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RESEARCH

Kea survival during aerial poisoning for rat and possum control

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Abstract: The kea (*Nestor notabilis*) is a highly intelligent and adaptable omnivorous New Zealand parrot. These traits potentially put kea at risk of poisoning during vertebrate pest poisoning operations. However, as kea fall prey to introduced pests, they also gain from pest control, creating a cost-benefit situation. Pest control in kea habitat is mainly by aerial 1080, the distribution of sodium fluoroacetate poison pellets by helicopter. Understanding the net outcome for kea of this pest control method is extremely important because kea are endangered and aerial 1080 use is controversial. We use 222 monitoring cases of individually marked kea at 19 aerial 1080 operations to model kea survival of aerial 1080 operations with respect to five variables. Proximity to human-occupied sites where kea scrounge human food was inversely related to survival; the odds of survival increased by a factor of 6.9 for remote kea compared to those that lived near scrounging sites. High survival in remote areas is explained by innate neophobia and a short field-life of prefeed baits, which together preclude acceptance of poison baits as familiar food. Elevated risk to kea living near scrounging sites is explained by learned neophilia, possibly exacerbated by lead poisoning. Survival was also related to the history of aerial 1080 treatment at a site; the odds of survival increased by a factor of 21.3 at sites with repeated operations compared with first time treatments. This effect is possibly due to selection for neophobic phenotypes. We suggest that 1080 poisoning risk management for kea should focus on reducing human food availability through an advocacy campaign. If most kea have not been fed by humans, then the long term outcome of the South Island aerial 1080 programme should be positive for the kea.

Keywords: aerial 1080; non-target risk; pest control; poisoning risk

Introduction

The use of aerial 1080 in New Zealand and consequences for native birds

Aerial 1080 (sodium fluoroacetate) operations are increasingly used in New Zealand to control mammalian pests. Pest control campaigns in 2014 and 2016 saw an unprecedented 554 000 ha and 729 000 ha, respectively, treated with aerially applied 1080 baits (New Zealand Department of Conservation unpubl. data). These operations target brushtail possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*) to reduce predation on native and endemic species and/or to reduce the incidence of bovine tuberculosis in livestock (Coleman & Caley 2000). Aerial 1080 baits are cereal-based pellets, weighing 6 g or 12 g, with a field life ranging from a few days to a few weeks depending on rainfall (Bowen et al. 1995; Frampton et al. 1999). Poison pellets contain 1.5 mg g^{-1} of 1080 toxin; hence a 6 g pellet contains 9 mg of active ingredient and a 12 g pellet contains twice this amount. The pellets are flung from a hopper slung under a helicopter at coverage rates of 1–3 kg ha^{-1} (Elliott & Kemp 2016). Most pellets fall to the ground, where they lie until they are consumed by animals or degraded by moisture. Rodents and possums find pellets at night by smell and directly consume them. Modern practice in New Zealand is to apply a single 'prefeed' of non-toxic baits 1–6 weeks prior to poison baiting (Veltman & Westbrooke 2011; Elliott & Kemp 2016) to improve kill rates (Coleman et al. 2007; Nugent et al. 2011).

Aerial 1080 operations can have both positive and negative effects on native birds. For example, Powlesland et al. (1999) found mortality rates of 9.7% and 55% for North Island robins (*Petroica australis longipes*) following two aerial 1080 operations. However, overall robin abundance increased in both cases one year after aerial 1080 baiting due to greatly improved recruitment in the absence of key mammalian predators. The Powlesland et al. (1999) study highlights the importance of assessing the net effect of aerial 1080 for native species at the population level over several years. Long term net outcomes are most often gauged by trends in relative abundance (e.g. O'Donnell & Hoare 2012; Greene et al. 2013; Van Vianen et al. 2018) or by detailed studies of reproductive success and survival (e.g. Powlesland et al. 1999, 2003). Understanding the net effect of aerial 1080 for native species is of considerable conservation importance in New Zealand because it is one of few proven pest control methods that can be applied on a large scale in rugged terrain at reasonable cost (Wright 2011), and because of public interest in the method (Green & Rohan 2012).

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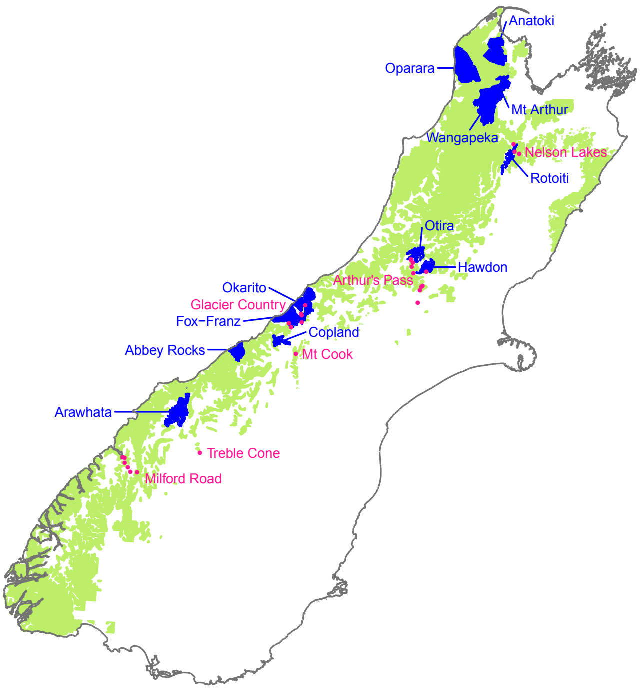

Figure 1. Map of South Island, New Zealand, showing forests and scrub inhabited by kea (light green), locations of our study sites (blue labels, blue shading shows aerial 1080 treatment boundaries) and sites where kea scrounge food from humans (pink).

The kea, a unique bird with positive and negative responses to 1080

A species for which a negative short term impact of aerial 1080 has been detected is the kea (*Nestor notabilis*) (Veltman & Westbrooke 2011), a large endangered parrot endemic to the South Island. Kea are sparsely distributed across about three million hectares of indigenous South Island forests and about 1.5 million hectares of adjoining sub-alpine shrublands, grasslands and herbfields (Fig. 1) (Robertson et al. 2007). Nearly all of the kea's range is legally-protected montane wilderness, administered by the New Zealand Department of Conservation (DOC). Roughly one-third (c. 27%) of the kea species range had aerial 1080 applied between 2014 and 2016 (DOC unpubl. data).

The kea is a distinctive member of the New Zealand avifauna (de Kloet & de Kloet 2005), possessing several traits that potentially elevate 1080 poisoning risk. Unlike kākā (*Nestor meridionalis*), kea's sympatric congener, which nest in tree cavities and forage predominantly in the forest canopy (Moorhouse 1997), kea nest underground (Jackson 1963) and frequently forage on the forest floor (Young et al. 2012; Greer et al. 2015). Kea are highly intelligent, omnivorous and adaptable, the latter particularly during the juvenile stage (Diamond & Bond 1991). Juvenile adaptability is a trait shared by many omnivorous generalists (Rozin 1976) and also by the congeneric kākā (Wilson et al. 1998; Loepelt et al. 2016). As such, kea are more likely than arboreal birds to encounter 1080 pellets and may be more likely than specialist feeders to eat them, thus giving rise to a potentially high negative impact from non target mortality. However, positive consequences of aerial 1080 for kea have also been reported (Kemp et al. 2018), attributable to the control of invasive exotic predators, particularly stoats (*Mustela erminea*), which die from secondary poisoning (Murphy et al. 1999). To balance this positive impact against non-target 1080 poisoning risk, and to find risk mitigation pathways, requires improved quantification of risk and an understanding of its spatial and temporal variability.

