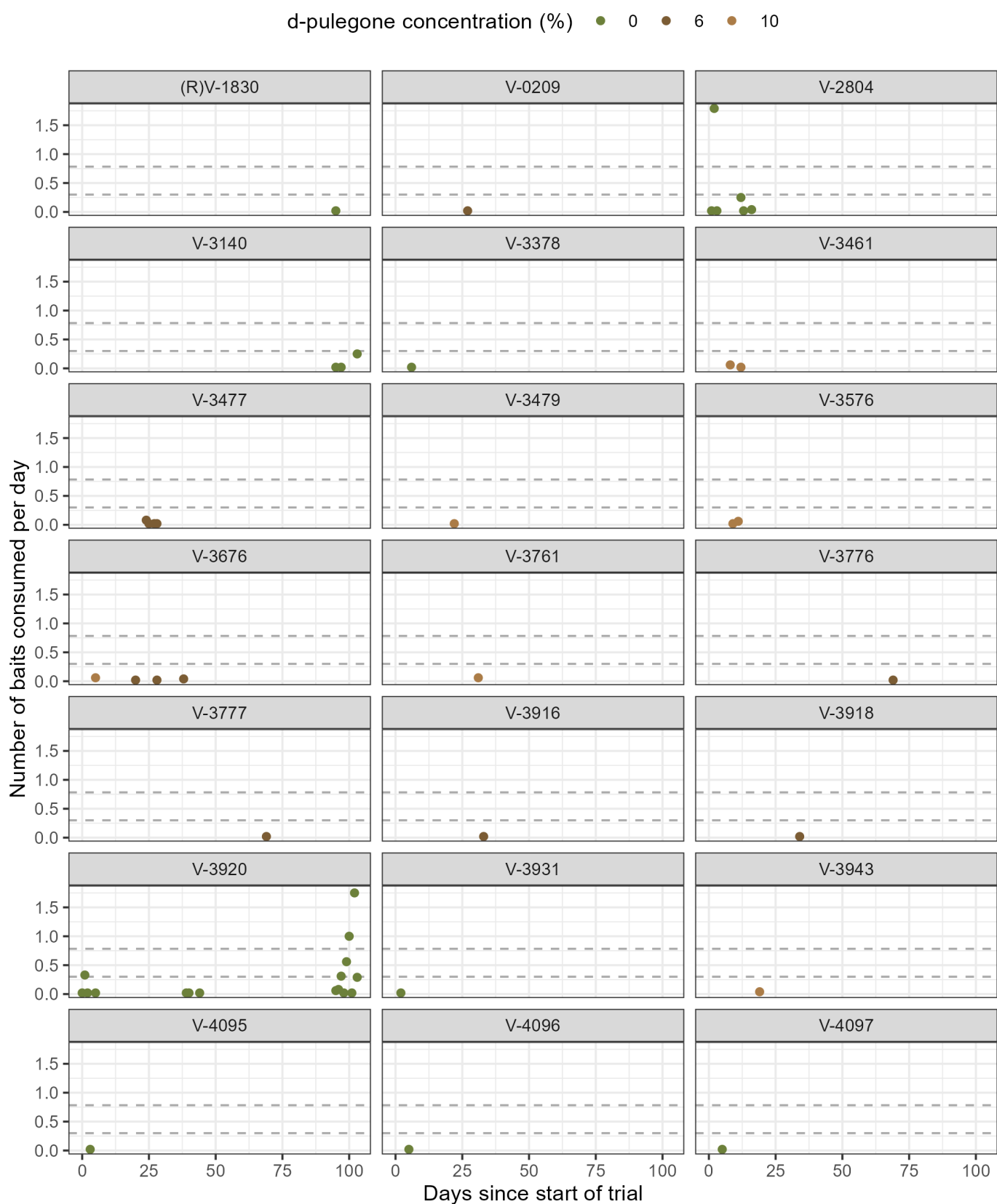


Figure 10. The estimated number of baits consumed per day by individually identified kea (each panel) grouped by d-pulegone concentration across the alpine and control trials. Dashed lines show the number of baits that represent the lower and upper estimates of the potential LD50 for a 900 g kea, based on the consumption of 1.8–4.7 g of bait with 0.15% 1080 loading (Orr-Walker et al. 2012).

