When to declare successful eradication of an invasive predator

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Short title: When to declare successful eradication

Abstract

Imperfect detection methods make it difficult to tell whether an invasive species has been successfully eradicated. However, management cannot continue indefinitely when individuals are no longer detected – at some point efforts must be reduced or ceased entirely. The risks of mistakenly inferring that an eradication attempt has been successful can be high: the species can bounce back and even expand its range, causing environmental and economic damage and rendering the initial eradication campaign redundant. This decision problem, balancing the risks of declaring eradication prematurely with the costs of continued management, is currently being contemplated by managers of the fox eradication program on Phillip Island, in Victoria, Australia. We used a Bayesian catch-effort model to analyse data on the number of foxes detected using different methods. We estimate that there were 11 foxes remaining on Phillip Island as of end of June 2012. Baiting was the most effective method for detecting and removing foxes per person-hour invested, and spotlighting was the most effective method for detecting without removal. We then projected forward into the future, assuming management effort continues at current levels but no further foxes are detected. Under this scenario, the mean estimate for the number of foxes remaining drops below a single fox after three years with no detections, and the probability that eradication has been successful is 0.69. This is the optimal time to declare eradication, given our estimated cost of declaring eradication prematurely. This framework indicates the minimum number of years for which management of foxes on the island must continue, and allows decision-makers to assess the trade-offs involved in any decision to declare eradication.
Introduction

The majority of documented extinctions in the last 500 years have occurred on islands, and of these, most vertebrates were driven to extinction by predation (Sax & Gaines 2008). When non-native predators invade predator-naive island systems, the effect on native wildlife can be devastating (Blackburn et al. 2004; Jones et al. 2008). This has motivated numerous campaigns to eradicate feral predators from islands (Towns & Broome 2003; Nogales et al. 2004; Howald et al. 2007; Oppel et al. 2011).

Eradication of invasive species presents a dual challenge for managers. Firstly, it is difficult to reduce a population to the point of eradication. Secondly, due to imperfect detection, it is difficult to know if successful eradication has been achieved (Regan et al. 2006). When monitoring and management stop detecting individuals, there comes a point when efforts must be reduced or ceased entirely. However, the risks of mistakenly assuming success can be high: the species can bounce back and render the eradication attempt redundant (Solow et al. 2008), or even escape the delimited area (Regan et al. 2006). Given these risks, and the costs of continued monitoring and management, how certain should managers be before declaring an eradication campaign successful?
This question is currently being contemplated by managers of the invasive fox eradication program on Phillip Island, Australia. Phillip Island is an approximately 100km² island off the coast of Victoria and is connected by a bridge to the mainland. Red foxes (Vulpes vulpes) were first seen on the island in the early 1900s, and threaten much of the island’s wildlife (Lade et al. 1996). In particular, the little penguin (Eudyptula minor) population has been reduced from ten colonies to only one colony, mainly due to fox predation (Dann 1992). This remaining colony is a popular tourist attraction, with almost 500,000 visitors per year paying to watch a nightly Penguin Parade (when penguins return to their nests after sunset, Phillip Island Nature Parks 2011).

Five different methods have been used to detect and remove foxes on Phillip Island: leg-hold trapping, baiting, hunting, spotlighting, and den searches. Since 1986, the number of hours invested in each method and the number of foxes detected and removed with each method have been recorded (Fig. 1). In 2006, the management strategy shifted from controlling fox damage to island-wide eradication. Since then, the number of foxes detected has dropped, while at the same time the amount of management effort stabilised (Fig. 1). Managers expect that in the near future they will stop detecting foxes, and are eager to plan ahead by determining how long management should continue when foxes are no longer detected. How long should they keep managing and searching before declaring the eradication program a success?

