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Research Article

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Wild kea response to non-toxic baits with and without deer repellent – implications for management

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ABSTRACT

1080 toxin (sodium fluoroacetate) is used in New Zealand for possum (*Trichosurus vulpecula*) and ship rat (*Rattus rattus*) control but can result in unintentional by-kill of native (e.g. kea *Nestor notabilis*) and non-native (e.g. deer) fauna. A newly developed deer repellent (Prodeer) in 1080 bait has proved highly effective in reducing deer by-kill while not impacting target pest efficacy. The ingredients in Prodeer bait are undisclosed due to commercial sensitivity, thus it is unknown whether this bait type increases acceptability and palatability to kea and increases risk over and above that posed by the standard (RS5) bait type normally used in aerial poisoning operations. During choice trials comparing kea responses to, and consumption of, non-toxic Prodeer and RS5 baits at alpine sites around Arthur's Pass National Park and central Westland we found kea Prodeer and RS5 consumption (per interaction and total) were not significantly different. Most individuals consumed substantially less of both bait types than the estimated lower 1080 LD50 threshold for kea, and vastly less than captive kea consume. We conclude that 1080 operations using Prodeer are unlikely to pose a risk significantly over and above that already presented to kea in standard RS5 1080 operations.

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Introduction

Since the 1960s, 1080 toxin (sodium fluoroacetate) has been used in New Zealand to control possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*) as they pose a significant threat to native biota (Morgan and Hickling 2000). Currently, aerially applied 1080 bait is the most effective means of controlling these target species on a landscape scale (Elliott and Kemp 2016). Though highly effective at removing target species, 1080 operations may result in unintentional by-kill of both native and non-native fauna including the large endemic parrot – kea (*Nestor notabilis*) and deer, particularly red (*Cervus elaphus*), sika (*Cervus nippon*), fallow (*Dama dama*) and whitetail

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(*Odocoileus virginianus*) (Nugent and Yockney 2004; Veltman and Westbrooke 2011; Morriss et al. 2020).

Despite herbivorous ungulates not being intentionally targeted by 1080 operations, deer mortalities occur, sometimes in high numbers (Morriss et al. 2020). This by-kill of deer can be contentious socially, and in some locations, hunter, community and iwi support for the use of 1080 is now contingent on inclusion of a deer repellent to protect game or local food resources. A new deer repellent formula (Prodeer) has been developed by bait manufacturer Orillion, which has been found to be highly effective in reducing by-kill of ungulates (Morriss et al. 2021) while not impacting target pest efficacy (Morriss and Arrow 2018).

Nationally Endangered kea (*Nestor notabilis*) are also at risk from 1080 operations due to their curious nature and omnivorous diet which means they sometimes ingest toxic baits and die (Spurr and Powlesland 1997; Kemp et al. 2019; Young et al. submitted). Unfortunately, however, little is known about the specific 1080 LD50 thresholds for kea specifically, since the estimates are based on Australian parrots of similar body size (McIlroy 1984; Orr-Walker et al. 2012), making it impossible to understand the amount kea must consume for lethal or sub-lethal effects. Aerial 1080 operations in 'kea habitat' must follow the Code of Practice (COP) for Aerial 1080 in Kea Habitat (Department of Conservation (DOC) 2020). This COP contains compulsory Performance Standards designed to minimise the risk to kea populations from aerial 1080 operations. To date, a precautionary approach has been employed (i.e. prohibiting the inclusion of additives, including deer repellent, in 1080 baits) due to the lack of information about how deer repellent affects the palatability of 1080 baits to wild kea, and therefore if or how it alters the level of risk for kea. Kea are known to scavenge directly on ungulate carcasses and readily consume protein via meat, viscera, and other animal parts when it is available (Schwing 2010).

Due to commercial sensitivity, the 'repellent' ingredients in the Orillion Prodeer bait formula have not been reported publicly and it is unclear whether they include any animal or protein-based components. Consequently, it is not known whether this deer repellent formula could enhance palatability to kea and thereby increase the risk relative to the standard (RS5) bait matrix (see DOC 2020). It is known, however, that a previous deer repellent cereal bait formula deployed in New Zealand comprised around 90% of the total ingredients of standard RS5 bait along with the deer repellent material comprising moisture, animal protein and fat. With the addition of deer repellent to the standard pellet mix, the fat content could go from 5% in RS5 to 5.4% in deer repellent bait and protein content could increase from 25% to 34% (DOC 2018).

In an initial feasibility trial of Prodeer bait palatability to captive kea at Willowbank Wildlife Reserve (Christchurch, New Zealand), consumption of both RS5 and Prodeer was high, with individuals consuming a hypothetical lethal dose (LD50) in at least 80% of trial sessions, regardless of bait type (McLean et al. 2022). This result suggested that there was no biologically meaningful difference in consumption between the two bait types because in almost all cases; kea ate more than the minimum needed for a lethal dose (2–4 g of a 6 g cereal pellet with 0.15% 1080; Orr-Walker et al. 2012). However, there are limitations with using captive birds for these studies, and thus, how these results translate to wild kea remains unknown. To date no studies have investigated the palatability of Prodeer bait compared with standard RS5 to wild kea, making it difficult to assess whether Prodeer use (for deer preservation) should be allowed in kea habitat.

Several areas in the South Island within 'kea habitat' (DOC 2020) contain deer herds of special interest to hunters, e.g. Dart, Lake Sumner Recreational Hunting Area (RHA), Rakaia/Wilberforce, and, as such, the appeal to use deer repellent will undoubtedly be ongoing at sites such as these. An increasing awareness of the magnitude and variety of risks kea face in general, including lead poisoning, human conflict, predation and non-target poisoning, has highlighted the need for a better understanding of the palatability of deer repellent baits compared with the standard RS5 bait type generally used in aerial poisoning operations in kea habitat. Thus, investigation of responses to Prodeer by wild kea is crucial for informed management decisions on the use of deer repellent in kea habitat. Here, we investigate the comparative palatability of non-toxic RS5 and Prodeer deer repellent baits to wild kea. Specifically, we assess whether there is any difference in (a) bait interaction rates and behavioural responses of kea when encountering RS5 vs Prodeer baits, and (b) consumption rate and feeding duration between RS5 and Prodeer baits.

Methods

Baits

All baits used in this trial were non-toxic (i.e. not containing 1080) 6 g RS5 cylindrical cereal pellets with a cinnamon lure and dyed green, designed to mimic 1080 cereal pellets that are used operationally. Baits were manufactured by Orillion Ltd (Whanganui, New Zealand). To compare palatability of Orillion's Prodeer-treated RS5 (hereafter 'Prodeer') versus untreated RS5 in wild kea, the two bait types were laid in piles on the ground, freely available to kea. Half the bait piles consisted of Prodeer while the other half did not. The two bait types had no perceivable difference in appearance to the human eye but there were obvious differences in smell. Prodeer had a 'mild rotten animal aroma', smelling like 'blood and bone fertiliser', or 'old socks' while still retaining a hint of cinnamon, while RS5 only had a strong cinnamon scent (authors' pers. obs). The Prodeer formula is not publicly available due to Orillion's IP protection, however, before the trial commenced a third party with advanced veterinary knowledge signed a confidentiality agreement with Orillion, was given access to the ingredients list, and confirmed to the authors that the product contained no ingredients that would be harmful to kea.

