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Rapid assessment of rat eradication after aerial baiting

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Summary

1. Eradication of introduced rodents on islands is increasingly implemented as a conservation tool. Aerial baiting, currently the main eradication technique, provides no information on whether eradication has been achieved. Success is usually evaluated after a standard period of 2 years with no sign of rodents.

2. We describe a novel approach to assess the success of eradication efforts based on a project to eradicate ship rats *Rattus rattus* from Isabel Island (82 ha), Mexico. We used detection and home-range parameters obtained from a capture–recapture study completed prior to aerial baiting to build a spatial-survey model that predicts probability of eradication after the treatment.

3. The spatial-survey model estimated a >99% probability of success after two surveys with no rats detected. This approach can be used to make eradication projects more cost-effective. Survivors, if any, could be located and dispatched by localized control methods. This avoids repeat aerial baiting of the whole island if failure becomes apparent.

4. This model is a useful tool for (a) assessing the probability of eradication within weeks, rather than years of an operation, and (b) predicting the required survey effort to achieve a probability of success consistent with the costs and risks of falsely declaring eradication success.

5. *Synthesis and applications*: Rapid assessment of success after rodent eradication efforts on islands results in financial savings by potentially reducing the duration of the projects. Improvements in biosecurity guidelines might also accrue as delays in detecting rats after an operation may confound their identification as offspring of survivors or re-invaders. Advanced techniques and predictive modelling will increase confidence among partners and donors and allow more efficient achievement of regional programmes.

Key-words: detection, invasive rodents, island restoration, modelling, pest management, *Rattus rattus*, surveillance, tropical islands

Introduction

The dramatic impacts of invasive rodents on islands, such as extinction of endemic species (Towns, Atkinson & Daugherty 2006; Angel, Wanless & Cooper 2009; Drake & Hunt 2009), are now being prevented and remediated through biosecurity and restoration programmes (Veitch, Clout & Towns 2011). Eradication techniques using toxic baits have been applied on about 532 islands in 26 countries with success rates of over 90% in recent years (Howald *et al.* 2007; Parkes, Fisher & Forrester 2011). Two general techniques to apply baits were developed in New Zealand and are now used internationally (Towns & Broome 2003). The first technique places baits in bait stations of various designs on transects or grids generally between 10 and 100 m apart. The stations are checked regularly and baits replaced as they are taken by animals (Thomas & Taylor 2002). The technique is labour intensive and restricted to islands where access to deploy and service the stations is possible. One advantage of the method is that the amount of bait taken and location of the stations being used by rodents provide information on rodent survival and the location of these survivors, which can be targeted by other means if required. The method itself thereby provides information on when to

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stop and declare success (Parkes 2011) because the same grid of bait stations (toxic baits may be replaced with nontoxic baits once detections cease) acts as a surveillance system to detect survivors or new invaders.

The second technique uses aerial broadcast of bait. Development of calibrated sowing buckets slung under a helicopter and the use of differential GPS increases the likelihood of complete spatial coverage of bait to put all rodents at risk. This method also allows larger and more topographically difficult islands to be cleared of invasive rodents (Howald *et al.* 2007). The disadvantage of the aerial technique is that the method itself provides no information on whether all rodents have been eliminated or, if not, on the location of survivors.

Current practice for aerial baiting projects is to carefully plan the operation as there is very limited opportunity to adapt or change tactics on the day of the treatment (Cromarty *et al.* 2002). For example, prebaiting experiments are usually conducted with nontoxic baits to confirm that baits are palatable and consumed by all rodents (Wanless *et al.* 2008). The operations are generally 'over-engineered' with double sowing, high bait densities, and spare capacity in case of mechanical failure in components such as sowing buckets (Cromarty *et al.* 2002). However, in most past cases, little or no effort has been put into immediate post-eradication surveillance because even if a survivor is found, there is no information on the distribution of other potential survivors that can direct a response. In this case, the sensible strategy may be to wait until any survivors could have produced enough offspring for the population to become easily detectable and, if this is the case, repeat the operation. On the basis of typical rodent rates of increase, no sign of rat presence 2 years after the baiting operation is widely accepted as confirmation of eradication success, assuming a reasonable detection effort is made (Howald *et al.* 2007; Russell, Towns & Clout 2008).