Scrounging by kea as a potential influence on 1080 poisoning risk

An outcome of the kea's adaptability that could possibly affect 1080 poisoning risk is the exploitation of humans for food by some individuals. Human food is obtained by stealing, soliciting, and scavenging food items, directly from people and indirectly from rubbish bins and open landfills. We use the term 'scrounging' to describe this phenomenon. Young kea are initially attracted to scrounging sites by the presence of other kea and then learn to scrounge by emulation, particularly of adult males (Diamond & Bond 1991; Gajdon et al. 2004). Scrounging by kea is patchy in the landscape and can only be observed daily in three main areas of intensive tourist activity: (1) Milford Road, (2) West Coast 'Glacier Country' (Fox and Franz Josef Glaciers), and (3) Arthur's Pass; and at some ski areas and high-use back-country huts, e.g. on the Milford Track (Fig. 1). Scrounging was previously common at Mt Cook Village, but now is rare following changes in rubbish collection and disposal practices. In contrast, efforts to prevent feeding of kea by visitors to the three places listed above have been unconcerted and, at present, unsuccessful; kea continue to scrounge daily at these sites. In the remote back-country, scrounging at tramping huts was common prior to 1984, when open rubbish pits were provided by the forest service. The closure of these pits and a new 'pack it in, pack it out' ethic has reduced kea visitation rates at huts to very low levels. At scrounging sites kea are constantly exposed to rewarding novel foods and become familiar with a wider range of food types than is normal in the wild. We hypothesise that these experiences could lead to suppression of innate neophobic behaviours that might otherwise protect kea from 1080 poisoning risk.

We evaluated the effect of proximity to scrounging sites, plus four other potentially important variables, on kea survival through aerial 1080 operations. Specifically, we investigated whether 1080 poisoning risk was:

(1) higher close to scrounging sites
(2) lower after repeated aerial 1080 treatments (i.e. at sites where aerial 1080 had been previously applied)
(3) higher with larger bait size
(4) lower for adult kea than juvenile kea
(5) different for males and females.

We could not evaluate whether prefeeding increased risk to kea because all aerial 1080 operations in the study used prefeed.

Methods

We utilised planned aerial 1080 operations in the South Island to evaluate the research questions listed above. Between 2008 and 2016, we monitored the survival of individual kea through 19 operations (n = 222 monitoring occasions) at 12 sites (Table 1; Fig. 1). Seven of these sites were utilised once, three sites were utilised twice, and two sites were utilised three times. The number of kea monitored per operation (and per site) ranged from 2 to 37 (Table 1; Fig. 2). We monitored 15 individuals

Table 1. Details of the aerial 1080 operations in the South Island, New Zealand, at which 1080 poisoning risk to kea was measured. Number of previous aerial 1080 treatments and years since prior aerial 1080 are the basis for assignment of 1080 history category scores. Counts of monitored kea are given by age and sex with numbers of deaths attributed to 1080 poisoning in brackets. AF=adult female, AM=adult male, FYF=first year female, FYM=first year male, JF=second year female, JM=second year male.

Operation	Month	Bait size (g)	Scrounge	Number of previous aerial 1080 treatments	Years since prior aerial 1080	1080 history category	AF	AM	FYF	FYM	JF	JM	Total
Arawhata 2008	Jan	12	Remote	3	4	2	2 (0)	7 (0)	0 (0)	0 (0)	0 (0)	1 (0)	10 (0)
Fox-Franz 2008	May	12	Adjacent	1	NA	1	3 (1)	7 (4)	0 (0)	0 (0)	3 (1)	4 (1)	17 (7)
Mt Arthur 2009	Jun	12	Remote	1	NA	1	2 (0)	9 (0)	0 (0)	0 (0)	0 (0)	2 (0)	13 (0)
Hawdon 2009	Sep	6	Adjacent	2	3	3	3 (0)	3 (0)	1 (0)	1 (0)	1 (0)	1 (0)	10 (0)
Okarito 2011	Sep	12	Adjacent	2	13	2	13 (2)	13 (2)	2 (1)	3 (1)	3 (2)	3 (0)	37 (8)
Wangapeka 2011	Sep	12	Remote	2	5	2	4 (0)	7 (0)	0 (0)	0 (0)	1 (0)	1 (0)	13 (0)
Abbey Rocks 2011	Oct	12	Remote	3	2	3	3 (0)	4 (0)	0 (0)	0 (0)	1 (0)	0 (0)	8 (0)
Copland 2012	Sep	12	Adjacent	3	6	2	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (0)
Hawdon 2012	Dec	6	Adjacent	3	3	3	6 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	6 (0)
Otira 2013	Jul	12	Adjacent	6	8	2	11 (2)	15 (3)	1 (0)	2 (0)	3 (0)	2 (0)	34 (5)
Mt Arthur 2014	Aug	12	Remote	2	5	2	1 (0)	3 (0)	0 (0)	1 (0)	0 (0)	2 (0)	7 (0)
Anatoki 2014	Oct	6	Remote	3	5	2	1 (0)	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (0)
Wangapeka 2014	Oct	6	Remote	3	3	3	4 (0)	2 (0)	1 (0)	1 (0)	0 (0)	0 (0)	8 (0)
Abbey Rocks 2014	Nov	6	Remote	3	3	3	8 (0)	10 (1)	2 (0)	0 (0)	0 (0)	1 (0)	21 (1)
Oparara 2014	Nov	12	Remote	1	NA	1	2 (0)	1 (0)	1 (1)	1 (1)	0 (0)	0 (0)	5 (2)
Hawdon 2014	Dec	6	Adjacent	4	3	3	4 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	4 (0)
Rotoiti 2014	Dec	6	Adjacent	1	NA	1	1 (1)	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	2 (1)
Oparara 2016	Sep	6	Remote	2	2	3	3 (0)	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)	5 (0)
Wangapeka 2016	Oct	6	Remote	4	2	3	8 (0)	8 (0)	2 (0)	0 (0)	0 (0)	0 (0)	18 (0)
Total							81 (6)	93 (10)	10 (2)	9 (2)	12 (3)	17 (1)	222 (24)

