Quantifying the success of feral cat eradication, San Nicolas Island, California

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Abstract: It is usually uncertain when to declare success and stop control in pest eradication operations that rely on successive reductions of the population. We used the data collected during a project to eradicate feral cats from San Nicolas Island, California to estimate both the number of cats remaining towards the end of the project, and the amount and type of surveillance effort required to declare successful eradication after the last known cat was removed. Fifty seven cats were removed between June 2009 and April 2010 and our model estimated that there was a 95% chance that a further 1 to 4 cats remained, with 1 cat being the most likely number. After this time a further two cats were detected and removed and the model predicted this outcome with a probability of 0.25. If managers wished to confirm eradication success at this point, we estimated that 55 km of effort searching for recent evidence of cats over the whole island without detecting any would provide 99% certainty that no cats remained (stopping rule 1). Alternatively, the optimal amount of search effort for evidence that minimized the joint cost of searching and the cost of wrongly declaring eradication was 75 km (stopping rule 2). The equivalent amount of camera-nights (26 cameras were available) required to declare successful eradication were 416 (stopping rule 1) and 1196 camera nights (stopping rule 2). During the confirmation phase, 270 km of sign search effort and 3294 camera-nights surveillance were used from late June 2010, when the last cat was removed, through August 2010, without detecting signs of survivors. Managers can be very confident that eradication has been successful.

Keywords: detection; *Felis catus*; monitoring; risk analysis; pest management

Introduction

San Nicolas Island is one of the four southern Channel Islands off the coast of California. The island is 5896 ha with a maximum elevation of 277 m above sea level and an annual rainfall of less than 20 cm. The island is home to two endemic mammals, the island fox (*Urocyon littoralis dickeyi*) and a deer mouse (*Peromyscus maniculatus exterus*). It is also home to one endemic, endangered lizard (*Xantusia riversiana*), 13 breeding terrestrial birds, and 5 breeding seabirds – including five species that are endemic to the Channel Islands (Schoenherr et al. 1999). Feral dogs (*Canis familiaris*) arrived on the island with sea otter hunters in the early 19th century but were removed when sheep ranching began in 1857. Sheep (*Ovis aries*) were removed in the 1940s when ranching ceased and the island passed to the USA navy (Schoenherr et al. 1999). Cats (*Felis catus*) were probably present as domestic animals when the island was farmed and were certainly present as feral animals since at least the late 1950s (Hillinger 1958). Cats prey on the deer mice and the endemic night lizard as well as many other non-endemic species (Kovach & Dow 1981), and harbour *Toxoplasma* sp. which is a risk to the island fox and the southern sea otter (*Enhydra lutris nereis*) (Conrad et al. 2005; Petersen et al. 1972).

Island Conservation began an attempt to eradicate cats on the island in June 2009 mainly using control tools such as leg-hold trapping and searching with trained dogs that have proved successful in other feral cat eradication projects (Wood et al. 2002; Campbell et al. in press). Towards the end of the eradication program, when cats were no longer being detected, the managers required guidance about how much more monitoring effort would be required to declare San Nicolas Island free of feral cats.

The aim of this paper was to provide managers with information on stopping rules that could be used to declare eradication success. Stopping rules were constructed to limit either the type I error rate, the probability of falsely declaring eradication success, or minimize the cost of type I and II error rates, i.e. the joint cost of monitoring and the cost associated with wrongly declaring eradication successful. Both these stopping rules have been used in previous studies on eradication of feral pigs (Ramsey et al 2009) and weed eradication (Regan et al 2006). We used the control and monitoring data collected during the project up until April 2010 to (a) assess the probability that one or more cats still remained on the island after this time, (b) estimate how much more monitoring should be used before declaring eradication successful under our two stopping rules, and (c) report whether this confirmation monitoring found any surviving cats that had not been detected in the final control or surveillance phases of the project.

Methods

Monitoring methods

Five methods were used to find cats and we summarize details of their implementation below. For a full account of the operational details behind the eradication program we refer readers to Hanson et al. (in press) and Will et al. (in press). Trapping was the main capture method used throughout most of the removal phase of the project and provided catch per unit effort data, which were used to estimate the size of the cat population. Other detection methods that did not involve removal of cats were searches for sign of cats with trained personnel, tracking dogs, or photos of cats from camera traps. Incidental removals of cats resulted from opportunistic encounters or from the use of tracking dogs.

Trapping

The trapping program on San Nicolas Island began on 21 June 2009 and was largely completed by 21 January 2010 with up to 236 radio-telemetered, soft-jawed Oneida Victor #1® traps with lures being deployed at any one time in both trail-set and cubby-set systems (see Hanson et al. in press; Will et al. in press for details of the different types of trap sets).

Up to the beginning of April 2010, 51 cats were trapped from over 30 000 trap-nights covering the entire island (Fig. 1). Information on the number of cats removed per unit time (1 week) and effort employed to remove them (number of trap-nights) was used in a catch-effort model (Seber 1982; Ramsey et al. 2009) to estimate the probability of detection (and removal) p and the population size of cats N_0 just prior to the start of the project.

We assumed the population was closed over the period of sampling (i.e. no additions or losses to the population through reproduction or natural deaths). As the majority of cats were removed within 6 months of the start of the project, we believed that any natural mortality was negligible. Additions to the population over this time were also believed to be negligible based upon the reproductive condition of captured females. We also combined the two types of trapping sets (trail and cubby) for the analysis thereby assuming a joint detection probability although in reality the effectiveness of the two sets may differ.

Assuming all cats within any particular sampling period i have the same probability of detection (i.e. being caught), then the number of cats removed during each sampling period, n_i, has the conditional distribution:

$$n_i \mid N_i, p_i^{trap} \sim Bin\left(p_i^{trap}, N_i\right) \qquad (1)$$

where N_i is the total number of cats available to be removed during occasion i, and p_i^{trap} is the probability of being removed by trapping during occasion i. The total number of cats in sampling period i is given by:

$$N_i = N_0 - x_{i-1},$$

where x_{i-1} is the cumulative number of cats removed by trapping prior to occasion i:

$$x_{i-1} = \sum_{j=1}^{i-1} n_j, \quad x_0 = 0.$$

and N_0 is the initial population size of cats just prior to the first removals. As the amount of trapping effort used during each sampling occasion varied, the detection probability of trapping within each sampling period p_i^{trap} was expected to vary in proportion to the amount of effort used. In a simple extension of Equation 1, we modeled p_i^{trap} as a function of trapping effort (g_i) by employing a linear-logistic link function:

$$\log\left(\frac{p_i^{trap}}{1-p_i^{trap}}\right) = \alpha_t + \beta_t\, g_i, \qquad (2)$$

where α_t and β_t are the intercept and slope parameters to be estimated, respectively.

