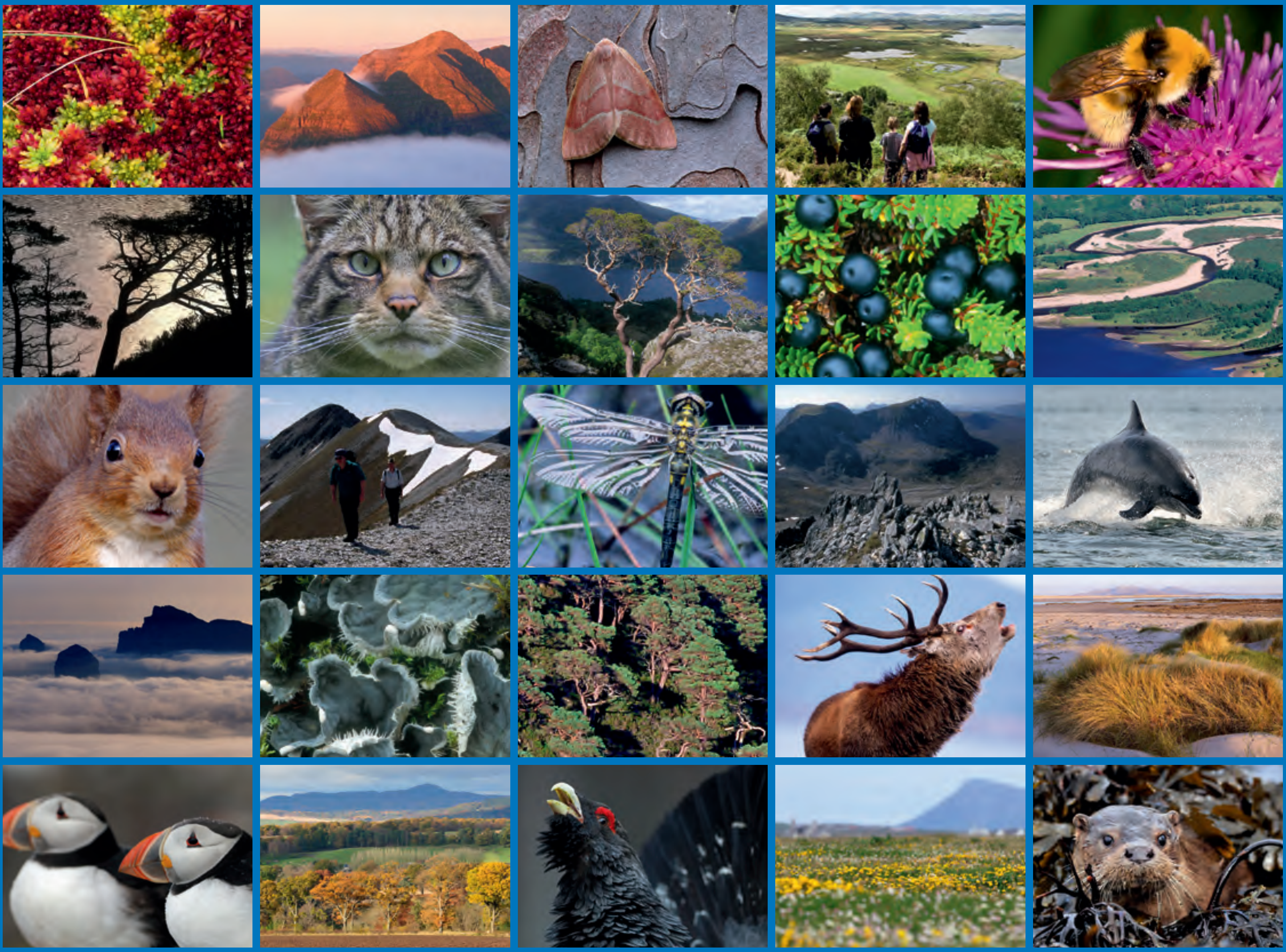
Scottish Natural Heritage
Commissioned Report No. 697

The role of brown rat (*Rattus norvegicus*) predation in determining breeding success of Manx shearwaters (*Puffinus puffinus*) on Rum



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COMMISSIONED REPORT

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The role of brown rat (*Rattus norvegicus*) predation in determining breeding success of Manx shearwaters (*Puffinus puffinus*) on Rum

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COMMISSIONED REPORT

Summary

The role of brown rat (Rattus norvegicus) predation in determining breeding success of Manx shearwaters (Puffinus puffinus) on Rum

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Keywords

Ecology; seabirds; brown rat; common rat; Norway rat; rodents; invasive non-native species; islands.

Background

Invasive rodents have been implicated in declines and extinctions of seabird populations worldwide, and the impact of rat species is regarded as one of the most significant global threats to seabirds (Jones *et al*., 2008). Consequently, hundreds of rodent eradication campaigns have been undertaken on islands worldwide (Howald *et al*., 2007). Smaller, burrow-nesting seabirds are thought to be more vulnerable to the effects of invasive rats than larger, ground nesting species (Jones *et al*., 2008), and it has been suggested that brown rats (*Rattus norvegicus*), also known as Norway rats or common rats, may have a negative impact on the globally-important Manx shearwater breeding colonies on the island of Rum. Brown rats were eradicated from the neighbouring island of Canna in 2005/2006 to restore breeding habitats for Manx shearwaters and other seabirds (Bell *et al*., 2011).

However, it has also been suggested that the severity of impacts of introduced rats on native island fauna may have been exaggerated, and that direct evidence for negative impacts is patchy (Towns *et al*., 2006). Indeed, some seabird colonies may be less vulnerable to rat predation because of biogeographical factors that limit rodent-seabird interactions, which could explain the long-standing co-existence of ship rats and seabirds on many Mediterranean islands (Ruffino *et al*., 2009). The cost of removing rats from Rum has been estimated at £4.6 million (Ratcliffe *et al*., 2009), and therefore it is important to establish whether these costs and any potential environmental impacts of an intensive rat eradication campaign are justified. However, the long-term security of Rum's globally-important Manx shearwater colonies is also a high priority. The aim of the present project was to investigate the role of brown rats in determining Manx shearwater breeding success on Rum, and specifically to detect and quantify any negative impacts through a rat removal study. Jones *et al*. (2008) noted that, although proving rat effects can be challenging, the lack of experimental approaches represent a significant gap in our current research; improving the experimental evidence of rat effects will provide a better basis for eradication campaigns and help prioritize seabird conservation strategies. The current study is intended to address this research gap, and provide evidence for future decisions regarding management of rodent populations on Rum and in similar environments.

Main findings

- In 2010 a removal experiment was initiated; the effect of removing rats from Manx shearwater colonies on the island of Rum was investigated by comparing Manx shearwater breeding success between sites treated with anticoagulant rodenticides with breeding success at untreated (control) sites. Three study sites of approximately 30ha each were used; Askival, Hallival and Clough's Crag. The Hallival study site was treated with rodenticides in 2010 and 2011, and the Askival study site was treated in 2012 and 2013.
- Levels of brown rat activity were measured at all three study sites 2-3 times each year using carbon-coated tracking plates. The level of rat activity during the first three years of the study was low across all three study sites and was approximately 100 times lower than the average level of rat activity previously recorded when using this technique on rural farms. Rat activity varied between sites and between years, and appeared to be higher in the final year of the study particularly at the untreated Clough's Crag site.
- Manx shearwater nest burrows were checked at each site twice each year; once during the egg stage (usually in late June) and once during the chick stage (usually in late August). Breeding success was defined as the percentage of burrows with a live chick when checked by endoscopy shortly before the main fledging period, and was calculated for burrows that were apparently occupied when checked during the egg stage, and for nest sites that were actually occupied when checked during the egg stage (to reduce the confounding effect of different burrow occupancy rates between sites).
- Breeding success was relatively consistent between sites for the first three years of the study but in 2013, Manx shearwater breeding success relative to the previous year declined by 30.5% at Clough's Crag (an untreated site), and by 25.6% at Hallival (also untreated), but declined by less than 10% at the treated site Askival.
- The effect of year and treatment on success of actually occupied Manx shearwater burrows was examined in a Generalized Linear Model (GLM). There was no overall effect of treatment, but a significant year*treatment interaction ($p = 0.036$) appeared to suggest that the treatment had a significantly different effect in 2013.
- The evidence suggests that in most years of the study there was no treatment effect because the level of rat activity was so low across all three study sites (including sites not treated with rodenticides). However, an increase in the level of rat activity in 2013, particularly at the (untreated) Clough's Crag study site relative to the treated site Askival, created a sufficient difference in the level of rat activity between these two sites for an effect to be detected.
- It is not known whether the levels of rat activity seen at the Clough's Crag site in 2013 are atypical, or whether the low levels of rat activity seen during the first three years of the study are more unusual; there are no long term data for the level of rat activity on Rum. It is possible that, through their remoteness and lack of resources to support rat populations outside the shearwater breeding season, many of the Manx shearwater colonies are largely protected from the negative effects of rats in most years. However, favourable conditions may sometimes allow greater over-winter survival of rat populations in the shearwater breeding areas particularly at lower elevations, and the frequency and extent to which this occurs is unknown. Further work is needed to investigate this in order to make a whole-island risk assessment.