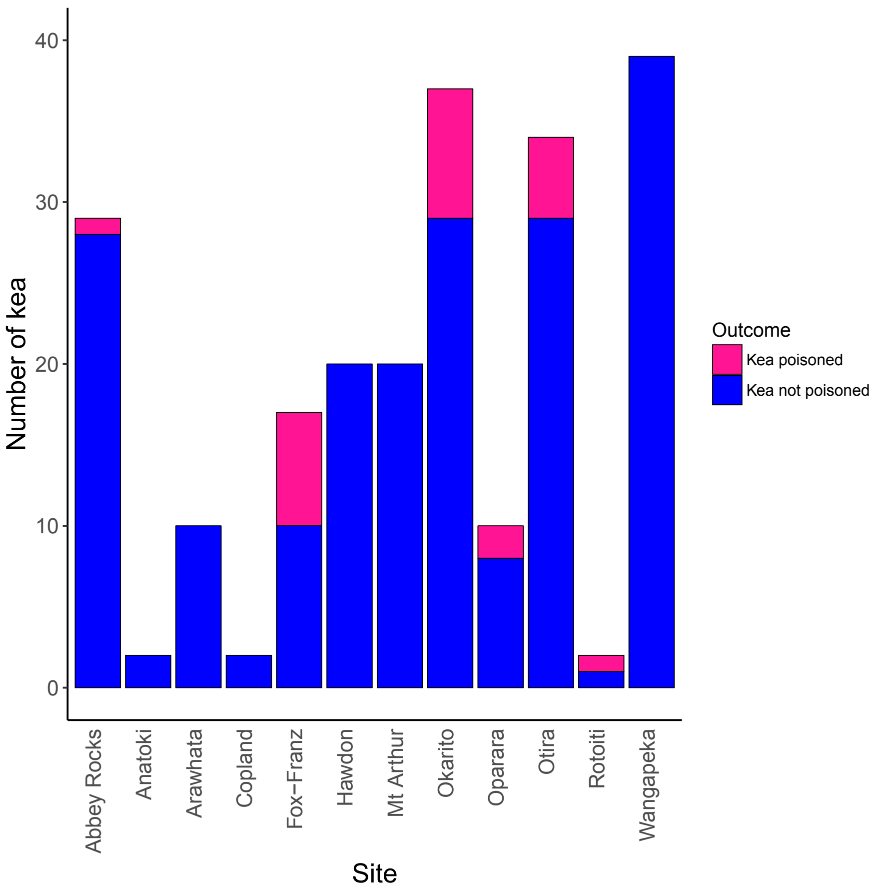

Figure 2. Sample sizes and distribution of kea deaths with respect to sites at which kea survival through aerial 1080 operations was monitored in the South Island, New Zealand. All of the recorded kea deaths are attributed to direct consumption of 1080 baits. Blue = kea not poisoned, pink = kea poisoned.

through a second aerial 1080 operation and then two of these were monitored through a third operation. Thus, the 222 monitoring occasions were obtained from 205 different kea. Monitoring was achieved using radio tags (n = 209 occasions) or by observation of unique leg bands at active nest sites (n = 13 occasions). Post aerial 1080 monitoring continued for at least 3 weeks, by which time baits become non toxic due to rain leaching poison from the bait matrix (Bowen et al. 1995). Radio tags emitting a 'mortality' signal, indicating that the transmitter was stationary, were retrieved as soon as possible, usually within 24 hours of receiving this signal, to determine whether the kea had died and the cause of death.

Factors affecting 1080 poisoning risk

Scrounging

We surmised that a history of scrounging might increase 1080 poisoning risk due to learned neophilia and/or suppressed neophobia. Scrounging histories could not be quantified for individual kea due to variability in the ages and locations at which birds were enrolled in the study. The scrounging histories of kea first caught as adults are cryptic at >5 km from scrounging sites because only adult male kea living <5 km from scrounging sites display an ongoing daily scrounging habit (scrounging by adult females is rare) (pers. obs., Jackson 1960; Wilson & Brejaart 1992). Adult females at all distances and adult males at >5 km from a scrounging site were never directly observed scrounging but may have scrounged as juveniles.

We addressed the problem of cryptic individual scrounging histories by dividing our study kea into two groups, 'adjacent' and 'remote' based on distance to the nearest scrounging site. To assign each kea to a group we calculated an average location (latitude and longitude) as the mean of all positions recorded for that kea during its monitoring history and measured the distance from there to the nearest scrounging site (shown in Fig. 1). By this method the monitored kea clearly comprised two distinct groups, (1) kea living adjacent to (<20 km) and (2) kea living remote from (>40 km) scrounging sites (Fig. 3), with 110 and 112 cases in each group, respectively (Fig. 4a). No monitored kea had average locations between 20–40 km from scrounging sites and none were recorded moving between groups during monitoring. We assume that this grouping correlates with the likelihood of kea with cryptic scrounging histories having scrounged as juveniles because movements of 5–10 km are common for kea, movements of 20 km are regular, but movements of >20 km are rare (DOC unpubl. data, Wilson & Brejaart 1992). Some kea in the 'adjacent' group likely had no history of scrounging, and some long-distance dispersers in the remote group probably scrounged as juveniles, but these exceptions make our results conservative. The qualitative nature of this variable necessitates cautious use of any quantitative predictions derived from it.

Assignment to a scrounging group of two kea monitored at the Oparara 2014 aerial 1080 operation was complicated by the erection of a research hut in the study area partway through the study. These two first-year kea, one male and one female, were initially enrolled (i.e. captured and radio tagged) as 'remote' study birds in April 2014, at c. 4 months of age. During spring 2014, the research hut was erected in the alpine zone about 800 metres from where these kea were caught. In the months leading up to this first-time aerial 1080 operation, these two kea were frequently observed at the hut, investigating the building and associated objects, materials and people. The occupants of the hut intentionally avoided feeding the kea, but unguarded food was possibly stolen. In the analysis presented here, these two kea were scored as 'remote'. We explored the consequences of alternative treatment of these two kea with

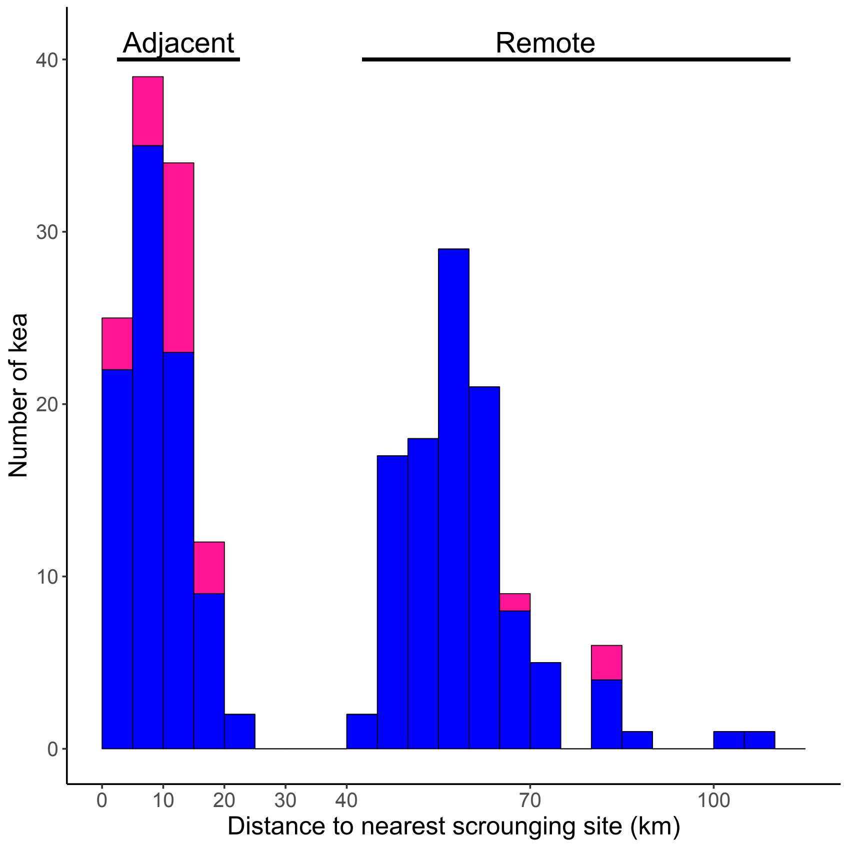

Figure 3. Histogram of distances between mean kea positions (obtained for each kea during monitoring history) and the nearest scrounging site where kea obtain food from humans (Fig. 1), showing a clear division of the sample into two scrounging groups 'adjacent' and 'remote'. All of the recorded kea deaths are attributed to direct consumption of 1080 baits. Blue = kea not poisoned, pink = kea poisoned.