Dog tracking data

Systematic searches of the island for cats were made using dogs, each with a GPS-collar, beginning in the week of 5 July 2009 and finishing the week of 13 September 2009. Search effort and pattern (kilometers covered) varied over the course of this period, being initially concentrated more on the eastern portion of the island before moving gradually west.

Only four cats were judged to be removed as a consequence of being found by the dog teams during this period – confirmation that a cat was killed was not possible using this method. In any case, these removals need to be incorporated into the catch-effort model above (Equations 1 & 2) so as to be included into the estimate of initial population size N_0. In addition, these cats would not be available for trapping so their removal also affects the number of cats available to be caught subsequently. We again used a binomial distribution to model the conditional distribution of m_i, the number of cats removed by dog teams during occasion i:

$$m_i \mid N_i, p_i^{dog} \sim Bin\left(p_i^{dog}, N_i\right) \qquad (3)$$

where p_i^{dog} is the probability of being removed by dog teams during occasion i. The removal of these cats due to dog tracking was incorporated into the catch-effort model as follows:

$$N_i = N_0 - x_{i-1} - v_{i-1},$$

where v_{i-1} is the cumulative number of cats removed by dog teams prior to occasion i:

$$v_{i-1} = \sum_{j=1}^{i-1} m_j, \quad v_0 = 0.$$

Equation 3 shows that the number of cats removed by trapping and dog teams is conditionally dependent on the population size at occasion i (N_i). As for trapping, the amount of search effort by dog teams also varied during each occasion. Hence the probability that dog teams detected a cat during occasion i, p_i^{dog}, was modeled as a linear-logistic function of search effort h_i:

$$\log\left(\frac{p_i^{dog}}{1-p_i^{dog}}\right) = \alpha_d + \beta_d\, h_i, \qquad (4)$$

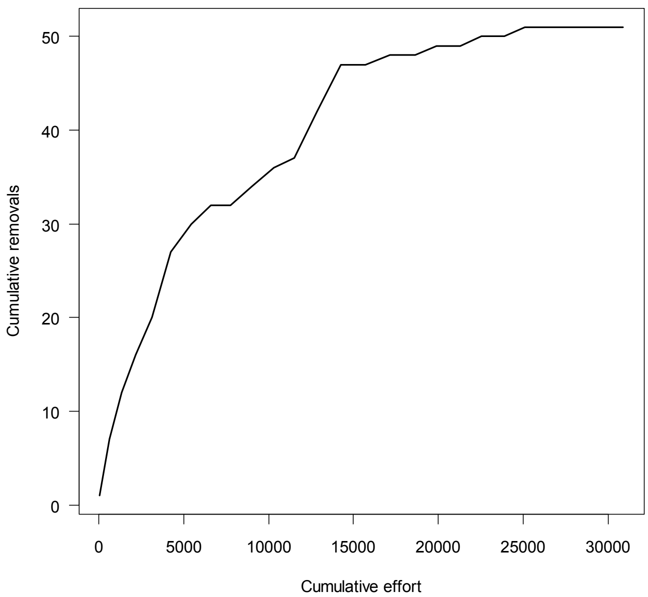

Figure 1. Cumulative number of cats removed by leg-hold traps and the cumulative effort (number of trap nights) between June 2009 and February 2010 on San Nicolas Island.

where α_d and β_d are the intercept and slope parameters to be estimated, respectively.

Opportunistic removals
In addition to the two formal removal methods, two cats were removed opportunistically between June 2009 and April 2010. The removal of these cats was also incorporated into the removal model so as to account for their presence in the estimate of population size N_0. However there was no formal modeling of detection probability for opportunistic removals.

Sign searches
Systematic searching of the island was undertaken looking for cat sign (scats, tracks, latrines, scratches) beginning in the week of 6 September 2009 and finishing the week of 10 January 2010. Only cat sign judged to be recently deposited was recorded during each session. Since sign searches are an indirect monitoring method where no cats are removed, a catch-effort removal model is not appropriate. However, it would still be desirable to estimate the probability of detecting cat sign and potentially model this probability using the amount of search effort. Here we approach the problem using a binomial-Poisson mixture model (Royle 2004). In the binomial-Poisson model, the abundance of cat sign available to be detected during occasion i was assumed to be drawn from a Poisson distribution with mean λ_i:

$$S_i|\lambda_i \sim Po(\lambda_i), \tag{5}$$

where S_i is the abundance of sign available to be detected during occasion i. With only one site (and repeated observations), it is not possible to estimate λ_i separately for each occasion. To reduce the number of parameters to be estimated, we must make some further constraints. The most logical constraint was to assume that the (log) mean abundance of sign (λ) at occasion i was a linear function of the (log) abundance of cats at occasion i:

$$\log(\lambda_i) = \alpha_s + \beta_s \log N_i . \tag{6}$$

Where α_s and β_s are the intercept and slope parameters to be estimated, respectively. However, S_i is the predicted amount of sign available to be detected. The amount of sign actually detected depends on the detection probability, which we modeled as a function of the amount of search effort:

$$y_i|S_i, p_i^{sign} = Bin(p_i^{sign}, S_i)$$

$$\log\left(\frac{p_i^{sign}}{1-p_i^{sign}}\right) = \alpha_r + \beta_r R_i , \tag{7}$$

where y_i is the abundance of sign actually observed during occasion i, which was assumed to be binomially distributed with probability p_i^{sign} from the total sign abundance S_i. As before, the probability of detecting sign p_i^{sign} was modeled as a linear-logistic function of search effort R_i with α_r and β_r the intercept and slope parameters to be estimated, respectively.