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Acknowledgements

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1. INTRODUCTION

The Scottish island of Rum (BNG NM 370 980) is the largest of the Scottish Small Isles, with an area of approximately 105km^2 and a maximum height of 812m at the summit of Askival. The island has approximately 30 permanent residents. Rum is designated as a Special Protection Area (SPA) with important breeding populations of golden eagle (*Aquila chrysaetos*), common guillemot (*Uria aalge*), black-legged kittiwake (*Rissa tridactyla*), Manx shearwater (*Puffinus puffinus*) and red-throated diver (*Gavia stellata*) (SNH, 2010). Almost the entire island is also designated as a National Nature Reserve and a Site of Special Scientific Interest. The island supports at least 23% of the global breeding population of Manx shearwaters (SNH, 2009); only the breeding colony within the islands of Skomer, Skokholm and Middleholm in Wales is potentially larger in size (Murray *et al*., 2003). However, it has been suggested (Furness, 1997; Smith *et al*., 2001) that the Rum shearwater colony is in slow decline, possibly due to reduced breeding success. In 2004, breeding success on Rum was reported to be the lowest recorded since 1999 (Mavor *et al*., 2005) and although there may be various reasons for this, it has been suggested that brown rats may be partly to blame. Rats have been implicated in numerous seabird extirpations and population declines worldwide (Atkinson, 1985; Jones *et al*., 2008) and it has been reported that the presence or absence of brown rats is the single most important influence on Storm-petrel *(Hydrobates pelagicus*) distribution in Orkney and Shetland (de León *et al*., 2006). However, previous studies have also suggested that rats do not actively predate shearwaters on Rum; Thompson (1987) reported that rats were present within the shearwater colonies but they largely scavenged remains of eggs or chicks during autumn and early winter. Thompson and Furness (1991) reported that breeding success of Manx shearwaters on Rum is mainly determined by rainfall and consequent flooding of burrows.

Elsewhere, the evidence for effects of rat presence on Manx shearwaters is intriguingly variable. Following removal of brown rats and black rats (*Rattus rattus*) from Lundy, Manx shearwaters bred successfully after a gap of nearly 50 years (Lock, 2006) and have continued to thrive on the island (Booker and Price, 2010); brown rats have also been anecdotally linked with Manx shearwater population declines on the Calf of Man (Mitchell *et al*., 2004). However, it has also been reported that removal of brown rats from other islands, including Cardigan Island in Wales, and Canna, adjacent to Rum, has not resulted in substantial re-colonisation by Manx shearwaters (Bullock, 2013; Ratcliffe *et al*., 2009). In a review of the effects of introduced rats on island ecosystems, Towns *et al*. (2006) reported that evidence for recovery of seabird populations following removal of brown rat populations is patchy, and seabirds can show variable responses. Towns *et al*. (2006) also noted that many reviews of the effects of invasive species have concluded that cause and effect relationships between introduced rats and declining indigenous species are equivocal because of other complicating factors, and that there is a general lack of comprehensive measurements of the responses of indigenous species to rat eradications by which to support such projects.

We aimed to investigate the impact of brown rats on Manx shearwater breeding success on the island of Rum in a controlled and replicated study. Specifically, we aimed to quantify the impact of rat predation on Manx shearwater breeding success by examining differences between areas treated with rodenticides (to remove or reduce rat populations) and untreated control areas. The project followed the basic principle of a removal experiment, which has previously been used to examine predator-prey interactions; the effects of predation are examined by removal or reduction of the predator population (Newsome *et al*., 1989; Pech *et al*., 1992). In the present study, the effect of controlling brown rats in one of three study sites each year was investigated by comparing the breeding success of Manx shearwater burrows between treated and untreated areas over four consecutive years. The null hypothesis was that there would be no difference in Manx shearwater productivity between treated and untreated areas.

2. METHODS

2.1 Study sites

The study sites were located in an area of the Rum Cuillin in the south west part of the island (Figure 1). The sites were near to (and from here on referred to as) Hallival, Askival and Clough's Crag. The study sites were all above the 450m contour in a varied upland landscape which supported a range of montane and sub-montane grassland, dwarf shrub heath and mire habitats (SNH, 2010); unlike many other Manx shearwater breeding sites in the UK, the colonies on Rum occur at relatively high altitudes. In 2011, the Clough's Crag study site was re-positioned to the north of the 2010 location in order to include a sufficient number of Apparently Occupied Burrows (AOBs), the position of the Askival site was also moved north in order to maximise separation from the new Clough's Crag site whilst still including the locations of the shearwater burrows used for the 2010 surveys. Each study site (28.27ha) was defined by a circle with 300m radius. A grid was plotted within each study site using Hawth's Tools in ArcMapTM 9.3.1 (Esri, California) to give 30m spacing between grid lines. The grid intercept points were uploaded onto handheld GPS units (Garmin, USA) for use in the field.

2.2 Assessment of rat activity

Surveys of rat activity were carried out 2-3 times each year, usually coinciding with the two surveys of Manx shearwater burrows. In all four years of the study, carbon-coated tracking plates were used to measure levels of rat activity; in 2010 oil-soaked chew-sticks were also used. The chew-sticks were made by soaking wooden sticks (18mm wide x 150mm long) overnight in vegetable oil and they were secured in position using metal tent pegs at grid points within each study area (Figure 2).

The tracking plates were sections of light-coloured vinyl floor tiles (100mm wide x 200mm long) onto which a suspension of carbon powder in industrial methylated spirit (IMS) was painted; the plates were then left to dry and the IMS evaporated to leave a thin, weatherproof layer of carbon. The tracking plates were deployed in 11 transects, between pairs of grid points, with 12 plates evenly spaced in 6 pairs along each transect; hence 132 tracking plates were deployed in each study site. Within the grid cells surveyed, the tracking plates were used at the density (400 tiles ha^{-1}) at which they had previously been used on farmland in the UK (Quy *et al*., 1993); the area surveyed with tracking plates at each study site was therefore 0.33 ha. Tracking plate transects were positioned such that a variety of different habitat types (rocky slopes, grassy plateaux) and elevations within the study site were sampled. Individual plates were positioned next to potential foci for rat activity, including shearwater burrows, entrances to bait stations, along watercourses and between rocks that might channel movement of rats. The following day, any rodent footprints on the tracking plates were recorded, and the marked plates were replaced or repainted. Each marked plate was scored according to the percentage of the surface area covered by rat prints (1 - 25% = 1, 26 - 95% = 2, more than 95% = 3) and the sum of the scores gave an index of activity. This was repeated, usually for three consecutive days, and an average index of activity was calculated in order to reduce the possibility of bias from weather-related fluctuations in activity. Tracking plates are less influenced by variation in environmental factors, such as availability of alternative food, than non-passive methods such as census baiting, and this method is considered to be a reliable census technique (Quy *et al*., 1993). The technique is similar to inkpad tracking tunnels that are used widely for monitoring invasive mammals; a technique considered to give reliable results for rat populations even in areas of relatively low population densities of 6 rats ha^{-1} or less (Brown *et al*., 1996).

