



How to prioritize rat management for the benefit of petrels: a case study of the UK, Channel Islands and Isle of Man

NORMAN RATCLIFFE,^{1*†} IAN MITCHELL,² KAREN VARNHAM,³ NANETTE VERBOVEN¹ & PAUL HIGSON¹

¹RSPB Scotland, 10 Albyn Terrace, Aberdeen AB10 1YP, UK

²JNCC, Dunnet House, 7 Thistle Place, Aberdeen AB10 1UZ, UK

³University of Bristol, Woodland Road, Bristol BS8 1UG, UK

Rats have been introduced to islands throughout the world. They have caused breeding failures, population declines and complete extirpation of vulnerable bird species. Such impacts can be difficult to diagnose in situations where extirpation occurred prior to the vulnerable species being recorded. Mitigating the impacts of rats on seabirds depends on quarantine measures for islands where rats are currently absent, and eradication or control campaigns on those where they are present. These measures can be challenging in terms of both costs and practicalities, and so can seldom be applied to all islands within a given region. Hence a prioritization exercise is often required to identify those islands where management would be most cost-effective. In this review we present a case study of rat management in the UK, Channel Islands and Isle of Man. We review rat management for the study area to date and present a simple scoring approach to prioritize islands for eradication campaigns, including those where the procellariiform priority species are currently absent. We recommend further research into rat management for the study area and on the applicability of this approach elsewhere in the world.

Keywords: eradication, invasive species, island restoration, petrels, prioritization, quarantine, rats, seabirds.

Seabirds have life histories characterized by longevity and low fecundity (Croxall & Rothery 1991, Weimerskirch 2002), and many species nest in colonies on the ground or in burrows. These traits make them extremely vulnerable to mammalian predation, so seabirds generally nest on offshore islands where such predators are absent. However, human activities have resulted in mammal predators being introduced to many seabird islands around the world, with catastrophic effects (Moors & Atkinson 1984). Three species of commensal rat (Black *Rattus rattus*, Brown *Rattus norvegicus* and Polynesian *Rattus exulans*) are amongst the most

common and destructive of these invaders, and their introduction to islands has often been associated with marked declines in, or complete extirpation of, seabird populations (Atkinson 1985, Towns *et al.* 2006, Jones *et al.* 2008). Where extirpation occurs, islands remain unsuitable as breeding habitat while rats persist, and seabird numbers may be limited by availability of breeding space as a consequence. Such limitation can be difficult to diagnose, as rats often reached islands centuries ago and may have extirpated the most vulnerable seabird species from islands long before ornithologists documented their presence (Martin *et al.* 2000, Heaney *et al.* 2002, de Leon *et al.* 2006).

Two conservation strategies are available to manage rats for the benefit of seabirds. Quarantine of breeding islands to prevent rat invasion is essential to prevent further losses of seabird numbers and contraction of their range (Russell & Clout 2005). Where rats are already present,

*Corresponding author:
Email: notc@bas.ac.uk

†Current address: British Antarctic Survey, Natural Environmental Research Council, High Cross, Madingley Road, Cambridge, CB3 0ET, UK.

rodenticides can be used either to reduce rat densities in the immediate vicinity of seabird colonies on an annual basis (Zino *et al.* 2001), or to eradicate them altogether (Courchamp *et al.* 2003, Howald *et al.* 2007). Typically, it is not possible to apply such management to all islands within a region owing to practicalities and limited conservation resources. Hence, prioritization is required to identify those islands where the greatest conservation gains can be made for the least cost (Brooke *et al.* 2007).

The UK, with its crown dependencies of the Channel Islands and Isle of Man, comprises hundreds of islands varying in size from the Great Britain mainland to small islets. Black Rats were first introduced to the archipelago during the 3rd century AD, but have been largely replaced by Brown Rats since their introduction in the 18th century AD (Harris *et al.* 1995). Since their initial colonization, rats have invaded a large proportion of the islands in the archipelago, but many of the smaller ones, with low levels of human habitation, have remained rat-free (Arnold 1993). Several studies within the study region have documented adverse impacts of rats on seabirds on islands where they co-occur (Brooke 1990, Zonfrillo 2002, Stoneman & Zonfrillo 2005, Swann *et al.* 2007). The archipelago therefore offers an ideal case study for prioritizing both quarantine and eradication management for rats. Moreover, the relevant governing bodies have recognized the threat that invasive species pose to native biodiversity, and have drafted a strategy that requests prioritization of remedial management (DEFRA 2007). To this end, we review rat management for the benefit of seabirds on islands in the study area, and present a simple approach to prioritizing future management, based on an ordinal scoring system that extends to islands from which vulnerable species are absent. We discuss the applicability of the approach to prioritization elsewhere in the world and recommend further research into rat management for the benefit of seabirds in the study area.

METHODS

Reviewing control programmes to date

We searched the published literature and institutional reports, and consulted seabird biologists, mammalogists, wardens and conservation officers to identify the islands in the UK, Isle of Man and

the Channel Islands where rat quarantine or eradication programmes have been conducted, the timing and duration of the work, the methods used and the outcomes in terms of the responses of both rats and seabirds.