In this study, we use a Bayesian catch-effort model (e.g., Ramsey, Parkes & Morrison 2009; Ramsey et al. 2011) to estimate the number of foxes that were present on Phillip Island in the
years from 1986 to 2012, and the effectiveness of each of the five management methods in
detecting and removing foxes. We then project ahead to consider the possibility that no foxes
are detected in the future, and estimate the future population size and the probability of
extinction (i.e., the probability of successful eradication). By considering the costs of
management and the risks of stopping management prematurely, we determine the best time
to declare foxes eradicated and redirect management effort (Regan et al. 2006; Ramsey, Parkes
& Morrison 2009; Rout, Salomon & McCarthy 2009). Our analysis provides a framework for
better decision-making about the termination of this eradication campaign, and provides a case
study for managers of other invasive species eradication programs.

Methods

Estimating population size

Effort and fox detection data were compiled in financial years, starting on the 1st of July and
ending on the 30th of June. Different management methods have different staff requirements:
leg-hold trap placement and baiting requires a single person, spotlighting requires two, while
hunting and den searching require six to eight people. We therefore measured effort by the
number of person-hours spent on each management method in each year. For leg-hold
trapping, baiting, hunting, and den searches, any foxes detected were generally removed
(although the occasional fox was seen but not removed while hunting). For spotlighting, most
foxes were detected but not removed. We analysed detections resulting in removal separately
from those not resulting in removal, to obtain estimates of management efficacy that can be
used to distinguish the best methods for searching from the best methods for reducing population size.

The numbers of foxes removed by leg-hold trapping, spotlighting and hunting were recorded directly from collected carcasses. The number of removals through baiting was estimated indirectly: before the eradication program began in 2006 it was inferred by the number of baits taken and the number of foxes identifiable by their prints before and after the baiting, while after 2006 it was assumed that 2.5 bait takes in an area meant one fox had been removed (Kirkwood et al. in review). This estimate accounts for multiple takes by one fox and caching without consumption. The number of removals through den searches was also estimated indirectly before 2006 by assuming each fumigated den contained a vixen and four cubs. After 2006 the dens were excavated to record the actual number of foxes removed (Kirkwood et al. in review).

For each management method $j$, the number of detections in each year $t$ was modelled as a binomial process:

$$p_{t,j} \sim \text{Binomial}(N_{t-1}, \lambda),$$

where $p_{t,j}$ is the probability of detecting a fox at time $t$ with method $j$, $\lambda$ is the annual growth rate of the population, and $N_{t-1}$ is the number of foxes in the population at the start of time $t$. The population growth rate incorporates reproduction and natural mortality. Due to the relative isolation of Phillip Island, immigration is minimal (3 immigrants found in 14 years, Berry & Kirkwood 2010), and we assumed the same for emigration. We assumed population changes occur before detections and removals in each year (Fig. 2), based on the fact that foxes have a
distinct breeding season with reproduction peaking in September and October on Phillip Island (Berry & Kirkwood 2010).

The probability of detecting a fox with method $j$ in year $t$ depends on the amount of effort invested in that method:

$$P(d_j | g_{t,j}) = \frac{b_j g_{t,j}}{1 + b_j g_{t,j}}$$

where $b_j$ describes the effectiveness of method $j$, and $g_{t,j}$ is the amount of effort invested in method $j$ at time $t$. The number of foxes on the island at the end of year $t$ is then estimated as:

$$N_{t+1} = N_t \lambda - \rho_t$$

where $\rho_t$ is the total number of foxes removed in year $t$.

