Costing eradications of alien mammals from islands

T. L. F. Martins[1,2], M. de L. Brooke[3], G. M. Hilton[2], S. Farnsworth[3], J. Gould[3] & D. J. Pain[2]

1 Centre for Ecology and Conservation, University of Exeter in Cornwall, Tremough, Penryn, UK
2 Royal Society for the Protection of Birds, Sandy, Bedfordshire, UK
3 Department of Zoology, University of Cambridge, Cambridge, UK

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Correspondence
M. de L. Brooke, Department of Zoology, University of Cambridge, Downing Street, Cambridge CB2 3EJ, UK.
Tel: 01223 336610;
Fax: 01223 336676
Email: m.brooke@zoo.cam.ac.uk

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Abstract

The ability to estimate costs of alien species eradications is essential for a rigorous assessment of priorities for island restoration. Using a global data file from 41 islands, mostly gleaned from the 'grey' literature, we show that the cost of vertebrate eradications can be satisfactorily predicted if island area and species to be eradicated are known. About 72% of the variation in cost can be explained by island area, whereas, for a given area, rodent eradications are 1.7–3.0 times more expensive than ungulate eradications. Costs per hectare decrease with island size. Restricting the analysis to roughly half the data set, the relatively homogeneous half concerned with New Zealand islands, we identify two further influences on cost: date of eradication and distance to the main airport (an indicator of remoteness). For a given area, costs have declined over time but increase with island remoteness. This information therefore provides conservation planners with a robust, if preliminary, estimate of the cost of any proposed eradication programme.

Introduction

Despite the expected economic benefits of biodiversity conservation (Balmford *et al*., 2002), current conservation resources fall well short of those needed to prevent major extinctions (Balmford *et al*., 2003). Estimates suggest that effective conservation outwith reserves across the world might cost US\$ 290 billion year^{-1} (1996 prices) whereas the establishment and maintenance of an ecologically representative global network of protected areas would cost US\$ 27.5 billion year^{-1}, as compared with a current expenditure on reserves of US\$ 6 billion year^{-1} (James, Gaston & Balmford, 1999). In the face of this shortfall, an important strand of conservation biology has investigated means of optimizing the selection of protected areas (review in Cabeza & Moilanen, 2001). However, no similar attention has hitherto been paid to the issue of prioritizing island restorations even though, in the last 400 years, more species have become extinct on small islands than on continents (Manne, Brooks & Pimm, 1999). Nevertheless, a significant proportion of conservation effort is now devoted to controlling or removing the major cause of these extinctions from islands (Johnson & Stattersfield, 1990): invasive alien vertebrate species. This effort has been catalysed *inter alia* by the development of anti-coagulant toxins and effective bait delivery systems, which now allow islands of up to *c*. 100 and 300 km^2 to be cleared of rats *Rattus* spp. and cats *Felis catus*, respectively (Cooper *et al*., 1995; NZ-DOC, 2003; Nogales *et al*., 2004), which are among the most damaging and widespread of alien vertebrate taxa. Such advances mean that a robust strategy for allocating the available funds is needed because a very large number of islands are apparently urgent candidates for restoration. For example, there are several hundred islands across the world where globally threatened bird species occur alongside harmful alien vertebrates (own data).

The prioritization of invasive alien species eradications on islands requires, for each candidate island, a system for objective estimation of the conservation gain and an internally consistent method of predicting its financial cost. Using a global data file on vertebrate eradications, we address the latter issue. We ask which variables, among a number of plausible candidates such as island area, isolation, topography, project date and taxa targeted, actually influence the cost of an eradication project. We hypothesize that larger, more isolated, more rugged islands will be more costly, that costs per unit area may decline over time as efficiency improves, and that smaller species such as rats may be more costly to eradicate than larger species such as goats. The results of this analysis therefore allow the first-pass estimation of the likely costs of projects still in the planning stage.

Methods

Our global data set comprises information on 41 invasive vertebrate eradication projects. Twenty of these (49%) were carried out on New Zealand offshore islands, nine (22%) either in the UK (1) or in the UK's Overseas Territories (8), four (10%) in the Seychelles, three (7%) on Australia's offshore islands, two (5%) in Mauritius and one each (2%) on USA islands, Indonesian islands and Antigua. Because New Zealand provided about half the data, we analysed both the entire data set and, separately, the New Zealand data set to investigate whether the latter yielded insights obscured by between-country noise.