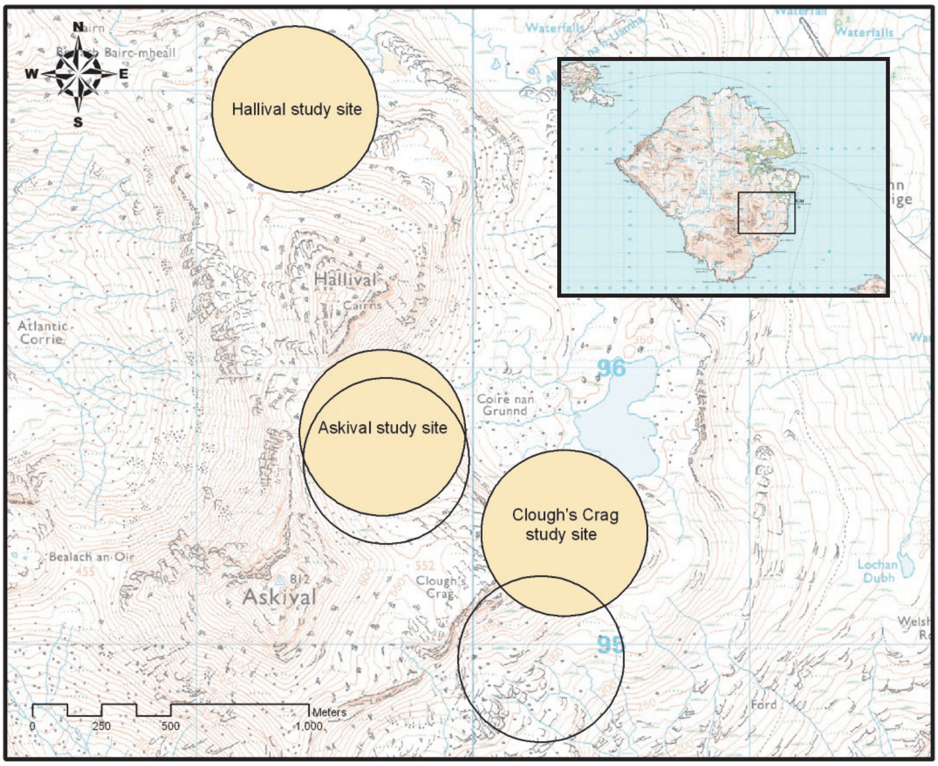

Figure 1. The study sites were located within an area of the Rum Cuillin in the south west quadrant of the island (inset). The study site locations were changed in 2011 in order to incorporate enough Manx shearwater burrows into the Clough's Crag site, and the Askival study site was repositioned at the same time to maximise site separation; 2010 study site locations are denoted by open circles, locations from 2011 onwards are denoted by shaded circles. Each study site (28.27ha) was defined by a circle with 300m radius. © Crown copyright and database rights 2014. Ordnance Survey 100051110.

Figure 2. A bait station, carbon-coated tracking plate and vegetable oil-soaked chew stick in position at the Hallival study site in 2010.

2.3 Removal or reduction of rat populations

Rodenticides were used to control rodent populations within one (treated) study site each year. Each study site incorporated all or a large part of a reasonably discrete Manx shearwater colony. It was expected that the home range of rats would be strongly influenced by the availability of food resources, as previously demonstrated in rural areas where, in response to abundant food resources, the home range of brown rats is often a few tens of metres (Lambert *et al.*, 2008) thus minimising the movement of rats between study sites during the shearwater breeding season. Conversely, we expected that outside the shearwater breeding season when food resources were scarce, home range size of rats would increase, and lead to increased movement between study sites thus minimising potentially confounding cross-over effects and maximising independence between years. In the treated study sites we deployed bait stations previously used for removal of rats from the neighbouring island of Canna (Bell *et al.*, 2011); these were each approximately 100cm long x 10cm diameter and were constructed from a section of corrugated plastic pipe with a removable lid (Figure 2). The bait stations were arranged in a grid of 250-264 stations with 30m spacing between bait stations and were secured in place by rocks or 15cm plastic ground anchors and nylon cord. We aimed to ensure that the distribution of bait stations was appropriate by matching this to the distribution of study burrows in order to provide adequate coverage of the shearwater burrows within the entire treated area. The bait stations were baited in June or earlier, each with a single (100g) bait block (Romax Rat CP, Barrettine, UK) containing 0.0375% w/w coumatetralyl (a ‘first-generation’ anticoagulant rodenticide) secured with a length of stiff wire. Thus we did not attempt to remove rats before the start of the breeding season, but timed rat control activities to begin at least 2-3 weeks in advance of egg-stage surveys of Manx shearwater burrows. The egg-stage surveys provided the baseline survey data against which subsequent productivity survey data were compared, and thus it was not appropriate to measure predation that occurred before the egg-stage surveys. The bait stations were checked 3-4 times during the Manx shearwater breeding season to record bait takes and replace bait blocks as required. The Hallival study site was treated with rodenticides in 2010 and 2011, and the Askival study site was treated in 2012 and 2013. Bait checks at each bait station recorded whether bait had been partly taken (PT) or completely taken (CT), or whether no bait had been taken (NT). Where bait had been taken the operator looked for and recorded signs that would indicate whether the bait had been taken by rodents (rodent teeth marks, droppings, nest material) or other species, e.g. insect droppings (frass) or other evidence. Where bait takes by rodents were recorded, the size of any rodent teeth marks that were found on bait blocks, and the size and shape of droppings that were found inside the bait station, were used to attribute the take to either rats or mice where possible (bait station checks were carried out by pest control technicians with experience of identifying signs of rodent activity according to standard industry practice e.g. Bjornson *et al.*, 1969; BPM, 2012). For partial takes, the percentage of the bait block taken was estimated (visually) by the operator.

2.4 Survey of Manx shearwater nest sites

Manx shearwater nest burrows were examined twice-yearly using endoscopy, a technique that was previously suggested as a potentially useful technique for survey of Manx shearwater burrows on Rum (Murray *et al.*, 2003). Endoscopy has previously been used to study nesting success in several shearwater and petrel species (Ambagis, 2004; Bicknell *et al.*, 2009; Rodríguez *et al.*, 2003; Seto and Conant, 1996). Burrow surveys began in late June shortly after the main egg laying period (the ‘egg-stage’ surveys). Burrows with signs of occupancy, including signs of digging, fresh droppings, nest material or one or more shearwater body feathers at the entrance (Walsh *et al.*, 1995) were chosen. We aimed to achieve a sample of ≥130 Apparently Occupied Burrows (AOBs) for each study site. Shearwater burrows were examined using an endoscope; either a SeaSnake® micro™ or microExplorer® digital inspection camera (Rigid, Ohio, USA) and were considered suitable for inclusion in the study only if the nest chamber could be fully examined. Study burrows were tagged using a ~25cm length of 25mm diameter white plastic tubing (numbered using chinagraph pencil and pushed into the ground at the side of the burrow entrance). The British National Grid Reference was recorded for each study burrow using a high-sensitivity hand-held GPS unit (e.g. Garmin eTrex Vista HCx). The study burrows were re-examined (usually in late August) shortly before the main fledging period (the ‘chick-stage’ surveys) using the same technique as for the egg-stage surveys. We timed the egg-stage surveys to coincide with the end of the peak egg-laying period for Rum, and timed the chick-stage surveys to coincide with the start of the fledging period in order to maximise the window of opportunity for predation by rats without missing late eggs of early fledging chicks. We aimed to avoid delays in sampling between sites to ensure that data were comparable between sites. If any burrows could not be found they were replaced with AOBs nearby; we aimed to achieve a final sample size of ≥130 burrows for each site. Overall productivity of each site was calculated as the percentage of burrows in the final (chick-stage) surveys containing a live chick. The burrows that were actually, rather than apparently, occupied (i.e. contained an adult shearwater, egg or chick) at the first (egg-stage) survey were also analysed as a separate sub-set of the data to reduce the effect of different occupancy rates between sites. The burrows used in 2013 and the bait points deployed at Askival are shown in Figure 3.