Study area

The trial sites encompassed the Kaimata Range and Haupiri and Trent catchments of the Otira-Kaipara Forest Conservation Area, and the Bald Range, Kelly Range, Griffin Range, and Taipo River of the Wanganui/Otira Catchments Conservation Area. All sites were situated outside of Arthur's Pass National Park, to the north and west.

Previous trials in this general area demonstrated there were large enough numbers of kea to provide sufficient visits to the sites to obtain an adequate sample size, and banding efforts in this area for previous trials meant that unique individuals were often able to be identified (see Young et al. accepted). The chosen study areas fall within and adjacent to the Arthur's Pass West and Otira-Taipo 1080 blocks which were both sown in spring 2022. While the possible effects of previous adjacent 1080 operations may have influenced some of the sample kea population (e.g. if the most neophobic individuals remained), some of the study area was outside the 1080-influenced sites and some individuals would not have been exposed to 1080 or previous related trials (see Young et al. accepted). The 1080 blocks were not due to be treated for at least another three years, minimising the risk of kea becoming accustomed to either bait as a possible food source and also reducing the likelihood of bait encounter by non-target species (rats, possums).

Six replicate trials (hereafter referred to as rounds) took place between late July 2023 and early January 2024, with ten sites established in each round. Sites were situated in alpine vegetation communities (most 1500-1750m asl) and chosen based mainly on helicopter landing access and suitable substrate (to allow for the installation of the study equipment). If after two rounds, a site had no kea visits, it was moved, with the remaining sites relocated after three to four rounds, regardless of kea vists. A total of 24 sites used over the study period (see Figure S1).

Site set up

Each trial site contained two subsites of approximately 500 g of non-toxic cereal bait, one Prodeer and one RS5, placed ca. 10 m apart. Each sub-site was monitored with three motion-triggered trail cameras (one Browning Dark Ops BTC-6 XD and two Bushnell Core DS 30PM) that were programmed with different settings to capture bait interactions. These were mounted onto two metal waratah standards, one 1.5–2 m away and one 3–4 m away from the bait pile. A single camera was mounted to the top of the nearer waratah and set to capture video (10 s video, 1 s delay for 24 h), while the farthest stand had one camera mounted at the top set to capture photos (capture number 3, 0.6 s interval), and one camera mounted near the bottom set to capture videos (10 s video, 0.6 s delay). This ensured a good capture range of both wide and close field activity (see Figure S2).

Sites were established on either bare rock or short-statured mat vegetation to avoid taller vegetation from false triggering the cameras. All cameras were set up facing a direction other than north to avoid the glare of the midday sun, which causes videos and photos to appear blurred and unusable for data scoring. An automated audio lure (an amplified 10 watt, 8 Ohm, 5 inch horn speaker – https://www.jaycar.co.nz/8-ohm-5-inch-horn-speaker/p/AS3180) was used at each site to play loud kea contact calls intermittently for five minutes at 6am, midday and 6pm daily. Audio lures were placed a minimum of 5 m from the bait piles, and faced away from the bait to ensure any kea present during the calling period would not be intimidated by the sound. A radio frequency identification (RFID) reader/logger (purpose-built by the Department of Conservation's Conservation Technology team) was placed at each sub-site. Each reader/logger was housed within a kea-proof wooden box and placed in front of the cameras with bait scattered directly in front of the box. If RFID-tagged kea stood within ca. 30 cm of the box, their unique identification number was electronically stored for collection along with the date and time. This increased the chances that every banded kea with an RFID tag could be accounted for over the duration of the trials, even if their identifying leg band was not recorded by the cameras.

Sites were established on the first fine weather window that ensured three consecutive nights of little to no precipitation to ensure adequate time for kea visitation before potential bait degradation. Sites were refreshed every three to six weeks at the beginning of the following available weather window, constituting the beginning of the next round (Figure S3). At each site revisit, fresh RS5 and Prodeer bait was replenished, and old bait was completely removed. Camera batteries and SD cards were replaced, and audio lure and RFID batteries were checked and replaced as required.

All research undertaken was approved by, and undertaken in accordance with, the Department of Conservation's Animal Ethics Committee (DOC-AEC431).

Data analysis

Video camera data were analysed to score kea encounters and interactions with, and consumption of, the baits. The higher-resolution still images and RFID reader data were used to determine presence and unique IDs of banded kea. Additionally, within each session, 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. Results presented below for within-session type analyses (proportion of TRUE interactions, duration of behaviours, bait consumption per interaction) include all uniquely identifiable birds (banded and unbanded) but total bait consumption analysis included only uniquely identified banded birds because it was not possible to estimate consumption by unbanded kea across the entire study duration. 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 in one session (i.e. actual consumption over a 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 = <2%; 2 = 3–25%; 3 = 26–50%; 4 = 51–75% and 5 = 76–100% of one bait.

Behaviours and bait interactions by individual kea were classified into three types of 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 exposure) was also generated to represent the presence of any observed interaction with bait. Five behaviours (shaking head, beak rubbing, fluffing or shaking, gagging, vomiting) were recorded but excluded from analyses as they were observed in less than 5% of interactions (i.e. there were insufficient data points to analyse). In addition, the *touch bait on beak* behaviour was excluded from the analyses as this behaviour was observed on all but one occasion.

The potential bait consumption per interaction was calculated for each uniquely identified bird by summing the amount of each bait type consumed by 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 = 0.76–1 (maximum consumption of 100% of a bait). We also calculated the total amount of

Table 1. Recorded behavioural responses of kea to the presence of bait in the Prodeer bait trial, with the number of observed interactions. 'Yes' indicates which responses had sufficient data for subsequent analyses.

Variable	Number of interactions	Included in analyses
(a) *Presence of behaviours (proportion)*		
Present in area approaching bait	521	Yes
Touch bait on beak	410	
Potential consumption	376	Yes
Bite	349	Yes
Consuming bait	319	Yes
Bait in mouth	214	Yes
Tossing bait	90	Yes
Bait residue on beak or in mouth	72	Yes
Shaking head	27	
Beak rubbing	14	
Fluffing shaking	1	
Gagging	1	
Vomiting	0	
(b) *Duration of behaviours (seconds)*		
Time spent interacting with bait	386	Yes
Time spent chewing or biting bait	338	Yes
Time spent consuming bait	303	Yes
(c) *Number of bait interactions (count)*		
Number of bait exposures	521	Yes
Number of baits tossed	89	Yes
Bait consumption per interaction	303	Yes
Total bait consumption	171	Yes

bait consumed by each banded individual over the trial period by summing their bait consumption across all rounds.

We analysed kea interactions and behavioural responses to fresh baits compared with weathered baits to assess whether there were any differences associated with bait condition, e.g. in relation to any changes in texture or Prodeer repellent concentration associated with weathering, degradation or moisture content. Before baits had been affected by any moisture (including drizzle, rainfall or snow) to make them appear visibly softer and swollen on camera they were classified as 'fresh', while baits that were visibly moistened were classified as 'weathered'.