Monitoring with camera traps
Cameras were deployed beginning in December 2009. Between January 2010 and April 2010, five photos were taken of a cat with distinctive markings that were judged to be the same individual (Karl Campbell, pers. comm.). The following treatment of camera monitoring data assumes cats could be individually identified from photos, which may not be true generally. From this assumption we modeled camera detections as follows:

$$c_i|N_i, p_i^{cam} \sim Bin(p_i^{cam}, N_i)$$

$$\log\left(\frac{p_i^{cam}}{1-p_i^{cam}}\right) = \alpha_c + \beta_c C_i \tag{8}$$

where c_i is the number of cats observed by cameras during occasion i (one in this case), p_i^{cam} is the detection probability of cameras, and C_i is the search effort (camera trap-nights) used during occasion i and α_c and β_c are the parameters to be estimated. Of note is the fact that neither sign searches nor camera detections contribute to the removal part of the general model.

Statistical framework for making inference regarding eradication success
Towards the end of an eradication project either eradication (E) was successful ($E = 1$) or animals still persist ($E = 0$). Evidence in support of either of these outcomes can be obtained through monitoring data. However, because monitoring methods have imperfect detection, we need probabilistic support for one of the outcomes. Cessation of monitoring too soon risks falsely declaring eradication (type I error), whereas continuation of monitoring may waste resources if, in fact, cats have already been eradicated (type II error). We explored two stopping rules for estimating the optimal amount of monitoring required to declare eradication success (e.g. Ramsey et al. 2009).

Stopping rule 1: Limiting type I errors
The first stopping rule aimed to limit type I errors – falsely declaring eradication successful. This was undertaken by setting an agreed target for the type I error rate. In consultation with the Island Conservation managers, it was decided that an appropriate level of risk would be a 95% level of confidence that eradication was successful (Karl Campbell, pers. comm.). In addition, we contrasted this with a 99% level of confidence that eradication was successful. Hence, the probability that at least one cat persisted following the confirmation period (i.e. Pr[E = 0]), given that no cats were detected, should be no higher than 0.05 (5%), or alternatively 0.01 (1%). For convenience, we denote the probability of one or more cats persisting (i.e. Pr[E = 0]) as π and the agreed target for the type I error rate of 0.05 as π_0.

Stopping rule 2: minimize the costs associated with both type I & II errors
The second stopping rule used an economic approach, first proposed by Regan et al. (2006) and modified by Ramsey et al. (2009) that calculated the net expected costs (NEC) of declaring eradication. The NEC is an estimate of the joint costs associated with both monitoring and the costs incurred if eradication is wrongly declared. Hence, the amount of monitoring that minimizes the NEC is optimal with respect to minimizing costs associated with both type I and II errors (see Regan et al. 2006 for additional discussion of NEC). Thus, the use of this stopping rule requires estimates of both the costs of monitoring and the costs of wrongly declaring eradication. For the cat eradication project on San Nicolas Island, the costs associated with wrongly declaring eradication were estimated as the total project costs to redo the entire program from the start. This figure was estimated to be approximately

\$US1.4 million (Island Conservation, unpubl. data). The costs associated with a unit effort of each monitoring technique are given in Table 1.

Table 1. Cost of different monitoring techniques per unit of search effort

Method	Trapping	Dog teams	Sign search	Camera traps
Cost \$	\$3.0/trap -night	\$40.7/km	\$76.2/km	\$1.7/trap -night

Bayesian analysis

We assume that any confirmation monitoring (*mo*) for cat presence is imperfect. If the outcome of monitoring for a given level of effort (g) resulted in cat detection, then $mo = 1$; otherwise $mo = 0$. We let the probability that monitoring with search effort g would detect a cat, given a cat is present, be equal to $\delta = \Pr[mo = 1 \mid E = 0, g]$. To avoid confusion with the catch-effort modeling of detection probability p, we denoted δ as the monitoring sensitivity. If cats were detected through monitoring, then the status of eradication would be clear: it would be incomplete (i.e. $\pi = 1$). However, we were concerned here with the outcome of monitoring where cats were not detected.

We used a Bayesian approach to estimate the conditional distribution of π given monitoring failed to detect any cats (i.e. $\pi \mid mo = 0$). The probability of cat persistence (π), the monitoring sensitivity (δ), and the outcome of monitoring *mo* with search effort g are related through Bayes' theorem (e.g. Ramsey et al 2009):

$$f(\pi \mid mo = 0, \delta, g) \propto f(mo = 0 \mid \delta, g)\, f(\pi) \tag{9}$$

where $f(\pi \mid mo = 0, \delta, g)$ is the posterior distribution of the probability of cat persistence, given monitoring with search effort g and monitoring sensitivity δ detected no cats; $f(\pi)$ is the prior distribution of the probability of cat persistence following completion of the removal phase (i.e. prior to confirmation monitoring); and $f(mo = 0 \mid \delta, g)$ is the likelihood that monitoring with search effort g and monitoring sensitivity δ will not detect cats, given that they persist (i.e. $E = 0$). Hence, to estimate $f(\pi \mid mo = 0, \delta, g)$, we need estimates of δ and an estimate of π prior to the collection of monitoring data. Because estimates of both these parameters are uncertain, they were modeled with independent probability distributions, f. Estimates of the prior probability or belief in a parameter can be derived from a number of sources, including data from comparable studies or expert opinion. We used expert opinion to formulate an initial estimate of $f(\pi)$ by asking employees of Island Conservation involved with the eradication project to provide an estimate of the success of the project. However, for the following analyses, we assumed a completely uninformative prior distribution for $f(\pi)$ that had equal weight to all possible values of π i.e. $\pi \sim Beta(1,1)$.
We used the posterior distributions of the detection parameters (α, β) to predict the monitoring sensitivity δ for each method for varying search effort g. We then predicted the amount of simulated monitoring required to declare eradication under the two stopping rules. The monitoring sensitivity δ for a given level of effort g was estimated as:

$$f(\delta) = \frac{\exp^{\alpha + \beta g}}{1 + \exp^{\alpha + \beta g}}. \tag{10}$$

The parameters α and β were sampled from their respective posterior distributions and g is the level of search effort for which prediction is sought. Given the overall monitoring sensitivity $f(\delta)$ calculated with Equation 10, the posterior distribution of $f(\pi \mid mo = 0, \delta, g)$ was then

$$f(\pi \mid mo = 0, \delta, g) = \frac{f(\pi)\, f(mo = 0 \mid \delta, g)}{f(mo = 0 \mid \delta, g)\, f(\pi) + f(1-\pi)}. \tag{11}$$

The amount of monitoring required to trigger stopping rule 1 for each monitoring type was calculated as the level of effort g required such that $E[f(\pi \mid mo = 0, \delta, g)] = \pi_0$ (i.e. the expected value (mean) of the posterior distribution of $f(\pi \mid mo = 0, \delta, g)$ was equal to π_0). An associated 95% credible interval was calculated as $\Pr(\pi \mid mo = 0, \delta, g) < \pi_0 = 0.025$ or 0.975.