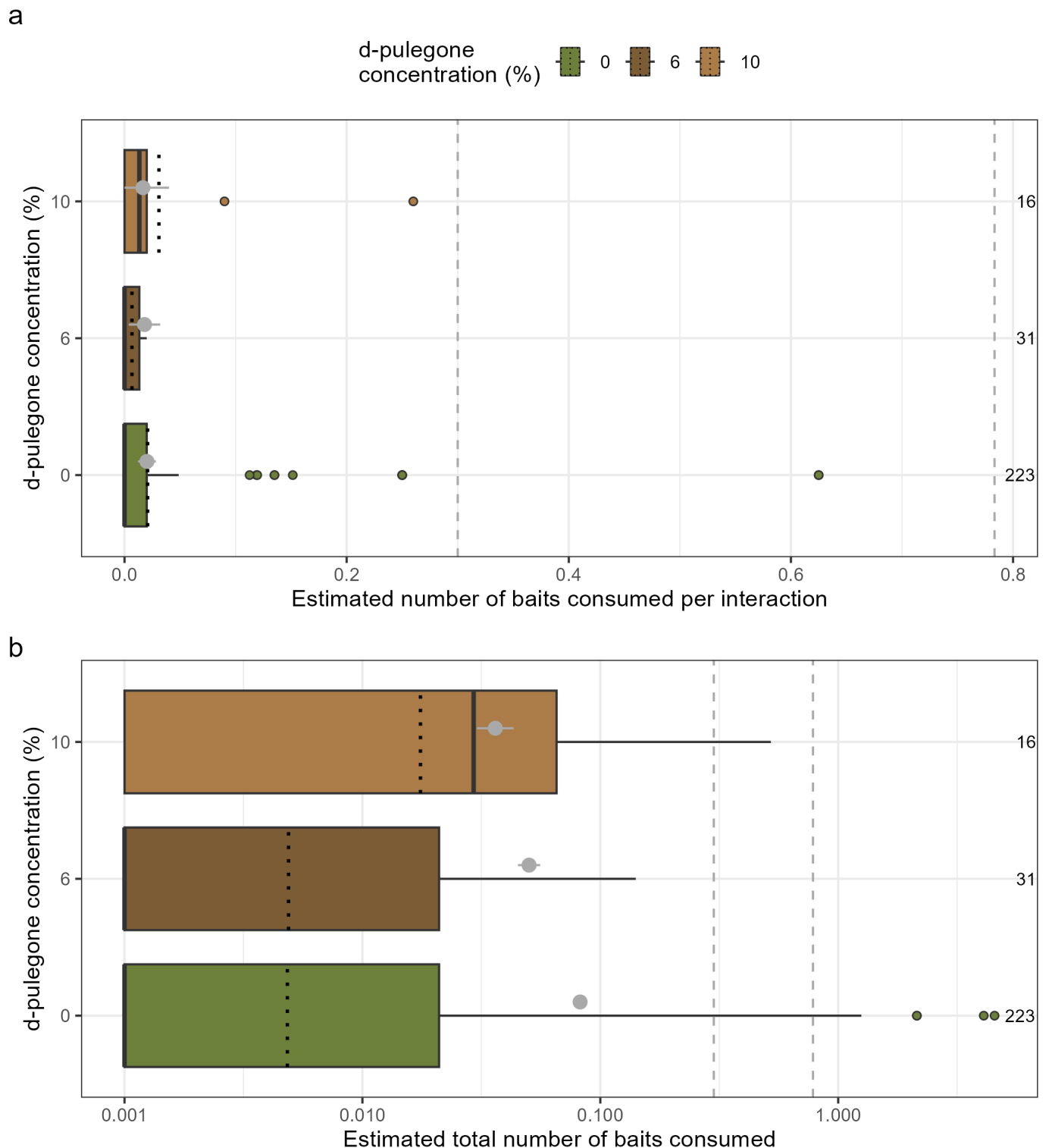


Figure 11. The estimated number of baits consumed during the alpine and control trial by individually identified kea grouped by d-pulegone concentration (a) per interaction and (b) across all sessions (expressed on a log₁₀ scale). Dashed lines show the number of baits that represent the lower and upper estimates of the potential LD₅₀ for a 900 g kea, based on the consumption of 1.8–4.7 g of bait with 0.15% 1080 loading (Orr-Walker et al. 2012). Numbers to the right of each boxplot indicate the number of identified kea in each group. Grey points and error bars represent the mean predictions ($\pm$ 95% confidence intervals) based on a Poisson mixed effects model where overlapping error bars indicate no significant difference between treatments.

green baits across all d-pulegone concentrations, and had high interaction rates with baits overall (i.e. 99% of visits to bait sites resulted in interactions). Where no repellent was present, 30% of Arthur's Pass kea then consumed enough bait to exceed the estimated lower LD50 threshold (see Orr-Walker et al. 2012). Our data aligns with previous studies (Kemp et al. 2019; Cieraad 2024) which state that consumption of 1080 baits by kea is strongly correlated with areas in which kea feeding behaviour has been modified by humans (scrounge sites). However, we caution that the Arthur's Pass choice trial site was specifically chosen for the high kea participation rates required to achieve good sample sizes (as well as having high numbers of banded individuals), and we acknowledge that choice trial results are likely not representative of interaction/consumption rates of wild kea presented with cereal baits.