We used logistic mixed effects models to determine whether the proportion of times kea performed each behavioural response (Table 1a) varied by bait type and/or bait condition. 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. Round and site were included as random effects.

We used generalised linear mixed effects models (Gamma family with a log link) to assess whether bait type and/or bait condition influenced the duration of observed behaviours (Table 1b) or the number of bait interactions (Table 1c). A small constant (0.001) was added to all values to allow inclusion of zero values, while round, site and bird were included as random effects.

All data analyses were conducted using R 4.4.0 (R Core Team 2024). Models were fitted using the 'lme4' package (Bates et al. 2015), with the mean (± 95% confidence intervals) model predictions for each bait type calculated using a Wald z-distribution approximation with the 'ggeffects' package (Lüdecke 2018).

Results

Bait interactions

Twenty-three identified banded kea were observed across all six rounds of the Prodeer bait trials (Figure 1). Of these, fifteen banded individuals were only present in one round, while three, four and one individual(s) were present in two, three and four rounds, respectively. The greatest number of banded kea was present in round one, with 16 individuals observed. In comparison, between two and eight banded individuals were observed in rounds two to six.

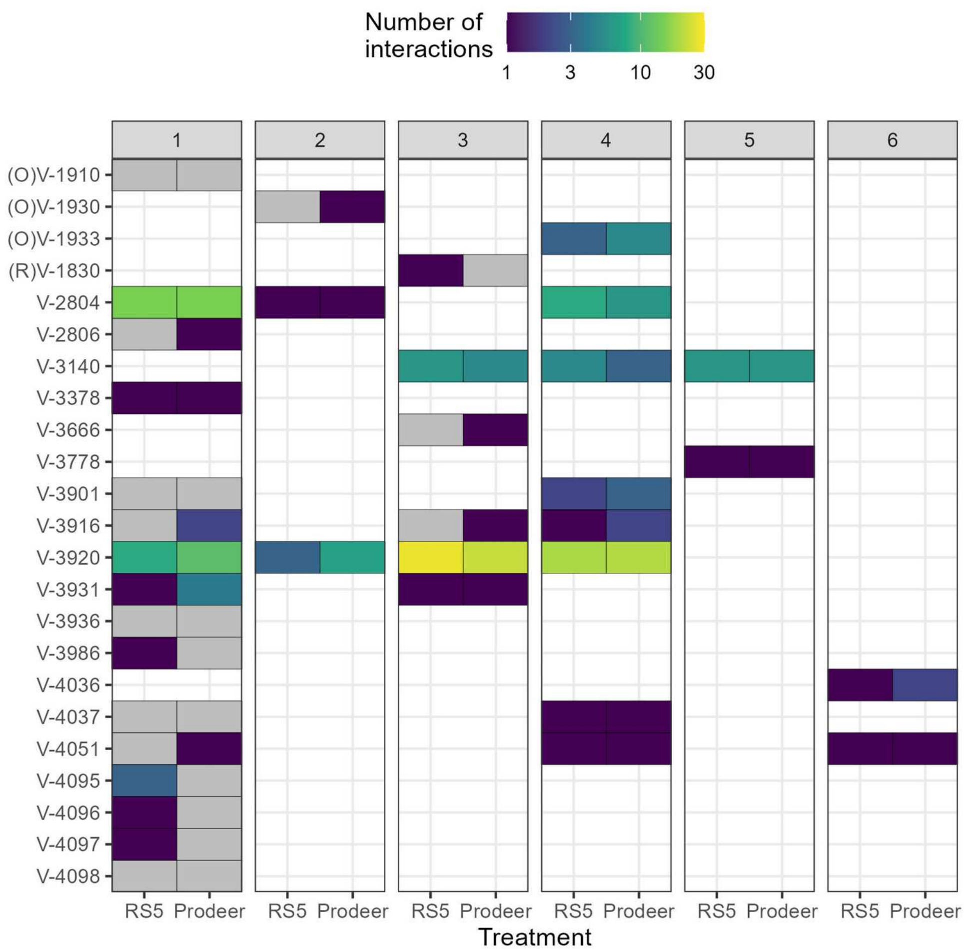

Figure 1. Interaction of 23 individual kea (identified by their metal V-band number) to six rounds (vertical columns) of exposure to different bait types. The shaded blocks indicate the number of times an individual interacted with each bait type in a given round, with light grey blocks showing when a bird was present but did not interact with bait. Empty blocks occur when a bird was not observed in a trial.