Defining eradication units

Rat eradication will only meet conservation objectives in the long-term if rats are unlikely to recolonize the island following their removal. Rats could recolonize an island by swimming from the mainland, with the likelihood of this occurring, declining with the width of the strait (Russell *et al.* 2008). Brown Rats can swim for up to 1 km in open, temperate seas (Russell *et al.* 2008), but examination of rat distribution in the UK shows that many islands remain rat-free despite being less than 1 km from the mainland. A maximum swimming distance of 300 m produced a better fit with observed distribution, and agrees with guidelines issued by Falklands Conservation (2008). Accordingly, we plotted a 150-m buffer around the mean high water mark (OS Boundary-line™ © Crown Copyright) using ESRI ArcGIS® 9; if the buffer of an island overlapped with that of the mainland, it was classed as an unsuitable target for rat eradication. If the buffers of two islands overlapped, they were pooled into a single eradication unit, as for eradication to be successful, both islands would need to be treated. Moreover, we assumed that American Mink *Mustela vison* were able to reach any island within 2 km of shore along the west coast of Scotland (Ratcliffe *et al.* 2008), and excluded such islands from further consideration for eradication campaigns as restoration of these would require a commitment to American Mink control in perpetuity.

Determining presence of rats in eradication units

We determined the presence or absence of Brown and Black Rats in each eradication unit by reference to Arnold (1993), various databases available through the National Biodiversity Network Gateway (<http://www.nbngateway.net>) and consultation with local naturalists familiar with the mammalian fauna of each island. We classified islands into those with and without rats and analysed their priority for eradication and quarantine management.

Scoring reintroduction risk

Rats are often reintroduced to islands accidentally in vessels and their cargoes (Moors *et al.* 1992), and the frequency and size of these tend to increase with the number of people inhabiting an island. Hence, the reinvasion likelihood, or the cost of effective quarantine, is positively related to the number of humans inhabiting an island. Moreover, the likelihood of other introduced mammalian predators occurring on an island (particularly feral or domestic Cats *Felis catus*, but also Western Hedgehogs *Erinaceus europaeus*, American Mink and feral Ferrets *Mustela furo*) increases with the size of the human population (de Leon *et al.* 2006). The presence of other predators may compromise the conservation goals of rat eradication if they are allowed to remain, and add to the costs of eradication and public relations problems if removed. Finally, issues of public relations, incidental or secondary poisoning of domestic animals and obtaining approval, increase with human population size (Genovesi 2007). We therefore took human population size in each eradication unit from the National Census as an index of the risk of a rat eradication project being unsuccessful. No unit in our study area that is inhabited by more than 100 humans is rat-free, and so we eliminated those units with a population above this threshold from further consideration owing to risk of reinvasion. Such islands might be considered for eradication campaigns in the future, however, once quarantine methods have been developed and proved effective on less populous islands. The remaining eradication units were awarded a risk score based on the number of inhabitants: 3 (0–10), 2 (11–50) and 1 (51–100).

Cost of eradication

We estimated the costs of eradication by multiplying the island area by £440, based on the cost per ha of eradicating rats from Canna/Sanday during 2005–2006 (R. Luxmoore pers. comm.). We opted to use the costs of this campaign, rather than earlier ones in the UK, as it is the most recent (and hence subject to the least change due to inflation) and because it is the only UK campaign that reported total costs (D. Appleton *in litt.*). Using a constant value is justifiable because Martins *et al.* (2006) and Howald *et al.* (2007) found area and costs of eradication are closely related, even where methods differ (e.g. aerial vs. hand broadcast of

bait). However, Donlan and Wilcox (2007) point out that many other factors can influence the overall expense of a project, so the estimated costs presented here should be viewed as approximate. Moreover, variations in cost per ha do not affect the rankings of islands, as it is a constant value and the only variable in the cost score is island area. We classed the cost of eradications into three cost scores: 3 (\leq £100 000), 2 ($>$ £100 000 \leq £200 000), 1 ($>$ £200 000).

Prioritization according to seabird species

Storm petrels are among the seabirds most vulnerable to rat predation owing to their small size, lack of predator defence behaviour and their habit of nesting in burrows or crevices where rats prefer to forage (Jones *et al.* 2008). There is no overlap of the distribution of rats with that of Leach's *Oceanodroma leucorhoa* or European Storm Petrels *Hydrobates pelagicus* in the UK (Heaney *et al.* 2002, Mitchell *et al.* 2004, de Leon *et al.* 2006), suggesting that introduction of rats to an island leads to extirpation of these species. While the distribution of rats and Manx Shearwaters *Puffinus puffinus* do overlap in the UK (Mitchell *et al.* 2004), there is evidence that rats can cause declines in density or complete extirpation of this species (Brooke 1990, Swann *et al.* 2007). All three species have highly restricted breeding distributions compared to most other seabird species (Mitchell *et al.* 2004), and it is likely that the presence of rats on otherwise suitable islands has contributed to their localized range. We therefore prioritized islands for eradication and quarantine according to their potential or actual importance for these three species of petrel. Burrow-nesting alcids such as Atlantic Puffin *Fratercula arctica* are also vulnerable to rat predation (Zonfrillo 2002, Jones *et al.* 2008), but we did not prioritize according to this species as it has a far wider range than any of the aforementioned petrels and it does co-occur with rats on many islands (Mitchell *et al.* 2004).

Suitability of units for priority species

We extracted counts of European and Leach's Storm Petrels and Manx Shearwaters from Mitchell *et al.* (2004) and calculated the percentage of the UK, Isle of Man and Channel Islands population contained in each eradication unit. We

summed these within each unit and ranked them in descending order to determine the unit's priority for rat quarantine measures.