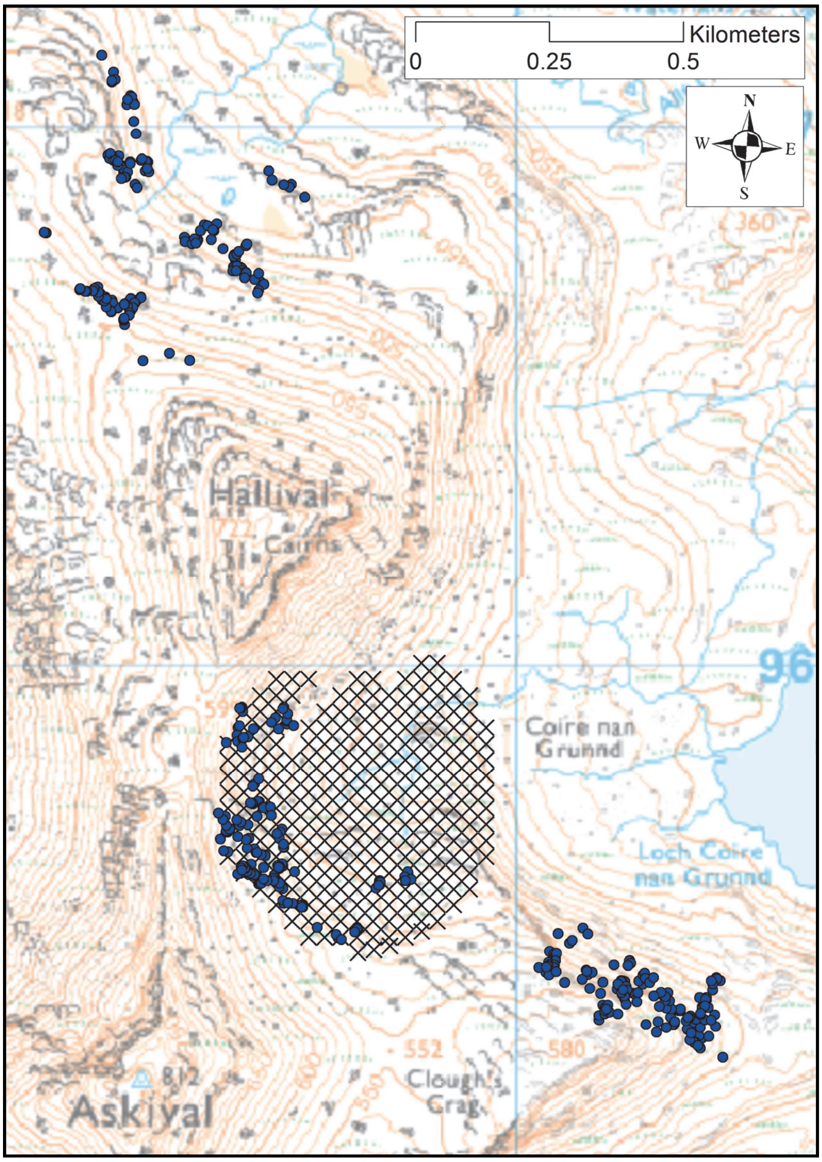

Figure 3. Location of study burrows (dots) and bait stations (crosses) in 2013 at the Hallival (top), Askival (middle) and Clough's Crag (bottom) study sites. © Crown copyright and database rights 2014. Ordnance Survey 100051110.

2.5 Data Analyses

We examined main effects of Site (Askival, Hallival and Clough's Crag) and Year (2010, 2011, 2012, 2013) and their interaction on the number of tracking plates marked by rats using a Generalized Linear Mixed Model with survey night (1, 2, 3) as a random effect (McDonald *et al*., 2000; Schall, 1991). We examined the main effects of Year (2010, 2011, 2012, 2013) and treatment (Treated, Un-treated) on success of occupied Manx shearwater nests using a Generalized Linear Model (O'Hara and Kotze, 2010). Data were analysed using GenStat 16th Edition (VSN International Ltd, Hemel Hempstead, Hertfordshire).

3. RESULTS

3.1 Rodent control

A total of 3,244 bait station checks was recorded; 715 (22%) with no bait take, 2,513 (77.5%) with partial bait take and 16 occasions (0.5%) the bait had been completely taken (Table 1). There were 2,529 bait takes in total; 243 (9.6%) of these were attributed to mice and a further 223 (8.8%) bait takes were recorded at bait stations that contained small rodent droppings that could have been left by mice or shrews; a further 4 bait stations (0.2%) contained possible evidence of small mammal activity. Seven (0.3%) bait takes were securely attributed to rats, and a further 9 (0.4%) were tentatively attributed to rats. The remaining bait takes were attributed to slugs which made characteristic smooth grooves and holes in the bait blocks and also to insects, although the percentage of bait taken by these species was low; detailed observations made during the bait checks are reported in sections 3.1.1 to 3.1.4.

Table 1. Bait takes attributed to rodents during bait station checks for study sites baited with rodenticides (Hallival in 2010 and 2011, Askival in 2012 and 2013). Figures in parentheses are takes that were tentatively attributed to rats (or other small mammals) if the evidence was ambiguous; remaining bait takes were attributed to slugs and other invertebrates or were not associated with any evidence of the species responsible (see sections 3.1.1. - 3.1.4 for further details).

Year	No take	Part take	Complete take	Takes attributed to mice	Takes attributed to rats	Evidence of mice or other small mammals (but species uncertain)
2010	355	108	0	47	0 (+1)	0
2011	106	644	11	174	3 (+8)	165
2012	179	805	2	7	1	4 (+4)
2013	75	956	3	15	3	54
Total	715	2513	16	243	7 (+9)	223 (+4)

3.1.1 2010

Bait stations were deployed at Hallival during the first two weeks of April 2010; 260 bait stations were deployed and were in place for up to one week before the bait was added (a single 100g bait block in each station). Bait stations were checked 4-5 days after the bait blocks were added, again 5 days later and again in mid-May when the bait was removed; each station was baited for 21-23 days in total. Evidence of bait consumption by mice was recorded at 47/260 (18.1%) of the bait points, slug damage (smooth grooves or holes in the bait) was recorded at 115/260 (44.2%), and possible consumption by rats was recorded at 1/260 (0.4%). One dead wood mouse was found in the final week of the rodenticide treatment; an examination of the stomach contents revealed that it had consumed rodenticide bait. In mid-May the rodenticide blocks were removed and replaced by 2 x 40g non-toxic monitoring blocks (Detex® Blox, Bell Laboratories, USA) in each station. A small number of bait stations were then checked in June and July, and then all were checked in late August when the non-toxic blocks were removed. In June, 8/20 (40%) bait stations checked contained evidence of mouse activity (droppings), 3/20 (15%) contained evidence of slug activity and 7/20 (35%) evidence of both mouse and slug activity, bait was taken from one station without any evidence of the species responsible. One bait station (near the edge of the study site, close to the ridge leading to the summit of Hallival) contained larger rodent droppings which were considered to be potentially within the size range for brown rats. A sample of these droppings was later examined visually in the laboratory, but it was not possible from the size and shape to determine conclusively whether they were produced by a small rat or large mouse. In July, 3/14 (21.4%) bait stations checked contained evidence of mouse activity, 2/14 (14.3%) contained evidence of slugs, bait was taken from the remaining 9/14 (64.3%) bait points but no evidence of the species responsible was found. In August, more rodent droppings were found at the bait point where the suspected rat droppings were found in June; these were larger than those found previously, and almost certainly produced by a rat. One of the Manx Shearwater study burrows was within 3m of this bait station and endoscopy confirmed the remains of an egg and an apparently healthy chick. A second bait station (further north) contained evidence of rat activity, and a further 9 bait stations contained droppings that could have been from either large mice or small rats. In total, 13/260 (5.0%) bait stations contained evidence of mouse activity, 27/260 (10.4%) contained evidence of slugs, 50/260 (19.2%) contained evidence of both mouse and slug activity. Small particles of non-toxic monitoring blocks remained in 10/260 (3.8%) bait stations, but they were otherwise completely consumed.