The rationale behind avoiding extensive surveillance immediately after aerial treatment is that it may not be cost-effective compared with the 'wait-and-see' strategy. Clearly, island topography and size will influence both practicality and cost. The immediate-reactive strategy is predicated on the possibility that evidence and location of survivors can be obtained so that animals can be killed immediately via localized control. The 'wait-and-see' approach has been considered reasonable for agencies and countries such as New Zealand, whose projects follow strict planning and have a clear understanding of the risks among partners, donors and government authorities. Because New Zealand is acknowledged as a pest-eradication leader (Towns 2011), many countries have adopted this approach.

Conversely, having a formal estimation of the probability of success shortly after an eradication operation would be useful in countries where rodent eradications are a novelty or when working on new environments. Confirmation of success within weeks instead of years may greatly increase confidence among partners and allow more efficient achievement of regional programmes. Applying active surveillance immediately after baiting operations will facilitate the identification of failed strategies and also minimize the potential for confusion between survivors and re-invaders (Russell *et al.* 2010). Reaction to survivors might be feasible and less expensive than re-treating the whole island in some cases, although the trade-off has not been formally assessed. Additional benefits of conducting post-eradication surveillance are consequent synergies with assessment of short-term impacts on nontarget species and biodiversity benefits. Assuming that this immediate search is worth the effort, the next step is the deployment of a surveillance system that results in a high level of confidence of success if no survivors are found.

There have been attempts to quantify eradication success for other mammal species. In these cases, eradication has been achieved by a series of control events such as hunts or trapping sessions. Solow *et al.* (2008) analysed the trapping data from a failed musk shrew eradication to describe how the probability of complete eradication based on record of removals can be calculated. Bayesian statistical methods were used to calculate probabilities of eradication for feral pigs removed by hunting (Ramsey, Parkes & Morrison 2009) and feral cats removed by trapping (Ramsey *et al.* 2011) on Californian islands. In contrast, rodent eradications are usually performed in a single event so analogous calculations and confirmation procedures are needed for both bait station and aerial methods.

Mexico has a successful history of eradicating several invasive mammal species from islands (Aguirre-Muñoz *et al.* 2011). Invasive rodents (ship or black rats *Rattus rattus* and house mice *Mus musculus*) have been eradicated from 13 islands between <1 and 267 ha, and several more projects are ongoing (Samaniego-Herrera *et al.* 2011, GECI 2012, unpublished data). A restoration project for Isabel Island was launched in 2007, and the rat eradication took place in 2009.

In this paper, we explore the practical and economic implications of conducting post-eradication surveillance on Isabel Island. We estimated the probability of success following the rat eradication using a novel spatial-survey model based on post-eradication surveillance data collected at 12, 19, 24 and 30 months following the operation. A pre-operation capture–mark–recapture study was conducted to estimate model parameters related to detection probabilities and home-range size. We also used the spatial-survey model to assess the survey effort that would have been necessary to declare success immediately following the eradication operation (i.e. < 1 month). We compare and discuss the trade-offs of employing the spatial-survey model with the application of the traditional 2-year waiting period.

Materials and methods

ISLAND DESCRIPTION

Isabel Island (82 ha) is located in the mouth of the Gulf of California, Mexico. It is of volcanic origin, topographically complex with cliffs and rocky beaches, and the maximum altitude is 85 m above sea level. The island is covered with tropical forest, which supports a rich vertebrate community (CONANP 2005), and it is internationally recognized as an important seabird-breeding site (RAMSAR 2011). There are no native terrestrial mammals. Ship rats were introduced since at least the 1920s (Canela 1991), and an eradication campaign using bait stations in 1995 failed (Rodríguez, Torres & Drummond 2006).

RAT ERADICATION

Owing to the size and ruggedness of Isabel Island, the most feasible option for achieving eradication was to aerially disperse bait pellets (25 ppm brodifacoum). Risk of failure is minimized if 100% of the island is treated aerially. However, due to a potential conflict with an ongoing project on blue-footed booby behaviour, a small percentage of the island (5%) had to be treated by hand broadcast of baits. The first and second bait drops were carried out on the 1 and 7 May 2009. On average, bait was applied at a rate of 20·61 kg ha^{-1} summing both drops, according to the GIS and confirmed by on-the-ground sampling (Samaniego-Herrera *et al.* 2010).