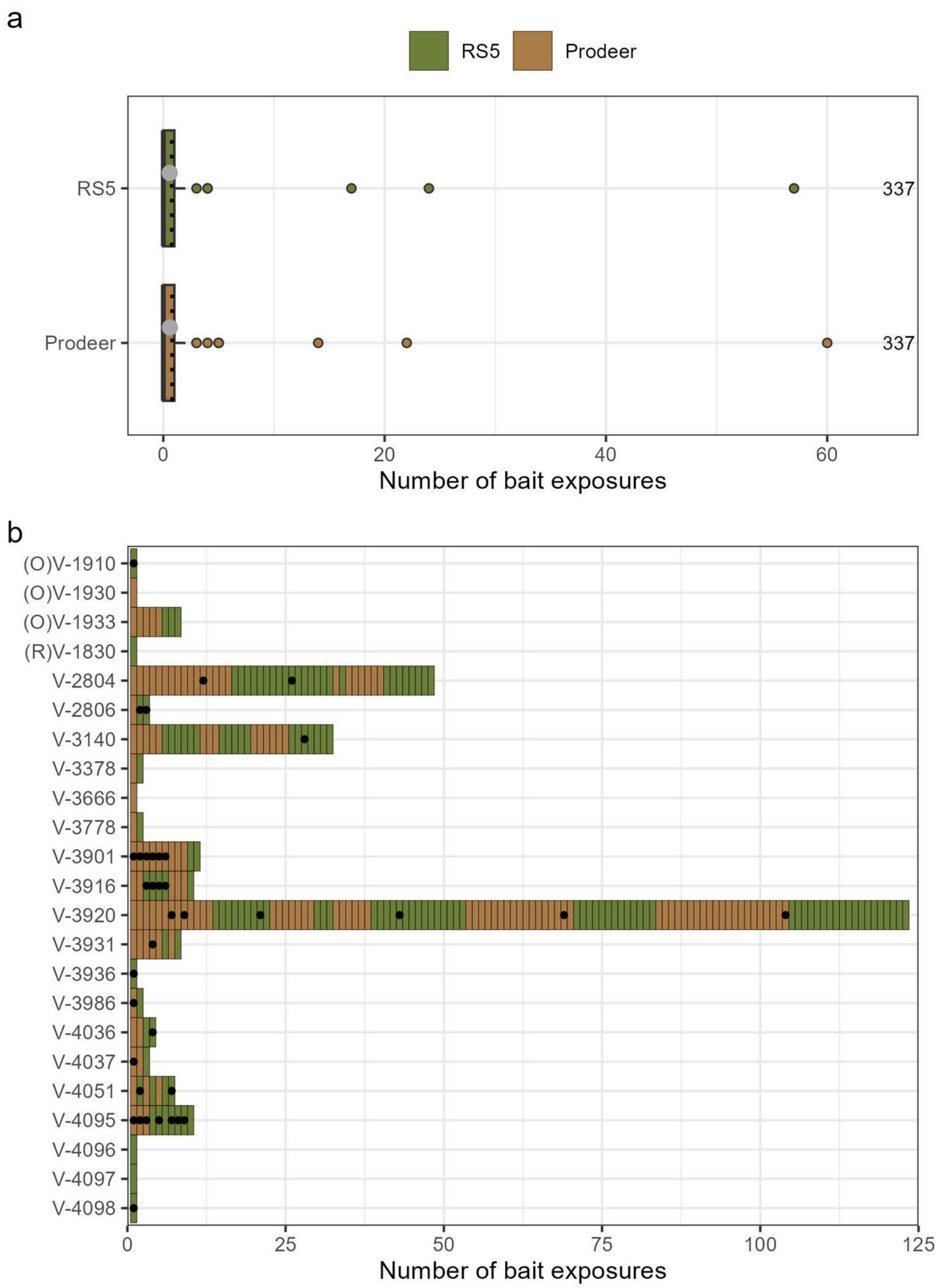

Figure 2. Number of times kea were (a) in the presence of different bait types and (b) the order of exposure to different bait types for individual banded kea (identified by their metal band number). Numbers to the right of each boxplot (in a) indicate the number of uniquely identified kea in each class (across all rounds). Grey points and error bars represent the mean predictions (± 95% confidence intervals) from mixed effects models. 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 range are indicated as points.

Across all rounds, individually identified kea were observed in the presence of bait on 720 occasions, with birds approaching bait 72.4% of the time irrespective of the bait type. Five banded individuals ((O)V-1910, V-3901, V-3936, V-4037 and V-4098) were present in the bait trials but were never observed approaching bait of any type (as depicted by grey blocks in Figure 1). Five banded individuals ((R)V-1830, V-3986, V-4095, V-4096 and V-4097) were observed in the presence of Prodeer bait but never approached it, while six banded individuals ((O)V-1930, V-2806, V-3666, V-3916, V-3916 and V-4051) never approached RS5 bait despite being observed in its presence.

We found no evidence that bait type affected the number of times that identified kea interacted with bait (Figure 2a, Table 2). In addition, the order in which banded kea were exposed to different bait types did not appear to influence the likelihood that they would interact with it (Figure 2b).

Bait type did not significantly affect the proportion of times that kea performed any of the recorded behaviours (Figure 3a). Model predictions showed that, on average, identified kea approached RS5 bait 72% of the time (95% prediction interval: 54%–85%) compared to 76% (59%–88%) for Prodeer bait. Tossing baits of either type was observed infrequently, with identified kea tossing RS5 and Prodeer-treated bait 20% (11%–33%) and 25% (15%–40%) of the time, respectively. Kea were observed to have bait in their mouth between 51% (44%–58%) and 58% (51%–65%) of the time for RS5 and Prodeer bait, respectively. However, kea were frequently observed with bait in their mouths, with 77% and 70% of identified birds observed biting or consuming bait every time that they encountered it. On average, kea were observed biting bait 89% of the time that they were exposed to it, irrespective of bait type (RS5: 75%–96%, Prodeer: 77%–96%). Similarly, kea were observed consuming bait 89% of the time, with no difference between bait type (RS5: 68%–97%, Prodeer: 67%–97%). In contrast, individuals were rarely observed with bait residue on their beaks or in their mouths, with this behaviour occurring 8% (3%–21%) and 9% (3%–24%) of the time with RS5 and Prodeer-treated bait, respectively.

Individually identified kea spent a significantly longer amount of time interacting with and consuming Prodeer bait than they did with RS5 baits (Fig. 3b, Table 2).

Table 2. Outputs from mixed effects models relating the bait type to observed behaviours of kea. Behaviours where there is a significant effect (at $\alpha = 0.05$) are highlighted in green. The mean (± SE) standardised beta value provides the estimated direction and strength of the relationship, where significant positive values indicate that kea were more likely to interact with Prodeer bait.

Response type	Behaviour	β	Z statistic	*P*-value
Number of interactions	Bait interactions	0.035 ± 0.087	0.397	0.691
Proportion of TRUE interactions	Present in area approaching bait	0.196 ± 0.198	0.989	0.323
	Bait in mouth	0.266 ± 0.203	1.308	0.191
	Bait residue on beak or in mouth	0.180 ± 0.283	0.635	0.526
	Tossing bait	0.310 ± 0.257	1.208	0.227
	Bite	0.131 ± 0.347	0.378	0.706
	Consuming bait	−0.053 ± 0.337	−0.159	0.874
Duration of behaviour (seconds)	Time spent chewing or biting bait	0.187 ± 0.122	1.532	0.126
	Time spent consuming bait	0.333 ± 0.131	2.536	0.011
	Time spent interacting with bait	0.410 ± 0.172	2.391	0.017
Number of baits	Baits tossed	0.033 ± 0.181	0.180	0.857
	Bait consumption per interaction	0.257 ± 0.147	1.744	0.081
	Total bait consumption	0.095 ± 0.446	0.213	0.832