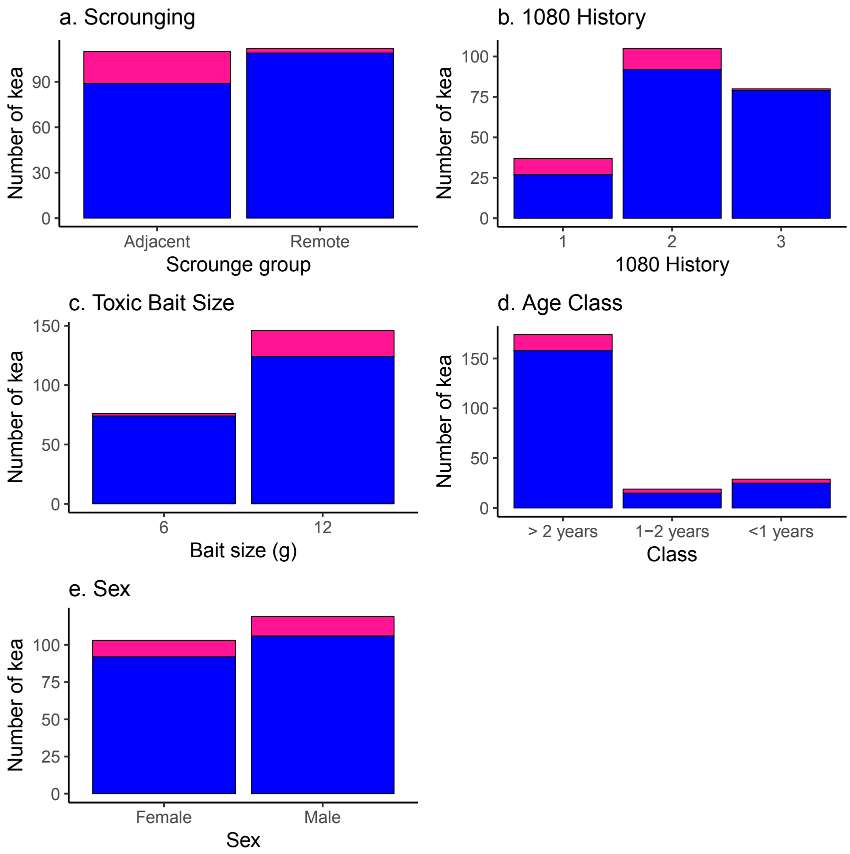

Figure 4. Numbers of kea monitored and the number that died with respect to the five modelled variables Scrounging, 1080 History, Toxic Bait Size, Age Class and Sex. Blue = kea not poisoned, pink = kea poisoned. Kea were assigned to a scrounging group based on distance to nearest scrounging site ('adjacent' ≤20 km, 'remote' ≥40 km, Fig. 3). 1080 History is a three-level categorical variable for which 1 = first time aerial 1080 treatment at site, 3 = repeated treatment 2–3 years after previous treatment, and 2 = intermediate history including partial block treatments and longer intervals between treatments.

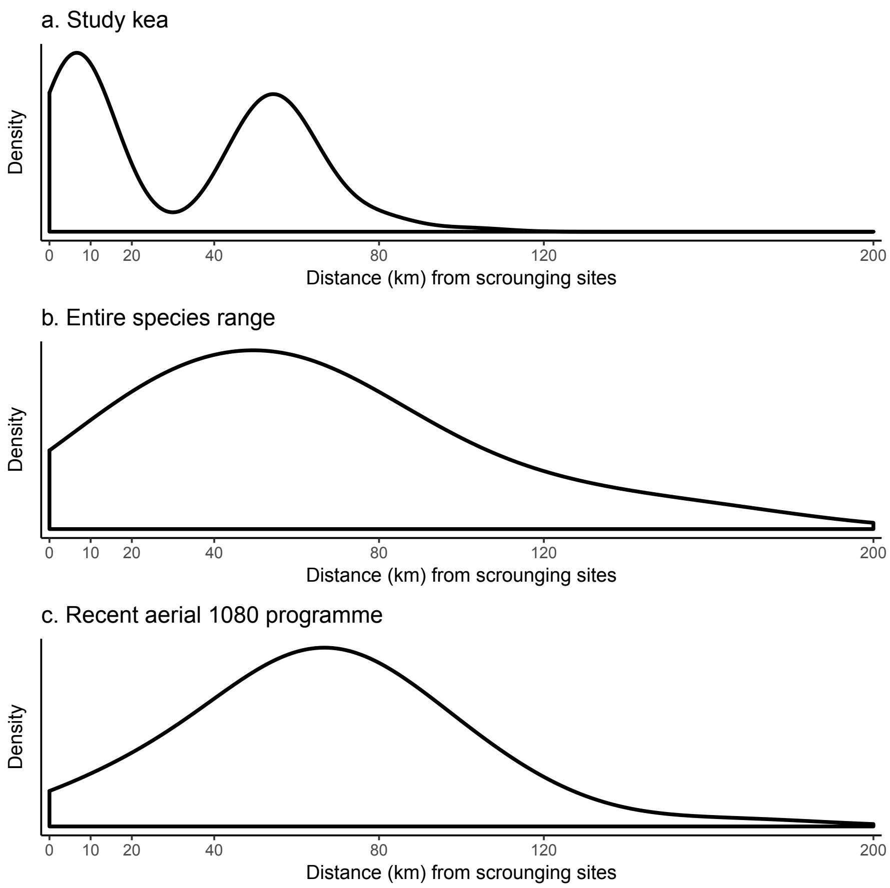

Figure 5. Kernel densities (smoothed histograms) of distance to scrounging sites for the 222 kea monitoring cases in this study (a), the 4.5 million hectare kea species range (b), and the 27% of the kea species range treated with aerial 1080 in the years 2014–2016 (c). Histograms were constructed using GIS generated distances between (1) mean locations for the individual study kea and the nearest scrounging site, and between (2) 500 000 and (3) 100 000 random points, generated within the relevant polygons, and the nearest scrounging site.

alternative analyses, in which the birds were (1) excluded from the dataset, or (2) classified as 'adjacent'.

We assessed the representativeness of our sample by visual comparison of kernel density (smoothed histograms) of distance to the nearest scrounging site for (1) our sample of monitored kea, (2) the kea species range, and (3) recent aerial 1080 use (2014–2016) in kea habitat (Fig. 5a–c). Plots for (2) and (3) were constructed using distances from the nearest scrounging site to 500 000 and 100 000 random points, respectively, generated within the relevant polygons. Random points and distances to scrounging sites were generated in the ESRI ArcMap geographic information platform. Comparing plots showed that our study kea poorly represented the South Island kea distribution (Fig. 5a, b). A representative sample would have 14% of kea within 20 km of scrounging sites, 19% 20–40 km from scrounging sites, and 67% >40 km away. Hence, kea adjacent to scrounging sites were greatly overrepresented in our study, and kea living 20–40 km were not represented. Similarly, our study kea do not reflect the full coverage of recent aerial 1080 use (Fig. 5a, c). During the period 2014–2016, 83% of aerial 1080 was applied >40 km from scrounging sites (Fig. 5c).

