Effectiveness of toxic baiting for the control of canines and felines

ABSTRACT

Lethal, toxic baiting has been widely adopted for the control of canines and felines. However, high variability in findings make it difficult to gauge the overall efficacy of this control method across studies. We conducted a meta-analysis of the efficacy of lethal baiting for the feral cat, red fox and dingo; our outcome of interest was apparent predator survival. Our dataset contained 121 effects from 34 studies, comprising 1402 individuals tested. When baits were distributed along tracks they increased the risk of predator death by 46% relative to controls. However, when baits were distributed more broadly across areas the risk of predator death was comparable between baited and unbaited areas. We found no evidence that baiting was more effective at reducing canine relative to feline populations. We additionally found no evidence that Eradicat® achieved greater cat death than other baits. Higher bait densities achieved a greater risk of predator death when baits were distributed along tracks, but not when baits were distributed across areas. We found no evidence that repeat bait applications over short periods of time achieve a greater risk of predator death than single bait applications; this was consistent across both design types. Similarly, we found no evidence for an effect of bait matrix (fresh meat, dry processed bait, mixture) for either design type. Our study shows that many accepted baiting practices have little empirical support and are premature given the available sparse evidence. Further, rigorous research is of high priority in this field.

Keywords

Lethal; population; bait; pest; management; control

INTRODUCTION

Wild felines are widely recognised for their significant environmental, social and economic impacts worldwide. For example, feral cats (*Felis catus*) impacts on islands alone are responsible for at least 14% of global bird, mammal, and reptile extinctions (Medina et al. 2011). They additionally drive the global transmission of diseases, like toxoplasmosis, that impact all of human, livestock and wildlife health, and cost economies tens of billions of dollars annually (Hoffmann et al. 2012; Legge et al. 2020). Canines similarly have significant environmental, social and economic impacts. In Australia, the red fox (*Vulpes vulpes*) consumes 42 species of threatened mammal and 14 species of threatened bird, and both foxes and dingoes (*Canis familiaris*) contribute to social and economic damage through livestock predation (Saunders et al. 2010; McLeod 2016; Stobo-Wilson et al. 2021; Woinarski et al. 2022). Therefore, effective control of both felines and canines is critical for environmental, social and economic reasons.

Management of wild felines and canines frequently involves lethal, toxic baiting. For example, over one third of global cat eradication programs rely heavily on baiting, and 75-85% of lethal fox and dingo control in Australia is achieved through baiting (West & Saunders 2003; Nogales et al. 2004; Reddiex et al. 2006; Campbell et al. 2011). Toxic predator baits are produced both commercially and made in-house by practitioners, with baits generally considered to be easy and cost-efficient to distribute at scale (Thompson & Fleming 1991). For these reasons, predator baiting occurs across vast spatial scales (1000's km2) and is commonly the only method of predator control available at these scales (Taggart et al. 2023).

Yet despite the widespread adoption of toxic baiting, an important question remains, how effective is baiting at controlling the target species? Current evidence paints a mixed picture. For example, Bengsen (2014) observed only 29% fox mortality (5/17 GPS-collared animals) during a coordinated landholder baiting program but Dexter & Meek (1998) report 100% fox mortality (6/6 radio-collared animals) despite distributing baits over an approximately equivalent area. Similarly, Comer et al. (2018) report the efficiency of feral cat baiting to have varied from 36% (4/11 GPS-collared animals) - 86% (6/7 GPS-collared animals) within the same study area over successive years. Such varied findings make it difficult to gauge the overall efficacy of toxic baiting across studies.

The issue of efficacy becomes even more pressing when we consider the complexities that lie behind the use of toxic baiting. For instance, toxic baiting can have the potential for unintended impacts on non-target species (Glen et al. 2007). Work on dingoes also suggests that baiting may change their behaviour or fracture their social structures, thereby potentially allowing their numbers to increase (Wallach et al. 2010; Allen 2014). Given these complexities, the extent to which toxic baiting can effectively reduce target populations becomes a vital piece of information when assessing and balancing its advantages and disadvantages.

Here, we conducted a meta-analysis of the effectiveness of lethal, toxic baiting for the control of feline and canine populations. Meta-analysis enables the collation of many individual study effects that vary in size and direction, but fundamentally address an equivalent question. In this way, meta-analysis facilitates the identification of an average effect, a quantification of the variability of effects across studies, and factors (moderators) that explain such variation. In this paper, we first asked the question, on average, does baiting work to lethally control predators, and if so, how well?

Our second aim was to identify the factors (moderators) that explain variation in effects across studies. We evaluated 5 species-related or procedural-related moderators. First, we compared felines vs canines. There have been some suggestions that feral cats might be more reluctant to take baits and are thus less easily controlled through baiting relative to foxes and dingoes (Algar & Burrows 2004). Second, we examined two moderators involving the baiting procedure, baiting density and repeated baiting. Increased bait densities could increase bait availability, thus enhancing efficacy (e.g. Ballard et al. (2020)). Similarly, it stands to reason that repeated bait distribution events over a short period of time would also have the same effect of increasing bait availability, and thereby increasing efficacy, relative to a single distribution of baits with no further distribution or replenishing thereafter. Third, we examined the effect of bait matrix (fresh vs dry processed baits), given potential differences in their palatability (Gentle 2005). Lastly, we tested if the effect varied depending on the outcomes measured. For instance, some studies GPS-collar and track individual animals through baiting events, and then use laboratory confirmation of the bait toxin in deceased animals to demonstrate with certainty that they did indeed die from bait consumption. Other studies quantify individuals prior to and post baiting events, with the assumption that missing animals have succumb to the lethal impacts of baiting. We tested if these outcomes measured influenced the efficacy observed.

We predicted that: 1) baiting would reduce predator survival; 2) canines would experience greater reductions in survival than felines; 3) higher bait densities would increase the risk of predator death up to a point, and beyond which the risk of predator death would plateau; 4) repeated bait applications within a short period of time would achieve greater predator control relative to single bait applications; and 5) fresh meat baits would achieve greater predator control than dry/processed baits. We provide all data and code to reproduce our analysis and manuscript.

Methods

In the reporting of our methods we follow the *MeRIT* guidelines (Nakagawa et al. 2023).

Identification of literature

Taggart et al. (2023) recently published a qualitative systematic review of baiting within the fields of conservation and pest management. Our study is follow-up from the qualitative systematic review where we now quantatively meta-analyse a sub-set of the papers identified by Taggart et al. (2023). For a detailed description of the systematic review conducted see Taggart et al. (2023). Briefly, they systematically searched titles and abstracts contained within Web of Science and Scopus. Their search string contained four main terms, the first focused on capturing baiting studies, the second focused on capturing studies within the fields of conservation or pest management, the third focused on capturing field studies as opposed to laboratory or simulation studies, and the last search term was constructed to remove common themes that were not of interest. They then supplemented their systematic searches in both Web of Science and Scopus with an equivalent search in Google Scholar to capture grey literature. Their systematic search identified 65 canid and felid baiting studies of relevance to our meta-analysis. Using these 65 studies as a starting point for our quantitative meta-analysis, PLT conducted backward and forward snowballing to identify additional relevant studies. Snowballing was conducted on 15th March 2022. This process was aided by Citation Chaser (Haddaway et al. 2022), which captures both published and grey literature, with backward and forward snowballing conducted manually for any articles that did not contain a DOI. Snowballing obtained a list of 2,232 references. PLT then identified 364 of these to be duplicates in Endnote and a further 121 to be duplicates in Rayyan (Ouzzani et al. 2016). PLT conducted title and abstract screening of the remaining 1747 papers in Rayyan and identified a further 37 for consideration in our meta-analysis. This gave a total of 102 papers for consideration in our meta-analysis (Figure 1).