3.1.2 2011

In late June, the bait stations at the Hallival study site, which had been in position since April 2010 were re-baited. Bait stations were checked after two weeks, and then four more times between July and November to record bait takes and replace bait blocks as required. Two bait stations contained possible rat signs (either toothmarks on the bait blocks or droppings) after two weeks (mid-July) although these were unclear, i.e. the toothmarks were unclear or the droppings were small enough to have been left by large woodmice. In early August, three bait stations contained clear signs of rat activity, and three contained possible signs. No further signs of rat activity were found during bait station checks until November, when three bait stations contained possible signs. Evidence of bait consumption by mice was recorded at 34 bait stations in July, 81 in August, and 59 in October. Very small droppings (probably from shrews) were found in 8 bait stations in July, none in August, and 17 in October. Evidence of mice or shrews was found in 140 bait stations in November, although the difference between the species was not noted. Evidence of slugs, which made distinctive smooth-edged grooves or holes in the bait blocks, was noted at 49 bait stations in July, 66 in August, 117 in October and 11 in November. Two dead shrews were found in November.

3.1.3 2012

Between 1st and 6th June 2012 250 bait stations were deployed and baited at Askival. The stations were checked 27th – 30th June, during which 234 part takes (PTs) were recorded; all but one of these was attributed to invertebrates (slugs, beetles) and in all but 3 cases ≤ 10% bait had been removed. There were no complete bait takes (CTs). One of the PTs was attributed to mice (mouse droppings were found in the bait station). The bait was replenished where necessary and the bait stations were checked again 17th - 18th July; 244 PTs were recorded, all of which were attributed to invertebrates and in all but one bait station ≥ 90% of the bait remained (one complete take was recorded, but there was no associated evidence of invertebrate or rodent activity). The bait stations were replenished where necessary and were checked again 13th – 15th August when 244 PTs were recorded; 231 of these were attributed to invertebrates, 2 were attributed to rodents, one was tentatively attributed to rodents, 2 were attributed to invertebrates and rodents, 3 were tentatively attributed to invertebrates and rodents (where the rodent species was not recorded or uncertain, but these were thought to be from small mammals rather than rats). One part take was attributed to mice. In all but 2 PTs ≥ 50% of the bait remained uneaten and in 163 PTs ≥ 90% of the bait remained. There were no complete takes. A single live rat was seen on 14th August; its movement (slow and unsteady) and behaviour (active during the day) suggested that it had consumed rodenticide bait. The bait stations were replenished where necessary and were checked again 18th – 20th September; 83 PTs were recorded, although slug activity was noted at 211 bait points. Thin scrape marks on the bait blocks were recorded at 84 bait stations; it was suspected that these were made by large ground beetles or mice. Mouse droppings were recorded at 5 bait stations, and rat droppings at one bait station. In all but 8 bait stations ≥ 90% of the bait remained un-eaten (there was one complete take, but there was no associated evidence of invertebrates or rodents). The bait stations were then removed.

3.1.4 2013

During the week commencing 29th April 2013, 242 bait stations were deployed and baited at Askival. The bait stations were checked 8-9 June, when a further 22 bait stations were deployed and baited (to achieve a more complete coverage of areas containing Manx shearwater study burrows used in previous years at Askival). The bait station checks revealed 49 part takes (PTs) attributed to rodents or rodents and slugs together (these bait stations contained signs of rodent activity where the rodent species was not clearly identified but thought to be from small mammals rather than rats), and there were no complete takes. Slug activity (characteristic smooth-edged holes and grooves in the bait) was recorded at a further 166 bait stations; 123 of these bait takes were estimated to be ≤ 10%; two were estimated to be ≥ 50%. Bait blocks were replaced at a total of 45 stations; where bait takes were either estimated to be ≥ 40%, where the bait was wet, or both. The bait stations were checked again 5th July; five PTs were attributed to mice, two CTs were recorded but no evidence of rodent activity was seen at those two stations. Slug activity was noted at a further 237 bait stations; 133 of these bait takes were estimated to be ≤ 10%, and one was estimated to be ≥ 50%. Bait blocks were replaced in 65 stations. The bait stations were checked for a third time on 13th August; 6 PTs were attributed to mice (nesting material was found in three bait stations, mouse droppings were found in two bait stations, and one contained a dead mouse). Slug activity was noted at a further 242 bait stations; 73 bait takes were estimated to be ≤ 10%, nine bait takes were estimated to be ≥ 50%. There were no complete takes. Bait blocks were replaced in 164 stations. All bait stations were checked and removed between 13th and 25th September. Twelve PTs were attributed to rodents; rat droppings were found in three of these stations, mouse droppings in three, and nesting material in one (the others contained signs of rodent activity where the rodent species was not clearly identified but thought to be from small mammals rather than rats). There was one complete take, but without any associated evidence of rodent activity. Slug activity was recorded at a further 239 bait stations; 100 of the bait takes associated with slug activity were estimated to be ≤ 10%, 12 were estimated to be ≥ 50%.

3.2 Rodent activity

In 2010, chew sticks were deployed at Askival (206), Hallival (260) and the first Clough's Crag site (197). The chew sticks were checked at all three sites in late April and checked again at Askival and Hallival in mid-May and late August. No signs of rat activity were recorded on chew sticks. Carbon-coated tracking plates were deployed at all three sites in April and checked each day for 3 subsequent days to record the percentage of the surface of each plate with rodent footprints, giving a total of 132 x 3 (396) tracking plate scores per site. Over 3 nights, 6/1188 (0.5%) tracking plate scores recorded rat footprints; 2/396 (0.5%) at Askival, 4/396 (1%) at Hallival and none at Clough's Crag (all positive plates were less than 25% covered by rat footprints, and usually had just a single footprint). A second tracking plate survey of rodent activity was carried out at Askival in early July 2010 and at Hallival in late May 2010 (i.e. after the rodenticide treatment at Hallival); 4/396 (1.0%) of tracking plate scores were rat positives at Askival and 1/396 (0.3%) at Hallival. A third tracking plate survey of rodent activity was carried out at Askival and Hallival in late August 2010; 5/380

(1.3%) tracking plate scores at Askival, and 4/396 (1.0%) at Hallival recorded rat footprints. Mouse prints were recorded on 61/396 (15.4%) plates at Hallival and 12/261 (4.6%) plates at Askival (mouse prints were not recorded at Askival on the first of the 3 nights). After 2010, carbon-coated tracking plates were used as the sole method for monitoring levels of rodent activity. Between 2010 and 2013 we collected tracking plate data for a total of 73 nights, and recorded 9,487 tracking plate scores; 149 (1.5%) out of the 9,636 possible observations were missing due to plates being lost or unreadable (Table 2).

Table 2. Percentage of n carbon-coated tracking plates marked by rats and mice at three study sites on the Isle of Rum between 2010 and 2014. Plates that were lost or unreadable are excluded. The tracking plate surveys recorded activity of rats and mice twice each year; once during the post-laying (usually late June) endoscopy surveys of Manx shearwater burrows at the three sites, and again during the pre-fledging (usually late August) surveys. Data from areas treated with rodenticides are shown in bold.