For the second stopping rule, the optimal amount of monitoring that minimized the net expected costs (NEC) was:

$$NEC = gC_s + C_e\, E[f(\pi \mid mo = 0, \delta, g)], \tag{12}$$

where, g is the amount of search effort, C_s is the unit cost of monitoring (per unit search effort), C_e is the cost of wrongly declaring eradication (US\$1.4m, and $E[f(\pi \mid mo = 0, \delta, g)]$ is again, the expected value of $f(\pi \mid mo = 0, \delta, g)$].

Posterior densities of $f(\pi \mid mo = 0, \delta, g)] = \pi_0$, monitoring sensitivity $f(\delta)$, and associated parameters (α, β) were obtained with Markov chain Monte Carlo (MCMC) sampling in OpenBugs software (version 3.03) (Thomas et al. 2006). Search effort g was standardized at a mean of zero and a standard deviation of 0.5, which speeded convergence of the MCMC algorithm. We used weakly informative priors for the logistic-regression coefficients specified with a Cauchy distribution with center zero and scale 2.5 as suggested by Gelman et al. (2008). A vague prior of $e^{U(0,10)}$ was given for the initial population size parameter N_0 in Equation 1. Sampling with five multiple chains revealed that convergence required approximately 50 000 samples as assessed by the convergence statistic $\hat{R}$ of Brooks and Gelman (1998). Therefore, after first ensuring the chains were well mixed, posterior summaries were taken from five chains containing 50 000 samples with a thinning rate of 10 (i.e. 25 000 samples). A copy of the OpenBUGS script used in these analyses is provided in Appendix 1.

Results

Initial population size and number of survivors

The mean of the posterior distribution (rounded to the nearest integer) of the population size just prior to the start of the eradication project N_0 was 59 cats (95% CI 58–61) and hence, given 57 known cat removals up to April 2010, the estimate of the mean number of remaining cats as of April 2010 was 2 with a 95% credible interval of between 1 and 4 cats. However, the distribution of the number of cats remaining was skewed and had a mode (most frequent value) of 1. Hence, the estimate of the most likely number of cats remaining in April 2010 was 1 (Fig. 2). This arises due to the fact that one cat was known to be present in April as it was detected by the cameras. However, following this analysis, a second cat was also detected by the cameras in June 2010. The probability of at least 2 cats remaining was estimated to be 0.25 (Fig. 2) so the fact a second cat was found was not too unexpected. Both cats were removed in June 2010.

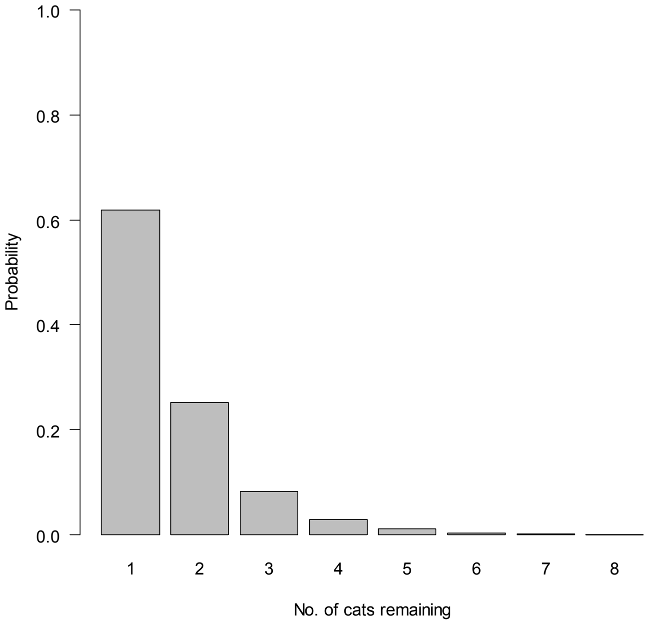

Figure 2. Posterior distribution of the number of cats estimated to still persist on San Nicolas Island from monitoring data collected up to 1 April 2010.

Table 2. Posterior summaries of parameters to estimate the relationship between detection probability and search effort (monitoring sensitivity).

Monitoring method		Parameters	Mean	SE
Trapping (p^{trap})		α_t	−2.42	0.195
		β_t	1.57	0.495
Dog teams (p^{dog})		α_d	−6.72	1.408
		β_d	2.20	1.189
Cameras (p^{cam})		α_c	−5.29	0.946
		β_c	5.23	1.558
Sign searches	Sign abundance (λ)	α_s	1.55	0.433
		β_s	0.75	0.159
	Detection (p^{sign})	α_r	2.00	0.829
		β_r	30.9	4.437