RODENT SURVEILLANCE

Prior to eradication, we confirmed that ship rats were the only rodent species present, based on extensive and intensive monitoring. Later, 2 weeks before the eradication, a 10 × 10 trapping grid with 20-m spacing was set in the middle of the forest to conduct a capture–mark–recapture study for six nights. Each day, all rats caught were individually marked using numbered Monel ear tags and then released at their capture site. Population parameters (density, g_0 and σ) were estimated using the spatially explicit capture–recapture software Density 4·4 (Efford, Dawson & Robbins 2004).

The primary objective of the post-baiting surveillance was to confirm rodent absence. Two types of surveillance took place: (i) trapping with Tomahawk traps in the same 10 × 10 grid employed before the baiting to confirm the absence in an area with known pre-baiting rat abundance, (ii) survey with wax tags in an island-wide grid to confirm the absence across island. Wax tags have been shown to be very effective detection devices for rodents (GECI, unpublished data). The trapping grid was set on four sessions after the baiting: May 2009 (500 trap-nights), April 2010 (400 trap-nights), November 2010 (500 trap-nights) and April 2011 (500 trap-nights); 10 days, 12, 19 and 24 months after the eradication, respectively (Fig. 1). The wax tag survey was conducted on a 200 × 200 m grid covering the whole island. Each of the 17 grid points was located with a GPS and marked on the ground. Wax tags were deployed around each point on four sessions with total efforts as follows: 340 tag-nights in April 2010 (four at each point for five nights), 272 tag-nights in November 2010 (four at each point for four nights), 136 tag-nights in April 2011 (two at each point for four nights) and 170 tag-nights in September 2011 (two at each point for five nights); 12, 19, 24 and 30 months after the eradication, respectively (Fig. 1).

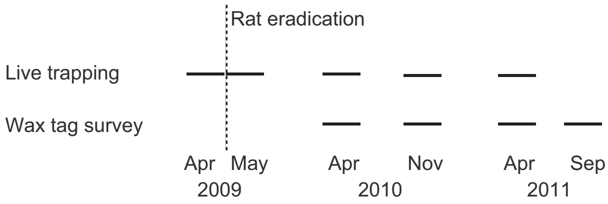

Fig. 1. Timetable of methods of rodent surveillance applied on Isabel Island, before and after the ship rat eradication operation.

EVALUATION OF THE ERADICATION

Two approaches were employed to confirm the success of the rat eradication operation. First, we report on the traditional 'wait-and-see' approach by taking into account the results of the post-operation surveillance conducted within 24 months after the baiting, as described above. Percentage of both trap and wax tag success is reported.

Secondly, a spatial-survey model written in R (R Development Core Team 2011) was used to quantify the probability of eradication given no detection of rodents during the wax tag surveys conducted on four occasions during 2010–2011. The model adopts a worst-case scenario for detecting a failed eradication by assuming that a single pregnant female survived. Clearly, a single animal is harder to detect than multiple animals, but a pest population can recover from a single pregnant female. We quantified the probability that a randomly located single pregnant female would be detected with the array of wax tags. The probability of detection of a rat with a home-range centre at location *i* by wax tag *j* at time *t* was calculated as follows:

$$P(\text{detecion})_{ijt} = g_0 \exp\left(\frac{-d_{ij}^2}{2\sigma^2}\right) \qquad \text{eqn 1}$$

where d_{ij} was the distance between home-range centre *i* and wax tag *j*, g_0 was the probability of detecting a rat if the wax tag was placed at the animal's home-range centre and σ was the spatial-decay parameter for a home-range kernel (Efford 2004). The estimated $P(detection)_{ijt}$ decays spatially from the wax tag location with a half-normal kernel. The g_0 and σ were randomly drawn from PERT distributions (Herrerias, Garcia & Cruz 2003) informed by our capture–mark–recapture study and software Density 4·4, assuming that wax tags perform as well as Tomahawk traps based on the previous field work. The probability that the single surviving female would be detected by any one of the *j* wax tags on the island was calculated as follows:

$$P(\text{detection})_{it} = 1 - \pi_{j=1}^{j}(1 - P(\text{detection})_{ijt}) \qquad \text{eqn 2}$$