	Askival				Clough's Crag				Hallival			
Year	Month	*n*	% mice	% rats	Month	*n*	% mice	% rats	Month	*n*	% mice	% rats
2010	April	396	0.0	0.5	April	360	0.0	0.0	April	390	1.0	1.0
2010	July	394	2.3	1.0	*No survey**				**May**	**396**	**1.5**	**0.3**
2010	Aug	380	4.6	1.3	*No survey**				**Aug**	**395**	**14.9**	**1.0**
2011	June	365	3.0	0.8	Aug	387	4.5	1.3	**June**	**392**	**4.9**	**1.0**
2011	Sept	262	3.4	0.4	Oct	373	4.0	0.0	**Aug**	**393**	**5.3**	**0.0**
2012	**June**	**394**	**0.8**	**0.8**	June	394	1.3	2.5	June	396	1.3	1.8
2012	**Aug**	**394**	**6.3**	**0.8**	Aug	264	1.5	4.5	Aug	395	2.8	0.8
2013	**June**	**395**	**2.0**	**1.0**	June	393	1.3	2.0	June	396	5.3	1.3
2013	**Aug**	**396**	**5.3**	**1.3**	Aug	392	1.8	13.8	Aug	395	11.4	2.3
Total		3376	2.9	0.9		2563	2.1	3.5		3548	5.4	1.0

Thirty plates (0.9%) were marked by rats at Askival, 89 (3.5%) were marked by rats at Clough's Crag and 37 (1.0%) were marked by rats at Hallival. Over the four years of the study 156 out of 9,487 (1.6%) tracking plates were marked by rats. Ninety-seven of 3,376 (2.9%) tracking plates at Askival were marked by mice, 54 of 2,563 (2.1%) were marked by mice at Clough's Crag and 191 of 3,548 (5.4%) were marked by mice at Hallival; for all three sites a total of 342 of 9,487 (3.6%) tracking plates were marked by mice over the four years of the study. The indices of rat activity (mean sum of tracking plate scores over 2-3 nights according to the method published by Quy *et al.,* 1993) varied between 0.00 and 22.00 (Table 3). Rats were completely absent during 2/24 tracking plate surveys (3/25 including the initial Clough's Crag site which was abandoned when insufficient numbers of Manx shearwater burrows were found at the site).

Table 3. Activity indices for brown rats at three study sites on the Isle of Rum between 2010 and 2014. Carbon-coated tracking plates were scored according to the percentage of the surface covered by rat footprints and the activity indices were calculated as the mean sum of scores for n nights. Plates that were lost or unreadable are excluded. The indices provide a quantitative measure of rat activity using a method that was previously calibrated against populations of known size on farms in the UK. Data from areas treated with rodenticides are shown in bold.

	Askival			Clough's Crag			Hallival		
Year	Month	*n*	Activity Index (± SE)	Month	*n*	Activity Index (± SE)	Month	*n*	Activity Index (± SE)
2010	April	3	0.67 (± 0.54)	April	3	0.00 (± 0.00)*	April	3	1.33 (± 0.27)
2010	July	3	1.67 (± 0.98)	*No survey**			**May**	**3**	**0.33 (± 0.27)**
2010	Aug	3	2.00 (± 0.82)	*No survey**			**Aug**	**3**	**1.33 (± 0.72)**
2011	June	3	1.00 (± 0.47)	Aug	3	2.00 (± 0.47)	**June**	**3**	**1.33 (± 0.54)**
2011	Sept	2	0.50 (± 0.35)	Oct	3	0.00 (± 0.00)	**Aug**	**3**	**0.00 (± 0.00)**
2012	**June**	**3**	**1.00 (± 0.82)**	June	3	4.00 (± 1.63)	June	3	2.33 (± 0.72)
2012	**Aug**	**3**	**1.00 (± 0.47)**	Aug	2	8.00 (± 2.12)	Aug	3	1.00 (± 0.47)
2013	**June**	**3**	**1.67 (± 1.36)**	June	3	2.67 (± 1.09)	June	3	1.67 (± 0.27)
2013	**Aug**	**3**	**2.00 (± 0.00)**	Aug	3	22.00 (± 0.47)	Aug	3	3.33 (± 0.98)

* Insufficient Manx shearwater burrows were found at the Clough's Crag site initially chosen for the study, and therefore no further rat activity surveys were completed for that site. A new Clough's Crag site was identified in 2011.

The effects of site (Askival, Clough's Crag, Hallival) and year (2010, 2011, 2012, 2013) on the number of tracking plates marked by rats (Figure 4) were estimated in a Generalized Linear Mixed Model (GLMM) with Poisson distribution and logarithmic link function (Table 4). There was a significant difference between sites and between years. There were no significant site*year interactions, indicating that changes in levels of rat activity over time did not significantly differ between sites.

Table 4. Tests of main effects (site, year) and their interaction (site.year) on the number of carbon-coated tracking plates marked by rats each night at three study sites (Askival, Clough's Crag, Hallival) during 2010 – 2013. The tracking plates were scored (and re-painted where necessary) for 2-3 consecutive days at each site twice each year to correspond with endoscopy surveys of Manx shearwater burrows. Survey night (1, 2, 3) was included as a random effect. Significant differences (F pr) are denoted in bold.

Fixed term	Wald statistic	n.d.f.	F statistic	d.d.f.	F pr
Site	30.35	2	15.18	53.0	**<0.001**
Year	13.19	3	4.40	53.0	**0.008**
Site.Year	3.61	5	0.72	53.0	0.610

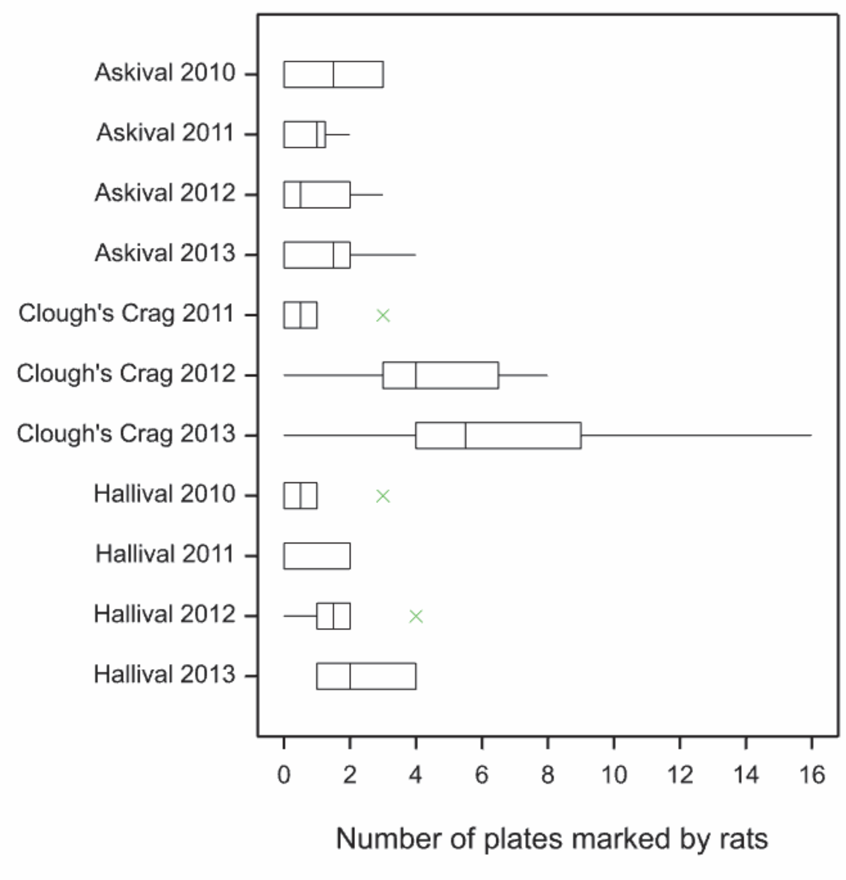

Figure 4. Schematic box plots of the number of carbon-coated tracking plates marked by rats each night at three study sites (Askival, Clough's Crag and Hallival) during 2010 – 2013. The tracking plates were scored (and re-painted where necessary) for 2-3 consecutive days at each site twice each year to correspond with endoscopy surveys of Manx shearwater burrows.