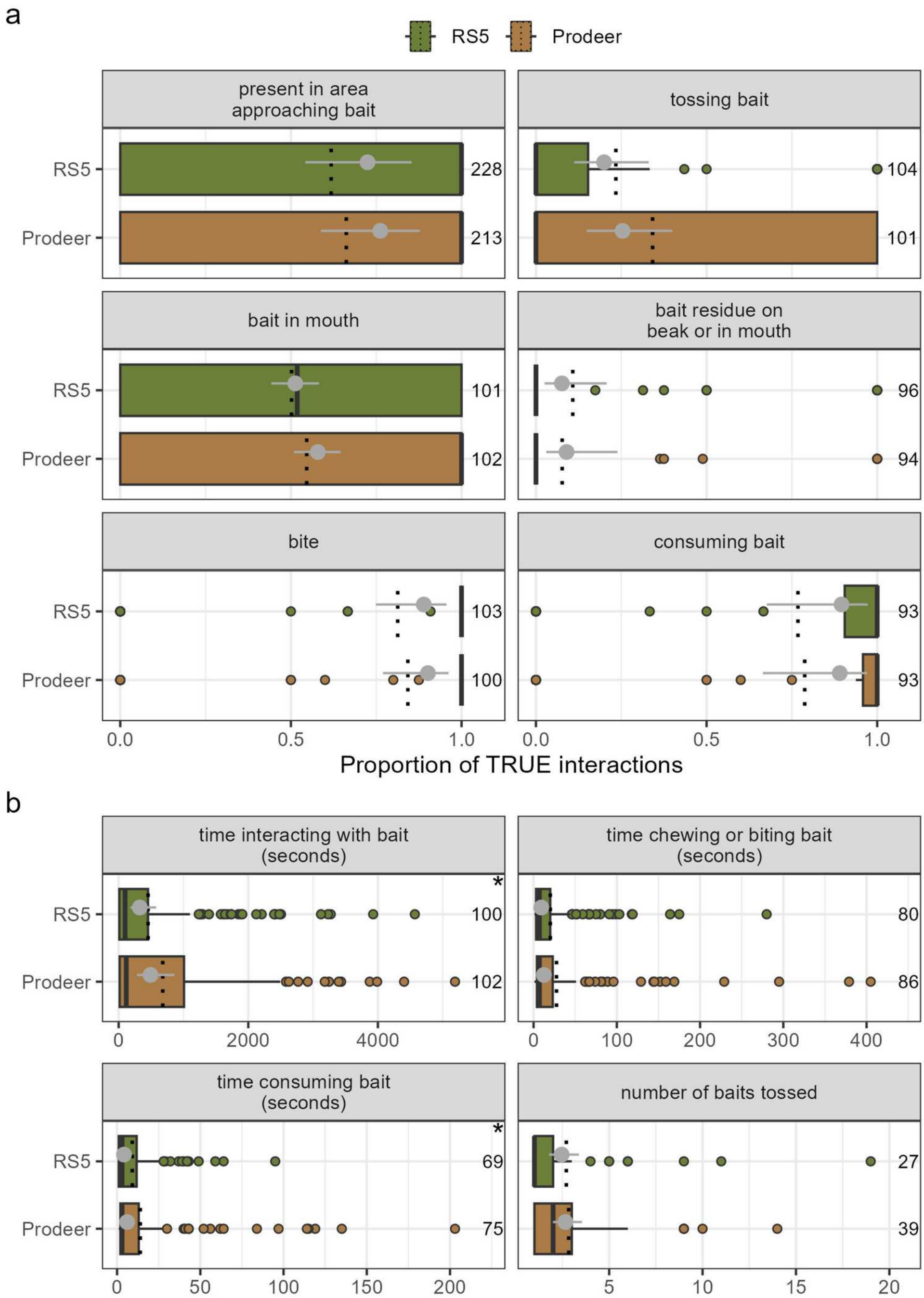

Figure 3. Interactions of uniquely identified kea with different bait types, with (a) the proportion of TRUE interactions observed for individual kea for each behaviour and (b) the duration or number of times interactions were observed. Numbers to the right of each boxplot indicate the number of identified kea in each class (across all rounds), while significant differences between treatments are indicated by asterisks in the top right corner of panels (Table 2). Grey points and error bars represent the mean predictions (± 95% prediction intervals) from mixed effects models.

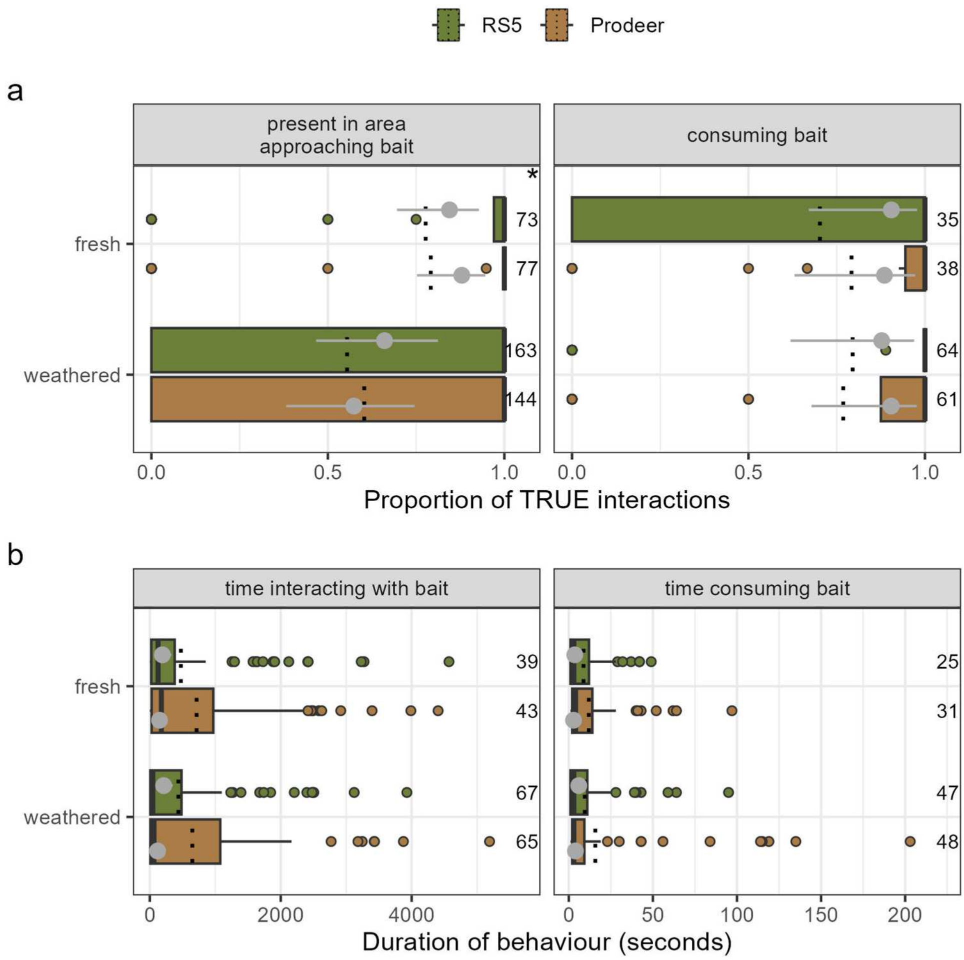

Figure 4. Effects of bait condition and bait type on (a) the proportion of TRUE interactions observed for individual kea for each behaviour and (b) the duration of time individual birds performed behaviours. Numbers to the right of each boxplot indicate the number of identified kea in each class (across all rounds), while significant differences between fresh and weathered baits are indicated by asterisks in the top right corner of panels (Table 3). Grey points and error bars represent the mean predictions (± 95% prediction intervals) from mixed effects models.

Table 3. Model outputs for mixed effects models relating the bait type and condition to observed behaviours of kea. Model terms where there is a significant effect (at α = 0.05) for a given behaviour are highlighted in green. The mean (± SE) standardised beta value provides the estimated direction and strength of the relationship, where significant positive values indicate that kea were more likely to interact with Prodeer bait.

Behaviour	Term	Beta	z-score	*p*-value
Present in area approaching bait	Treatment – Prodeer	−0.294 ± 0.378	−0.778	0.436
	Bait condition – weathered	−1.691 ± 0.342	−4.944	<0.001
	Treatment – Prodeer × Bait condition – weathered	0.663 ± 0.450	1.473	0.141

(*Continued*)

Table 3. Continued.