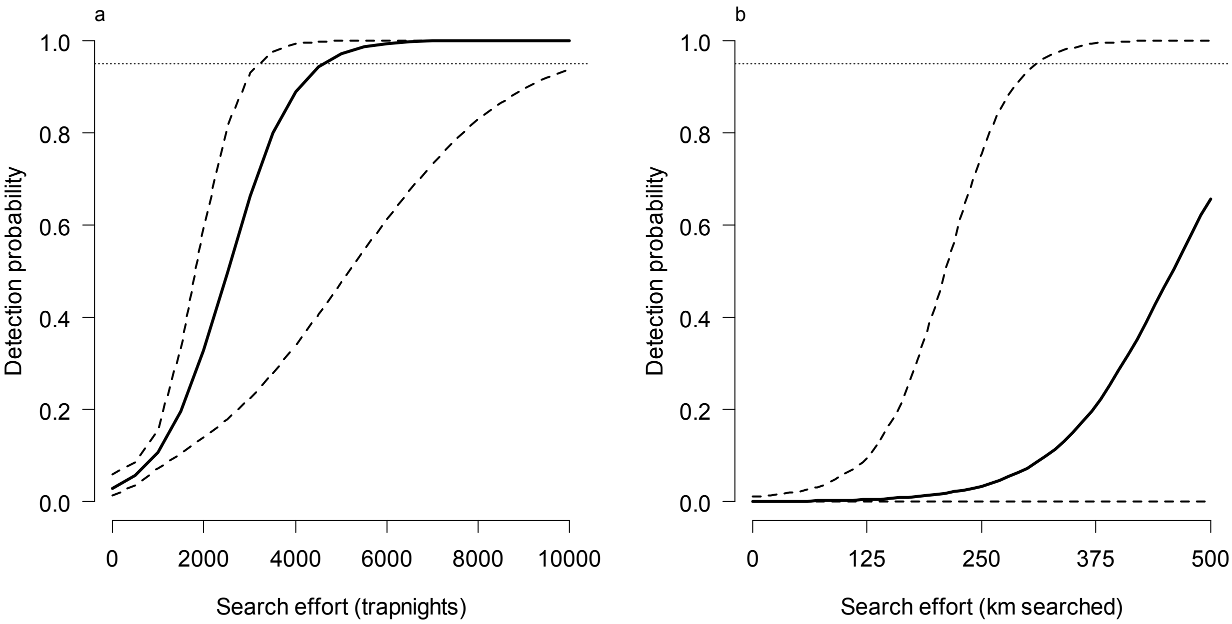

Figure 3. Relationships between detection probability and search effort for leg-hold traps (a) and dog teams (b) estimated by the Bayesian catch-effort model. Dashed lines indicate the 95% credible interval. Dotted line indicates a 95% detection probability.

Monitoring to quantify eradication

Monitoring sensitivity

Table 2 gives the detection parameters estimated by fitting equations 1-8 to the cat removal and sign data. The relationship for trapping (Fig. 3a) indicated that an effort of approximately 4500 trap-nights would be required to have a 95% probability of removal (95% CI 0.39–1.00). This equates to 643 traps set for 7 nights. In contrast, the relationship for dog teams indicated only low probabilities of removal (<0.1) for moderate to high search effort (250 km) with a high level of uncertainty (Fig. 3b).

Our model of sign searches had two components. The first component predicts the abundance of cat sign based on the population abundance of cats (Fig. 4a) while the second component is the probability of detecting cat sign with increasing search effort (Fig. 4b). From both of these relationships we can predict the abundance of cat sign expected to be found for a given amount of search effort, conditional on the abundance of cats. For example the relationship between the amount of cat sign expected to be found and search effort, given a cat abundance of one, is given in Fig. 4c. This relationship predicts that five counts of cat sign would be expected to be found after 40 km of searching if there was only a single cat

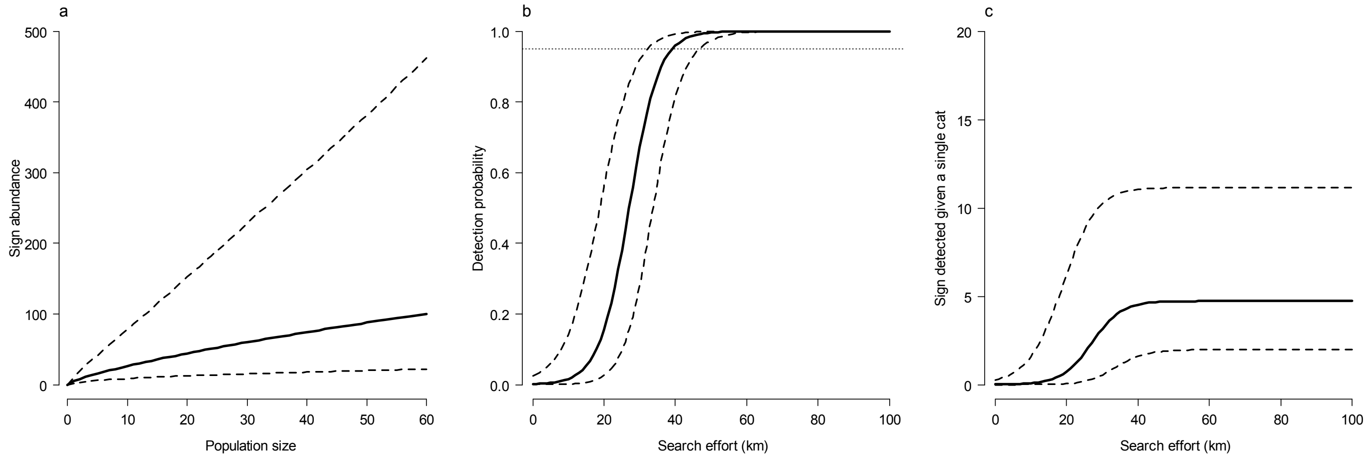

Figure 4. Results from the binomial-Poisson mixture model fitted to the cat sign data predicting relationships between (a) the abundance of cat sign and the abundance of cats, (b) the probability of detecting cat sign and search effort, and (c) the expected abundance of cat sign detected and search effort, given the presence of a single cat. All relationships used parameters given in Table 2.

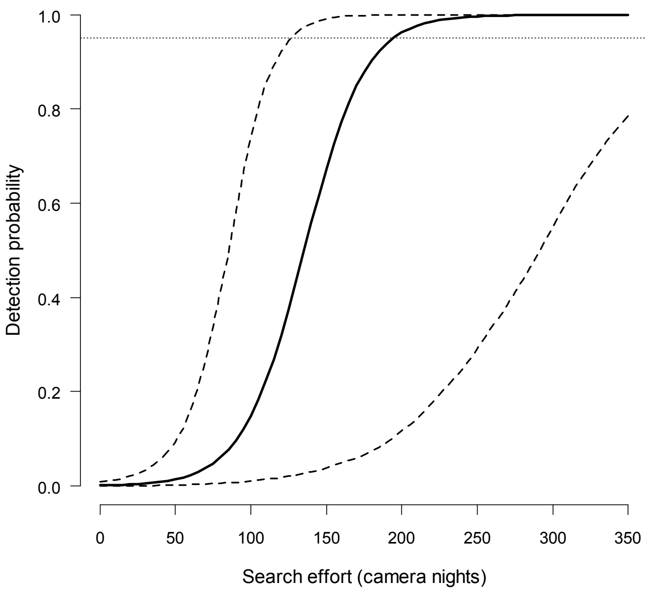

Figure 5. Relationship between detection probability and search effort (camera-nights) predicted by the catch-effort model fitted to the number of cats detected by cameras. Horizontal line indicates a 95% probability of detection.

on the island (Fig. 4c) (95% CI 2–11).