For each of the eradication units occupied by rats, we developed a score of their relative suitability for petrels were rats to be eradicated. On some islands, relict populations of petrels remain, or historic accounts attest to their presence prior to extirpation: all these were awarded a suitability score of 6. In many cases, however, petrels are likely to have been extirpated prior to their presence being documented, and so suitability has to be inferred from habitat characteristics. Both Leach's and European Storm Petrels forage on the continental shelf edge or beyond, and Manx Shearwaters in the Minches and Irish Sea (Stone *et al.* 1995), and so all three occur only on those islands to the north and west of mainland UK (Mitchell *et al.* 2004). Furthermore, European Storm Petrels require boulder scree, boulder beaches or ruined dry-stone structures as nesting habitat, and the other two require deep, free-draining soil for burrowing (Cramp & Simmons 1977). On this basis, we awarded a score of 6 to islands to the north or west of Britain with extensive breeding habitat, a score of 4 to those occurring there with limited breeding habitat, and a score of 2 to islands to the east of Britain. The doubling of the scores for habitat suitability is designed to give potential gains equal weighting in the final score to the combined scores of cost and risk. This was necessary to avoid islands that were unsuitable for petrels receiving a high priority because rats could be eradicated from them at a low cost and risk.

Final prioritization of cost-benefit

The risk, cost and suitability scores for each island were summed and then ranked in descending order. Those islands suitable for petrels that are inexpensive to restore and where eradication has a high likelihood of success would obtain a top score of 12, while islands with the opposite characteristics would receive a bottom score of 4.

RESULTS

Island rat eradication campaigns in the UK

Since the late 1950s, 12 rat eradication projects have been initiated in the UK, treating a total area of 2617 ha (Table 1). All have involved eradication of Brown Rats and, on Lundy, Black Rats were eradicated as well. The frequency of eradication projects and the size of islands treated have both increased markedly since the early 1990s (Table 1). The largest unit treated was Canna/Sanday (1314 ha), and the most populous was Lundy (28 people). All have used cereal bait treated with rodenticide, presented loose or embedded in wax blocks. Bait was placed in boxes or pipes that were deployed in a grid over the entire area of each island, though often at higher densities in areas where rats were known to be more abundant. Post-eradication monitoring for rats has usually been conducted for 2 years, using chewable markers deployed in a grid over each island.

Table 1. Islands in the UK from which rats have been eradicated, presented in chronological order. ID numbers are plotted in Fig. 1 to show the location of each island.

ID	Island	County	Year treated	Area (ha)	Human popn	Source
A	Fidra	East Lothian	1959	10	0	A. Lauder pers. comm.
B	Cardigan Island	Dyfed	1968	16	0	Brooke 1990
C	Flat Holm	S. Glamorgan	1985	19	5	W. Murray pers. comm.
D	Ailsa Craig	Kyle & Carrick	1991	99	0	Zonfrillo 2001
E	^a Scilly Islands	Cornwall	1993	128	0	IOSET unpubl. data
F	Handa	Sutherland	1997	309	0	Stoneman & Zonfrillo 2005
G	Puffin Island	Gwynedd	1998	32	0	Ratcliffe & Sandison 2001
H	Eynhallow	Orkney	1998	75	0	P. Thompson pers. comm.
I	Ramsey	Dyfed	1999	261	2	Bell <i>et al.</i> 2000
J	Lundy	Devon	2003	345	28	Lock 2006
K	Canna/Sanday	Lochaber	2005	1314	12	Bell <i>et al.</i> 2007
L	Looe Island	Cornwall	2006	9	4	K. Varnham pers. obs.

^aAll uninhabited islands have been treated by Isles of Scilly Environmental Trust in a programme extending from 1993 to present. The largest of these is Sampson at 38 ha.

All projects on isolated eradication units in the UK have apparently been successful in removing rats, though some projects are too recent for that outcome to be confirmed. However, some failures have occurred on the Isles of Scilly and on Looe Island, owing to invasion from neighbouring untreated islands or the mainland (Heaney *et al.* 2002, Isles of Scilly Environmental Trust (IOSET) unpubl. data, Cornwall Wildlife Trust pers. comm.). In each case, the reinvaded islands were within 300 m of populous islands or the mainland. These would not have been considered as suitable eradication units in this study, and so lends support to our simple buffer approach. The reinvaded islands in the Isles of Scilly are now subject to annual treatment to prevent reinvasion by rats (IOSET unpubl. data).

Handa has not been reinvaded despite it being 300 m off the UK mainland shore, which might be due to the opposite shoreline being unpopulated moorland that is poor habitat for rats, such that a source population is small or lacking. In contrast, the reinvaded islands in Cornwall all had suitable rat habitat on the opposite shores (a settlement in the case of Looe and farmland in the case of the Scilly Isles). As such, our approach of eliminating all islands with a strait of < 300 m may have overlooked some restoration opportunities where habitat on the opposite shore is unsuitable for rats.

Initial responses of seabirds to rat eradication have been encouraging. Puffins have recolonized Ailsa Craig (Zonfrillo 2002) and their range and numbers have increased on Handa (Stoneman & Zonfrillo 2005). Manx Shearwaters have increased from 700 to 2000 pairs on Ramsey and from 308 to 1120 pairs on Lundy since rats were eradicated (RSPB unpubl. data). However, not all eradication projects have succeeded in restoring seabird populations: rat eradication on Cardigan Island has so far failed in its aim of establishing a new Manx Shearwater colony (Brooke 1990).