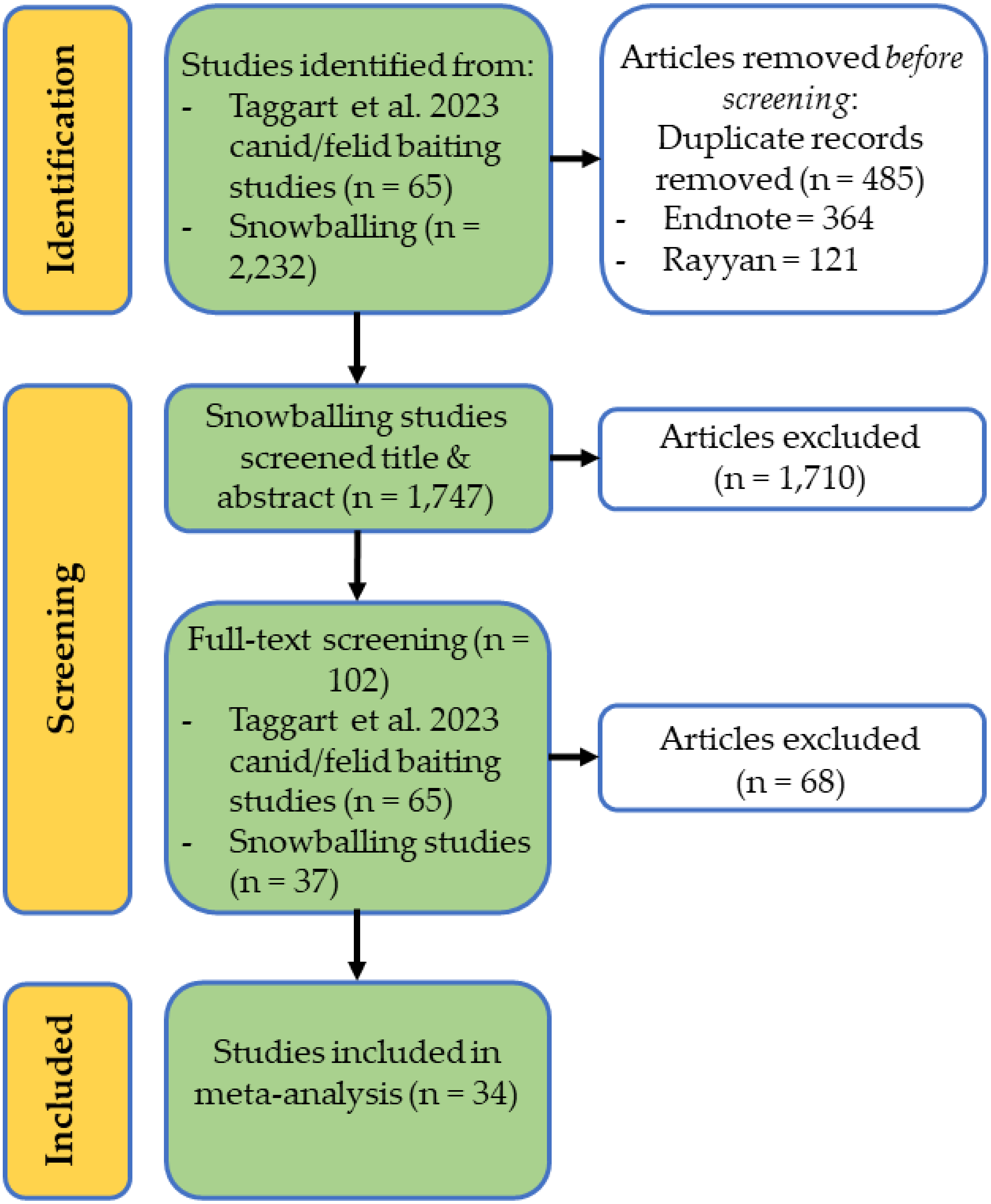

Fig. 1. Modified PRISMA diagram showing the search process and the number of articles/reports considered at each step (orange boxes). For each step, green boxes represent articles/reports included and unfilled boxes represent articles/reports excluded.

Inclusion criteria and full text screening

To be included in our meta-analysis studies had to: 1) distribute toxic baits for the lethal control of feral cats, foxes or dingoes in a defined area or transect; and 2) have tracked a known number of individuals prior to and post baiting; or 3) quantified the number of individuals present prior to and post baiting. We made one exception to these criteria, Algar et al. (2007), who quantified the number of individual feral cats present prior to baiting and the number of baits taken, as opposed to the number of individuals present post baiting. We deemed this study suitable as there is limited evidence that feral cats cache baits and hence it seemed reasonable to assume that cats that had taken baits died. Studies frequently did not demonstrate with absolute certainty that the death of disappearance of predators was specifically due to the consumption of a toxic bait, such as through laboratory confirmation of 1080 in deceased animals. Rather, most studies made the assumption that if animals were alive immediately prior to baiting and died or disappeared immediately post the baiting event, then this was attributed to the lethal impacts of toxic bait consumption. We made this same assumption - i.e. the death or disappearence of individuals post baiting events were attributed to the lethal impacts of the baiting event.

Full-text screening was conducted by YZF. We excluded 68 papers during the full-text screening process that did not meet our inclusion criteria, typically because they did not quantify the number of individuals both prior to and post baiting. This gave a total of 34 papers from which data were extracted.

Data extraction

Data extraction was predominantly conducted by YZF, with assistance from PLT. All information was extracted at an equivalent level to which authors reported baiting impacts on predator survival. For example, some studies distributed baits on a single occasion and quantified the impact on predator survival in association with this single event, but other studies distributed baits on multiple occasions within a short period of time or replenished all taken/missing baits before quantifying the impact on predator survival; information for these studies was accordingly extracted at these different reporting levels. This difference in reporting/data capture and extraction was captured and accounted for in analysis through the use of a repeat baiting moderator that indicated if a single or multiple bait applications within a short period of time had occurred prior to estimating impacts on predator numbers. In this context, authors were said to have employed repeat baiting if any additional baits were deployed/distributed shortly after a main initial deployment; this included the daily replacement of taken/missing baits and the complete replacement/re-distribution of all baits. For each paper we additionally extracted information pertaining to authors affiliations, year of publication, target species/predator, toxin used, toxin concentration and total volume, bait matrix, bait brand, time between repeat bait applications, method of bait distribution, bait density, duration of baiting, study area, temperature and rainfall. Our final raw dataset can be found at *open_source_respository_to_be_inserted_after_review*.

Outcomes

Our outcome of interest was apparent predator survival. This was calculated from the proportion of the pre-baiting individuals that died or disappeared post baiting, i.e. the number of individual predators present must have been quantified prior to and post baiting. Examples included the number of radio-collared individuals alive pre and post baiting, the number of individuals identified by pelage pre and post baiting, the distinct number of genotypes pre and post baiting, and the number of feral cats that took baits out of a total number of individuals alive prior to baiting - this latter example was only applicable to the single Algar et al. (2007) study described above.