3.3 Manx shearwater productivity

In total 3,259 burrow checks were made; 1,574 during the egg stage and 1,685 during the chick stage. Of the burrows checked during the chick stage, 238 could not be adequately surveyed because the burrow was too long or complex, leaving 1,447 valid burrows from which productivity of Apparently Occupied Burrows was calculated and 1,088 valid occupied burrows (Table 5). In total, 70 valid burrow checks were on burrows (at Askival) that were also being used for a long-term study of Manx shearwater productivity on Rum. These burrows had a stone-covered inspection hatch dug into the tunnel between the entrance and the nest chamber to allow physical checking of the contents. This allowed us to confirm the result after checking each of these burrows by endoscopy; contents of 65/70 (92.9%) were correctly identified.

Table 5. Productivity of Manx shearwater burrows at three study sites on the island of Rum between 2010- and 2014. Two of the sites were in turn each treated with rodenticides for two consecutive years during the shearwater breeding season; data for treated sites are shown in bold. Productivity was calculated as the percentage (%) of burrows that contained a live chick (successful burrows) during the second (pre-fledging) survey for all AOBs (Table 5a) and separately for burrows that were actually occupied (i.e. those that contained an adult Manx shearwater, chick or egg at the post-laying survey; Table 5b). Burrows that were lost between the first and second surveys were replaced with alternative AOBs to achieve a final sample of ~130 AOBs per site, but these were not included in the sample of actually occupied burrows.

(a)	Askival			Clough's Crag			Hallival			Total		
	n	*Successful burrows*	%	*n*	*Successful burrows*	%	*n*	*Successful burrows*	%	*n*	*Successful burrows*	%
2010	129	80	62.0		*no sample*		**128**	**58**	**45.3**	257	138	53.7
2011	129	82	63.6	115	73	63.5	**141**	**83**	**58.9**	385	238	61.8
2012	**132**	**87**	**65.9**	132	102	77.3	129	92	71.3	393	281	71.5
2013	**146**	**84**	**57.5**	135	62	45.9	131	61	46.6	412	207	50.2
Total	536	333	62.0	382	237	62.7	529	294	54.6	1447	864	59.7

(b)	Askival			Clough's Crag			Hallival			Total		
	n	*Successful burrows*	%	*n*	*Successful burrows*	%	*n*	*Successful burrows*	%	*n*	*Successful burrows*	%
2010	89	63	70.8				**69**	**41**	**59.4**	158	104	65.8
2011	106	74	69.8	99	69	69.7	**104**	**75**	**72.1**	309	218	70.6
2012	**116**	**82**	**70.7**	109	91	83.5	105	83	79.0	330	256	77.6
2013	**103**	**65**	**63.1**	100	53	53.0	88	47	53.4	291	165	56.7
Total	414	284	68.6	308	213	69.2	366	246	67.4	1088	743	68.4

The subsequent success of burrows (defined as containing a live chick when checked shortly before fledging) that were apparently and actually occupied when checked (usually in late June) at the egg stage in treated and control areas is shown in Table 6. Success of apparently occupied burrows was 4.3% lower at sites treated with rodenticides compared to those at untreated sites. Success of actually occupied burrows was 1.9% lower at sites treated with rodenticides compared to those at untreated sites.

Table 6. Productivity of Manx shearwater burrows by treatment group. Successful burrows were those that contained a live chick when checked (usually in late August) shortly before the fledging period.

	Apparently Occupied Burrows			*Actually Occupied Burrows*		
	n	*Successful burrows*	%	*n*	*Successful burrows*	%
Treated	547	312	57.0	392	263	67.1
Control	900	552	61.3	696	480	69.0
Total	1447	864	59.7	1088	743	68.3

For each study site, the percentage of occupied burrows (when checked at the egg stage) that contained a live Manx shearwater chick when checked shortly before fledging was plotted against the closest (in time) index of rat activity for that site (Figure 5). The slope of the fitted line was negative, but there was no significant relationship between percentage of occupied burrows with chicks and index of rat activity (β = -7.94, t = -1.07, p = 0.311).

The effects of year (2010, 2011, 2012, 2013) and treatment (treated, control) on success of occupied burrows (live chick found during pre-fledging checks, no chick found during pre-fledging checks) were estimated in a Generalized Linear Model (GLM) with Bernoulli distribution and logarithmic link function (Table 7). There was a significant difference between years (p < 0.001), and a significant interaction between year and treatment (p = 0.036), indicating that the effect of the rodenticide treatment on the success of occupied burrows was not equal across all years.

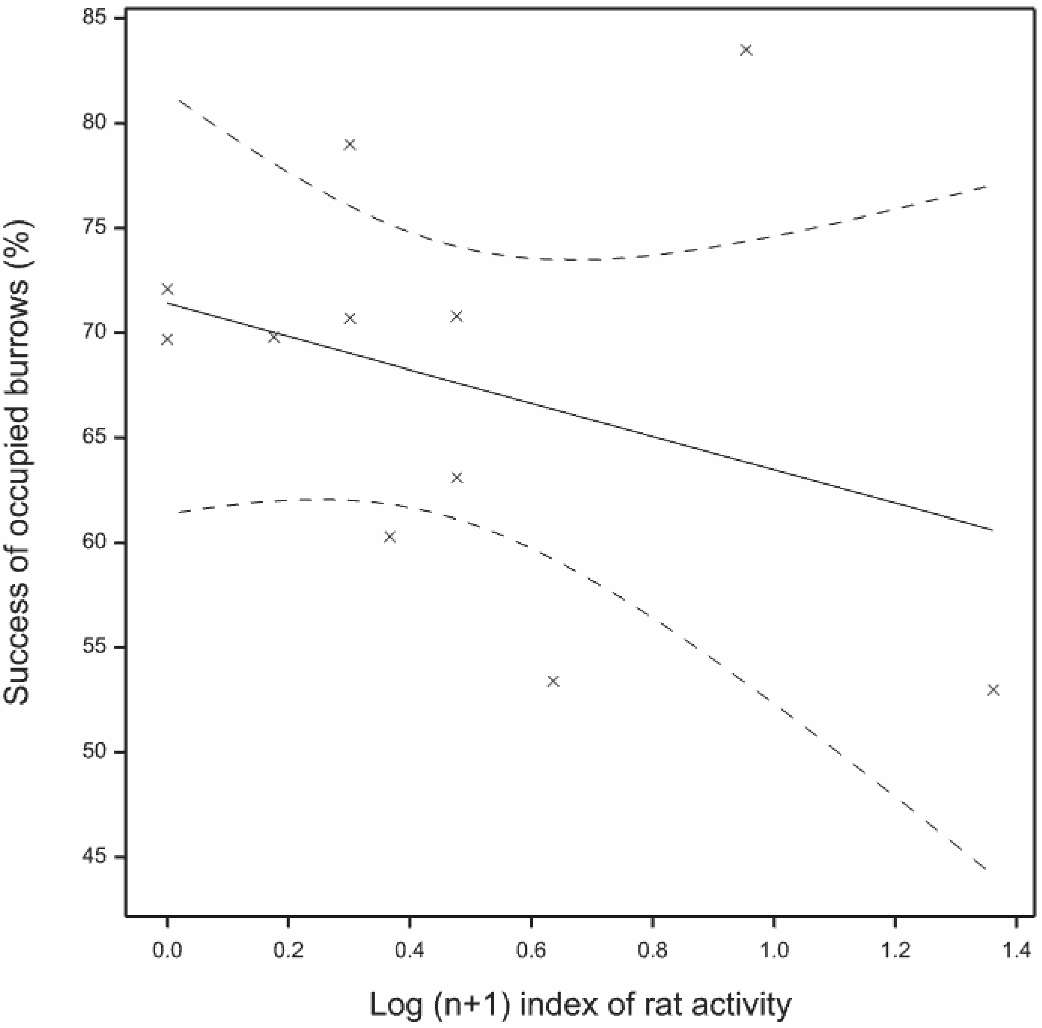

Figure 5. Fitted and observed relationship with upper and lower 95% confidence limits for a linear regression of Log (n+1) index of rat activity (from carbon-coated tracking plates) against success of occupied Manx shearwater burrows (calculated as the percentage of burrows occupied at the egg stage that subsequently contained a live chick when checked by endoscopy shortly before the main fledging period).