Priorities for further eradication campaigns

We identified a total of 274 potential eradication units in the UK, Isle of Man and Channel Islands that are discrete from the UK mainland: 80 are known to have rats on them but only 19 of these had fewer than 100 human inhabitants.

A prioritized list of these 19 eradication units is presented in Table 2. High scores were awarded to

several units within the Western Isles. Pre-eminent among these is the Shiant's owing to their extensive talus screes that offer ample potential nesting habitat for European Storm Petrels. Rats are known to prey on other seabird species on these islands (Stapp 2002, *contra* McDonald *et al.* 1997 and Key *et al.* 1998), and so their removal could also produce broader conservation benefits. However, as the Shiant's host one of the few remaining populations of Black Rats in the UK, such an initiative may prove controversial (as on Lundy: Appleton 2007), even though this species is non-native, and abundant and widespread globally. The Calf of Man is also a high priority as it formerly held a huge colony of the eponymous Manx Shearwater, which has now declined to just 34 pairs owing to predation by Brown Rats (Brooke 1990, Mitchell *et al.* 2004). Owing to the restricted world range of Manx Shearwater (Mitchell *et al.* 2004), restoring this site could lead to increases in population of global significance at a relatively low cost or risk.

Hellisay/Gighay and Sandray have less petrel nesting habitat than the Shiant's, and so do not score as highly. Indeed, neighbouring rat-free islands in the Barra archipelago with similar habitats host relatively few nesting petrels (Mitchell *et al.* 2004). Taransay has extensive nesting habitat for all three species of petrel, but receives a lower score owing to the expense of eradicating Brown Rats from this relatively large island.

The co-occurrence of Brown Rats with a large proportion of the national Manx Shearwater population on Rum is cause for concern. Research during the 1980s showed that rats were relatively rare in this high-altitude colony during the breeding season, and predation was negligible (Thompson & Furness 1991), but recent monitoring has found that predation rates on viable eggs and chicks have increased (A.D. Ramsay unpubl. data). Experimental control of rats in the worst affected colony on the mountain of Hallival is being considered to quantify the impact of rat predation on Manx Shearwater productivity (A. Douse pers. comm.).

Gairsay in Orkney has a low human population and is relatively small, which means that a rat eradication campaign would be inexpensive and has a high chance of success. It is in a suitable location for European Storm Petrels, as colonies occur on neighbouring rat-free islands (de Leon *et al.* 2006), but has limited breeding habitat and feral cats.

Table 2. Prioritization of islands on which rat eradication is deemed feasible according to the criteria in the Methods section. RS, risk of reinvasion score; CS, cost of eradication score; HS, the habitat suitability for petrels score; TS, sum of the three scores (see Methods for details). The table is sorted in descending order of TS. ID numbers are plotted in Fig. 1 to show the location of each island. Cost is expressed in thousands of pounds, rounded to the nearest whole number, and Area in ha.

ID	Eradication unit	Admin area	Area	Popn	Cost	RS	CS	HS	TS
1	^b Shiants	Western Isles	212	0	93	3	3	6	12
2	^a Calf of Man	Isle of Man	260	2	114	3	2	6	11
3	Taransay	Western Isles	1475	0	649	3	1	6	10
4	Hellisay/Gighay	Western Isles	238	0	105	3	2	4	9
5	Gairsay	Orkney	240	3	106	3	2	4	9
6	Sandray	Western Isles	385	0	169	3	2	4	9
7	^a Rum	Lochaber	10 463	22	4604	2	1	6	9
8	^b Inchcolm	Fife	5	2	2	3	3	2	8
9	Inchkeith	Fife	20	2	9	3	3	2	8
10	Caldey Island	Dyfed	120	50	53	1	3	4	8
11	Out Skerries	Shetland	128	76	56	1	3	4	8
12	Wyre	Orkney	311	18	137	2	2	4	8
13	Graemesay	Orkney	409	21	180	2	2	4	8
14	Rathlin Island	Co. Antrim	1400	75	616	1	1	6	8
15	^a St Agnes/Gugh	Isles of Scilly	1480	73	651	1	1	6	8
16	^a Eigg	Lochaber	3049	67	1342	1	1	6	8
17	^b Herm/Jethou	Channel Islands	269	62	118	1	2	4	7
18	Egilsay	Orkney	650	37	286	2	1	4	7
19	Muck	Lochaber	559	30	246	2	1	4	7

^aUnits known to currently host breeding Manx Shearwaters.

^bUnits hosting Black Rats.

The islands of Inchkeith and Inchcolm are small, sparsely populated and inexpensive to restore, but the absence of petrels from neighbouring rat-free islands in the Firth of Forth (Mitchell *et al.* 2004) indicates these are too remote from the shelf-edge feeding areas to be suitable for petrels. The remaining units have low scores mainly because they are large, populous and have other mammalian predators on them, making eradication expensive and prone to failure.

Priorities for quarantine

A list of islands without rats that contain over 1% of the total UK, Channel Islands and Isle of Man population of any one of the three species of petrel is presented in Table 3. Of outstanding importance were St Kilda, Skomer, Skokholm, Mousa, Treshnish and Priest Island, all of which host over 10% of the total population of at least one species.