Effect size calculation

We used the log odds (i.e. log(number of individual predators that died or disappeared post baiting/number of individual predators that were present prior to baiting)) as our effect size in meta-analytic models. Zero values (i.e. no individual predators died or disappeared post baiting) are problematic for the calculation of log odds ratios, so a small adjustment of 0.5 was added to any zero value to ensure that the log odds was defined. As such, any result on the efficacy of baiting is likely conservative. Given that only 16 effects contained both experimental and control groups, we were unable to use traditional contrast-based meta-analysis approaches, which require data from both groups to calculate effect size (e.g. log odds ratio). Therefore, we used a long form armed-based approach instead, where each row of data, or entry, is represented by the odds (natural logarithm) of individual predators dying or disappearing for an individual treatment/control group. Throughout our manuscript, we discuss apparent survival, log odds and risk of dying. Apparent survival is our outcome of interest, which is measured and quantified on the log odds scale. We then transform log odds to percentage risk of dying to aid reader interpretation.

Moderators

Due to the relatively low number of effect sizes within each data set (track/road-distribution vs. area-distribution studies), we limited the number of moderators included in models to only those considered to be the most important based on biological plausibility. These were bait matrix (3 levels: 1) fresh meat bait; 2) dry processed sausage bait; 3) mixed), predator family (2 levels: 1) canines; 2) felines), repeat bait applications (2 levels: 1) single; 2) repeated), and bait density. We also recorded the year of publication, to examine potential time-lag bias, i.e. the tendency for studies with large effects to be published earlier, and classified each study based on the strength of evidence it provided as determined by its study design (4 levels: 1/strongest) GPS- and radio-collaring of individual animals; 2) quantification of unique individuals; 3) quantification of individuals from signs; 4/weakest) quantification of individual cats from signs prior to baiting, bait uptake as post baiting measure - Algar et al. (2007) only). The grouping of dingo and foxes together under ‘canine’ was additionally supported based on there being no observable differences in baiting efficacy between the two predators.

Data analysis

All analysis was conducted in R version (4.4.1) (Team 2023) and plots created in *ggplot2* (vers. 3.5.1, Wickham 2016) by YZF. We fitted multilevel meta-analytic and multilevel meta-regression models run using the `rma.mv()` function within the *metafor* package (vers. 4.6.0, Viechtbauer 2010). Due to baits being distributed either along tracks, trails and roads, or across areas, we split our data in two and conducted equivalent analyses for both design types. It was not possible to include track/road baiting and area baiting studies in the same meta-regression models for two reasons: 1) this made the assumption that an X unit change in the risk of predator death along a track was equivalent to the same X unit change in predator death more broadly across an area; and 2) the spatial units of bait density differed between the two design types (baits per km Vs baits per km2), meaning that when bait density was included as a moderator in models the interpretation of parameter estimates would be nonsensical if both design types were included in the same model.

We first tested for an overall effect of baiting on the log odds of predator death. We included baiting treatment (treatment vs. control) as a fixed effect. Our data contained several potential sources of non-independence that we controlled for by including the corresponding random effect. In total, there were four random intercepts: paper identity, study identity (some papers might have multiple studies), effect size identity (for identifying the pairs of treatment and control group comparisons), and entry ID (individual treatment or control effect) as random intercepts. Random intercepts that did not account for any heterogeneity (i.e. ~ 0%) were dropped from the final model. We report on measures of I^2, which quantify the proportion of variation explained by specific random effects relative to total heterogeneity (excluding sampling variance). Given that we conducted an arm-based analysis we also included random slopes for baiting treatment within each paper identity and effect size identity. We also assumed that the within-study variance was not constant between the control and treatment groups by estimating separate within study variances. We conducted the moderator analyses on just the treatment group data, after removing all control group data. Therefore, the moderator analyses represent how the treatment group results varied depending on the moderators.

We were unable to include our strength of evidence moderator in main effect models as it was highly related to all of species, repeat baiting and bait matrix, as determined by variance inflation factors. Additionally, all effect sizes assigned to category 4 of the strength of evidence moderator came form Algar et al. (2007). As a result, we conducted a sensitivity analysis by removing all effects derived form Algar et al. (2007) and re-running our analysis. All results remained identical despite removing all effects derived from Algar et al. (2007) and thus we kept these effects in our data and models.

Publication Bias

We ran two analyses to detect potential publication bias: 1) small study effects, where effect sizes from studies with small sample sizes are over-estimated (hereafter referred to as the small study bias) and 2) time lag bias (i.e. when initial findings are dominated by studies reporting larger effects). For small study bias, we entered the effect sizes' standard error as a moderator. For time lag bias, we entered the year of publication (centered) as a moderator. Both moderators were entered simultaneously in a multilevel multiple regression with paper ID and effect size ID included as random factors. For the track/length baiting studies, we also included bait density to control for heterogeneity in effect sizes due to the moderator.

Results

Data description

Our final dataset contained 34 papers, that provided a total of 121 effects. Of these 121 effects, 16 contained both experimental and control groups, and 105 had only an experimental group. Sixty-eight effects came from track/road-distribution studies, 50 from area-distribution studies, and 3 effects could not be classified as either design type. Ninety-two effects related to the baiting of feral cats, 10 to fox baiting and 19 to dingo baiting. Overall, 106 effects came from mainland Australia, 9 from 5 different Australian islands, 4 from mainland New Zealand and 2 from two Galapagos Islands. Together, 1402 individuals were tested.

Details of the specific bait used, or methods employed, were often incomplete (Table 1). Nonetheless, based on the available details, when feral cats were targeted in baiting, dry/processed baits were by far the dominant bait base used. A large proportion of these dry/processed baits used to target feral cats were

Eradicat, but bait brand information was not provided for approximately half of all feral cat effects. Most baits targeting feral cats were surface laid, and a greater proportion were distributed on-ground as opposed to via air. When foxes were targeted in baiting, dry/processed baits were again the dominant bait base used, and only about a third were Foxoff. Fox baits were typically buried or tethered and were largely distributed on-ground. In contrast to feral cats and foxes, when dingoes/dogs were targeted in baiting fresh meat was the dominant bait base. This was typically red meat that was surface laid and distributed by air.

Table 1. Summary of baiting methods used by species targeted.

		Feral cat (number of effects (proportion of total effects))	Red Fox (number of effects (proportion of total effects))	Dingo (number of effects (proportion of total effects))
Bait base	Dry/processed	82 (0.88)	7 (.070)	3 (0.16)
	Fresh meat	6 (0.08)	2 (0.20)	12 (0.63)
	Mixture (dry & fresh)	0 (0.00)	1 (1.0)	4 (0.21)
	Whole animal carcass	4 (0.04)	0 (0.00)	0 (0.00)
	Total effects	93	10	19
Bait brand	Bait-tek	2 (0.02)	0 (0.00)	0 (0.00)
	Curosity	3 (0.03)	0 (0.00)	0 (0.00)
	Eradicat	29 (0.31)	0 (0.00)	1 (0.05)
	Foxoff	0 (0.00)	3 (0.30)	0 (0.00)
	Oakleigh	1 (0.01)	0 (0.00)	0 (0.00)