Aerial 1080 history

We expected that 1080 poisoning risk at a given site might decrease with repeated aerial 1080 operations through selection for innately cautious phenotypes and/or the creation of bait shy individuals via sublethal poisoning (conditioned aversion). We devised a three-tier classification system based primarily on the time since previous aerial 1080 treatment. Kea at sites treated with aerial 1080 for the first time were assigned to category 1. Kea at sites that had been comprehensively treated (entire block) within the previous 3 years were assigned to category 3. Six operations did not clearly fall into either of these categories due to extended inter-treatment intervals and/or partial treatments of blocks. Kea in these operations were assigned to category 2. Four of the 19 operations in the study were first time treatments. Eight of the operations were at sites treated within the previous 3 years. The remaining seven operations were at sites previously partially treated and/or treated 4 or more years prior (Table 1). Our sample comprised 37, 105 and 80 kea in categories 1–3, respectively (Fig. 4b).

Bait size

The aerial 1080 operations used either 6 g or 12 g poison pellets (Table 1) with equal toxin concentration (1.5 mg g^{-1}). Because a 12 g bait contains twice as much toxin we expected that these larger pellets might elevate risk to kea. Our sample comprised 76 and 146 records for 6 g and 12 g pellets, respectively (Fig. 4c).

Age

Kea have an extended juvenile phase, in which independence is attained at 1–6 months of age, followed by sexual maturity at 3–4 years (JRK unpubl. data). Pre-adult kea tend to congregate into dynamic mixed-age flocks and can range over tens of square kilometres (Jackson 1960; Wilson & Brejaart 1992). Once mature, kea mate for life. Adult kea are relatively sedentary, with core ranges spanning only a few square kilometres and social interactions are primarily with the mate and any recent offspring (JRK pers. obs.; Jackson 1960; Wilson & Brejaart 1992). We expected that younger kea might be more susceptible to 1080 poisoning because they are in a phase of intensive learning and heightened behavioural flexibility.

Kea can be accurately assigned to yearly age classes until 2 years of age based on cere and eyelid colouration and plumage condition. Ceres and eyelids are bright yellow at hatching and start fading to grey after 2 years. The rate of fading is variable after 2 years of age and some adult females retain faint yellow markings, making age cryptic beyond 2 years. We modelled age as a three-level categorical variable comprising 'first-year' (0–1 years), 'juvenile' (1–2 years), and 'adult' (3+ years) (Table 1). More adult than young individuals were monitored, with 174 adults : 29 juveniles : 19 first-years (Fig. 4d).

Sex

Sex was determined using body measurements (Bond et al. 1991) and/or by observing breeding behaviour (only female kea incubate eggs). We expected that risk might vary between the sexes due to dimorphic body size (females 750–800 grams, males 900–1050 grams), and/or to the breeding biology of kea in which males forage more than females (adult males provide food to females) (Table 1). The sex ratio of monitored birds was approximately even, at 119 females : 103 males (Fig. 4e).

Statistical analysis

After 3 weeks from the day of poison application, each monitored kea was scored as having either survived (0) or died (1). We modelled this binary response using mixed-effects models on the logit scale, with the predictor variables described above as fixed effects (Scrounging, 1080 History, Bait Size, Age and Sex). Balance within the dataset was visually assessed using pairwise plots (see Appendix S1 in Supplementary Material). Non-independence of observations within sites was addressed by specifying site as a random effect. We did not address the additional non-independence of the 17 monitoring occasions involving birds that we had previously monitored because their 1080 history was modelled as a fixed effect. Social interactions among kea may also cause non-independence, but we believe this effect will be limited because most of our birds were adult kea, which are largely solitary and unlikely to be influenced by the behaviour of other kea. We could not test for overdispersion in our data because established statistical methods applicable to binary data are lacking.

Our model set comprised all possible additive combinations of the predictor variables, with no interactions due to limited sample size. Modelling was implemented in R (R Core Team 2016) using package MuMIn version 1.40.4. (Barton 2018). We used Information Theoretic methods (AIC_c) to rank models and assess the relative importance of the five modelled variables (Akaike 1973; Burnham & Anderson 2002). For supported variables we use the odds ratio to express the magnitude of the effect, calculated as exponentiated model coefficients. For example, the odds ratio showing the effect of variable y in a two-factor additive model is:

$$OR_y = \frac{e^{\beta_i+\beta_x+\beta_y}}{e^{\beta_i+\beta_x}} \quad (1)$$

where β_i, β_x and β_y are the model coefficients for the intercept, variable x, and variable y, respectively. We used the or_glm function in the oddsratio package version 1.0.2. for R (Schratz 2017) to calculate odds ratios and associated 95% confidence intervals.

Table 2. Ranking of the top ten alternative models by AIC_c of factors affecting kea survival through aerial 1080 operations. Scrounging = 2-level categorical variable (adjacent versus remote). 1080 History = 3-level categorical variable, scored per aerial 1080 operation based on time since previous aerial 1080 treatment (Table 1). k = number of parameters in the model.

Model	k	Delta AIC_c	Weight
Scrounging + 1080 History	5	0	0.352
Scrounging + 1080 History + Age Class	7	1.359	0.179
Scrounging + 1080 History + Sex	6	2.366	0.108
Scrounging + 1080 History + Bait Size	6	2.466	0.103
Scrounging + 1080 History + Age Class + Sex	8	3.86	0.051
Scrounging + 1080 History + Age Class + Bait Size	8	4.045	0.047
Scrounging + 1080 History + Sex + Bait Size	7	4.938	0.03
Scrounging + 1080 History + Age Class + Sex + Bait Size	4	5.037	0.028
1080 History	3	6.51	0.014
Scrounging	9	6.663	0.013