If some months had passed since the eradication operation or since a previous survey, the modelled population was allowed to grow with a per capita annual growth rate adjusted for time since previous survey. The growth rate was randomly drawn from a PERT distribution with min = 3, likely = 7 and max = 10 (Innes 2005). Offspring then dispersed from the mother's home-range centre in a random uniform direction (0,2 π) and random distance drawn from a log-normal distribution with mean = 4 and variance = 0·7 (King *et al.* 2011). The probability of detecting at least one of the rats [$P(detection)_t$] was calculated by taking the product in equation 2 across all rats and wax tags.

The $P(detection)_t$ indicates how well the area was searched, but it is not a useful measure of confidence in a successful eradication given no rats were found. The metric of interest is the probability of rat absence (eradication success) given no detection [$P(success|no\ detection)_t$], which requires a prior probability of success and Bayesian logic. A simple thought experiment illustrates why management decisions should not be based solely on the $P(detection)_t$. Two identical islands were subjected to aerial baiting for rat eradication. The operation was well managed on the first island with complete bait coverage, but the second island was poorly managed, resulting in gaps in bait coverage (influencing our prior probability of success). Post-baiting surveillance was identical on both islands [equal $P(detection)_t$], and no rats were discovered. Intuitively and quantitatively (via Bayesian logic), our confidence in success is higher on the first than on the second island.

The probability of rat absence (eradication success) given no detection [$P(success|no\ detection)_t$] at time t was calculated as follows:

$$P(\text{success}|\text{no detection})_t = \frac{P(\text{success})_t}{1 - P(\text{detection})_t * (1 - P(\text{success})_t)} \quad \text{eqn 3}$$

where $P(success)_t$ is the prior belief that the eradication operation was a success. This was informed by the reported proportion of successful island eradication of rats and was drawn from a PERT distribution with min = 0·5, likely = 0·8 and max = 0·9 (Parkes, Fisher & Forrester 2011).

The $P(success|no\ detection)_t$ was calculated following subsequent wax tag surveys by updating the priors and incorporating a time-adjusted annual probability of re-introduction $P(Intro)_{t+1}$ drawn from PERT distribution with min = 0·001, likely = 0·01 and max = 0·03:

$$P(\text{success})t + 1 = P(\text{success}|\text{no detection})t * (1 - P(\text{Intro})t + 1) \quad \text{eqn 4}$$

The PERT distribution is conservative given biosecurity measures implemented to prevent new incursions.

Uncertainty was incorporated into the modelling and propagated through to the predicted $P(success|no\ detection)_t$. This was done by repeating the model 1000 times and, in each iteration, a new random starting location and new parameter values were drawn for each animal. The resulting uncertainty in the predictions was assessed with 95% credible intervals, on which inference and management decisions should be based. For example, managers must set a threshold $P(success|no\ detection)_t$ above which the lower 95% credible interval should exceed. Parameter distributions were considered conservative and the same across the island, as most of the island was covered by homogeneous native forest.

We used the spatial-survey model to assess the spacing or number of wax tags necessary to declare success immediately following the bait drop. We quantified the probability of detecting a single rat randomly located on the island a week following the eradication and did not allow for reproduction. This was done by varying wax tag spacing from 50 to 200 m. The resulting median and credible intervals of the predicted $P(success|no\ detection)_t$ for all spacings were graphed relative to a target threshold of 0·90.

COSTS

Costs of both the eradication operation and the post-eradication surveys were calculated. Costs per hectare are reported. On the basis of these figures, cost per surveillance event and hypothetical response to localize survivors was estimated.

Results

RODENT SURVEILLANCE

Prior to eradication, the 10 × 10 trapping grid resulted in an average of 51·8 ± 4·5 captures per day; 159 individuals were marked and released in six nights. Population parameters for April 2009 resulted as follows: density = 38·4 ± 3·2 ind ha^{-1}; g_0 = 0·169 ± 0·022; σ = 14·8 ± 0·8.