		Feral cat (number of effects (proportion of total effects))	Red Fox (number of effects (proportion of total effects))	Dingo (number of effects (proportion of total effects))
	Pedastop fresh red meat	1 (0.01)	0 (0.00)	0 (0.00)
	Pedastop fresh white meat	1 (0.01)	0 (0.00)	0 (0.00)
	In-house fresh animal carcass	4 (0.04)	0 (0.00)	0 (0.00)
	In-house fresh fish	2 (0.02)	0 (0.00)	0 (0.00)
	In-house mixture (dry & fresh)	0 (0.00)	1 (0.10)	0 (0.00)
	In-house fresh red meat	4 (0.04)	4 (0.40)	11 (0.58)
	In-house other	1 (0.01)	0 (0.00)	4 (0.21)
	Information not provided	45 (0.48)	2 (0.20)	3 (0.16)
	Total effects	93	10	19
Bait presentation	Buried	2 (0.02)	3 (0.30)	0 (0.00)
	Buried & tethered	0 (0.00)	2 (0.20)	0 (0.00)
	Physical bait station	2 (0.02)	0 (0.00)	0 (0.00)
	Surface laid	31 (0.33)	2 (0.20)	15 (0.79)

		Feral cat (number of effects (proportion of total effects))	Red Fox (number of effects (proportion of total effects))	Dingo (number of effects (proportion of total effects))
	Suspended	2 (0.02)	0 (0.00)	0 (0.00)
	Tethered	0 (0.00)	0 (0.00)	4 (0.21)
	Information not provided	56 (0.60)	3 (0.30)	0 (0.00)
	Total effects	93	10	19
Bait distribution method	Aerial deployment	34 (0.37)	2 (0.20)	14 (0.74)
	On-ground deployment	57 (0.61)	8 (0.80)	5 (0.26)
	Aerial & on-ground deployment	1 (0.01)	0 (0.00)	0 (0.00)
	Information not provided	1 (0.01)	0 (0.00)	0 (0.00)
	Total effects	93	10	19

How effective is baiting?

There was a significant effect of baiting on survival when baits were distributed along tracks/roads (estimate (contrast - log(odds)): 3.03; 95% CI: 2, 4.05; *p* value = 6.7764^{-9}), with baited tracks increasing the risk of predator death by 46% relative to unbaited tracks. However, no significant effect of baiting on survival was observed when baits were distributed across areas (estimate (contrast - log(odds)): 0.71; 95% CI: -0.47, 1.89; *p* value = 0.24) (Figure 2). Despite this, we noted that the mean risk of dying within the baited/treatment group was approximately equivalent for track/road- and area- distribution studies, and available data for unbaited areas was sparse (only 5 effects). Given that both the random intercepts of study identity and entry identity did not account for any of the variation in effects (i.e. ~ 0), we retained only the two random slopes (paper identity and effect size identity) in the above analyses.

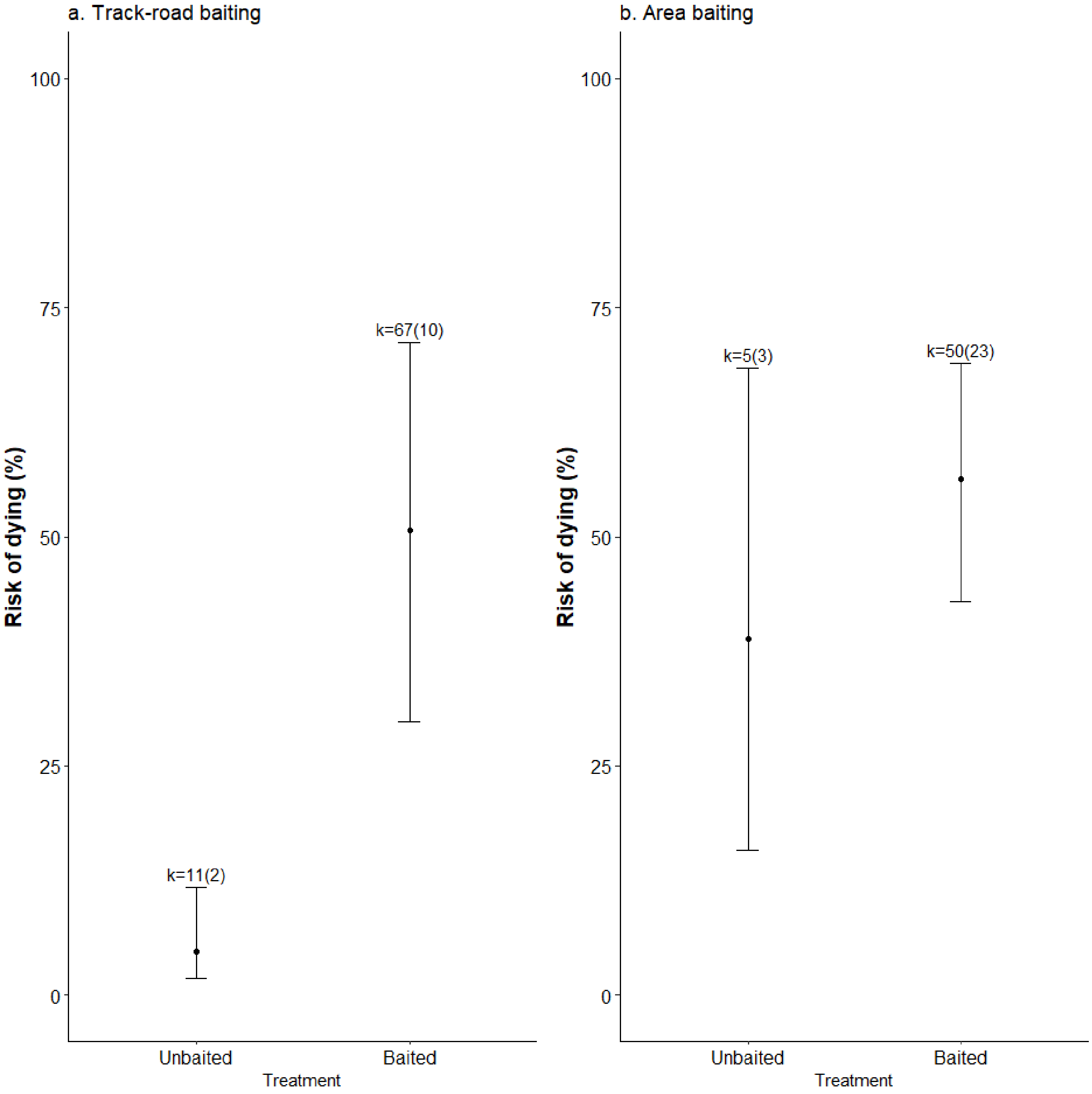

Fig. 2. Marginal means and 95% confidence interval of the risk of dying for baited vs unbaited plots for (a) track/road-distribution studies, and (b) area-distribution studies. k refers to the number of effect sizes and number of papers in parenthesis.

Table 2. Model parameter estimates for moderators in track/road-distribution studies. For categorical moderators' parameter estimates are based on estimated marginal means. For the only continuous moderator, bait density, we presented the estimate from the metaregression model.