We ran the analysis using a population growth rate of $\lambda = 1.32$, the estimated growth rate of a low density fox population in Western Australia (Marlow et al. 2000; Devenish Nelson et al. 2010). This population was not harvested before being sampled, making this growth rate indicative of a natural population growth rate independent of removals. We used a uniform prior distribution $N_0 \sim U(1, 1600)$ for the number of foxes on the island before data began to be systematically collected in 1986. The upper limit of 1600 foxes was derived by considering the size of Phillip Island (100km$^2$) and the maximum fox density estimated in Australia (16 foxes/km$^2$) (Saunders et al. 1995; Marks & Bloomfield 1999). We used uniform prior distributions for the effectiveness parameters, $b_j \sim U(0, 10)$, and generated posterior distributions for the population size $N_t$ and the effectiveness parameters $b_j$ using Markov chain Monte Carlo (MCMC) sampling in OpenBUGS (Lunn et al. 2009). To achieve convergence, we
ran 6 chains for 100,000 iterations with a thinning rate of 10, and then generated posterior distributions from a further 100,000 iterations.

To assess the fit of this model, we compared the number of detections predicted by the mean estimates of $N_t$ and $b_j$ for each method in each year, with the actual number of foxes detected that year. To see how well our model outputs predicted the actual removals and detections, we analysed these data with a standardised major axis (SMA) regression. Unlike the ordinary least squares method, which accounts only for error in the response variable, SMA regression accounts for error in both the response and predictor variables.

Planning for eradication

Next we explored scenarios where management continues into the future, but no further foxes are detected. We ran the catch-effort model with the same parameter values and prior distributions as previously, but we created effort and detection data that continued up to ten years into the future. For the amount of effort allocated to each method in each year, we used the yearly average number of person-hours spent on each method over the eradication program (2006-2012): $g_{t,\text{leg-hold trapping}} = 404.03$, $g_{t,\text{baiting}} = 349.77$, $g_{t,\text{hunting}} = 187.45$, $g_{t,\text{spotlighting}} = 436.58$, $g_{t,\text{den searches}} = 311.50$. For each year from $T = 2013$ to 2022, we ran a separate model using real data for 1987-2012 and generated data (with no detections) from 2013 onwards. We calculated the posterior distribution for the population size in the final year $N_T$, and the probability of successful eradication $P(N_T \leq 1)$. We ran the analyses using the same prior distributions, and for the same number of iterations as previously.
The best time to declare successful eradication and stop management depends not only on the probability that eradication has been successful, but also on the cost of management and the consequences of declaring eradication prematurely. To determine the best time to declare successful eradication under this scenario, we calculated the net expected cost of declaring foxes eradicated after $d$ years with no removals or detections (Regan et al. 2006):

$$C_m \cdot (1 - P(N_T \leq 1 \mid d)) + C_p,$$

where $C_m$ is the yearly cost of management, $1 - P(N_T \leq 1 \mid d)$ is the probability that foxes are still present despite $d$ years with detections, and $C_p$ is the cost of declaring foxes eradicated when they are still present. The optimal year to declare eradication ($d^*$) is the year in which the expected cost of doing so is the lowest (Regan et al. 2006).

Managing foxes on Phillip Island currently costs around AU$160,000 per year. If foxes were declared eradicated, and management was stopped while foxes were still present, the population could rebound to levels seen before the eradication program began in 2006. Further eradication attempts would then have to re-do the work the eradication program has accomplished over the past six years, at a total cost of six times the current yearly management cost. We used this as a baseline estimate for $C_p$ (AU$960,000). However, mindful of uncertainty in estimating the consequences of declaring eradication prematurely, we found the optimal solution for a range of possible costs.

Results
According to our model, at the end of June 2012 there were an estimated 11 foxes remaining on Phillip Island (mean = 11.4, 95% credible interval = [4.6-19.6]). Our analysis shows that in 1987 there were around 125 foxes on the island, and this rose to over 200 foxes in 1996 (Fig. 3). Numbers have decreased since 2004, and have continued to decrease with the eradication program implemented in 2006 (Fig. 3). Our estimates of management effectiveness show that baiting is the most effective method for detecting and removing foxes per person-hour of effort ($b = 6.9 \times 10^{-4}$), followed by leg-hold trapping and spotlighting (both with $b = 2.4 \times 10^{-4}$) (Fig. 4a).