The relationship between detection probability of camera traps and search effort (camera nights) is given in Fig. 5. Approximately 195 camera nights were required to have a 95% probability of detection. This equates to 26 cameras each operating for 8 nights.

Stopping rule 1: Limiting type 1 errors

Under a completely uninformative prior belief in persistence of cats following the eradication phase, the amount of search effort for cat sign that triggered the 5% and 1% stopping rules was 45 km of search effort (upper 95% CI – 57 km) and 55 km of search effort (upper 95% CI – 64 km) respectively (Fig. 6a). Using camera traps as the method, the amount of monitoring effort that triggered the 5% and 1% stopping rules was 277 camera nights (upper 95% CI – 446 camera nights) and 427 camera nights (upper 95% CI – 523 camera nights) respectively (Fig. 6b). Under the current camera layout this translates to 11 nights (upper 95% CI – 15 nights) and 16 nights (upper 95% CI – 20 nights) for each of the 26 camera traps under the 5% and 1% stopping rules, respectively.

Stopping rule 2: Monitoring that minimizes the costs of types I and II errors

Calculation of the net expected costs of monitoring using Equation 12, the unit costs of monitoring (Table 1) and the estimate of the cost of wrongly declaring eradication (US$1.4m) under an uninformative prior belief in persistence of cats revealed that the optimal amount of cat sign searches that minimized the net expected costs (NEC) of type I and type II errors was 75 km (Fig. 7a). The equivalent amount of camera trap monitoring that minimized the net expected costs was 1196 camera nights (Fig. 7b). For the array of 26 cameras used, this equates to 46 nights' monitoring for each camera. Both these estimates are somewhat larger than those estimated under stopping rule 1, especially for camera traps. This was due mainly to the comparatively cheap cost of monitoring using camera traps, meaning that more monitoring was optimal with respect

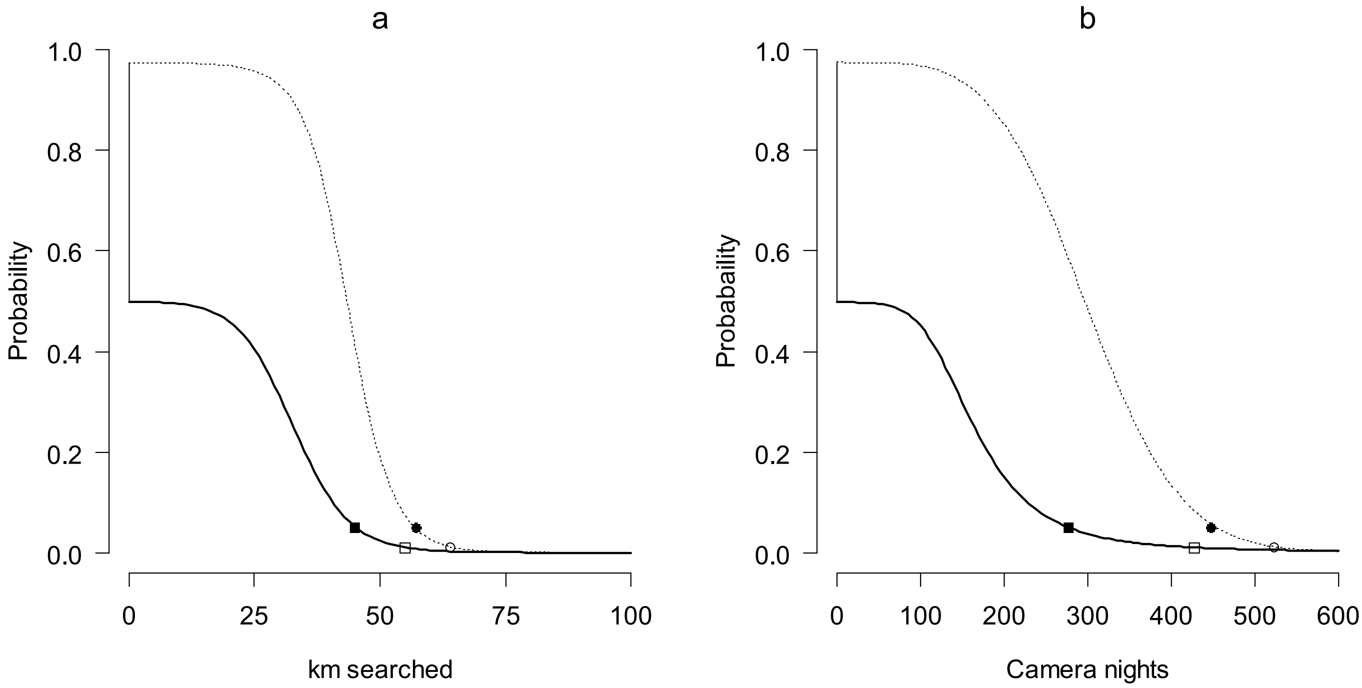

Figure 6. Monitoring effort, for (a) cat sign searches and (b) camera traps, that triggered the stopping rule for limiting the type I error rate. Solid line is the mean of the probability that at least one cat persists on the island if none were detected for a given monitoring effort and the dotted line is the upper 95% credible interval. Solid and open squares indicate the monitoring effort that triggered the 5% and 1% stopping rules, respectively. Closed and open circles indicate the upper 95% credible interval of the 5% and 1% stopping rules, respectively.

to the cost associated with wrongly declaring eradication. The fairly low estimate of the amount of cat sign searches was mainly due to the high estimated detection probability of cat sign searches. However, this should probably be treated with some caution, which we discuss in more detail below. Of note was the asymmetry in the expected costs above and below the optimum (minimum) value, with little increase in expected costs when monitoring effort exceeded the optimum, especially for camera traps (Fig. 7b).

Confirmation monitoring

Between late June 2010 through August 2010, 3294 camera nights and 270.3 km of search effort over the whole island were expended and no further cats or sign were found. This amount of search effort equates to posterior probabilities of cat persistence < 0.0003 for both camera traps and sign searches. Based on the above analyses, managers have more than enough evidence to satisfy both stopping rules. Hence, managers should declare the feral cat eradication from San Nicolas Island successful.