Moderator	Estimate (ln odds)	SE	95% CI lower (ln odds)	95% CI upper (ln odds)	Risk of dying (%)	95% CI lower (%)	95% CI upper (%)
Bait density (centered)	0.06	0.02	0.02	0.11			
Predator							
Canine	0.09	0.31	-0.53	0.70	52.18	37.09	66.89
Feline	0.06	1.44	-2.76	2.89	51.59	5.96	94.72
Bait matrix							
Dried/Processed	0.11	1.07	-1.98	2.20	52.69	12.10	90.01
Mix	0.44	1.51	-2.52	3.39	60.80	7.47	96.75
Fresh	-1.67	2.01	-5.61	2.26	15.82	0.37	90.57
Repeated baiting							
No	-0.05	1.00	-2.02	1.91	48.63	11.74	87.07
Yes	1.12	2.11	-3.01	5.26	75.47	4.70	99.48

Table 3. Model parameter estimates for moderators in area-distribution studies. For categorical moderators' parameter estimates are based on estimated marginal means. For the only continuous moderator, bait density, we presented the estimate from the metaregression model.

Moderator	Estimate (ln odds)	SE	95% CI lower (ln odds)	95% CI upper (ln odds)	Risk of dying (%)	95% CI lower (%)	95% CI upper (%)
Bait density (centered)	-0.00	0.01	-0.02	0.02			
Predator							
Canine	-0.12	0.17	-0.46	0.22	46.97	38.73	55.37
Feline	0.21	0.69	-1.14	1.56	55.24	24.18	82.68
Bait matrix							
Dried/Processed	0.24	0.59	-0.92	1.39	55.94	28.57	80.12
Fresh	-0.25	0.91	-2.04	1.54	43.82	11.52	82.37
Repeated baiting							
No	0.18	0.54	-0.87	1.24	54.52	29.43	77.51
Yes	0.05	0.88	-1.68	1.78	51.26	15.72	85.57

I^2 values revealed high heterogeneity in the treatment results for both track/road- (I^2_{Total}: 56.48%) and area-distribution studies (I^2_{Total}: 73.16%), highlighting the importance of follow-up moderator analyses. All moderator analyses were conducted with paper identity and effect size identity as random factors. Study identity was dropped from the analyses because it did not account for any of the heterogeneity (Table 4).

Table 4: I^2 heterogeneity in baiting treatment effect accounted for by each random effect

Random effect	Track/road-distribution studies	Area-distribution studies
Total	64.97	74.01
Paper identity	60.88	52.89
Study identity	0.00	0.00
Effect size identity	4.08	21.12

Does the effectiveness of baiting differ for canines and felines?

We found no evidence that baiting was more effective at reducing canine relative to feline survival, after controlling for bait density, repeat bait applications and bait matrix (*p* value for track/road-distribution studies = 0.99, *p* value for area-distribution studies = 0.61) (Table 2 & 3, Figure 3 & 4).

In 78% of studies where feral cats were targeted in baiting and the brand of bait could be identified, the authors used Eradicat® baits. We therefore also tested, post-hoc, if Eradicat® achieved a greater probability of feline death relative to other bait brands/types. We found no evidence to support this (*p* value = 0.24). For area-distribution studies, there was no difference in the probability of feline death when Eradicat® was distributed (risk of dying: 61%; 95% CI: 43, 77), compared to if another bait brand/type was used (risk of dying: 40%; 95% CI: 17, 69). There was insufficient information available to enable an equivalent test for track/road-distribution studies.

Do higher bait densities achieve greater lethal predator control?

Higher bait densities achieved a greater risk of predator death when baits were distributed along tracks/roads (estimate (log odds) = 0.06; 95% CI: 0.02, 0.11; *p* value = < 0.01) (Table 2, Figure 3). This was after controlling for predator family, repeat bait distribution and bait matrix. For each additional bait distributed per km track, the risk of predator death increased by 1%. However, the same effect did not hold when baits were distributed across areas (estimate (log odds) = 0; 95% CI: -0.02, 0.02; *p* value = 0.85), although the range in bait densities for area-distribution studies was limited (Table 3, Figure 4).

Do repeated bait applications achieve greater predator control relative to single bait applications?

We found no evidence that repeat bait applications, within a short period of time, achieved greater predator control (Table 2 & 3, Figure 3 & 4). This was after controlling for predator family, bait density and bait matrix. This lack of an effect was consistent across studies distributing baits along tracks/roads and across areas (*p* value for track/road-distribution studies = 0.41, *p* value for area-distribution studies = 0.84). When the interval between repeat bait applications was reported, the mean interval was 6 (range: 1, 18) days.

Does the bait matrix influence the effectiveness of baiting?

We found no evidence that bait matrix influenced the risk of predator death (Table 2 & 3, Figure 3 & 4). This was after controlling for predator family, bait density and repeat bait applications. This lack of an effect was consistent across studies that distributed baits along tracks/roads and across areas (*p* value for track/road distribution studies = 0.41, *p* value for area-distribution studies = 0.52).