The data comprise (1) information on the eradication itself, namely species eradicated (rat or others), year of eradication, cost in US$ and status of the eradication (successful or unsuccessful two years after the project), and (2) island topographical and geographical data, specifically area (km^2), distance to the nearest main airport (km), maximum altitude (m) and 'ruggedness' (see below).

On the grounds that goods and personnel are readily moved between international airports but that such movement often becomes more difficult and expensive when by sea or when to local airports, we took the distance of each island from the nearest main airport as a measure of isolation, termed 'remoteness'. This distance was measured from The Times Atlas of the World (1999), with main airports being those marked in the atlas by an airport symbol enclosed in a circle.

Insofar as the steepness of the terrain may influence costs, our 'ruggedness' variable is intended to capture this, independent of both area and max altitude (which we also include as separate variables). Because altitude tends to increase with area, we take the standardized residuals from the regression of $\log_{10}$ max altitude on $\log_{10}$ area ($\log_{10}$ altitude $= 1.67 + 0.434 \log_{10}$ area) as our ruggedness variable. Costs were converted from the local currency to US$ at prevailing exchange rates and adjusted to 2003 prices. A summary of data used is given in Table 1.

The 41 projects targeted species in various combinations (Table 1): there were 29 rodent, four ungulate, two cat, one rabbit *Oryctolagus cuniculus*, one brushtail possum *Trichosurus vulpecula* and four (rodent + other) eradications. Because we were interested in the impact, if any, of species targeted on cost, it was necessary to categorize these projects before analysis. A priori, we have three main taxon categories: rodents, cats and ungulates. The methods deployed to eradicate these three groups are markedly different (although, even within taxon groups, there is substantial variation in methods in a database as wide-ranging as ours). We therefore aim to estimate costs separately for each of these groups, regardless of whether they are statistically distinguishable. This then leaves the question of how to treat the single eradications of rabbit and possum, and those islands from which rodents plus other species were removed. Kapiti Island was cleared of brushtail possums using trapping, shooting and hunting with dogs (Brown & Sherley, 2002), a method that is broadly similar to that used in most cat eradications. We therefore include Kapiti with the cat eradications. Round Island was cleared of rabbits using a brodifacoum-baiting operation, similar to most rat eradications, and is therefore pooled with those.

Considering the four islands from which rodents plus other species were removed, the removal of rats and cats on Tuhua was a carefully planned combined operation, involving secondary poisoning of cats which ate and were themselves then poisoned by rats that had already ingested brodifacoum (Nogales *et al*., 2004). On Pitcairn, secondary poison was a major component of the eradication, coupled with some trapping and hunting (Nogales *et al*., 2004). On Inner Chetwode and Stanley, the eradication of wekas *Gallirallus australis* and rabbits, respectively, was achieved via their consumption of brodifacoum, intended for rats. In the light of these details, we do not consider that these operations provide sufficient data to examine the very important question of the extent to which the costs of simultaneous eradications of more than one species are additive. Instead, we treat all four eradications as rodent eradications in the analysis. None of them generates notable outliers from the overall rodent cost-estimation function.

Hence, in the worldwide analysis, we have four ungulate eradications, three 'cat' eradications (i.e. including the eradication of possums from Kapiti Island) and 34 'rodent' eradications (including the eradication of rabbits from Round Island). For New Zealand, we have 16 rodent eradications (including Tuhua, Stanley and Inner Chetwode), three ungulate eradications and one possum eradication (Kapiti).

General linear models (GLMs, Minitab 13.1) were used to examine the variables that predict *costs of eradication*. Full models containing all potential explanatory variables were developed, with stepwise deletion of least significant variables, until a minimum adequate model was obtained in which all variables were significant ($P<0.05$). Because of the small number of observations ($n = 41$ islands) relative to explanatory variables ($n = 7$), we did not attempt to test for non-linear effects or interactions among variables.