The 95% credible intervals on the effectiveness of management for fox removal only overlapped for the equally-effective leg-hold trapping and spotlighting. Spotlighting was the most effective method for detecting without removal ($b = 6.8 \times 10^{-4}$), although a few detections without removal occurred while hunting (Fig. 4b). Again, the 95% credible intervals did not overlap for these methods. The relationship between the model-predicted and actual number of fox detections was very close to a one-to-one relationship (Fig. 5), with an estimate of $m = 1.01$ for the slope of the line (95% confidence interval = [0.90-1.1]) and $c = -0.04$ for the y-intercept (95% confidence interval = [-1.9-1.8]).

If management continues as under the eradication program for ten years from July 2012, but no further foxes are detected beyond 2012, the probability that foxes will have been successfully eradicated in 2022 is 0.96 (Fig. 6). The mean estimate of population size drops below a single fox after three years of management without detection, with lower and upper 95% credible bounds of 0.03 and 2.95 respectively. The probability of successful eradication at this point (i.e., the probability that $N_t \leq 1$) is 0.69 (Fig. 6).
The net expected cost of declaring foxes eradicated is quite high in 2013-14 (Fig. 7), due to the cost of declaring eradication prematurely. As the number of years without detection increases, this cost decreases and then increases again as the yearly costs of management accumulate (Fig. 7). Given our best estimates of the yearly cost of management \(C_m = \text{AU}\$160,000\) and the cost of declaring eradication prematurely \(C_p = 6C_m\), the optimal time to declare foxes eradicated is in 2015, after three years of management without detections. The net expected cost of this optimal decision is \text{AU}\$619,616.

If the cost of declaring eradication prematurely is higher than our baseline assumption, it is optimal to continue management for longer (Fig. 8). It can be optimal to continue management for up to nine years with no detections if the cost of declaring eradication prematurely is 100 times the yearly cost of management (for \(C_m = \text{AU}\$160,000\), \(C_p = \text{AU}\$16\text{ million}\)). The net expected cost of the optimal decision increases correspondingly as the cost of declaring eradication prematurely increases (Fig. 8).

**Discussion**

It can take years of management and searching to be reasonably confident in the success of an eradication program. For foxes on Phillip Island, the probability of success is greater than 0.9 after seven years without detection, and greater than 0.95 after nine years. This estimate of success may be optimistic, because management will select for wary foxes that avoid baits, leg-hold traps, and other management activities, effectively reducing detection probabilities and management efficacy over time (Kirkwood et al. in review). However, this decrease could be
offset by improvements in management efficiency through time as staff gain experience and

skills.

Our past and present population estimates are within a realistic range and are consistent with a

previous analysis of the fox population on Phillip Island. Berry & Kirkwood (2010) compiled

biological information of foxes killed on the island between 1994 and 2008, such as their age,

size, gender, and reproductive status, and used this to estimate the minimum population size

over that time. Their analysis found that the population size was > 140 foxes during the late

1990s, with a minimum estimate of approximately 90 foxes during the early 2000s (Berry &

Kirkwood 2010). Our model replicates this trend, with an estimated peak of 204 foxes in 1996,

decreasing to 162 in 1999, and stabilising around 140 foxes in the early 2000s (Fig. 3).

In developing a reasonable model of this fox population, we have enabled further questions

about its management to be answered. In this study, we considered a future where

management continues in the same way it has been under the eradication program. However,

further work could also shed some light on how the different management methods should be

prioritised in the future. For example, we could examine the best time to switch from the

current management strategy to a monitoring only strategy, or the best way to allocate a

management budget between the different methods (McCarthy et al. 2010).

We used an exponential function to describe the relationship between the probability of

detecting a fox with a given method and the number of hours spent applying that method. This

exponential function is based on assumed random and independent encounters where all

individuals have the same rate of detection (Moore et al. 2011). If the rate varies among
individuals, the probability of missing an individual will decrease more slowly as the amount of effort invested is increased, reducing the marginal benefit of increased management effort (McCarthy et al. 2010). For an eradication decision to be robust to uncertainty in the form or parameterisation of this function, it is best to continue management for longer than predicted by the optimal solution (Rout, Thompson & McCarthy 2009).