Interestingly, the choice trials showed that the proportion of interactions with baits increased with increasing d-pulegone concentration (see further discussion on understanding kea responses below), whereas consumption decreased, both in terms of total consumption per individual, and bait consumed per interaction. However, among these human-influenced Arthur's Pass kea, this effect was largely driven by increased interactions and reduced consumption at the highest concentration of d-pulegone (50%), with no significant differences detected between 0%, 6%, and 10% d-pulegone concentrations. Results from the choice trials should provide a worst-case scenario indication of bait interactions and consumption rates of kea classified as scrounge-affected (DOC, 2020). Whilst these choice trials are necessary in building our understanding, we urge caution with these results and note that these are likely not indicative of wider kea populations. Challenges with working in this area also prevailed, with bait trials being disrupted on numerous occasions by some deliberate provisioning of human foods and frequent inclement weather. While the choice trial sessions were designed to be balanced and regular, these factors made achieving that impossible. We detected a potential repellent effect of d-pulegone at 6% and 10% during early observations in the choice trials, prior to beginning the alpine trials. As 6% and 10% are more realistic concentrations to work with operationally (i.e. less likely to repel target species than 50%), it was decided that it was not a priority to further investigate the 50% concentration in the alpine trials.

Lower bait interaction and consumption by wild kea in alpine trials

The alpine trials provide a more realistic indication of responses to and consumption of baits among wild kea whose feeding behaviour is less affected by human food sources. At these alpine sites, consumption of baits was significantly lower when 6% and 10% d-pulegone was added to baits. The proportion of interactions that resulted in consumption was also significantly lower with increasing d-pulegone concentration. Based on overall bait consumption results, even at lower d-pulegone concentrations (6%, 10%) the repellent may be effective for kea in a relatively wild setting. Repellent at the concentrations tested also shows promise for reducing consumption even in individuals that have previously been observed scrounging. This suggests that kea foraging decisions and feeding behaviours are situational and could be site specific. They are also most certainly influenced by past experiences of individuals and any associations they may have had with novel food items including 1080 baits (discussed further below).

Could d-pulegone prevent kea deaths?

Based on these results, baits surface-coated with at least a 6% d-pulegone concentration could have the potential to reduce bait consumption by wild kea at sites classified as scrounge affected (see DOC 2020). Despite considerable interest in baits overall, very small quantities were consumed per interaction, per day, and over the whole trial period for identifiable (banded) kea. At the alpine sites, when considering daily bait consumption per individual, two of the 21 banded kea consumed an amount greater than the estimated lower LD50 threshold for kea; in both of these instances, kea consumed only non-repellent (control) baits. For the 31 banded village kea, eight consumed non-repellent baits in amounts greater than the lower LD50 estimate, and consumption was reduced when repellent was present ($n = 2$ for 6%, $n = 3$ for 10%, and $n = 1$ for 50% d-pulegone baits). It appears as though the presence of a primary repellent does not necessarily deter kea from approaching and interacting with baits, but it may reduce consumption in individuals to a level below the estimated LD50. If this is the case, as our study suggests, then this could lower mortality rates during 1080 operations in susceptible (particularly scrounge-affected) sites. During the 2022 Otira-Taipo and Arthur's Pass West aerial 1080 operations, 1080 related mortality rates of radio-monitored kea were 29% (7 of 24) and 22% (4 of 18), respectively (Young et al. 2025). The use of repellent at high-risk sites such as these could lower the risk to kea while not reducing efficacy against target pests, and could thus significantly reduce kea mortality to below current levels.

A major limiting factor in these types of studies is the fact that it is not possible to determine the amount of 1080 kea must consume to obtain a lethal dose and over what time period. The published estimates for lethal dosing for kea are based on calculations of similar sized Australian parrots (see McIlroy 1984; Orr-Walker et al. 2012) and overall, it is considered that parrots are particularly susceptible (McIlroy 1984). When considering the high kea mortality rates (c. 26% overall) during recent 1080 operations in this area, we should hypothetically observe that, for non-repellent (control) RS5 baits at least, a similar percentage of individuals should consume bait in quantities over the LD50 threshold (i.e. 1.8–4.7 g of a 6 g bait, or 0.3–0.8 of a 6 g bait with 0.15% 1080 loading). However, in this study, only 9.5% (2/21) of individuals at the alpine sites exceeded the lower threshold, suggesting that either the mortality rate should be lower than observed, or that the lower LD50 estimate currently extrapolated from Australian parrots is higher than it actually should be for kea. It is likely the latter is true since the majority of wild kea at scrounge-influenced sites consume significantly less bait than is estimated to be required for 50% of birds to obtain a lethal dose. There is no way to determine this unless studies such as those conducted by McIlroy (1984) are undertaken, which seems unlikely given kea are a fully protected, endangered species.