In GLMs, *success* was treated as a binary categorical variable and *taxon* as a three-level categorical variable (see above). The remaining explanatory variables were modelled as covariates. The GLM is robust to departures from normality of explanatory variables, but nevertheless we normalized the heavily right-skewed distributions of *island area* and *remoteness* by $\log_{10}$ transformation. *Year of eradication*, *ruggedness* (see above) and *max altitude* were untransformed. The response variable, *cost of eradication,* was $\log_{10}$ transformed to remove a strong right-skew. All statistical tests were two-tailed.

Results

Our a priori expectation was that island area would have a very strong influence on costs. This expectation was met (Fig. 1), and the linear regression of cost on area gives $\log_{10}$ cost of eradication (US$) $= 4.27$ (SE 0.069) $+ 0.770$ (SE 0.076) $\times \log_{10}$ island area (km^2) [$F_{1,39} = 102$, $P<0.0001$, R^2(adjusted) $= 71.7\%$].

Because slope of the regression is significantly less than 1, costs per unit area decline with increasing island area. Although such a cost–area relationship is intuitively obvious, its influence is so overwhelming that clarifying its slope is of greater value in providing an accurate estimate of

Table 1 The 41 eradication projects analysed in this study

Island	Country	Year	Area (km^2)	Airport (km)	Successful (1 = yes, 0 = no)	Cost	Rodent	Cat	Ungulate	Other	Source
Ascension	UK Overseas Territory	2003	88.00	1081	1	815 661	0	1	0	0	Royal Society for the Protection of Birds
Bird	Seychelles	1996	1.01	270	1	5169	1	0	0	0	www.islandconservation.org/islanderad.html
Bottom	Falklands	2001	0.08	1375	1	3201	1	0	0	0	R. Ingham (pers. comm.)
Breaksea	New Zealand	1990	1.70	531	1	48 796	1	0	0	0	Pestlink, NZ Department of Conservation database
Campbell	New Zealand	2003	113.00	1050	1	1 249 726	1	0	0	0	Pestlink, NZ Department of Conservation database
Chetwode (inner and outer)	New Zealand	1996	2.78	75	1	43 778	1	0	0	Weka	Pestlink, NZ Department of Conservation database
Curieuse	Seychelles	2000	3.00	45	1	67 290	1	0	0	0	J. Millett (pers. comm.)
Cuvier	New Zealand	1993	1.70	105	1	16 968	1	0	0	0	Pestlink, NZ Department of Conservation database
Denis	Seychelles	2000	1.40	80	1	56 994	1	0	0	0	J. Millett (pers. comm.)
Double	Falklands	2001	0.09	1375	1	370	1	0	0	0	R. Ingham (pers. comm.)
Double Islands (Larger Island)	New Zealand	1989	0.19	96	1	3271	1	0	0	0	Pestlink, NZ Department of Conservation database
Double Islands (Smaller Island)	New Zealand	1989	0.08	96	1	1919	1	0	0	0	Pestlink, NZ Department of Conservation database
Ducie	Pitcairn Islands	1998	0.60	2700	1	32 191	1	0	0	0	Wildlife Management International
Enderby	New Zealand	1993	7.10	910	1	10 698	0	0	Cattle	0	Pestlink, NZ Department of Conservation database
Flat	Mauritius	1998	2.00	60	1	64 381	1	0	0	0	J. Hartley (pers. comm.)
Fregate	Seychelles	2000	2.20	45	1	61 916	1	0	0	0	J. Millett (pers. comm.)
Great Barrier	New Zealand	1987	32.30	93	0	32 975	0	0	Goat	0	Pestlink, NZ Department of Conservation database
Green Island	Antigua	2001	0.43	40	1	16 115	1	0	0	0	www.islandconservation.org/islanderad.html
Hawea	New Zealand	1986	0.09	531	1	36 101	1	0	0	0	Pestlink, NZ Department of Conservation database
Kapiti	New Zealand	1986	19.70	50	1	149 498	0	0	0	Possum	Pestlink, NZ Department of Conservation database
Korapuki	New Zealand	1987	0.18	96	1	3858	1	0	0	0	Pestlink, NZ Department of Conservation database
Lord Howe	Australia	2001	14.60	700	1	48 125	0	0	Goat	0	Parkes, Macdonald & Leaman (2002), Anon. (2003)
MacQuarie	Australia	2000	122.50	1200	1	2 356 350	0	1	0	0	G. Copson (pers. comm.)
Mokohinau	New Zealand	1991	1.00	111	1	21 621	1	0	0	0	Pestlink, NZ Department of Conservation database
Mou Waho	New Zealand	1996	1.40	312	1	8243	1	0	0	0	Pestlink, NZ Department of Conservation database
Oeno	Pitcairn Islands	1998	0.60	2400	1	32 191	1	0	0	0	Wildlife Management International
Otata	New Zealand	1991	0.22	36	1	8208	1	0	0	0	Pestlink, NZ Department of Conservation database
Outer	Falklands	2001	0.20	1375	1	895	1	0	0	0	R. Ingham (pers. comm.)
Palmyra	USA	2001	2.29	1300	0	111 007	1	0	0	0	B. Flint (pers. comm.)
Pitcairn	Pitcairn Islands	1998	5.00	2500	0	225 334	1	1	0	0	Wildlife Management International
Ramsey	UK	2000	2.53	150	1	28 972	1	0	0	0	I. Bullock (pers. comm.)
Raoul	New Zealand	1986	29.38	1160	1	551 470	0	0	Goat	0	Pestlink, NZ Department of Conservation database
Red Mercury	New Zealand	1992	2.25	110	1	24 126	1	0	0	0	Pestlink, NZ Department of Conservation database
Round	Mauritius	1986	1.50	40	1	48 286	0	0	0	Rabbit	J. Hartley (pers. comm.)
Rurima	New Zealand	1984	0.08	348	1	7366	1	0	0	0	Pestlink, NZ Department of Conservation database
Sandy Lacepede	Australia	1986	4.49	1100	1	51 653	1	0	0	0	www.islandconservation.org/islanderad.html