When estimating the consequences of declaring eradication prematurely, we have focused on the possibility that the fox population will rebound to previous levels, and have limited our estimate to the management cost of reducing the population back down to an eradicable size. Reductions in the fox population since 2006 have been correlated with increases in several species of ground-dwelling birds, for example, the abundance of masked lapwings (Vanellus miles) seen across the island has increased, as have the number of hooded plover (Thinornis rubricollis) eggs hatched and fledged (Phillip Island Nature Parks 2011, Kirkwood et al. in review). Also, few little penguin deaths due to fox predation have been recorded since 2008. In 2010-11 the average number of little penguins crossing the beach nightly during the Penguin Parade was the highest since counting began in 1977 (Phillip Island Nature Parks 2011, Sutherland & Dann submitted) and the population on Phillip Island has doubled since the 1980s (Harris & Bode 1981; Sutherland & Dann 2012). These increases in birds that are vulnerable to fox predation likely resulted from multiple factors, but their correlation with each other and with reductions in the fox population are highly suggestive. If we consider these as environmental benefits of fox control, they could be reversed if fox eradication is declared prematurely and the population rebounds. Although it would be difficult to estimate these benefits in a way that is commensurable with the monetary cost of management, our
framework (particularly Fig. 8) can be used to uncover the hidden trade-offs implicit in any
decision to declare eradication, and assess whether these trade-offs are acceptable to the
decision-maker.

This paper joins two recent island case studies (Ramsey, Parkes & Morrison 2009; Ramsey et al.
2011) in combining quantitative modelling with a simple decision framework to provide
decision support for real-world eradication problems. Increased application of these methods
facilitates more informed and transparent decisions about eradication campaigns on islands,
which will ultimately maximise the chance of conserving vulnerable island biodiversity.

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Figure 1: The history of the fox eradication campaign on Phillip Island, in terms of a) person-hours of effort invested in each management action, and b) number of foxes detected. All methods were used to remove foxes, and some foxes were seen but not removed when spotlighting and hunting.
**Figure 2:** Order of events in each year within our Bayesian catch-effort model

[Diagram showing the order of events: population size (N_{t-1}), natural population change (\lambda), removals (\rho_t), resulting in the population size (N_t) at time = t.]

**Figure 3:** Estimated population size $N_t$ of foxes on Phillip Island through time. Showing mean estimate (solid line) and 95% credible interval (dotted lines).
Figure 4: Detection curves for the different management methods, calculated with the mean estimates of $b_j$, the effectiveness of method $j$. Showing a) The probability of detecting and removing an individual fox, and b) The probability of detecting but not removing an individual fox.
Figure 5: The model-predicted versus actual number of fox detections. Each point represents a single method in a single year. The solid line was fitted using a standardised major axis regression (see text).
Figure 6: The estimated fox population size (left axis, solid line = mean, dotted lines = 95% credible interval) and the probability foxes have been successfully eradicated (right axis, dashed line) under a future scenario where management continues but no further foxes are detected. The annual number of person-hours spent on each management method is described in the text.
Figure 7: The net expected cost of declaring eradication in different years (solid line), if management continues as it has been but no further foxes are detected. The current yearly cost of management is AU$160,000, and we assume the cost of declaring eradication prematurely is six times the current yearly management cost. The optimal year to declare foxes successfully eradicated (dotted line) is 2016, after four years without detection.
Figure 8: The optimal year (left axis, solid black line) and the net expected cost of declaring eradication in the optimal year (right axis, solid grey line) for a range of different cost ratios. Our baseline assumption for foxes on Phillip Island (a cost ratio of 6) is marked with the black dotted line.