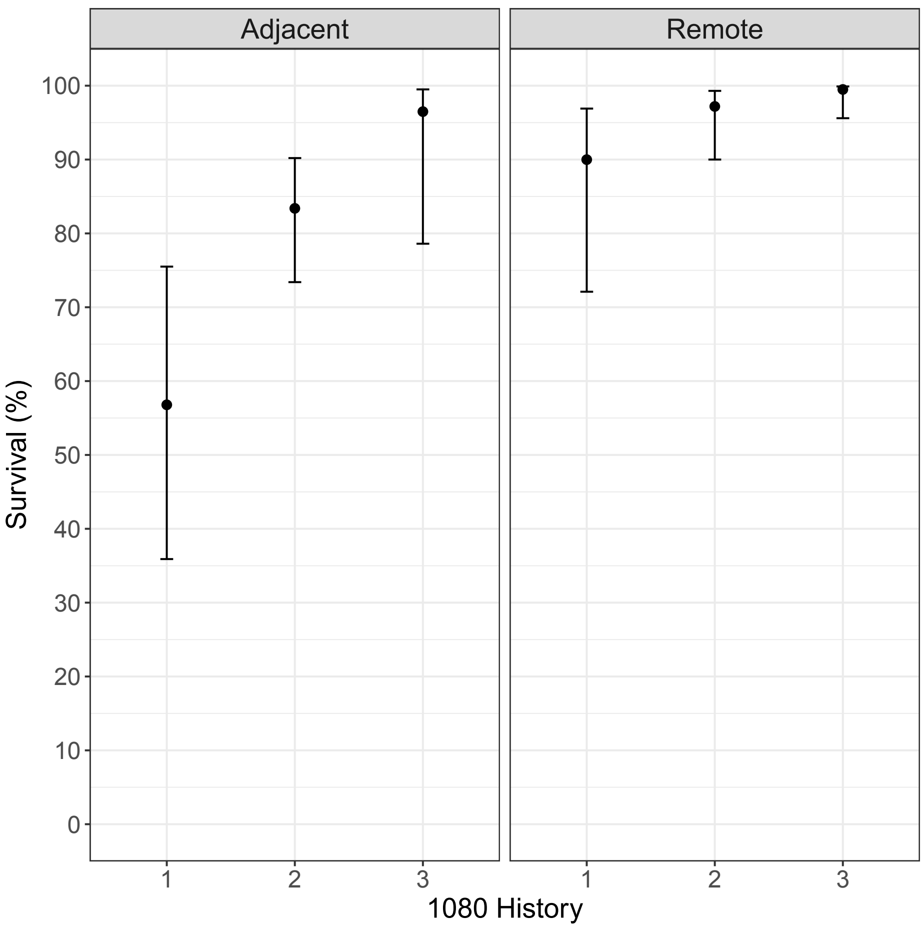

Figure 6. Survival rates for kea exposed to aerial 1080, estimated using the best-supported model, with respect to Scrounging ('remote' ≥40 km from scrounging sites, 'adjacent' ≤20 km) and 1080 History (1 = first time aerial 1080 treatment at site, 3 = repeated treatment 2–3 years after previous treatment and 2 = intermediate history including partial block treatments and longer intervals between treatments). Error bars are 95% binomial confidence intervals.

Results

We recorded 24 kea deaths, all within six operations (n = 222 kea monitoring cases; Table 1). Poison-pellet cereal matter present in the digestive tracts of all necropsied corpses (n = 17) indicated that primary poisoning was the cause of death. Necropsies were not conducted in seven cases owing to advanced decomposition that resulted from logistical delays retrieving corpses from the field. The seven deaths were considered for the study as due to 1080 poisoning.

Membership of the 'adjacent' scrounging group was strongly supported by AIC_c as a negative influence on the chance of a kea surviving an aerial 1080 operation (Table 2; Fig. 6). The odds of survival was 6.9 times higher for kea in the 'remote' group than for the 'adjacent' group (95% CI = 2.1–31.6). An effect of 1080 History was also supported (Table 2). The odds of survival was 21.3 times higher at sites with a recent aerial 1080 treatment than at first time treatments (95% CI = 3.6–406.9). The best-supported model contained both Scrounging and 1080 History. The Age Class variable also had moderate support. However, because this result may be an artefact of small sample sizes of young kea, we present further results for the best-supported model only. There was little to no support for Bait Size and Sex as predictors. The random effect of Site was non-zero for all models that did not include both Scrounging and 1080 History, but was near-zero for all models that included both.

Support for Age Class was absent in two alternative analyses in which two first-year kea poisoned during the Oparara 2014 operation were either excluded or scored as 'adjacent' for scrounging (see Methods). The survival rates predicted by the best-supported model (Scrounging + 1080 History) for remote first time treatments improved considerably in the alternative analyses (Appendix S2), but neither alternative suggested different conclusions or recommendations.

Discussion

Mechanisms behind 1080 poisoning risk

Our finding of lower poisoning risk from aerial 1080 operations for remote kea than for kea living adjacent to scrounging sites can be explained if scrounging causes suppression of innate neophobic behaviours that protect against poisoning from novel foods (Rozin 1976; Galef et al. 1998; Galef & Whiskin 2001). Suppression of neophobia could potentially be learned through frequent exposure to rewarding novel foods, and/or a direct result of sublethal lead poisoning. Lead poisoning is prevalent among kea near scrounging sites (McLelland et al. 2010; Reid et al. 2012) and this could potentially contribute to suppressed neophobia through effects on brain function, thermoregulation, immune system function and body condition (Newth et al. 2016). We could not assay our study birds for blood lead levels for logistical reasons, so we could not distinguish the relative importance of learned neophilia versus lead poisoning. Thus, in remote sites, initial interactions with 1080 pellets may comprise a mixture of neophilia and neophobia, in which kea may approach novel objects (neophilia), but initial interactions with the novel item are cautious (neophobia). The short field life of the 1080 pellets used in kea habitat appears to preclude their acceptance as a familiar rewarding food in the remote context. Thus, the potential for high 1080 poisoning risk to kea does not necessarily manifest under current baiting practices.

Our finding of lessened risk where aerial 1080 had been used in recent years could be explained by (1) learned aversion (bait shyness) induced by sublethal 1080 doses, and (2) selection for neophobic individuals due to mortality of neophilic ones from 1080 poisoning. However, bait shyness can be precluded by using prefeed, at least in some animals (Ross et al. 2000), and all the operations in this study were prefed. Therefore, we favour the latter explanation that strong selection pressure applied by aerial 1080 results in an increasing prevalence of innate neophobic behaviours. Possibly the effect of 1080 history differs between 'remote' and 'adjacent' groups, but we had insufficient data to test for such an interaction. To enable this idea to be tested, we recommend further radio-tag monitoring of kea at remote first-time treatments, if DOC's and/or TbFree New Zealand's South Island aerial 1080 programme expands.

Our study found moderate support for an effect of Age Class on 1080 poisoning risk, which may reflect the enhanced behavioural plasticity observed for juveniles within the genus *Nestor* (Wilson et al. 1998; Loepelt et al. 2016). We caution that our data set contained relatively few young kea, and that two poisoned first-year kea were scored as 'remote' although they are known to have scrounged around a newly built hut. Therefore, we recommend further monitoring of young kea through aerial 1080 operations to improve our understanding of how kea age influences 1080 poisoning risk.

Utility of estimates and extrapolation to other sites

While primarily aiming to evaluate for a qualitative relationship between scrounging and 1080 poisoning risk, our study has generated a useful estimate of survival of remote kea through a repeated aerial 1080 operation. With only one death out of 60 remote monitoring occasions in repeated operations, the lower 95% confidence limit for kea survival in this context is 95.6% (Fig. 6). Given the high magnitude of benefits from predator control measured for kea and other species with similar nesting ecology, such as kākā and whio (*Hymenolaimus malacorhynchos*) (Moorhouse et al. 2003; Whitehead et al. 2008; Kemp et al. 2018), we expect to see strong kea population growth resulting from long term aerial 1080 programmes in remote areas.