EVALUATION OF THE ERADICATION

For the ‘wait-and-see’ approach, surveillance conducted within 2 years after the eradication, totalling 1900 trap-nights and 918 tag-nights, yielded zero detections of rodents across all habitat types. The spatial-survey model of wax tag data collected 12 months following the operation estimated the lower credible interval (2·5 percentile) of the probability of success to be 0·69 (Table 1). The subsequent lower credible intervals calculated at 19, 24 and 30 months were >99%.

The analysis of different theoretical spacing of the detection devices showed that the probability of success has a negative relationship with spacing (Fig. 2). Setting the threshold of success as a lower credible interval equal to or exceeding 0·90, 50 m spacing of detection devices would have been required to declare success following a single survey immediately after the eradication operation.

COSTS

The total cost of the rat eradication operation was USD 268,421 ($3,273 per ha). Costs per item are described in

Table 1. Median and 95% credible intervals (CI) of estimated probability of ship rat eradication following wax tag surveys on Isabel Island, Mexico

	Probability of success		
Months after the rat eradication	Median	Lower CI	Upper CI
12	0·91	0·69	0·98
19	1·00	0·99	1·00
24	1·00	0·99	1·00
30	1·00	0·99	1·00

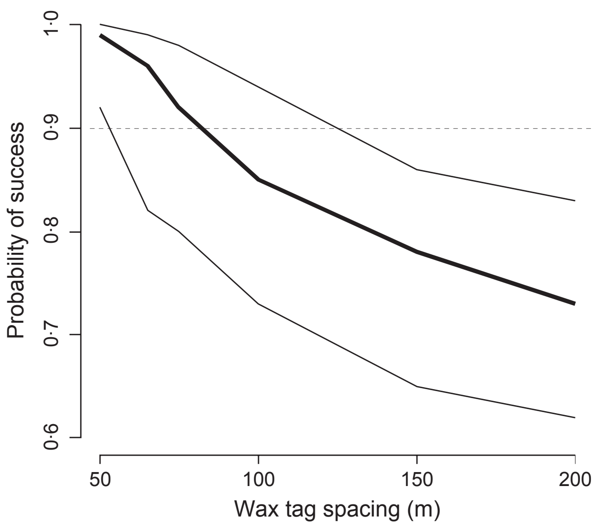

Fig. 2. Relationship between the median and 95% credible intervals (CI) of the probability of success after the rat eradication on Isabel Island and the spacing of wax tags (detection devices). The horizontal dashed line is the threshold above which the lower CI should be above.

Table 2. The cost of the four surveys conducted after the eradication was USD 39,750 (average of USD 9,938 per survey).

Discussion

Our results suggest that the use of wax tags is an easy, cheap and practical option when the objective is to determine the presence/absence and location of insular rodents (e.g. for preliminary assessments or after an eradication), and no native rodents are present. Efficacy and convenience of wax tags as detection devices has been documented for several rodent species and environments (Thomas, Brown & Henderson 1999; Samaniego-Herrera *et al.* 2009; Sweetapple & Nugent 2011), and they have been used to build auxiliary models to estimate population abundance (Russell, Abdelkrim & Fewster 2009).We were fortunate that our initial surveillance design deployed several systems including the one that proved most useful to validate eradication (the wax tags) while there were rats to detect, rather than attempting to assess their detection characteristics at the end of the project when no or few detection events are possible (see the problem with late deployment of camera traps to detect cats on San Nicolas Island; Ramsey *et al.* 2011). As a general point, managers need to ensure they collect appropriate data before and during eradication attempts to facilitate the establishment of quantitative stopping rules at the end of the eradication (Parkes 2011).

Table 2. Approximate cost, per item, of the principal phases of the ship rat eradication implemented on Isabel Island, Mexico, in May 2009. Currency is USD as for 2009

	Aerial baiting	Post-eradication surveys
Preparation and plan	68,250	
Helicopter	76,500	
Aerial bucket	1,660	
Bait	17,761	
Boat expenses	13,750	3,750
Staff	78,000	26,000
Island housing	2,500	5,000
Travel expenses	10,000	5,000
TOTAL	268,421	39,750