Behaviour	Term	Beta	z-score	*p*-value
Consuming bait	Treatment – Prodeer	0.209 ± 0.496	0.42	0.674
	Bait condition – weathered	0.201 ± 0.497	0.405	0.686
	Treatment – Prodeer × Bait condition – weathered	−0.484 ± 0.671	−0.721	0.471
Time consuming bait	Treatment – Prodeer	0.230 ± 0.190	1.213	0.225
	Bait condition – weathered	0.339 ± 0.208	1.631	0.103
	Treatment – Prodeer × Bait condition – weathered	0.176 ± 0.272	0.649	0.517
Time interacting with bait	Treatment – Prodeer	0.257 ± 0.239	1.074	0.283
	Bait condition – weathered	−0.225 ± 0.267	−0.841	0.401
	Treatment – Prodeer × Bait condition – weathered	0.324 ± 0.345	0.937	0.349

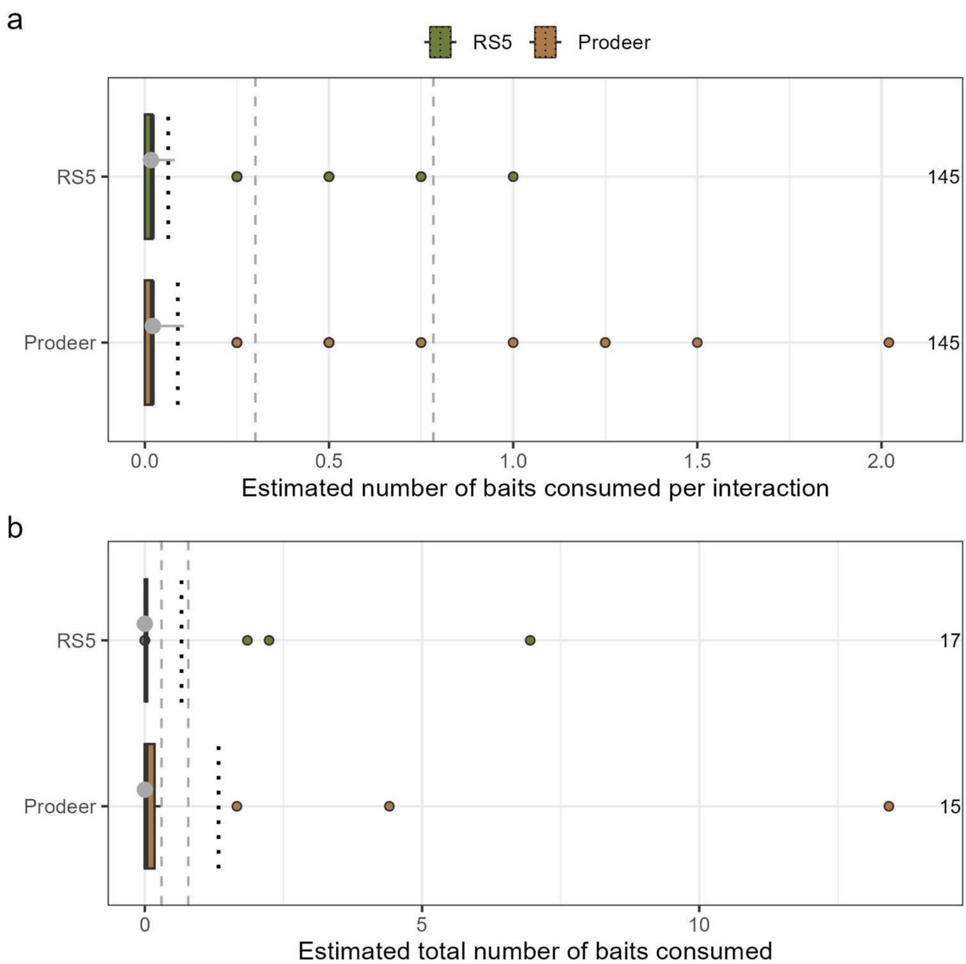

Figure 5. Estimated (a) bait consumption per interaction by uniquely identified kea and (b) total bait consumption across all rounds by banded kea for each bait type. Dashed lines show the number of baits that represent the lower and upper estimates of the potential LD50 for a 900 g kea based on the 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 box plot represent the number of uniquely identified kea and banded kea in panels a and b, respectively. Grey points and error bars represent the mean predictions (± 95% confidence intervals) from mixed effects models (Table 2).

On average, kea were observed interacting with RS5 baits for 325 s (183–577 s) compared to 492 s (281–860 s) for Prodeer baits. While the time that kea spent consuming Prodeer bait (6.0 s; 3.4–10.8 s) was also significantly longer than that observed for RS5 bait (4.2 s; 2.3–7.4 s), the actual length of time spent performing this behaviour was relatively short. We did not detect significant differences in the length of time that kea spent chewing or biting bait nor in the number of baits tossed.

Bait condition significantly affected the proportion of times that individual kea approached bait (Fig. 4, Table 3), with kea more likely to approach fresh bait (0.88 ± 0.45 vs 0.57 ± 0.40). There was no evidence that bait condition influenced the proportion of interactions where kea consumed bait nor the time that they spent interacting with or consuming bait (Figure 4, Table 3).

Bait consumption

Consumption of bait was observed in 58% of bait interactions. However, the amount of bait consumed per interaction did not vary significantly by bait type, with individually identified kea consuming 0.017 ± 0.809 (0.003–0.082) RS5 baits per interaction compared to 0.022 ± 0.810 (0.004–0.106) Prodeer baits (Figure 5a, Table 4).

Table 4. Estimated amount of bait eaten by banded kea across all rounds of the Prodeer trial, with individuals shown in decreasing order of the total amount of bait consumed. Columns from left to right reflect the number of times an individual identified 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 of each repellent concentration. Shading indicates where, over the whole trial period, an individual 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	Number of bait interactions	Number of times bait consumed	% of bait interactions resulting in consumption	Total bait consumed	Prodeer	RS5
V-3920	117	97	82.9	20.37	13.42	6.95
V-2804	46	32	69.6	6.65	4.41	2.24
V-3140	31	21	67.7	3.51	1.66	1.85
(O)V-1933	8	4	50	0.31	0.29	0.02
V-3916	6	3	50	0.06	0.06	0.00
V-3931	7	3	42.9	0.06	0.04	0.02
V-4037	2	2	100	0.04	0.02	0.02
V-2806	1	1	100	0.02	0.02	0.00
(R)V-1830	1	1	100	0.02	0.00	0.02
V-3778	2	1	50	0.02	0.00	0.02
V-4051	5	1	20	0.02	0.00	0.02
V-3666	1	1	100	0.02	0.02	0.00
V-4096	1	1	100	0.02	0.00	0.02
V-3378	2	1	50	0.02	0.00	0.02
V-4095	4	1	25	0.02	0.00	0.02
V-4097	1	1	100	0.02	0.00	0.02
V-3986	1	0	0	0.00	0.00	0.00
V-4036	3	0	0	0.00	0.00	0.00
V-3901	5	0	0	0.00	0.00	0.00
(O)V-1930	1	0	0	0.00	0.00	0.00