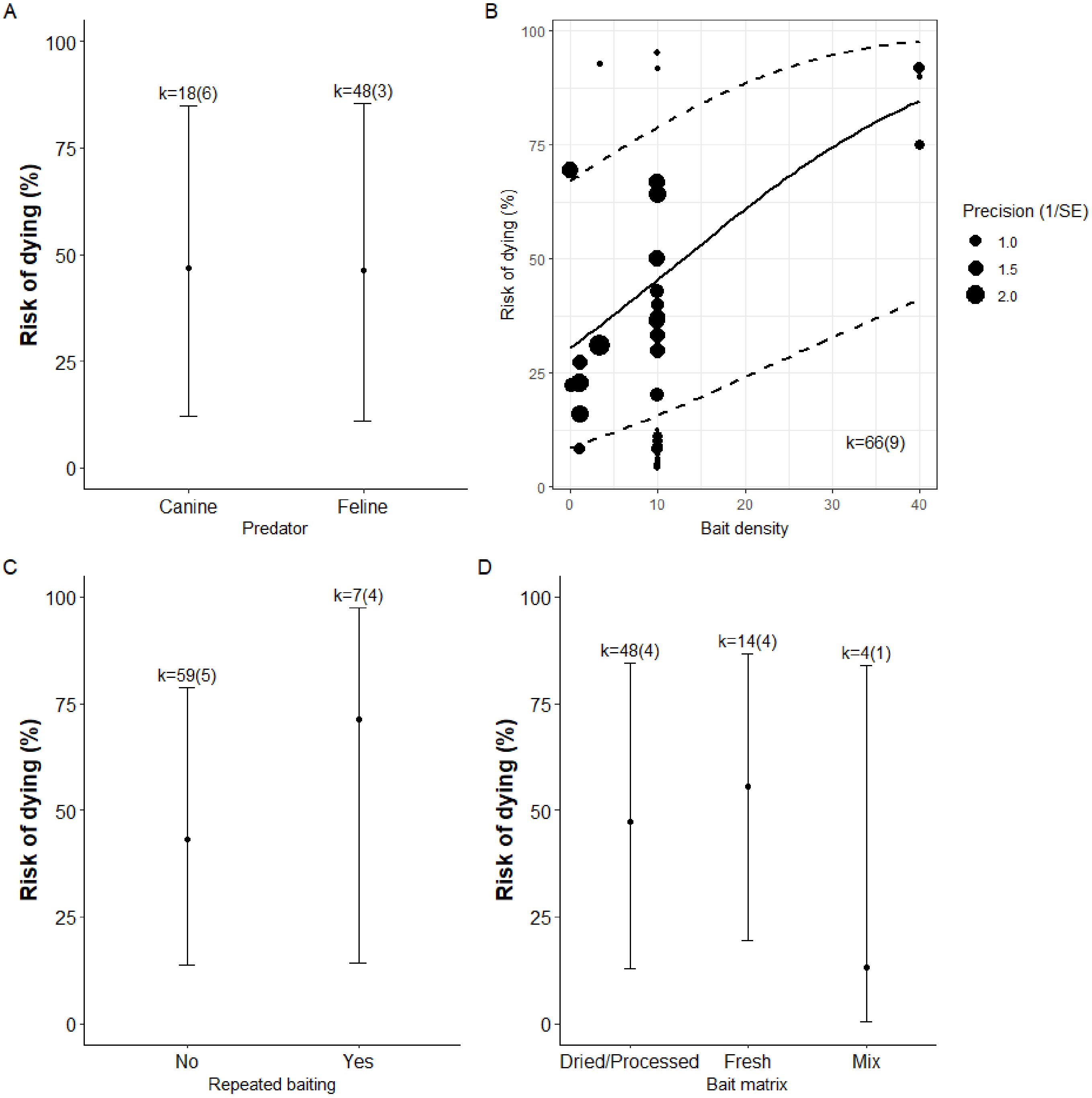

Fig. 3. Moderator effects on the effect of baiting in track/road-distribution studies. Each categorical moderator plot (A, C, D) includes the estimated marginal mean effect size (circle) and 95% confidence interval (error bars around the mean effect size). (B) Shows the continuous relationship between the percentage risk of dying and bait density. Size of each point corresponds to the precision (inverse of standard error). k refers to the number of effect sizes and number of papers in parenthesis.

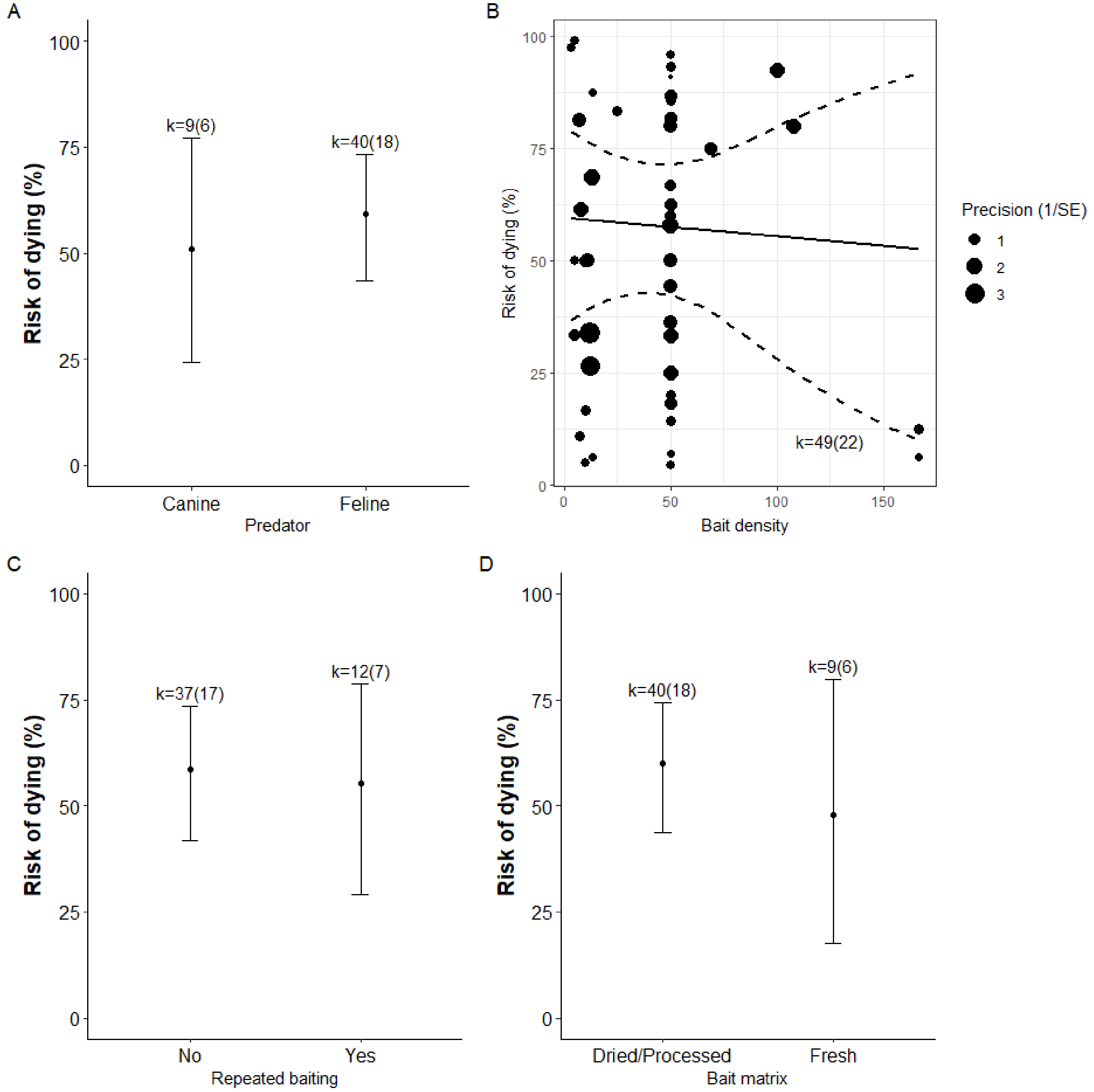

Fig. 4. Moderator effects on the effect of baiting in area-distribution studies. Each categorical moderator plot (A, C, D) includes the estimated marginal mean effect size (circle) and 95% confidence interval (error bars around the mean effect size). (B) Shows the continuous relationship between the percentage risk of dying and bait density. Size of each point corresponds to the precision (inverse of standard error). k refers to the number of effect sizes and number of papers in parenthesis.

Publication bias

Both small study bias and time lag bias (Figure 5) tests were non-significant for both track/road- and area-distribution studies (*p* values: 0.37 and 0.80 respectively).