Table 1 Continued

Island	Country	Year	Area (km^2)	Airport (km)	Successful (1 = yes, 0 = no)	Cost	Rodent	Cat	Ungulate	Other	Source
Sangalaki	Indonesia	2003	0.14	500	1	2800	1	0	0	0	www.islandconservation.org/islanderad.html
Stanley	New Zealand	1992	1.00	99	1	17 064	1	0	0	Rabbit	Pestlink, NZ Department of Conservation database
Tawhitinui	New Zealand	1983	0.23	51	1	4225	1	0	0	0	Pestlink, NZ Department of Conservation database
Top	Falklands	2001	0.12	1375	1	2974	1	0	0	0	R. Ingham (pers. comm.)
Tuhua	New Zealand	2000	12.80	129	1	67 543	1	1	0	0	Pestlink, NZ Department of Conservation database

For each island, the year of the project, area, distance to nearest international airport and cost (expressed as US dollars adjusted to year 2003) are shown. The table also indicates whether or not the eradication was successful and whether it did (code 1) or did not (code 0) target various categories of vertebrate. All rodents were *Rattus* spp. and all cats were *Felis catus*.

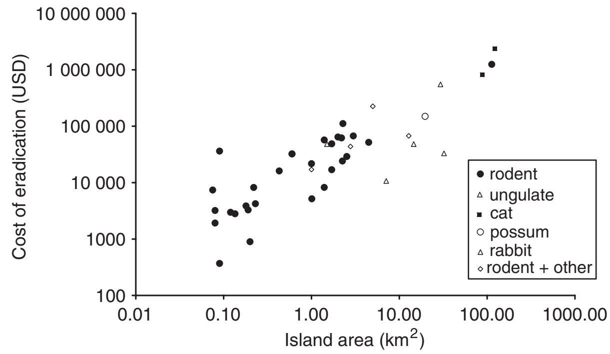

Figure 1 Cost of island eradications as a function of island area, for different taxa eradicated. The full data set is plotted.

Table 2 Significant variables in the minimum adequate model of eradication costs using the full data set

Response variable	*F* (d.f.)	*P*	Estimate (SE)
Constant		<0.001	4.10 (0.14)
Island area	79.7 (1,37)	<0.001	0.85 (0.067)
Taxon	3.77 (2,37)	0.032	–
Ungulate			0.00 (0.00)
Rodent			0.22 (0.15)
Cat			0.20 (0.19)
Deleted variables			
Success	0.13 (1,32)	0.72	
Remoteness	1.05 (1,33)	0.31	
Maximum altitude	1.83 (1,34)	0.19	
Ruggedness	0.77 (1,35)	0.39	
Year	1.03 (1,36)	0.32	

Non-significant variables are listed at the bottom, in the order in which they were deleted from the full model.

costs than is determining the role of other, secondary variables.