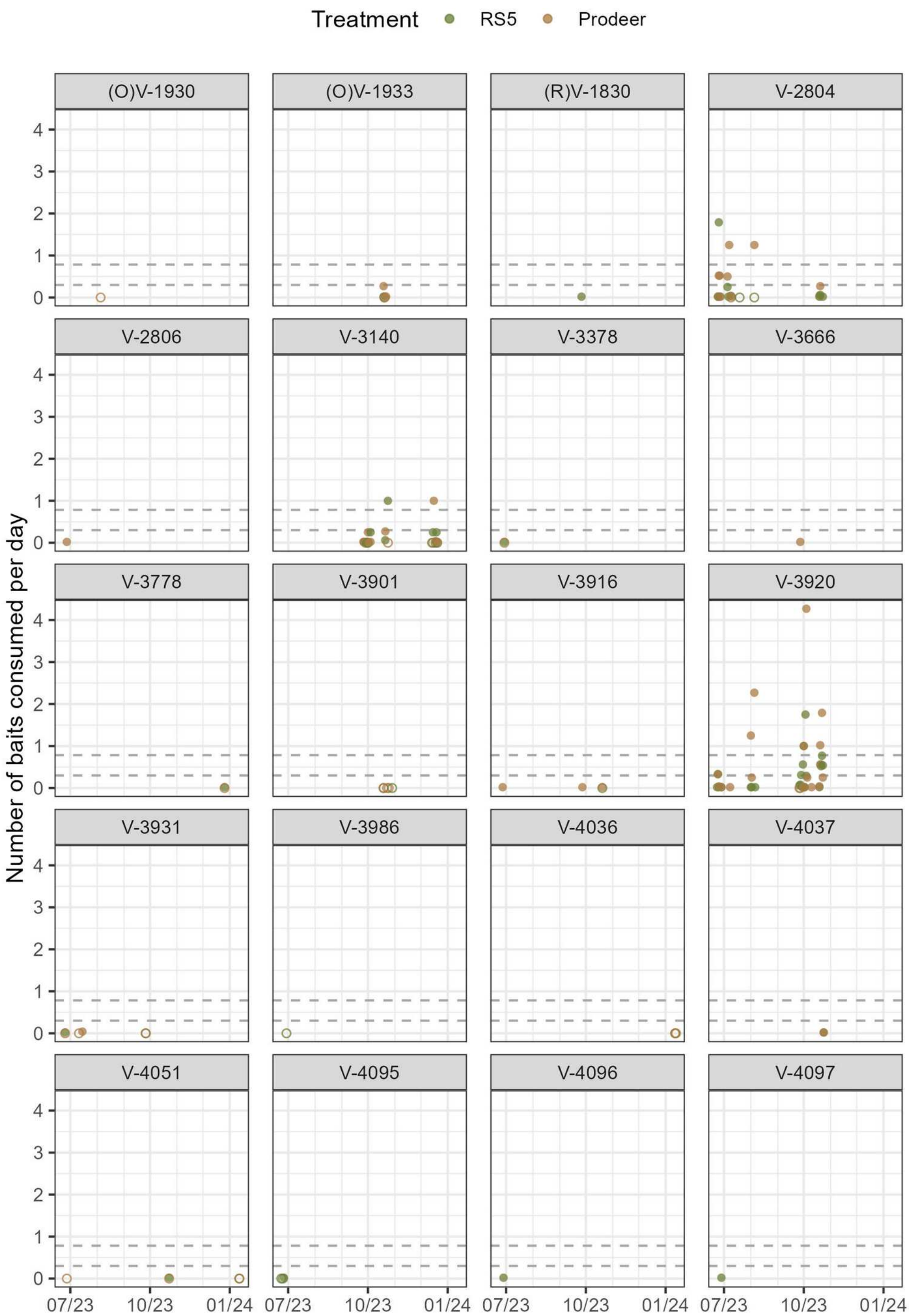

Figure 6. Estimated number of baits consumed per day by banded kea (each panel) grouped by bait type across the trial period. Hollow circles indicate occasions when an individual interacted with a given bait type but was not observed consuming any bait. Dashed lines show the number of baits that represent 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).

Individual kea consumed greater than the lower LD50 limit during one interaction on 29 occasions, with the maximum amount of bait consumed in one interaction being 2.02 baits (i.e. 12 g of bait) (Figure 5a). This behaviour was observed in three banded birds (V-2804, V-3140 and V-3920 – Table 4), as well as four unbanded but uniquely identified individuals.

Overall, 80% of banded kea that interacted with bait was observed consuming it on at least one occasion, with the total bait consumption per bird across the trial period ranging from 0.00–6.95 RS5 baits and 0.00–13.42 Prodeer baits (Table 4, Figure 5b). Bait type was not significantly associated with total bait consumption by banded birds across the trial period (Table 4). Ten banded individuals consumed bait on just one day (Figure 6), while one individual (V-3920) consumed bait over 97 interactions on 25 days and consumed over 20 baits in total (Table 4). Three banded individuals (V-2804, V-3140, V-3920) consumed greater than the lower and upper estimates of 1080 LD50 (0.3 and 0.8 baits, respectively) on a single day (Figure 6), with this behaviour observed for both bait types (Table 4). However, most banded individuals consumed 0.04 or fewer baits per day ($\leq$0.24 grams) and 0.31 baits or fewer ($\leq$1.84 grams) over the whole trial period.

Discussion

Overall, there was no statistically significant difference in the effect of bait type on any of the behavioural responses measured, including number of interactions, approaches to and touching baits. Importantly, there was no significant difference in the amount of bait consumed per interaction nor for total bait consumption for known (banded) individuals. Generally, only very small quantities of bait were consumed per interaction, with most interactions resulting in an amount less than the lower estimated LD50 threshold for kea.

For banded kea, bait acceptability was moderate for both bait types, with nine and 13 of the 20 banded birds eating some quantity of Prodeer and RS5 respectively (and six kea eating some of both bait types). Overall, bait palatability was similar between the two bait types – i.e. for known, banded kea whose overall bait consumption could be accounted for over the course of the trial period, cumulative total bait amount consumed was generally low, however, three banded individuals consumed greater than the lower LD50 estimate. All three individuals consumed both Prodeer and RS5 bait types at these higher quantities (> LD50 lower threshold estimate of 0.3 baits) on multiple occasions. Incidentally, one kea ate more than 20 baits, consuming twice the number of Prodeer baits as RS5, and another consumed nearly seven baits, with twice as much Prodeer consumed than RS5. For the two individual kea that ate substantially more bait than most, both consumed significantly more than the estimated upper lethal dose regardless of bait type. This suggests that a small proportion of individuals in a population may always exceed the LD50 uptake, regardless of bait type, and would have died in an operational situation whether Prodeer was used or not. All other kea consumed much smaller bait quantities over the trial period but either at similar rates for both types or a negligible amount of either one or the other. Both acceptability and palatability of baits are important aspects to understand when considering risk to kea during 1080 operations and our results suggest that differences between the bait types are negligible for the majority of the population.

Because this is the first study where non-toxic RS5 1080 bait mimics without a kea repellent additive have been presented to wild kea, the 1080 LD50 topic is worthy of further discussion. This study provides the most realistic insight (to date) of how wild kea, at least at 'scrounge influenced' sites (see DOC 2020), might respond when they encounter 1080 baits, how much they might realistically consume, and how this might translate to mortality outcomes during 1080 operations. Our results show that, regardless of bait type, most individuals consume minute quantities, lower than the suggested lower LD50 estimate (see Orr-Walker et al. 2012) yet a higher-than-expected mortality outcome occurs (Young et al. accepted). One possibility is that the LD50 for kea is lower than the current estimate (see Young et al. accepted and Young et al. submitted).