The estimated survival rates derived from our analysis for kea adjacent to scrounging sites should be treated with caution due to the qualitative nature of our method for assigning kea to the 'adjacent' and 'remote' groups (see Methods). In addition, aerial 1080 operations near scrounging sites vary in size, shape and location relative to scrounging sites, and the intensity of scrounging activity varies from place to place. Further, our samples possibly contained disproportionate numbers of scrounging kea – these being presumably easier to catch for the same reason that they are more prone to ingesting 1080 pellets – hence possibly leading to over-estimated risk. Interpolation of survival rates to kea living 20–40 km from scrounging sites is especially to be avoided, for the reasons given above and because the shape of the relationship between kea risk and distance is unknown. Notwithstanding these cautions, we conclude that 1080 poisoning risk near scrounging sites is cause for concern. Benefits from predator control would need to be high and of extended duration (i.e. more than two breeding seasons) to achieve a positive net outcome under our lowest mean survival estimate of 56.8% survival at first time aerial 1080 treatments adjacent to scrounging sites (Fig. 6). Should survival fall between the point estimate and the lower 95% confidence limit of 35.9%, achieving a positive net outcome in these circumstances is beyond reasonable expectations. Only 33% of the kea species range lies within 40 km of scrounging sites and only 17% of recent (2014–2016) aerial 1080 applications have been within this range (Fig. 5). Thus, costs to the kea population from aerial 1080 use adjacent to scrounging sites might have been offset by benefits accrued in remote areas. However, the limitations of our study and the potential to rapidly reduce the prevalence of scrounging by kea are such that we recommend immediate mitigation action for the benefit of kea population recovery and to address concern about kea welfare.

Managing aerial 1080 poisoning risk

Approaches to managing 1080 poisoning risk to kea near scrounging sites potentially include (1) reducing scrounging by removing the rewards that kea obtain from anthropogenic sources, (2) not prefeeding aerial 1080 operations near scrounging sites, (3) using low-strength 1080 pellets (0.8 mg g^{-1} pellets are available for use in New Zealand), (4) adding bird repellents to baits, (5) aversion training of individual kea at scrounging sites, and (6) spatial solutions such as attracting kea out of treatment blocks during aerial 1080 operations, and capture and holding of kea during aerial 1080 operations. However, not all these options are currently viable. Not prefeeding will almost certainly compromise pest control effectiveness (Coleman et al. 2007; Nugent et al. 2011), reducing benefits to native species other than kea. Bird repellents and aversion training are potentially viable solutions, but both require research and development (Orr-Walker et al. 2012; Cowan et al. 2016; Crowell et al. 2016). Spatial solutions involving catching and holding kea would be stressful for the birds and some will always avoid capture. Attracting kea away from 1080 blocks may not succeed, especially for adult females due to their more sedentary nature. The remaining two options – reducing scrounging and using lower strength 1080 pellets – are potentially viable and could be immediately implemented. Managers should focus first on preventing the establishment of new scrounging sites, which is a real risk in the context of rapidly expanding tourism in New Zealand. Second, the attractiveness of established scrounging sites should be actively reduced through careful management of waste and of human behaviour. The effectiveness of any such programme should be tested by re-evaluating aerial 1080 poisoning risk near managed scrounging sites after 5 to 10 years of management. Scrounging may never be eliminated, but the current level of effort to prevent scrounging is very low (JRK pers. obs.) and the recent reduction of scrounging rates at back-country huts suggests similar reductions are achievable at Arthur's Pass, Glacier Country, and Milford Road. A successful scrounge-reduction programme would have the additional benefit of reducing mortality arising from other hazards such as lead and cars. Using lower strength 1080 pellets is not current best practice, but the recent change from 0.8 mg g^{-1} to 1.5 mg g^{-1} was based on theory (Frampton et al. 1999) and benefits to pest control efficacy of the higher concentration have not been experimentally demonstrated in the field.

Potential for prefeed to affect 1080 poisoning risk

We were unable to quantify the effect of prefeeding on 1080 poisoning risk to kea because all of the operations in the study were prefed. However, risk to remote living kea is clearly not elevated to concerning levels by a single application of prefeed at the sowing rates used in this study. Changes to 1080 baiting practices, such as using two rounds of prefeeding (e.g. Nugent et al. 2011) or longer life baits such as Wanganui Number 7 pellets (Bowen et al. 1995), could elevate risk to kea and therefore should be accompanied by kea monitoring. The high survival of remote adult kea is consistent with studies of kākā, in which adults exhibited a disinclination to explore potential new food sources (Wilson et al. 1998; Loepelt et al. 2016). Juvenile kākā, conversely, learned to exploit novel foods more readily. For kea, which learn socially (Diamond & Bond 1991; Gajdon et al. 2004), 1080 poisoning risk to juveniles may be naturally mitigated through these learning processes. However, young kea sometimes forage and explore independently of adults, at which time they may investigate baits. If so, their investigation of baits may be coupled with a cautious testing strategy (Rozin 1976) within which a single prefeed application may provide sufficient familiarisation time to elevate 1080 poisoning risk to a concerning level. We recommend behavioural studies of the process by which foods become accepted by kea to improve understanding of the role of prefeeding in determining 1080 poisoning risk, and the potential implications of multiple prefeed applications.

Summary

In summary, we are confident that aerial 1080 application is not cause for concern for kea in repeated aerial 1080 operations at remote sites, particularly when the operations are designed to maximise predator control benefits to kea, as risk to kea is easily offset by these benefits. Proximity to scrounging sites is strongly associated with elevated 1080 poisoning risk, but this risk is not well quantified. We recommend (1) the implementation of a scrounge-management programme, (2) research to improve our understanding of the links between scrounging, neophobia and 1080 poisoning risk, (3) further measurement of risk to young kea, and (4) further measurement of risk at first treatments in remote sites. If the South Island aerial 1080 programme comprises mostly remote repeated operations, then a positive long term net outcome for kea is likely.

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References

Akaike H 1973. Information theory and an extension of the maximum likelihood principle. In: Petrov BN, Csaki F eds. Budapest: Akademiai Kiado, Proceedings of the 2nd International Symposium on Information Theory. Pp. 267–281.

Barton K 2018. MuMIn: Multi-Model Inference; R package version 1.40.4. https://CRAN.R-project.org/package=MuMIn (accessed May 2018).

Bond AB, Wilson KJ, Diamond J 1991. Sexual dimorphism in the kea *Nestor notabilis*. Emu 91: 12–19.

Bowen LH, Morgan DR, Eason CT 1995. Persistence of sodium monofluoroacetate (1080) in baits under simulated rainfall. New Zealand Journal of Agricultural Research 38: 529–531.

Burnham KP, Anderson DR 2002. Model selection and multimodel inference: a practical information-theoretic approach. 2nd edn. New York, Springer-Verlag. 488 p.

Coleman JD, Caley P 2000. Possums as a reservoir of bovine TB. In: Montague TL ed. The brushtail possum. Biology, impact and management of an introduced marsupial. Lincoln, Manaaki Whenua Press. Pp. 92–104.

Coleman JD, Fraser KW, Nugent G 2007. Costs and benefits of pre-feeding for possum control. New Zealand Journal of Zoology 34: 185–193.

Cowan P, Booth L, Crowell M 2016. Repellents with potential to protect kea and other native birds from aerial poisoning for possum and rat control. New Zealand Journal of Ecology 40: 29–41.

Crowell M, Martini M, Moltchanova E 2016. Effect of the addition of bird repellents to aerially applied 1080 baits on rat and possum abundance. New Zealand Journal of Ecology 40: 49–59.

Diamond J, Bond AB 1991. Social behavior and the ontogeny of foraging in the kea (*Nestor notabilis*). Ethology 88: 128–144.

Elliott G, Kemp J 2016. Large-scale pest control in New Zealand beech forests. Ecological Management & Restoration 17: 200–209.

Frampton CM, Warburton B, Henderson RJ, Morgan DR 1999. Optimising bait size and 1080 concentration (sodium monofluoroacetate) for the control of brushtail possums (*Trichosurus vulpecula*). Wildlife Research 26: 53–59.