The absence of rats from these islands at present may lead to the complacent view that they are permanently inaccessible to rats. In reality, all islands have to be considered at risk of rats being introduced from vessels mooring or anchoring near the shore overnight, during delivery of stores, or fol-

lowing shipwrecks (Moors *et al.* 1992, Russell & Clout 2005). Several of the islands in Table 3 are inhabited or are popular destinations for tourist excursions and yachtsmen, and so are at particular risk of rats being introduced. Indeed, rats have been detected for the first time on Eynhallow in 1998 and on Annet in 2005; in both cases they were eradicated shortly afterwards (Table 1).

Effective quarantine requires strict controls on mooring by vessels and checks of the contents of freight, monitoring for presence of rats in the vicinity of harbours and anchorages and contingency plans for their eradication (including stores of poison bait, equipment and a plan for their deployment) in the event of rats being detected (Moors *et al.* 1992). On only four of the islands listed in Table 3 (St Kilda, Annet, Mousa and Priest Island) are these quarantine measures carried out routinely as part of a management plan.

DISCUSSION

Prioritization of islands for rat eradication has received increased attention in recent years (Baccetti *et al.* 2007, Brooke *et al.* 2007), with the focus being on co-occurrence of rats with

Table 3. Table of priority islands for rat quarantine, ranked by the sum of the percentage of the UK, Isle of Man and Channel Islands petrel populations each host. Islands with less than 1% of the total are not included. ID numbers are plotted in Fig. 1 to show the location of each island.

ID	Island	Admin area	Manx Shearwater	European Storm Petrel	Leach's Storm Petrel
1	^a St Kilda	Western Isles	2	4	95
2	^a Skomer	Dyfed	34	0	0
3	^a Mousa	Shetland	0	26	0
4	^a Skokholm	Dyfed	15	10	0
5	^a Treshnish	Argyll and Bute	0	20	0
6	^a Priest Island	Ross and Cromarty	0	17	0
7	^a Bardsey	Gwynedd	5	0	0
8	^a Auskerry	Orkney	0	4	0
9	^a Annet	Isles of Scilly	0	4	0
10	^a North Rona	Western Isles	0	1	2
11	^a Flannans	Western Isles	0	0	3
12	Yell Sound Is	Shetland	0	2	0
13	^b Copeland	Co. Down	2	0	0
14	Shillay	Western Isles	0	1	0
15	^a Sule Skerry	Orkney	0	1	0
16	Eilean nan Ron	Sutherland	0	1	0

^aSite of Special Scientific Interest SSSI (under the GB Wildlife & Countryside Act 1981) and Special Protection Area SPA (under the EC Birds Directive 79/409/EEC) that includes breeding petrels as qualifying feature.

^bArea of Special Scientific Interest (under the Nature Conservation and Amenity Lands (N.I.) Order 1985, with 1989 amendment) and SPA that includes breeding petrels as a qualifying feature.

threatened species. This approach is laudable, but risks overlooking opportunities to restore seabirds to islands from which they have already been lost. Our study is one of the few examples of prioritization that includes islands where target species are absent owing to rats (see also Falklands Conservation 2008). Had we neglected to include such islands, rat management measures for storm petrels would have been limited to quarantine alone, and only Rum, Eigg, Calf of Man and St Agnes/Gugh, the only islands where Manx Shearwaters and rats currently co-occur, would have been considered eligible for eradication campaigns.

Our simple scoring approach for prioritizing islands is admittedly crude, but uses minimal information that will be readily available for many archipelagos around the world. It allows prioritization to be conducted quickly and inexpensively as a desk-study. Research can then be initiated on the shortlist of islands to produce a refined priority list. Studies should include detailed quantification of habitat availability to estimate the number of the target species the unit might support if rats were absent, and a feasibility study to refine the estimated costs and the likelihood of success. The predicted percentage increase in the regional population following eradication could be divided

by the estimated cost of the campaign and this multiplied by the likelihood of success to produce a priority statistic on a continuous scale. Based on the findings of this review, we recommend such studies should be conducted for the Shiant, Hellisay/Gighay, Sandray, Taransay, Calf of Man, and Gairsay.

One risk of relying on existing data is that knowledge of the occurrence of rats and petrels on islands within an archipelago may be incomplete, as both are difficult to detect, and observers only visit remote islands infrequently. This could result in quarantine priorities and eradication opportunities being overlooked. Additional survey work for rats and target species needs to be directed to islands where the presence or absence of either is unconfirmed before a prioritization exercise can be regarded as comprehensive.

Effective quarantine is required to conserve important petrel colonies on the islands listed in Table 3. All but three of these islands are designated for protection under UK Government and/or European Commission legislation on the basis of their breeding petrel populations. There is an obligation on the responsible government agencies to implement effective quarantine, as legislation demands that the 'petrel interest' listed for