The challenges of understanding kea behavioural responses to baits and risk

There was an increase in specific types of investigative responses, including attempting to smell the bait (naring) and picking bait up in the beak, with the 50% d-pulegone concentration during the choice trials (compared to responses at lower bait concentrations). However, the duration of time spent interacting with bait (time spent within a body length

of bait) decreased for the 50% d-pulegone baits. These results could suggest that kea attempt an initial brief investigation of the strong repellent due to a large olfactory influence but spend less time lingering after the initial investigation due to a dislike of the smell. Ideally, a repellent, particularly a primary one, should be active via a volatile cue to prevent the bird from sampling or ingestion of the repellent-treated product (Wager-Page & Mason 1996). Recent research using volatile scent-based cues on captive kea at Willowbank Wildlife Reserve shows that d-pulegone was aversive to kea at 25% concentration, supporting our findings that it may be an effective deterrent as an olfactory repellent (XJ Nelson 2023, University of Canterbury, pers. comm.). In European starlings (*Sturnus vulgaris*), exposure to d-pulegone volatiles (i.e. scent only) induced avoidance behaviour, however, surface-coating apples with d-pulegone produced a much stronger response, significantly lowering consumption (Wager-Page & Mason 1996). This suggests that while d-pulegone is moderately effective as an olfactory repellent, it acts more strongly on the taste senses; thus the repellent should be applied such that it can also function as a taste-based repellent for the strongest effect.

At higher d-pulegone concentrations we also observed an increase in behaviours such as tossing baits away and rubbing/wiping the beak after touching baits. These responses may be an act of displeasure after initial interaction with bait. There were very few (< 5) discernible adverse reactions observed throughout the trials, e.g. fluffing up, shaking, gagging, or vomiting. It could be that either this repellent, at the concentrations tested here does not induce any obvious or extreme chemesthetic or gustatory effects in kea, or, that these are not effective immediately and therefore were not captured in this study. Orr-Walker et al. (2012) also observed no adverse effects of d-pulegone-treated baits in captive kea over a seven-day trial. Whether prolonged exposure to d-pulegone has toxic effects in the long term remains unknown (Wager-Page & Mason 1996).

When kea are presented with the secondary repellent anthraquinone, if enough repellent is ingested to induce an emetic response (vomiting, etc.), a learned negative association with the bait should occur to deter them from interacting with similar baits upon future encounters. However, there are many drawbacks to that approach for wild kea and, given evidence from this study and previous trials (e.g. Nichols & Bell 2019; Kemp et al. 2022; Weston et al. 2022; Yockney et al. 2022; Young et al. 2025), it is apparent how little bait wild kea consume overall. This lends further support to the use of a primary repellent to deter kea upon immediate association with bait rather than use of a secondary repellent. Pre-feeding of non-toxic baits is designed to increase the consumption rates of bait by target species, but may also act to increase its attraction for non-target species. Our findings highlight that the foraging decisions being made by kea are likely to be situational and context specific, likely based on their learned experiences with novel food items at a given site. Given the very small quantities of bait consumed by wild kea per interaction in our study, we urge caution with secondary repellents, which require individuals to consume greater quantities of bait. Kea that repeatedly consume low doses of baits with secondary repellents may not be sufficiently repelled, and there is a theoretical risk that they could be subject to a pre-feeding effect, accustoming them to this novel food source (see Young et al. 2025).

An aversion to bait may result from individual experience of a sub-lethal 1080 dose during previous 1080 operations. It