Discussion

Eradication of pests that is achieved by a succession of removal events that eventually reduce the population to zero has three phases. The first is the series of events (hunts, trap success, etc) that reduce the pest population to such low levels that further efforts often do not find and remove any more animals. The second phase attempts to validate or assess whether in fact this lack of detection means eradication may have been achieved. Assuming no more pests are found, the third phase is one of surveillance to confirm the assessment and it may continue until a decision is made to stop and declare the eradication a success. Clearly, detecting survivors and interpreting the lack of such detections to set stop rules are critical elements of this strategy. The process also usually collects spatially-explicit data on the numbers of animals removed or seen and on the effort to do this as it proceeds. This allows managers to change their tactics as results dictate; flexibility in planning is therefore desirable.

In contrast, eradication operations that rely on a single control event (e.g. aerial baiting for insular rodents) either succeed or fail on the day. It would be possible to apply the second and third phases, as above, to such operations but the control operation itself provides no information on potential survivors or where they might be located. Further, the cost to find this out with a new post-baiting monitoring system is arguably prohibitively costly, or at least more so than simply waiting for any failure to be revealed (as the population recovers) and try again. In this strategy flexibility is constrained by the need for meticulous planning to maximize the chances of success of the single control event (Cromarty et al. 2002). The San Nicolas Island cat eradication is clearly of the first type, that relies on a series of control events to progressively reduce the population and our paper addresses the validation and surveillance phases of this kind of operation.

The number of cats removed in this project was less than population estimates indicated by previous research on the island. Hillinger (1958) reported large numbers were present in the late 1950s, Schwartz (1994) thought there were more than 100 in the late 1970s, and Kovach & Dow (1981) caught 64 in 1980 and estimated there were up to 200 left. Therefore, the current project's total of 57 cats removed in phase 1

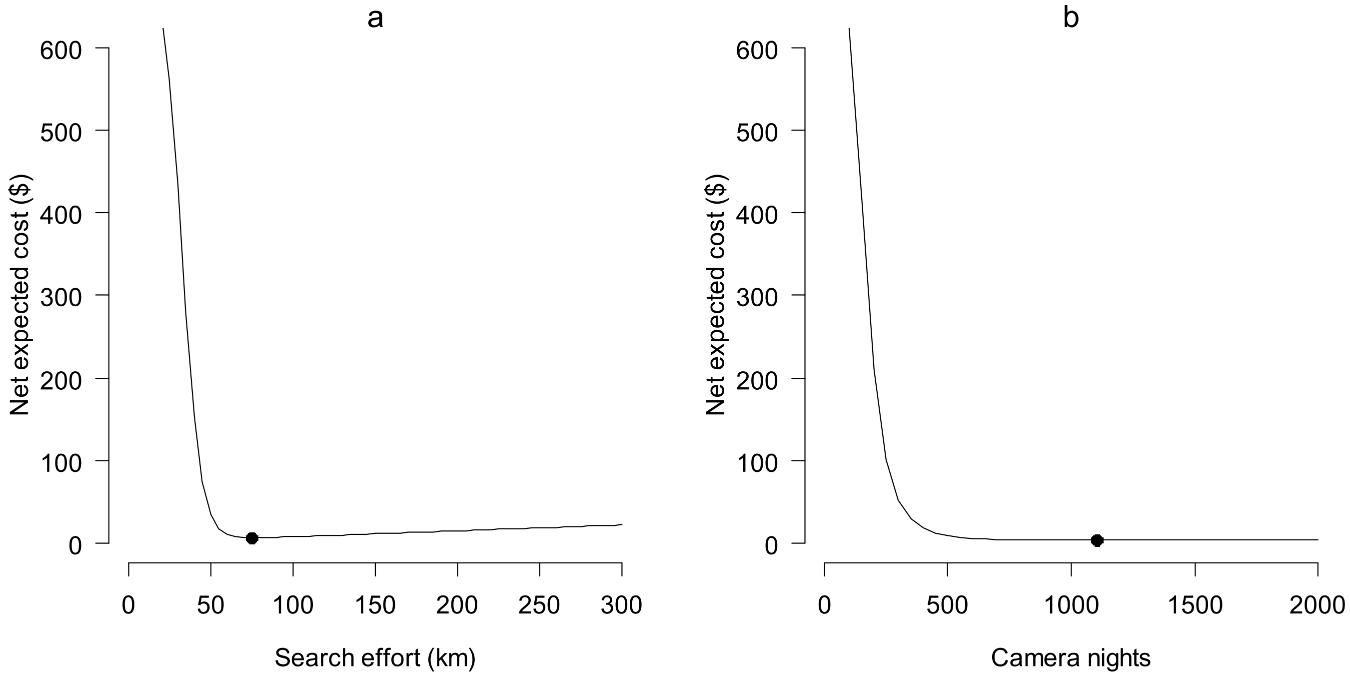

Figure 7. Amount of monitoring effort for (a) cat sign searches and (b) camera traps compared with the net expected costs ($ 1000) of type I and type II errors (Equation 12). The solid circle shows the amount of monitoring effort that was optimal (i.e. that minimized the net expected costs).

might have given some cause to suspect cats were not being detected or caught. It was therefore pleasing to note that the actual number of survivors of phase 1 (two) was within the predicted range and that no further cats were detected from the recommended confirmation monitoring after these two cats were removed.

Our estimates are heavily reliant on the removal rate achieved by trapping, which did not detect any cats after mid-November 2009. The only alternative method that contributed data past the end of the trapping programme was use of cameras, which detected one cat at the time of analysis and a second following the present analyses. Hence, no other monitoring method was able to exert a significant influence on the population estimate as they were not used either at the end, or past the end, of the trapping programme. In addition, the detection probabilities of the other methods used, particularly the passive methods, are themselves conditional on the population size at each sampling occasion as estimated by the trapping programme. This dependence has implications for the design of future eradication projects with the best inferences being obtained when passive monitoring methods and removal methods are carried out in tandem.