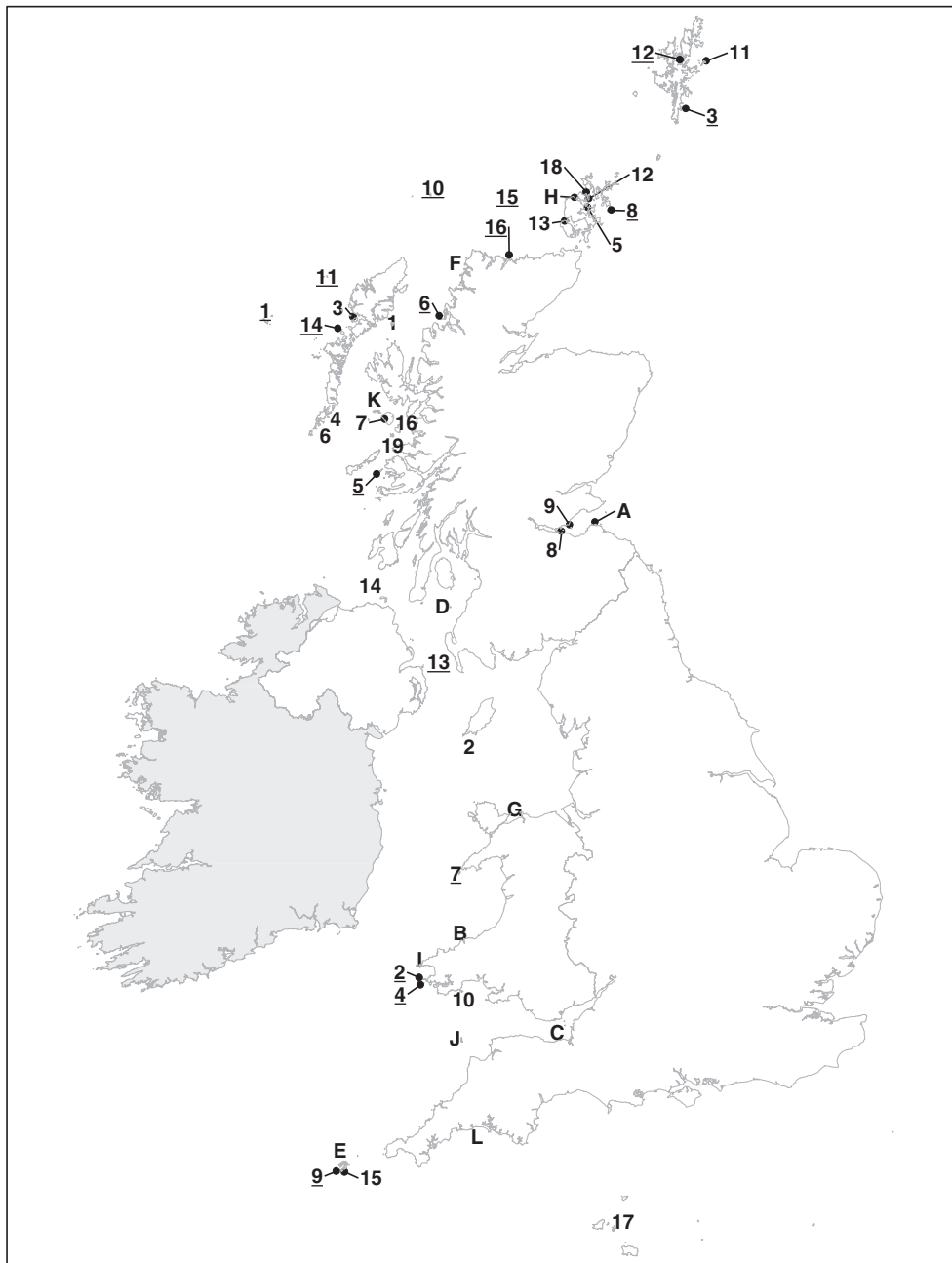


Figure 1. Map showing locations of island in the UK from which rats have been eradicated (letters – see Table 1), should be prioritized for eradication (numbers – see Table 2) and should be prioritized for quarantine measures (underlined numbers – see Table 3). The Republic of Ireland (grey shading) was not included in the prioritization exercise.

these sites is maintained. Common standards for quarantine need to be developed and incorporated into site management plans. These should include mitigation measures to reduce the likelihood of rats invading the island, monitoring of rat presence/absence and contingency planning for eradi-

cation should rats be detected (see previous section, Moors *et al.* 1992).

Given that petrels tend to be site-faithful and colonial, social facilitation methods may be required to encourage them to newly colonize islands following rat eradication. Playback of courtship

calls through loudspeakers at night can be used to attract pre-breeding storm petrels ashore far from their breeding colonies (Fowler & Hounscome 1998), and to encourage adult birds to breed in suitable nest-sites (Podolsky & Kress 1989, Bolton *et al.* 2004). Petrel chicks can also be translocated to artificial nest-sites just prior to them fledging, such that they return to breed at the island in future years (Carlile *et al.* 2003), though this was unsuccessful on Cardigan Island (Brooke 1990).

A common problem with assessing the efficacy of rat management as a tool for conserving petrel populations is a lack of adequate monitoring of their numbers and productivity prior to, and following, rat eradication. Estimates of these parameters is difficult for nocturnal, cavity-nesting petrels (Mitchell *et al.* 2004), but nonetheless ought to be attempted if the success of the project is to be measured in terms of benefits for target species rather than an absence of rats. Ideally, monitoring would be extended to nearby islands on which rats remain, and from which they have always been absent, such that effects of management and time can be separated.

We are grateful to the following for providing information about rat distribution and management: Pete Ellis, Eric Meek, Martin Scott, Jamie Boyle, Mike Peacock, John Stuart, James Robinson, Gregor Woulahan, Helen Booker, Paul St Pierre, Leigh Lock, Wendy Murray, Alan Lauder, Steph Elliot, Ben Jones, John Bowler, Stuart Benn, Dave Sexton, Alice Helyar, Sugoto Roy, Dave Beaumont, Charles David, Jamie Hooper, Janice Dockerrill, Liz Charter, Debra Marriott, Andrea McConnell, Bob Swann, David Barnden, Robin Sellers and Matt Murphy. Helen Baker, Geoff Hilton, Mike Brooke, Robbie McDonald and Jeremy Wilson provided helpful comments on an earlier draft.