We subsequently investigated the effect of other secondary variables on the estimation of costs. A full GLM including all variables was reduced to give a final minimum adequate model, which contained $\log_{10}$ island area and taxon as significant predictors of cost (Table 2). Parameter estimates for the taxon effect indicate that eradication of rodents might be costlier per unit area than ungulates. The difference is large: according to this model, rodent eradications are estimated to be *c*. 1.7 times more expensive per unit area than ungulate eradications. Including the taxon variable in the model has a minor influence on the estimate of the slope of the area effect.

Success was the first variable to be dropped from the model; there was no evidence of a difference in costs between successful and unsuccessful operations. However, our data set comprises only three unsuccessful eradications (Pitcairn, Palmyra, Great Barrier), and hence this is a weak test. None of the remaining variables that were dropped from the model approached significance.

We developed a similar model using only data from eradications conducted in New Zealand. The success

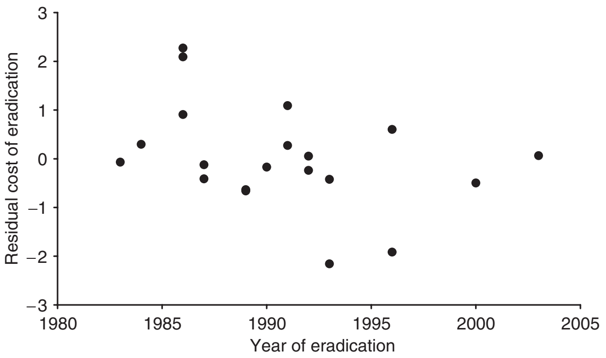

Figure 2 Relationship between year of eradication and costs of restoring New Zealand islands. *Y*-values are standardized residuals from a general linear model, with $\log_{10}$ cost of eradication as response variable and $\log_{10}$ island area, taxon eradicated and remoteness of island ($\log_{10}$ distance from nearest airport) as explanatory variables [i.e. the minimum adequate model for New Zealand eradications (see Table 3) with the year variable removed].

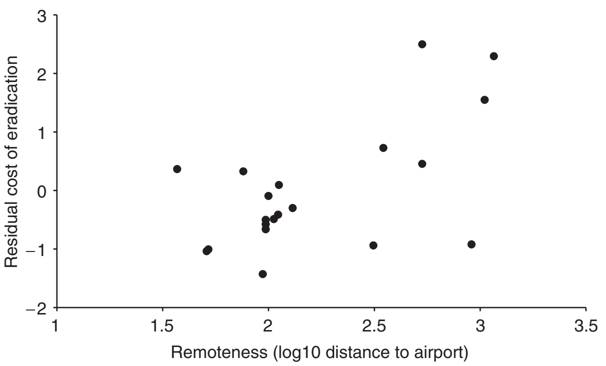

Figure 3 Relationship between remoteness of island and costs of restoring New Zealand islands. *Y*-values are standardized residuals from a general linear model, with $\log_{10}$ cost of eradication as response variable and $\log_{10}$ island area, year of eradication and taxon eradicated as explanatory variables [i.e. the minimum adequate model for New Zealand eradications (see Table 3) with the remoteness variable removed].

variable was not considered, because there was only one New Zealand failure. We combined the single possum eradication (see Methods) with the rodent eradications to create a two-level *taxon* variable (rat/possum vs. ungulate).

A model with area, taxon, year of eradication and remoteness as explanatory variables gave a good fit to the data (Table 3). As in the global model, rodent/possum eradications were significantly more expensive per unit area than ungulate eradications, in this case by a factor of three. In addition, in the New Zealand Model, costs were lower in more recent eradications (Fig. 2), and higher for more remote islands (Fig. 3).