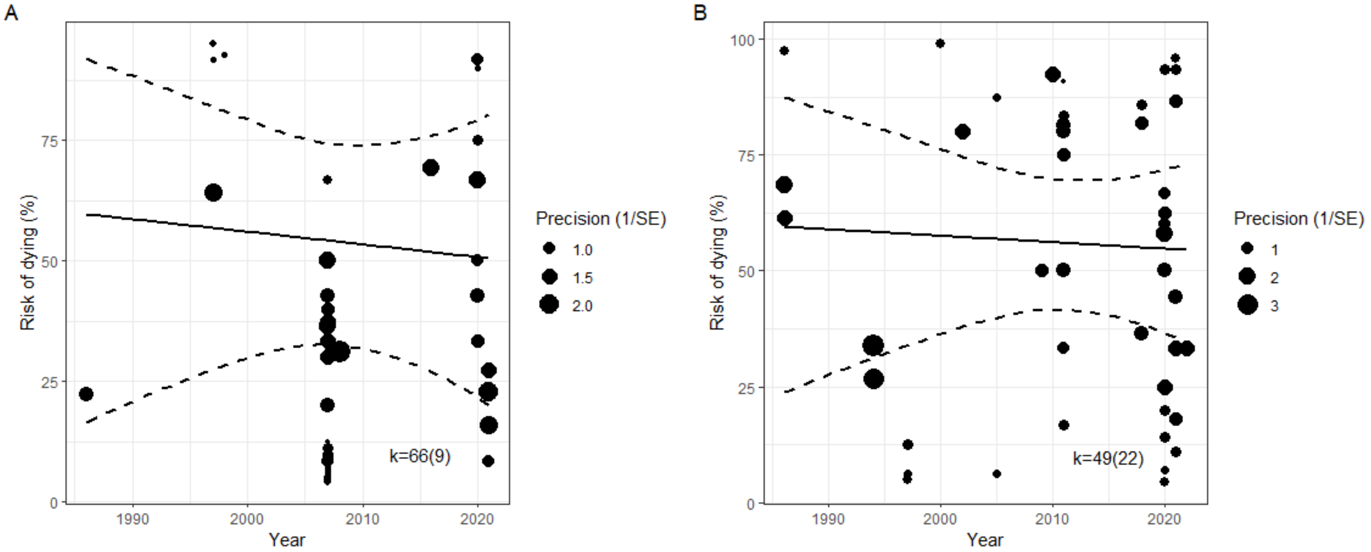

Fig. 5. Relationship between percentage risk of dying and year of publication for (A) track/road- and (B) area-distribution studies. Size of each point corresponds to the precision (inverse of standard error). k refers to the number of effect sizes and number of papers in parenthesis.

Discussion

We conducted the first meta-analysis of the efficiency of toxic baiting for the control of feral cats, red foxes and dingoes. Overall, baiting appeared to consistently reduce apparent predator survival, with some evidence that greater bait densities did achieve increased predator death. However, counter to our predictions, baiting was not more efficacious for canines relative to felines, nor did repeat bait applications within a short period of time or bait matrix influence the risk of predator death. Our findings are directly and practically relevant to those who engage in the lethal management of mammalian predators through toxic baiting.

Baiting increases the risk of predator death

When baits were distributed along tracks they increased the risk of predator death by 46% relative to controls. In contrast, when baits were distributed more broadly across areas the risk of predator death was comparable between baited and unbaited areas. When assessing power in meta-analysis, it is important to consider the number of papers included, the number of effect sizes extracted, and the number of unique units summarised. While our study summarised 34 papers, 121 effect sizes and 1402 individuals overall, we had only five effects from three papers in the unbaited control group for area-distribution studies. This low sample size and high variability in the unbaited control group data likely explains the lack of difference in the risk of predator death between baited and unbaited areas. This is supported by the fact that the mean risk of dying within the baited/treatment group was approximately equivalent for track/road- and area-distribution studies. The similarity between estimates of predator survival for each design type suggest that reductions in predator survival observed following the distribution of baits along tracks and roads may represent an equivalent general reduction in survival for the broader area or population; however further work would be needed to confirm this.

The relationship between track/road baiting and predator death may be clearer relative to that for area-distribution studies due to predators preferentially using tracks to improve movement efficiency and prey detection. For example, the placement of camera traps on roads increases rates of detection for all of cats, foxes and dingoes relative to off road cameras (Read et al. 2015; Geyle et al. 2020; Wysong et al. 2020b), and GPS tracking studies show preferential use of roads and similar linear features by felids and canines (Robley et al. 2010; Bischof et al. 2019; Wysong et al. 2020a). Our results therefore appear consistent with the movement ecology of these species.

Although baiting appears to consistently reduce predator survival in the immediate short-term, directly following the baiting event, it is important for land managers to consider the duration over which this effect may be maintained. To achieve meaningful reductions in predator damage it is likely that reduced populations would need to be maintained over periods longer than the immediate short-term – it is unclear how long the average effect of baiting we describe may persist. For both track/road- and area-distribution studies the average risk of predator death achieved from baiting was below annual maximum population growth rates for all of feral cats, foxes and dingoes (Hone et al. 2010, 2017). Therefore, when predator populations are increasing at, or close to, their maximum annual growth rates, we would expect populations to be rapidly replenished and continue to increase through time if not subject to further ongoing control. Over longer time periods, rapid immigration, compensatory reproduction, behavioural changes in the remaining, post-baiting population, or other factors may all contribute to the extent to which baiting effectively achieves and maintains reduced predator numbers or impacts (Molsher 1999; Greentree et al. 2000; Wallach et al. 2010; Allen 2014; Campbell et al. 2019).

Baiting is equally effective for felines and canines

Our results suggest baiting may be equally effective for the management of felines and canines. Felids are generalist, opportunistic ambush predators, with the domestic/feral cat being no exception (Woinarski et al. 2019). They are typically said to be visually driven and to prefer fresh meat (Kitchener et al. 210AD; Bradshaw et al. 1996). For these reasons feral cats are argued to be reluctant to scavenge and consequently less amenable to control via baiting. In contrast, dingoes and foxes are well documented scavengers (Allen 2010; Forsyth et al. 2014; Spencer & Newsome 2021). While additional studies are needed to improve the precision in our estimates for feline and canine survival post baiting, our results nonetheless do not support the idea that cats are reluctant to scavenge and are consequently less amenable to control by baiting relative to canines.

One explanation for baiting appearing to be equally effective for felines as it is for canines would be if a majority of feline studies distributed Eradicat® baits. Eradicat® is a manufactured sausage bait specifically designed for uptake by feral cats and may help to overcome their supposed reluctance to scavenge or consume baits. Indeed, in 78% of studies where feral cats were targeted in baiting and the brand of bait could be identified, the authors had used Eradicat® baits. However, for studies where baits were distributed across areas, we found no evidence that Eradicat® baits did achieve a greater risk of cat death relative to other bait types, and data was too sparse to enable an equivalent comparison for track/road distribution studies. This suggests that the use of Eradicat® baits is unlikley to be the reason why reductions in survival achieved with baiting were largely indistinguishable for canines and felines.

Alternatively, due to the perception that feral cats are reluctant to scavenge or consume baits, practitioners may make additional, concerted efforts to deploy baits at times when alternate prey abundance is expected to be low, increasing the probability that cats do take baits when they are available (Algar et al. 2007; Christensen et al. 2013). Although canine baiting programs also consider the optimal time to deploy baits to maximise uptake, the timing of bait deployments may be viewed to be less critical to baiting success. Irrespective of why the baiting of feral cats may be equally effective to that of canine baiting, the current available data suggest that this is the case.

Higher bait densities increase the risk of predator death

Our results demonstrate that higher bait densities do achieve a greater risk of predator death when baits are distributed along tracks/roads. We could not demonstrate an equivalent effect for studies distributing baits more broadly across areas, but we note that the range in bait densities for area distribution data was limited. The ability of predators to find baits in the environment is key to baiting success and therefore greater bait densities should be directly related to population reduction (Bengsen et al. 2008; Fancourt et al. 2021). Although we did not test for non-linear relationships due to sparse data, we hypothesise that the relationship between bait density and the risk of predator death is non-linear and likely follows some form of effort-outcome relationship where at high bait densities, the population reduction achieved per additional unit of baiting diminishes (Hone et al. 2017).

Although others have shown a positive relationship between bait density and population reduction, and suggest that higher densities do achieve greater population control, the relationship is unlikely to be this clear-cut (Ballard et al. 2020). Indeed, Rees et al. (2023) present data that provide support for a non-linear relationship, suggesting that 2-3 fold increases in bait density may have limited impact on population reduction.

Repeat bait applications do not increase the risk of predator death compared to single applications

We found no evidence that repeated bait applications within a short period of time achieved a greater risk of predator death relative to single applications. There are a number of possible reasons why this may be the case.