REFERENCES

- Appleton, D.** 2007. *Public Engagement: the Lundy Experience. Proceedings of the Conference 'Tackling the Problem of Alien Mammals on Seabird Colonies.'* Edinburgh: National Trust for Scotland.
- Arnold, H.R.** 1993. *Atlas of Mammals in Britain.* London: ITE Research Publications No. 6.
- Atkinson, I.A.E.** 1985. The spread of commensal species of *Rattus* to oceanic islands and their effect on island avifaunas. In Moors, P.J. (ed.) *Conservation of Island Birds*: 35–81. Cambridge: International Council for Bird Preservation.
- Baccetti, N., Capizzi, D., Corbi, F., Massa, B., Spano, G. & Sposimo, P.** 2007. *Alien mammals on Italian islands: impact on seabird populations, management options and priorities for resource allocation. Proceedings of the Conference 'Tackling the Problem of Alien Mammals on Seabird Colonies.'* Edinburgh: National Trust for Scotland.
- Bell, M.D., Bullock, I. & Humpridge, R.** 2000. *The Eradication of Rats from Ramsey Island, Wales.* Sandy: Unpublished report to the Royal Society for the Protection of Birds.
- Bell, E., Garner-Richards, P., Floyd, K., Boyle, D., Swann, B., Luxmoore, R. & Patterson, A.** 2007. *Canna Seabird Recovery Project — Phase I: Brown Rat Eradication. Proceedings of the Conference 'Tackling the Problem of Alien Mammals on Seabird Colonies.'* Edinburgh: National Trust for Scotland.
- Bolton, M., Medeiros, R., Hothersall, B. & Campos, A.** 2004. The use of artificial breeding chambers as a conservation measure for cavity-nesting procellariiform seabirds: a case study of the Madeiran Storm Petrel (*Oceanodroma castro*). *Biol. Conserv.* **116**: 73–80.
- Brooke, M.** 1990. *The Manx Shearwater.* Calton: T. & A.D. Poyser.
- Brooke, M. de L., Hilton, G.M. & Martins, T.L.F.** 2007. Prioritizing the world's islands for vertebrate-eradication programmes. *Anim. Conserv.* **10**: 380–390.
- Carlile, N., Priddel, D., Zino, F., Natividad, C. & Wingate, D.B.** 2003. A review of four successful recovery programmes for threatened sub-tropical petrels. *Mar. Ornithol.* **31**: 185–192.
- Courchamp, F., Chapuis, J.L. & Pascal, M.** 2003. Mammal invaders on islands: impact, control and control impact. *Biol. Rev.* **78**: 347–383.
- Cramp, S. & Simmons, K.E.L. (eds)** 1977. *The Birds of the Western Palearctic.* Vol. 1. Oxford: Oxford University Press.
- Croxall, J.P. & Rothery, P.** 1991. Population regulation of seabirds: implications of their demography for conservation. In Perrins, C.M., Lebreton, J.-D. & Hiron, G.J.M. (eds) *Bird Population Studies. Relevance to Conservation and Management*: 272–296. Oxford: Oxford University Press.
- DEFRA** 2007. *The Invasive Non-Native Species Framework Strategy for Great Britain: Protecting our Natural Heritage from Invasive Species.* London: Department for Environment, Food and Rural Affairs.
- Donlan, C.J. & Wilcox, C.** 2007. Complexities of costing eradications. *Anim. Conserv.* **10**: 154–156.
- Falklands Conservation** 2008. Rat Eradication in the Falkland Islands. http://www.falklandsconservation.com/wildlife/conservation_issues/rat_eradication-main.html.
- Fowler, J.A. & Hounscome, M.V.** 1998. Migration and arrival of immature Storm Petrels *Hydrobates pelagicus* in Shetland. *Ringed Migration* **19**: 91–94.
- Genovesi, P.** 2007. Limits and potentialities of eradication as a tool for addressing biological invasions. In Nentwig, W. (ed.) *Biological Invasions. Ecological Studies*, Vol. 93: 385–400. New York: Springer.
- Harris, S., Morris, P., Wray, S. & Yalden, D.** 1995. *A Review of British Mammals: Population Estimates and Conservation Status of British Mammals Other than Cetaceans.* Peterborough: Joint Nature Conservation Committee.
- Heaney, V., Ratcliffe, N., Brown, A., Robinson, P.J. & Lock, L.** 2002. The status of European Storm-Petrels *Hydrobates pelagicus* and Manx Shearwaters *Puffinus puffinus* on the Isles of Scilly. *Atlantic Seabirds* **4**: 1–16.