Thus, for a hypothetical 10 km^2 island situated 100 km from an airport, costs would decrease from US$ 251 500 if rodents were eradicated in 1983 (the earliest date for which we have data), to US$ 88 600 if the operation were done in 1993, to only US$ 31 200 if it were done in 2003 (the latest date for which we have data).

Table 3 Significant variables in the minimum adequate model of eradication costs using only New Zealand data

Response variable	*F* (d.f.)	*P*	Estimate (SE)
Constant		0.032	92.7 (39.3)
Island area	49.4 (1,15)	<0.001	0.82 (0.12)
Remoteness	12.1 (1,15)	0.003	0.64 (0.18)
Year of eradication	5.23 (1,15)	0.037	−0.045 (0.20)
Taxon[a]	11.9 (1,15)	0.004	
Ungulate			0.00 (0.00)
Rodent			0.51 (0.15)
Deleted variables			
Ruggedness	0.52 (1,12)	0.49	
Maximum altitude	0.23 (1,13)	0.64	

[a]For the purposes of this analysis, we used a two-level taxon variable: rodent/possum and ungulate.
Non-significant variables are listed at the bottom, in the order in which they were deleted from the full model.

Similarly, for a hypothetical 10 km^2 island from which rodents/possums were eradicated in 2000, the predicted cost would increase from US$ 9800 if it were 10 km from an airport, to 42 700 if 100 km from an airport to 185 500 if 1000 km from an airport.

Discussion

Our results indicate that island area is the primary determinant of the cost of an eradication (Fig. 1). Seventy-two per cent of the variation in cost of an eradication can be explained by area alone. Detecting this strong effect was made easier by the fact that the areas of the islands in our data set span more than four orders of magnitude. Thus, decision makers considering potential eradication programmes need only know island area, distance from airport (at least in the New Zealand region) and species to be eradicated to make internally consistent and robust first-pass estimates of the likely cost. Of especial consequence is whether the programme will target rodents or ungulates, the former being 1.7–3.0 times more expensive for a given island area. This reflects substantial differences in the methods typically used to conduct the work (Courchamp, Chapuis & Pascal, 2003). Although other variables failed to enter our model, it seems almost inevitable that these variables do exert some influence on costs. In particular, more rugged islands are likely to be more costly than flat islands.

Although the explanatory power of the regression of cost on area is very high, the confidence intervals around the cost of a particular eradication, especially on a small island, remain rather large as a proportion of predicted cost. Clearly, local factors that are not captured in this generic analysis may have an important influence on the costs of a given eradication. However, the absolute precision of cost prediction is not the main issue here. These models provide a means by which several or many potential eradications can be compared in a consistent manner at the pre-planning stage, particularly when combined with an internally consistent means of estimating conservation benefits (Brooke *et al.*, in prep.).

The regression coefficient for island area (Fig. 1 and results) is less than unity, implying that eradication programmes on larger islands cost less per hectare than those on smaller islands. Such a relation was demonstrated by Towns & Broome (2003) for New Zealand eradications. These authors also considered that there had been efficiency gains, reducing per hectare costs over time, but they did not present detailed multivariate statistics to support this claim. Our analysis now detects such gains. When increased efficiency is coupled with the lower per hectare cost of larger islands, the number of candidate islands clearly expands for a given budget. But when assessing the case for eradications on candidate islands of different size, it is crucial to know the slope of the regression of cost on island area, which our analysis now provides.

The lower per hectare cost of programmes on larger islands should not automatically be considered an argument for targeting eradication expenditure towards larger islands. Although, on average, the populations of threatened species will be larger and potentially more viable on larger islands, there may be counter-arguments in favour of targeting several small islands. For example, several small islands might harbour populations of several different endangered species, and their smaller size could facilitate quarantine measures against accidental re-introductions of aliens.

Few of the eradications used in our calculations were undertaken in developing countries. Even those that were undertaken in developing countries were carried out by visiting experts from the developed world. Thus, in contrast to protecting reserves in developing countries, which may be cheaper because land and labour costs are low (Balmford *et al.*, 2003), there is at present no case to be made that the costs of eradications are significantly affected by the development status of countries (although this situation may certainly change in the future).

The results presented here offer a much-needed tool for comparing the costs of future eradications among sets of candidate islands and, in due course, for the assessment of global priorities for restorative island conservation.

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