Due to individual behavioural differences, not all predators within populations will consume baits, meaning that not all predators within a given population will be susceptible to baiting. This may arise due to predator populations being repeatedly exposed to baiting for prolonged periods enabling individuals to develop an aversion to baits if they have experienced sub-lethal impacts previously, or due to other inherent individual differences in animal personalities (Wolf & Weissing 2012). For example, some foxes are known to cache baits, and if cached baits are consumed once the 1080 has degraded to sub-lethal levels, foxes could be expected to develop bait aversion (Saunders et al. 1999). If foxes then associate this illness with the bait, individuals may learn to avoid baits in subsequent encounters. This would effectively reduce the number of foxes susceptible to baiting. In a similar manner, individual cats and dingoes are also known to avoid baits at times but the exact reason for such avoidance behaviours are not well known (Allen et al. 1996; Ratcliffe et al. 2010). For any bait application, we could then expect there to only ever be a proportion of the population that are susceptible and likely to consume baits when they are encountered. Single bait applications may kill the majority of bait-susceptible predators, with subsequent applications shortly after being of limited benefit among largely wary individuals.

The lack of a repeat baiting effect may also be due to baited areas being small or repeat baiting events being too far spaced in time. Rapid immigration into small, baited areas may negate carry-over effects from one bait application to another a short time after (Gentle et al. 2007). Such an explanation is supported by findings from Greentree et al. (2000), and also by Molsher (1999) who found that local fox abundance did not decline even when baits were applied monthly. Palmas et al. (2020) also found that following a 44% reduction in local feral cat abundance, the population rapidly recovered to pre-control abundance within three months due to rapid compensatory immigration. Similarly, repeated bait applications may be too far spaced in time, giving predator populations time to recover prior to subsequent bait applications. However, this is unlikely here given repeat bait applications were typically only approximately 6 days apart.

Here we test the difference in the risk of predator death between single bait applications and repeat bait applications within a short period of time, such as replenishing baits daily or a subsequent bait distribution one week after the first. We do not test the difference between single bait applications and repeat bait applications at any and all time points into the future. It would be expected that repeated bait applications at distant time points in the future could further increase the risk of predator death; indeed may island eradications of predators employ distant, repeated bait applications.

Fresh baits are not more effective than dried baits

We found little evidence that bait matrix influenced the risk of predator death. This was in contrast to our prediction that fresh meat baits would achieve a greater risk of predator death, especially for canines, and is in contrast to several bait palatability trials. For example, Gentle (2005) inserted trackers into fresh meat and dry processed fox baits to assess whether they were eaten or cached following removal. He found that fresh meat baits were eaten at a vastly higher rate relative to dry processed baits. Similarly, there is some evidence that both dingoes and cats also prefer fresh meat baits. Increasing the attractiveness and palatability of dry processed baits has been a long, and is an ongoing, focus among those studying baiting (Johnston et al. 2020; Cox et al. 2022). Despite these previously described palatability effects, the lack of effect we show here suggests that any influence of bait matrix is likely small and not as critical as we predicted. Objective evidence for a more effective bait matrix, that achieves a greater risk of death, is currently limited.

Future directions

Lethal, toxic baiting is a complicated issue that requires assessment and understanding from multiple directions. In this context, it is important to appreciate that what one study can achieve is limited, however powerful, well-designed, and expensive such a study might be; no single field or laboratory study can resolve the complexities or methodological challenges associated with baiting (Ioannidis 2010; IntHout et al. 2016; Amaral & Neves 2021). We consider our meta-analysis the first piece of a complex puzzle that summarises how well baiting works and the factors that influence its efficacy across the currently available literature. However, the questions we address and baiting methods generally require ongoing assessment; collaborative research through a prospective meta-analysis or similar could be very powerful for this purpose (Nakagawa et al. 2024).

Further research should focus on three main areas: 1) tracking the fate of a known number of individuals through baiting events, particularly using GPS and radio telemetary. Many studies present indices of population change that make quantifying the outcome of baiting challenging and difficult to compare. 2) Improved reporting and design. It is critical that researchers thoroughly report all fundamental information, including the bait brand/type, how it was presented, the concentration or amount of toxin in each bait, the density at which baits were distributed, the total area/distance over which baits were distributed, and if baits were replenished/refreshed and when this was done. However, arguably of greater importance is the design of the baiting program itself. Adequate unbaited controls are critical, and their absence significantly limits the utility of the information gained and the conclusions that can be drawn. 3) Studies that use atypical methodologies. Many studies follow similar or even equivalent methodologies regarding the specific baits used, how and where they are distributed, and the density at which distribution occurs. This greatly reduces variation in moderator data and presents challenges when comparing baiting effectiveness across moderator gradients. Optimising and improving the baiting process will require testing baiting effectiveness across wide moderator gradients. We note that many of these reccomendations have been advocated for by others (Hayward et al. 2015).

We had a strong bias towards Australian studies in our analysis. Although predator baiting, especially of feral cats, is applicable worldwide (Nogales et al. 2004; Campbell et al. 2011), many predator baiting studies outside of Australia have not focused on the effectiveness of the baiting for the control of the target predator. Rather, for example, studies have described how baiting has contributed to the eradication of feral cats from an island, without reporting suitable baiting efficiency data to enable extraction for inclusion in meta-analyses of baiting efficency. Accordingly, we encourage practitioners to document and report on the efficency of predator baiting programs outside of Australia.

Our study has focused specifically on the predators themselves and the impact baiting has on them. However, discussion of predator baiting cannot occur in the absence of consideration of lethal non-target impacts to individuals and populations, or consideration of predator impacts and their reduction post baiting (i.e. faunal or livestock response). Systematic and quantitative summaries of these topics would be valuable and important. Such work is also relevant to improving the effectiveness of baiting for the control of predators themselves. For example, high bait takes rates by non-target species have previously been suggested to be a cause of low mortality for target predators (McIlroy et al. 1986; Algar et al. 2007).

Conclusions

Our study is the most comprehensive analysis of predator baiting to date. However, it is limited to the available, suitable data, which is sparse, highly variable, and at times of poor quality. Nonetheless, based on the currently available published and readily accessible grey literature, we demonstrate that the evidence for the superiority of a number of routine and accepted baiting practices is weak. We encourage all practitioners to publish their findings or make their data available for collective analyses through other means; such information will facilitate significant improvements to baiting methodology.

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Supplementary material

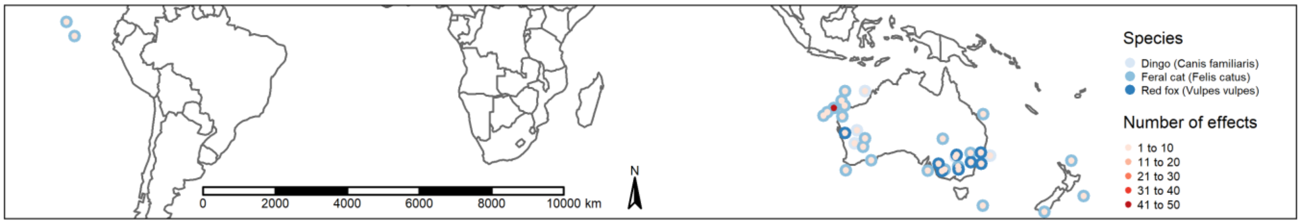

Fig. 6. Distribution and number of effects by species