- Howald, G.R., Donlan, C.J., Tershy, B.R., Croll, D.A., Russell, J., Saunders, A. & Clout, M. 2007. Invasive rodent eradications on islands. *Conserv. Biol.* **21**: 1258–1268.
- Jones, H.P., Tershy, B.R., Zavaleta, E.S., Croll, D.A., Keitt, B.S., Finkelstein, M.E. & Howald, G.R. 2008. Severity of the effects of invasive rats on seabirds: a global review. *Conserv. Biol.* **22**: 16–26.
- Key, G., Fielding, A.H., Goulding, M.J., Holm, R.S. & Stevens-Woods, B. 1998. Ship rats *Rattus rattus* on the Shiant Islands, Hebrides, Scotland. *J. Zool., Lond.* **245**: 228–233.
- de Leon, A., Minguéz, E., Harvey, P., Meek, E., Crane, J. & Furness, R.W. 2006. Factors affecting breeding distribution of Storm-petrels *Hydrobates pelagicus* in Orkney and Shetland. *Bird Study* **53**: 64–72.
- Lock, J. 2006. Eradication of brown rats *Rattus norvegicus* and black rats *Rattus rattus* to restore seabird populations on Lundy Island, Devon, England. *Conserv. Evid.* **3**: 111–113.
- Martin, J.L., Thibault, J.C. & Bretagnolle, V. 2000. Black rats, island characteristics, and colonial nesting birds in the Mediterranean: consequences of an ancient introduction. *Conserv. Biol.* **14**: 1452–1466.
- Martins, T.L.F., Brooke, M. de L., Hilton, G.M., Farnsworth, S., Gould, J. & Pain, D.J. 2006. Costing eradications of alien mammals from islands. *Anim. Conserv.* **9**: 439–444.
- McDonald, R.A., Hutchings, M.R. & Keeling, J.G.M. 1997. Status of ship rats *Rattus rattus* on the Shiant Islands, Outer Hebrides, Scotland. *Biol. Conserv.* **82**: 113–117.
- Mitchell, P.I., Newton, S., Ratcliffe, N. & Dunn, T. (eds). 2004. *Seabird Populations of Britain and Ireland*. London: T. & A.D. Poyser.
- Moors, P.J. & Atkinson, I.A.E. 1984. Predation on seabirds by introduced animals, and factors affecting its severity. In Croxall, J.P., Evans, P.G.H. & Schreiber, R.W. (eds) *Status and Conservation of the World's Seabirds*: 667–690. Cambridge: ICBP Technical Publication No. 2.
- Moors, P.J., Atkinson, I.A.E. & Sherley, G.H. 1992. Reducing the rat threat to island birds. *Bird Conserv. Int.* **2**: 93–114.
- Podolsky, R.H. & Kress, S.W. 1989. Factors affecting colony formation in Leach's Storm-petrel. *Auk* **106**: 332–336.
- Ratcliffe, J. & Sandison, W. 2001. Puffin Island – will removing rats bring back the puffins? *Nat Cymru* **1**: 23–26.
- Ratcliffe, N., Roy, S., Craik, C. & Scott, M. 2008. Modelling the benefits of mink management options for terns in west Scotland. *Ibis* **150**(S1): 114–121.
- Russell, J.C. & Clout, M.N. 2005. Rodent incursions on New Zealand islands. In Parkes, J., Statham, M. & Edwards, G. (eds) *Proceedings of the 13th Australasian Vertebrate Pest Conference*: 324–330. Lincoln, New Zealand: Landcare Research.
- Russell, J.C., Towns, D.R. & Clout, M.N. 2008. *Review of Rat Invasion Biology: Implications for Island Biosecurity*. Wellington: Science for Conservation 286, Department of Conservation.
- Stapp, P. 2002. Stable isotopes reveal evidence of predation by ship rats on seabirds on the Shiant Islands, Scotland. *J. Appl. Ecol.* **39**: 831–840.
- Stone, C.J., Webb, A., Barton, C., Ratcliffe, N., Reed, T.C., Tasker, M.L., Camphuysen, C.J. & Pienkowski, M.W. 1995. *An Atlas of Seabird Distribution in North-west European Waters*. Peterborough: Joint Nature Conservation Committee.
- Stoneman, J. & Zonfrillo, B. 2005. The eradication of Brown Rats from Handa Island, Sutherland. *Scot. Birds* **25**: 17–23.
- Swann, R., Aiton, D., Foster, S., Graham, K., Graham, A., Ramsay, A. & Young, A. 2007. *The Impact of Brown Rats on Canna's Breeding Seabirds. Proceedings of the Conference 'Tackling the Problem of Alien Mammals on Seabird Colonies'*. Edinburgh: National Trust for Scotland.
- Thompson, K.R. & Furness, R.W. 1991. The influence of rainfall and nest site quality on the population dynamics of the Manx Shearwater *Puffinus puffinus* on Rhum. *J. Zool., Lond.* **225**: 427–437.
- Towns, D.R., Atkinson, I.A.E. & Daugherty, C.H. 2006. Have the harmful effects of introduced rats on islands been exaggerated? *Biol. Inv.* **8**: 863–891.
- Weimerskirch, H. 2002. Seabird demography and its relationship with the marine environment. In Schreiber, E.A. & Burger, J. (eds) *Biology of Marine Birds*: 115–135. Boca Raton: CRC Press.
- Zino, F., Oliveira, P., King, S., Buckle, A., Biscoito, M., Costa-Neves, H. & Vasconcelos, A. 2001. Conservation of Zino's Petrel *Pterodroma madeira* in the archipelago of Madeira. *Oryx* **35**: 128–136.
- Zonfrillo, B. 2001. Ailsa Craig – before and after the eradication of rats in 1991. *Ayrshire Bird Report 2000*: 4–10.
- Zonfrillo, B. 2002. Puffins return to Ailsa Craig. *Scot. Bird News* **66**: 1–2.

Received 10 February 2009;
revision accepted 27 May 2009.