is not possible to determine, for any monitored kea sample, every individual's encounters with, and decisions made to investigate, eat, or avoid toxic cereal pellets through a 1080 operation. However, we do know from the hundreds of hours of trail camera video and still footage captured during this and other related studies (Weston et al. 2022; Yockney et al. 2022; Young et al. 2024; Young et al. 2025), that wild kea do readily approach and investigate baits when they encounter them. This therefore suggests that when kea do encounter baits during a 1080 operation, they are also likely to at least approach, investigate and sometimes consume it. We acknowledge that studies like this could overestimate the frequency of kea encounters with bait given that audio calls were played to attract kea to the site and that bait was presented in higher quantities than in a more realistic scenario (during aerial 1080 operations, baits would be scattered over vast areas at rates of c. 1–2 kg per hectare). If repellents were effective and/or previous sublethal 1080 dosing led to ongoing avoidance of toxic baits following initial exposure, these could both offer potential solutions to mitigate risk to kea during 1080 operations. Historically, 1080 has been used at concentrations of 0.08% rather than current practise (0.15% 1080) and still had high efficacy on possum kill rates (Innes et al. 1995). An option could be to trial this lower concentration 1080 during an operation and measure kea mortality outcomes alongside pest-kill efficacy. Kea clearly have high sensitivity to 1080 and any research that can be undertaken in an attempt to lower the risk is imperative.

Summary and recommendations

We were unable to explore here the reasons why previous d-pulegone trials showed promise as a kea repellent at 0.17% (by weight, interspersed in the bait matrix) (Orr-Walker et al. 2012) and why concentrations of up to 4% (surface coated d-pulegone) did not. After conducting the pilot investigations on Arthur's Pass village kea, we concluded that either wild kea behaved differently than captive or human-adjusted kea in their responses to repellent baits and it took more repellent to produce an effect (see Young et al. (2025) for supporting evidence in similar anthraquinone repellent bait trials) and/or that lower concentrations of surface-coated repellent did not perform in the same manner as when the repellent was interspersed throughout the bait matrix. Baits used for the choice trials were fresh and only ever presented to kea for a maximum of several hours. If effective, this surface-coated version should have greater immediate impact, at least until the surface coating has worn through. Therefore, we assume that if the repellent formulation using fresh, surface-coated baits with some nominal concentration is effective for use with kea, the effects should be reasonably evident. Thus, the decision to move to higher concentrations when a repellent effect was not obvious was justified as a method to determine a minimum suitable concentration to use. It is unlikely that a 50% d-pulegone surface-coated bait would be a realistic option for operational use, as it would also likely deter target species (possums and/or rats) from baits. However, until this is tested it remains unknown.

As a first step towards the operational use of repellent bait, we recommend that the chemical intricacies of the repellent bait manufacture are understood and stability and shelf-life longevity are tested thoroughly before any further work with the repellent baits is carried out on wild animals. We propose testing that the repellent stabilisation processes are adequate by carrying out controlled weathering and degradation trials

to assess whether there is any loss in repellent concentration over time. Future work should also undertake an analysis of the estimated costs required to operationalise d-pulegone including the manufacturing, production, storage, and longevity of d-pulegone treated baits (see Crowell et al. 2016).

We also recommend carrying out pen trials using captive individuals to test the efficacy of this repellent on possums and rats, including at 0%, 6%, 10%, and 50% concentrations. Past work shows that possums are not significantly deterred by the original 0.17% d-pulegone, and rat kill rates remained adequate in field trials where d-pulegone was incorporated into the 1080 bait (Crowell et al. 2016). Pen trials are easier and less resource intensive than field trials and are a sufficient place to start. If an optimal concentration can be found that both maximises the kea repellent effect while not reducing pest control efficacy, then it may be feasible to test those concentrations in future field trials. Such trials should directly determine the efficacy of the repellent through a 1080 operation by measuring kea survival in adjacent sites with and without d-pulegone treated baits and measure pest efficacy outcomes (Crowell et al. 2015).

We note the challenges of offering a short-term repellent to modify kea behaviours, particularly where there may be ongoing access to novel food rewards within the wider setting. A complementary way to prevent kea from investigating and ingesting novel food sources is to remove positive association in the first place. Work to discourage access to human food sources through preventing intentional and incidental access to human foods should remain a priority (Kemp et al. 2019).

Whilst application of a primary repellent for kea may be a useful tool at sites with a higher risk of mortality (e.g. scrounge-affected; Kemp et al. 2019), this approach may not necessarily be beneficial across all operations in kea habitat. Further cost-benefit analysis, incorporating the net benefits to the kea population, financial costs, and potential reductions in operational effectiveness or capacity should be carried out to inform decision making.

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Additional information and declarations

Author contributions: LMY, KAW, IJY, MH, and JWB 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 input from ALW, KAW, MH, IJY, JWB and LMH.

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Supplementary Material

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

Appendix S1. d-pulegone bait trial comparisons showing non-toxic baits tethered to wooden planks and trail cameras mounted behind them.

Appendix S2. Locations of all alpine and control sites surrounding Arthur's Pass.

Appendix S3. The estimated amount of d-pulegone treated bait eaten by individual identified kea across all rounds of the alpine and control trials.

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