If cats progressively get harder to detect as the eradication project proceeds, then the estimates of detection probability may be misleading depending on when the associated detection techniques were deployed. This is more likely for monitoring methods that are used primarily at the beginning of the program. Searches for cat sign were not used right to the end of the removal phase and, hence, may have a more optimistic estimate of their detection probability than if they were used right down to the end of the removal phase. Dog team searches, on the other hand, may have the opposite problem as they were used while cats were still abundant on the island. A high abundance of cat scent/sign and the presence of a population of over 500 island foxes may have overwhelmed the ability of dogs to track the scent of individual cats. Whatever the effect, to reduce possible bias in the estimate of detection probabilities for different monitoring methods, it is essential that they are continued right to the end of the removal phase, in order to evaluate their effectiveness at detecting the last few individuals.

While the data for camera traps were collected at the end of the eradication phase, their use in the project came late when only a few (two as it turned out) cats remained on the island. While cameras were effective at detecting these individuals, the estimate of detection probability was highly dependent on the assumption that only a single cat was photographed with corresponding implications for the estimate of the number of cats still persisting on the island. In particular, the design of camera trap monitoring needs further consideration if a robust camera detection probability is to be estimated. One method that could contribute to improved estimates of camera detection probability is the release of marked (and sterilized) individual cats into the population to determine the effectiveness of cameras to detect these individuals, akin to the approach used by Ball et al. (2005) for possums.

The confirmation phase began with the removal of the last two known cats in late June 2010. The optimal amount of monitoring to achieve a high level of certainty that no further cats persist depends on whether decision-makers are more concerned with limiting type I errors (i.e. making a false declaration of success that may carry adverse ‘political’ consequences) or in jointly minimizing costs associated with both type I and II errors (i.e. ensuring there are no adverse financial consequences given that confirming eradication of cats may cost more than the removal effort itself). For the confirmation monitoring undertaken on San Nicolas Island, the project managers expended over three times the effort in both searches and camera surveillance recommended for the confirmation phase without finding a cat or evidence to suggest the presence of a cat. Thus, monitoring continued well past the level at which managers could be very sure no cats remained (< 0.0003) even though the recommended monitoring effort was based on their initial estimates of tolerable persistence risk (i.e. a 5% probability of persistence) and financial risks ($ cost of the project). Regarding stopping rule 1, this highlights the difficulties associated with equating managers' perceptions of risk with a probability value. Hence, there exists a need to make the risks associated with this stopping rule more transparent for decision makers. Regarding stopping rule 2, there was considerable asymmetry with regards to the expected costs of over- or under-monitoring with respect to the 'optimal' amount (Figure 7). Undertaking less monitoring than the optimal amount resulted in rapidly escalating expected costs, while undertaking more monitoring did not increase expected costs to the same extent. Given that un-modeled sources of variation could mean that detecting survivors may be more difficult than predicted by the model, managers are likely to compensate and undertake more monitoring than required. Indeed, in this case, stopping rule 2 indicated that there was little financial penalty in doing so.

Whatever the form of stopping rule used, perhaps the main advantage of risk analyses such as those performed here is that they allow managers to justify the rationale for declaring eradication success and why the amount of effort expended was appropriate. Traditionally, the termination of such projects has been based mainly on intuition. For the current project, managers can be very confident that eradication of feral cats from San Nicolas Island has been achieved.

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Appendix 1. OpenBugs catch-effort model used to estimate cat abundance and detection probability for different methods

```
model {
for(i in 1:K) {

	n[i] ~ dbin(p1[i], N[i]) # trapping
	m[i] ~ dbin(p2[i], N[i]) # dog searches
	y[i] ~ dbin(p3[i], S[i]) # sign searches
	c[i] ~ dbin(p4[i], N[i]) # cameras
	N[i] <- N0-cumx[i]
	cumx[i]<- sum(n[1:i])-n[i]+sum(m[1:i])-m[i]+sum(o[1:i])-o[i]

	S[i] ~ dpois(lambda[i])
	log(lambda[i])<- a[4] + b[4]*log(N[i])

	logit(p1[i])<- a[1] + b[1]*((trapnights[i]-mueff)/(2*sdeff))
	logit(p2[i])<- a[2] + b[2]*((dog.dist[i]-mudist)/(2*sddist))
	logit(p3[i])<- a[3] + b[3]*((sign.dist[i]-mudist)/(2*sddistS))
	logit(p4[i])<- a[5] + b[5]*((camnights[i]-mucam)/(2*sdcam))
}
# standardise variables
mueff<- mean(trapnights[])
sdeff<- sd(trapnights[])
mudist<- mean(dog.dist[])
sddist<- sd(dog.dist[])
mudistS<- mean(sign.dist[])
sddistS<- sd(sign.dist[])
mucam<- mean(camnights[])
sdcam<- sd(camnights[])

# prior on initial population size N0
  u1<- sum(n[1:K]) + sum(m[1:K]) + sum(o[1:K]) #total cats caught
  u2<- log(u1)
  N0<- exp(u)
u~dunif(u2,10) # lower bound on N0 set to total cats caught

#cauchy priors for regression coefficients using 'ones' trick
  tau<- 1/(2.5*2.5)
  C<- 1000000

for(i in 1:5) {
  a[i] ~ dnorm(0.0, 1.0E-6)
  onesa[i]<- 1
  La[i]<-tau*1/(1+(a[i]*tau)*(a[i]*tau))
  pa[i]<- La[i]/C
  onesa[i]~dbern(pa[i])
	}

 for(i in 1:5) {
  b[i] ~ dnorm(0.0, 1.0E-6)
  onesb[i]<- 1
  Lb[i]<-tau*1/(1+(b[i]*tau)*(b[i]*tau))
  pb[i]<- Lb[i]/C
  onesb[i]~dbern(pb[i])
  }

prior.pi ~ dbeta(1,1) # uninformative prior of eradication prob

# simulated monitoring effort data provided in effS and effC (20 values)
for(mo in 1:20) {

# monitoring sensitivity (delta)
Sign[mo]<- 1/(1+exp(-(a[3] + b[3]*((effS[mo]-mudistS)/(2*sddistS)))))
Cam[mo]<- 1/(1+exp(-(a[5] + b[5]*((effC[mo]-mucam)/(2*sdcam)))))
```

```
# f(pi | mo=0,delta,g)
Sign.pi[mo]<- (prior.pi*(1-Sign[mo]))/((1-prior.pi) + (1-Sign[mo])*prior.pi)
Cam.pi[mo]<- (prior.pi*(1-Cam[mo]))/((1-prior.pi) + (1-Cam[mo])*prior.pi)
  }

}
```