The island-wide grid of wax tags was originally deployed as part of a qualitative 'wait-and-see' assessment of success. However, *a posteriori*, we realized that these data in conjunction with empirical estimates of g_0 and σ could be used to generate quantitative estimates of the probability of eradication success. This novel spatial model of survey data, developed and applied to confirm success on Isabel Island, has important applications in the broad context of pest management. For Isabel Island, the high (0·99) probability of success obtained in 2011 from the spatial-survey model coincided with the result of the traditional 'wait-and-see' approach (zero-rat signs after 2 years), as both suggested that the 2009 rat eradication was successful. Because the model was built during a late phase of the project, the optimum scenario for immediate confirmation was determined afterwards and therefore not applied. Due to the spacing of wax tags (grid of 200 m), two surveys were necessary to achieve statistical confidence of success. To achieve a satisfactory probability of success immediately following the initial operation, the wax tags needed to be spaced at 50 m intervals. This would have required 14 times the actual number of points where wax tags were deployed, or 236 points. However, labour would not have increased significantly. A survey based on wax tags at 50 m spacing conducted on the island immediately following baiting would have provided strong evidence of success and avoided the need to conduct subsequent surveys.

If signs of survivors had been located immediately after the baiting (when most of the staff are still present), we estimate a response using hand broadcast baiting and trapping at the site (and the surrounding half hectare) would have cost an additional *c.*USD 1,500 per ha. So, assuming survivors were located at two sites after an aerial operation, the cost to detect and remedy the failure would be *c.*USD 3,000, which is economically sensible given the total cost of the baiting operation was USD 268,421 or 3,273 per ha. A rough estimate of the costs of surveying (with a low risk of falsely declaring eradication) immediately after the aerial baiting plus contingent costs to remove any survivors detected suggest this insurance approach would be about 6% of the costs of the 'wait-and-see' strategy if the eradication failed. Setting the acceptable risk (probability that a survivor would be detected) is an area requiring further analysis as the decision will often reflect both monetary and sociopolitical considerations.

Isabel Island represents the 8th successful case of rat eradications in Mexico (Samaniego-Herrera *et al.* 2011). The rigorous planning and 30 month period of post-eradication surveillance with no rat signs has given funders and authorities confidence of success, overcoming the 'can't-be-done' feeling left by the failed 1995 attempt. We conclude that it is possible to generate a similar or even higher level of confidence in a significantly shorter period of time through the use of spatial-survey models.

The Isabel Island case illustrates how modelling can be used to make other eradication projects more cost-effective. An important application of the model to upcoming eradication operations elsewhere is the *a priori* prediction of the survey effort required to meet a target probability of success immediately following an operation. The benefits of this are clear. Funders are supplied with accurate estimates of project costs and objective measures of success. This facilitates logistical and financial planning, provides immediate evaluation of success and in the case of failure identifies the locations of survivors and where focused follow-up control should be applied.

The more obvious limitations to applying these models are island size and accessibility. The additional cost and effort depend on the level of certainty desired, but could be minimized by combining the surveys with other activities included in the project. Also, detection parameters should ideally be based on the specific target population, although patterns for several mammal species and habitat types have been recently been investigated (Efford, Dawson & Borchers 2009; Clayton *et al.* 2011). Once islands are declared rodent-free, the model can also assist biosecurity programmes in detecting invaders or responding to incursions (Moore *et al.* 2010; Jarrad *et al.* 2011; Rout *et al.* 2011).

Pest eradication for island restoration is a growing field worldwide. Improving methods and the timing to confirm success is important for ensuring high efficacy and efficiency. The spatial-survey model is an advance that can be applied to most pest-eradication operations. Although the applicability of this method of declaring success is limited for large islands (e.g. thousands of hectares), the potential benefit for numerous ongoing projects on smaller islands with new challenges is vast (e.g. tropical islands). Deciding whether to use the model as a formal confirmation method should be made at the planning stage, taking into account cost, feasibility and risks of delaying confirmation of success. Rapid confirmation of success or failure is most needed in cases where technical adjustments are being tested in response to new environmental conditions. Further, if survivors are detected immediately after the operation, the small number present will be easier to remove than a more fully recovered population detected at a later date. Lastly, if the management team is confident about eradication success, subsequent restoration plans, such as the reintroduction of endangered species, can be implemented sooner rather than later.

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