It is not clear, given the LD50 for kea are simply estimated based on Australian parrots of similar body size (McIlroy 1984; Orr-Walker et al. 2012), what the actual 1080 LD50 thresholds are for kea specifically, whether the timing and amount of ingestion matters, and if and how other factors e.g. age, sex, weight, hunger levels, play a role. Whether the effects of 1080 in kea are cumulative over a matter of hours, days or weeks of ingestion is also not known. In this study we investigated bait consumption per interaction (i.e. a best-case scenario if a kea only ever consumes toxic bait once), daily bait consumption and the total 1080 consumption over the trial period (worst case) for banded individuals. In the latter scenario, if detrimental impacts of 1080 in the body are cumulative over a longer time period, then this metric is worthy of further investigation. McIlroy (1984) reported the susceptibility of 48 Australian bird species to 1080 poisoning and found for these species that there was wide variability in both the time until signs of poisoning appear (i.e. 1–60 h and up to 2.5 days) and the time until death (i.e. 1–262 h or up to 11 days). Parrots were also highly sensitive to 1080 compared with other bird groups (McIlroy 1984). Our findings therefore suggest it is entirely feasible to consider that if kea hypothetically consume sub-lethal doses of 1080 over the course of several weeks, and if this consumption occurred every few days, then a cumulative dose in the longer term could certainly be lethal. Also feasible is that a sub-lethal dose could lead to bait aversion if the dose induces negative symptoms in a short enough timeframe that kea associate the ill effects with the bait and do not resume consumption after initial exposure (see Young et al. submitted).

Kea spent significantly longer interacting with Prodeer baits compared with RS5 baits (average of 492 vs 325 s for Prodeer and RS5, respectively) although the percentage difference in the two durations was small. To humans, Prodeer clearly has a different smell compared with RS5 cereal baits (see Methods), however, it is unclear if and how this difference is detected by kea. It is possible that the Prodeer smell was more attractive thus leading to significantly longer periods of interaction. Alternatively, Prodeer may be more novel to kea compared with RS5 baits. Many of these kea have potentially been previously exposed to repellent baits during recent d-pulegone (Young et al. submitted) and anthraquinone (Young et al. accepted) repellent trials in the area, as well as during previous 1080 operations in spring 2022, which may have affected their choice whether or not to participate and how they responded.

Due to the reasonable numbers of banded kea in the area, the history of all the individually identifiable kea in the trials is well documented. Seventy-eight percent (18 of 23) of the banded kea present in this trial were also present in one or more of the other trials. Any potential bias in participation against some individuals due to their experience with previous trials is unlikely to impact on the outcome of this particular trial because regardless of lower participation rates, we were only comparing the relative consumption of these two bait types. However, we do acknowledge that the influences of these past trials and 1080 exposure could have affected kea behavioural responses and interactions to baits in general during this study.

Having a subset of banded individuals in this study was useful because behavioural responses to baits and total bait consumption, and any changes to these can be assessed over time. However, there is a possibility banding these individuals altered their behaviour, for example, by reducing neophobia (due to learned trust after previous exposure to humans during the banding process). Alternatively, those individuals perhaps exhibited more neophilic tendencies in the first place, rendering them more likely to be captured for banding. There is a known link between proximity to humans and risk to kea in 1080 operations, with human-adjacent populations having higher mortality rates (Kemp et al. 2019). McLean et al. (2024) demonstrated that kea adjacent to human areas contacted novel objects faster than kea in remote areas. There is a potential risk that both the banded sample in this study could over-inflate the general kea population's interest in, and consumption of baits and that this could be further exacerbated by the study being carried out in an area adjacent to human activity (see Kemp et al. 2019; DOC 2020). However, data from unbanded individuals were included in most of the analyses, with the exception of total bait consumption; therefore, we have incorporated a representative sample of both banded and unbanded kea during this study as best we could. Nevertheless, we acknowledge that these results will be most applicable to kea populations in 'scrounge-adjacent' sites which are most at risk of consuming baits (Kemp et al. 2019; Cieraad 2024).

If Prodeer is richer in proteins and/or fats, it may be that these properties are more attractive to some kea at certain times of year, for example when adult males are provisioning nests during winter and spring. If so, risk may vary temporally. We carried out this work during autumn, winter and spring, which incorporates the kea nesting season when males would be foraging for protein-rich foods to provision nests, so our trial period probably represents the highest-risk time of year. Some kea habitat may be more resource-rich than others, e.g. Westland's lowland forest c.f. eastern beech forest (Greer et al. 2015; Nichols and Bell 2019), and there could be differences in how novel food items are perceived and treated.

For both Prodeer and RS5, kea were significantly less likely to approach weathered bait but spent significantly more time consuming it if they did approach. It is unclear what would cause kea to approach weathered bait less than fresh bait but potentially it is less interesting in appearance than intact cylindrical bright green baits are, especially if it has lost its shape and become dull-coloured with no clear texture or bright appearance against the ground. However, kea spent more time consuming weathered baits (of both types) than fresh baits, presumably due to weathered baits' softer and more palatable condition. It would be a concern if weathered baits become more palatable to kea while remaining toxic. 1080 breaks down in the bait after ca. 100 mm rainfall (Poutu et al. 2021) so toxicity after that period should be negligible, however, baits can soften prior to this due to, for example, wet ground, snowfall freeze–thaw or dew. During bait weathering trials, Prodeer palatability to farmed red deer (*Cervus elaphus*) did not change in response to a wide range of bait weathering and degradation conditions (Morriss and Nugent 2019), suggesting Prodeer retains its repellent properties long after moisture exposure. While kea consumed more weathered bait, consumption did not differ between bait types, again suggesting there is still no extra risk from Prodeer compared with RS5. This does however further highlight the need for careful timing of 1080 deployment several days prior to a heavy rainfall event to lessen the time period that bait toxicity is retained.

Conclusions

Until now, the lack of knowledge around the impact of Prodeer use on wild kea populations has made it difficult to justify decisions to include or exclude Prodeer at sites of special interest for deer herds that also fall within kea habitat. Outcomes from these trials will help inform decision making around this issue going forward. If preference by kea for Prodeer had been evident, this would have suggested that they would be at increased risk in future 1080 operations that deploy Prodeer baits within their habitat. However, the amount of Prodeer consumed by kea per interaction, per day, and in total was not significantly greater than RS5 consumption. The acceptability of Prodeer was also no different from RS5 bait. Based on our results, we conclude that overall, 1080 operations incorporating the use of Prodeer are not likely to pose a risk significantly over and above that already presented to kea using the standard RS5 prescription.

How to minimise non-target impacts whilst maximising the overall population benefit to kea through predator control operations across a range of kea habitats remains poorly understood (Weston et al. 2023). Given the multitude of risks that kea currently face (Kemp et al. 2022; Weston et al. 2023), the priorities for future research should be to maximise the population benefits of landscape-scale predator control for kea, whilst continuing to understand and minimise non-target impacts (Weston et al. 2024).

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Data availability statement

Data may be made available on request to the corresponding author.

Disclosure statement

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