Gajdon GK, Fijn N, Huber L 2004. Testing social learning in a wild mountain parrot, the kea (*Nestor notabilis*). Learning & Behavior 32: 62–71.

Galef BGJ, Rudolf B, Whiskin EE, Choleris E, Mainardi M, Valsecchi P 1998. Familiarity and relatedness: effects on social learning about foods by Norway rats and Mongolian gerbils. Animal Learning and Behavior 26: 448–454.

Galef BGJ, Whiskin EE 2001. Interaction of social and individual learning in food preferences of Norway rats. Animal Behaviour 62: 41–46.

Green W, Rohan M 2012. Opposition to aerial 1080 poisoning for control of invasive mammals in New Zealand: risk perceptions and agency responses. Journal of the Royal Society of New Zealand 42: 185–213.

Greene TC, Dilks PJ, Westbrooke IM, Pryde MA 2013. Monitoring selected forest bird species through aerial application of 1080 baits, Waitutu, New Zealand. New Zealand Journal of Ecology 37: 41–50.

Greer A, Gajdon GK, Nelson XJ 2015. Intraspecific variation in the foraging ecology of kea, the world's only mountain- and rainforest-dwelling parrot. New Zealand Journal of Ecology 39: 254–261.

Jackson JR 1960. Keas at Arthurs Pass. Notornis 9: 39–58.

Jackson JR 1963. The nesting of keas. Notornis 10: 319–326.

Kemp JR, Mosen C, Elliott GP, Hunter CM 2018. Effects of the aerial application of 1080 to control pest mammals on kea reproductive success. New Zealand Journal of Ecology 42: 158–168.

de Kloet RS, de Kloet SR 2005. The evolution of the spindlin gene in birds: sequence analysis of an intron of the spindlin W and Z gene reveals four major divisions of the Psittaciformes. Molecular Phylogenetics and Evolution 36: 706–721.

Loepelt J, Shaw RC, Burns KC 2016. Can you teach an old parrot new tricks? Cognitive development in wild kaka (*Nestor meridionalis*). Proceedings of the Royal Society B 283: 20153056.

McLelland JM, Reid C, McInnes K, Roe WD, Gartrell BD 2010. Evidence of lead exposure in a free-ranging population of kea (*Nestor notabilis*). Journal of Wildlife Diseases 46: 532–540.

Moorhouse R 1997. The diet of the North Island kaka (*Nestor meridionalis septentrionalis*) on Kapiti Island. New Zealand Journal of Ecology 21: 141–152.

Moorhouse RJ, Greene TC, Dilks PJ, Powlesland RG, Moran L, Taylor GE, Jones A, Knegtmans JW, Wills D, Pryde M, Fraser I, August A, August C 2003. Control of introduced mammalian predators improves kaka *Nestor meridionalis* breeding success: reversing the decline of a threatened New Zealand parrot. Biological Conservation 110: 33–44.

Murphy EC, Robbins L, Young JB, Dowding JE 1999. Secondary poisoning of stoats after an aerial 1080 poison operation in Pureora forest, New Zealand. New Zealand Journal of Ecology 23: 175–182.

Newth JL, Rees EC, Cromie RL, McDonald RA, Bearhop S, Pain DJ, Norton GJ, Deacon C, Hilton GM 2016. Widespread exposure to lead affects the body condition of free-living whooper swans *Cygnus cygnus* wintering in Britain. Environmental Pollution 209: 60–67.

Nugent G, Warburton B, Thomson C, Sweetapple P, Ruscoe WA 2011. Effect of prefeeding, sowing rate and sowing pattern on efficacy of aerial 1080 poisoning of small-mammal pests in New Zealand. Wildlife Research 38: 249–259.

Orr-Walker T, Adams NJ, Roberts LG, Kemp JR, Spurr EB 2012. Effectiveness of the bird repellents anthraquinone and D-pulegone on an endemic New Zealand parrot, the kea (*Nestor notabilis*). Applied Animal Behaviour Science 137: 80–85.

O'Donnell C, Hoare J 2012. Quantifying the benefits of long-term integrated pest control for forest bird populations in a New Zealand temperate rainforest. New Zealand Journal of Ecology 36: 131–140.

Powlesland RG, Knegtmans JW, Marshall I 1999. Costs and benefits of aerial 1080 possum control operations using carrot baits to North Island robins (*Petroica australis longipes*), Pureora Forest Park. New Zealand Journal of Ecology 23: 145–159.

Powlesland RG, Wills DE, August ACL, August C 2003. Effects of a 1080 operation on kaka and kereru survival and nesting success, Whirinaki Forest Park. New Zealand Journal of Ecology 27: 125–137.

R Core Team 2016. R: a language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Reid C, McInnes K, McLelland JM, Gartrell BD 2012. Anthropogenic lead (Pb) exposure in populations of a wild parrot (kea *Nestor notabilis*). New Zealand Journal of Ecology 36: 56–63.

Robertson CJR, Hyvonen P, Fraser M, Pickard CR 2007. Atlas of bird distribution in New Zealand. Wellington, The Ornithological Society of New Zealand. 296 p.

Ross JG, Hickling GJ, Morgan DR, Eason C 2000. The role of non-toxic prefeed and postfeed in the development and maintenance of 1080 bait shyness in captive brushtail possums. Wildlife Research 27: 69–74.

Rozin P 1976. The selection of food by rats, humans, and other animals. Advances in the Study of Behaviour 6: 21–76.

Schratz P 2017. R package 'oddsratio': Odds ratio calculation for GAM(M)s & GLM(M)S. R package version 1.0.2. https://CRAN.R-project.org/package=oddsratio (accessed May 2018).

Van Vianen J, Burge OR, MacFarlane AT, Kelly D 2018. The effects of single aerial 1080 possum-control operations on common forest birds in the South Island, New Zealand. New Zealand Journal of Ecology 42: 169–178.

Veltman CJ, Westbrooke IM 2011. Forest bird mortality and baiting practices in New Zealand aerial 1080 operations from 1986 to 2009. New Zealand Journal of Ecology 35: 21–29.

Whitehead AL, Edge K-A, Smart A, Hill G, Willans M 2008.

Large scale predator control improves the productivity of a rare New Zealand riverine duck. Biological Conservation 141: 2784–2794.
Wilson K-J, Brejaart R 1992. The kea: a brief research review. In: Joseph L ed. Issues in the conservation of parrots in Australasia and Oceania: challenges to conservation biology. Royal Australian Ornithologists Union Report no. 83. Victoria, Royal Australian Ornithologists Union. Pp. 24–28.
Wilson PR, Karl BJ, Toft RJ, Beggs JR, Taylor RH 1998. The role of introduced predators and competitors in the decline of kaka (*Nestor meridionalis*) populations in New Zealand. Biological Conservation 83: 175–185.
Wright J 2011. Evaluating the use of 1080: predators, poisons and silent forests. Wellington, Office of the Parliamentary Commissioner for the Environment. 85p.
Young LM, Kelly D, Nelson XJ 2012. Alpine flora may depend on declining frugivorous parrot for seed dispersal. Biological Conservation 147: 133–142.

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Supplementary Material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. Pairwise plots of modelled predictor variables of kea survival of aerial 1080 operations.

Appendix S2. Survival rates for kea exposed to aerial 1080, estimated using the top model, with respect to Scrounging and 1080 History, with respect to three alternative categorisations of two juvenile kea monitored through the Oparara 2014 operation.

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