No suspected signs of rat predation on Manx shearwater burrows were found, apart from in 2013 when several (unmonitored) burrows were seen within the Clough's Crag study site with large amounts of downy Manx shearwater chick feathers around the entrances (Figure 6). Chick remains were found on several rocks nearby, and the tracking plates near these nests confirmed the presence of rats. Success of occupied burrows was significantly lower in 2013 than in 2012 at Hallival (Pearson $X^2 = 16.70$, $p < 0.001$, 1 d.f.) and significantly lower in 2013 than 2012 at Clough's Crag (Pearson $X^2 = 22.62$, $p < 0.001$, 1 d.f.) but not lower in 2013 than in 2012 at Askival (Pearson $X^2 = 1.42$, $p = 0.233$, 1 d.f.). In 2013 there was a highly significant difference in rate of occupancy (burrows containing an adult, chick or egg) of AOBs between the three sites (Pearson $X^2 = 15.05$, $p = 0.001$, 2 d.f.). Occupancy of burrows was significantly lower in June 2013 than in June 2012 at Hallival (Pearson $X^2 = 16.70$, $p < 0.001$, 1 d.f.), but not at Askival (Pearson $X^2 = 1.78$, $p = 0.182$, 1 d.f.) or Clough's Crag (Pearson $X^2 = 2.27$, $p = 0.132$, 1 d.f.).

Table 7. Accumulated analysis of deviance from a Generalized Linear Model of the effects of year and treatment on success of occupied Manx shearwater burrows. Significant effects (p < 0.05) are shown in bold.

Change	d.f.	Deviance	Mean Deviance	Deviance Ratio	Approx. Chi pr.
+ Year	3	32.299	10.766	10.77	**<.001**
+ Treatment	1	1.308	1.308	1.31	0.253
+ Year.Treatment	3	8.541	2.847	2.85	**0.036**
Residual	1080	1317.113	1.220		
Total	1087	1359.262	1.250		

Figure 6. In August 2013, several nests were seen within the Clough's Crag study site with Manx shearwater chick feathers around the entrance, remains of chicks were found on rocks nearby. The burrows were not monitored as part of the study, but were in an area where tracking plates confirmed the presence of rats.

4. DISCUSSION

The aim of this project was to quantify levels of brown rat predation on Manx shearwater nests on the island of Rum. In order to achieve this we carried out a removal study over four years with the expectation that the impact of rats would be revealed by differences in shearwater nesting success between areas treated with rodenticides to remove or reduce rat populations and untreated (control) areas. Switching the treatments between sites incorporated inter-site variation, and repeating treatments at the same sites for two consecutive years incorporated inter-year variation. The use of cross-over designs in impact studies has sometimes been criticised, as there could potentially be carry-over effects between study periods, and while this criticism is found mainly in the medical literature e.g. Greenwald (1976), Senn (2002), the same might apply to ecological studies. In this case, the effect of a rodenticide treatment could potentially influence the population of rats in that area in subsequent (untreated) years. However, we suspected that the home range of rats would be small within study years, when food resources were abundant, and would expand in response to reductions in food supply outside the Manx shearwater breeding season. We therefore expected that rats would move between sites between years, leading to a reasonable degree of independence between study years. We also expected that rats would not frequently move between study sites within years, which could have otherwise led to confounding effects between treated and untreated sites. An alternative analysis of the data could consider the cross-over as an element of the treatment, resulting in three treatments; T-T-C-C (Hallival), C-C-T-T (Askival) and C-C-C-C (Clough's Crag). This would examine the effect of historical and recent treatments compared to an untreated control. However, more replicates of each of these three treatments would be required to incorporate inter-site variation, which was not possible within the present study.

We defined nesting success as the percentage of Manx shearwater burrows that contained a chick shortly before the main fledging period. It is possible that rat predation could occur after this time, and it is possible therefore that we underestimated levels of rat predation, which would make detection of a treatment effect more difficult. However, we maximised the time period between the egg-stage checks and the chick-stage checks in order to provide the largest possible window of opportunity for rat predation within the limits of the study. Furthermore, many chicks were well-developed by late August when the majority of chick-stage checks were carried out, and it seems likely that chicks would be less vulnerable to rat predation by this stage. We also found that endoscopy incorrectly identified the burrow contents in approximately 7% of burrows; this would result in a false negative rather than a false positive, and potentially lead to a small degree of overestimation in the level of rat predation. However the methods used were consistent between sites; any sources of error applied equally to all sites and bias was therefore minimised.

In analyses that did not take into account inter-site and inter-year variation, there was little difference in Manx shearwater nesting success between treated and untreated sites, and no significant linear relationship between levels of rat activity and nesting success. However, during the first three years of the study, the level of rat activity recorded at all three sites was low, and the opportunity to manipulate population levels by the use of rodenticides was therefore also relatively low. In 2013 an increase in the level of rat activity at one of the untreated sites (Clough's Crag) provided our best opportunity to detect a treatment effect. In Generalized Linear Models that did take into account inter-site and inter-year variation, a significant interaction between year and treatment indicated that the treatment effect varied by year. Breeding success for 2010 – 2012 was largely consistent with published productivity data for Manx shearwaters which report an average of 0.69 chicks fledged per AOB (JNCC, 2014). However the breeding success for 2013 appeared to be substantially lower at the two untreated study sites. In 2013, breeding success fell by 30.5% at Clough's Crag (untreated) relative to 2012, and by 25.6% at Hallival (also untreated), but fell by less than 10% at the treated site Askival. No obvious signs of predation by rats were found at any of the surveyed study burrows. However, in 2013 several (unmonitored) burrows were seen within the Clough's Crag study site with large amounts of downy Manx shearwater chick feathers around the entrances. Remains of chicks were found on several rocks nearby, and the tracking plates near these nests confirmed the presence of rats. The reduction in Manx shearwater breeding success at Hallival in 2013 relative to 2012 also appeared to coincide with an upward trend in the level of rat activity at that site. The occupancy rate of Manx shearwater burrows was significantly lower in 2013 than in 2012 at Hallival, but this cannot explain the reduced success of occupied burrows in 2013 at that site. The decline in Manx shearwater breeding success cannot clearly be attributed to changes in climatic conditions; total annual rainfall recorded at the nearby Tiree weather station for the years 2010 to 2013 was 988.9 mm, 1509.8 mm, 1191.8 mm and 1210.3 mm; 84.3%, 128.8%, 101.6% and 103.2% of the average of 1172.6 mm recorded during 1931–2014 (Met Office, 2015).

It is possible that levels of rat activity at Askival would have remained lower than at Clough's Crag in 2013 for reasons other than the use of rodenticides. Askival and Hallival could be less vulnerable to incursion by rats than Clough's Crag due to other environmental characteristics (e.g. elevation). Apart from in 2013, a low density of rats was consistently detected at all three sites; indices of rat activity in 2010-2012 were typically 10-100 times lower than the mean activity index of 98.0 recorded at 14 farmsteads with a mean rat population size of 143 (Quy *et al.*, 1993). It is likely that, in general, the elevated areas of Rum where the shearwater colonies are located are not able to support a high density of rats throughout the year. The mixture of moorland, heath and rock provides little food or harbourage for rats, and with harsh conditions during winter it is unlikely that rats could survive in large numbers outside the shearwater breeding season. Recently, Ruffino *et al.* (2009) proposed that the coexistence of black (ship) rats (*Rattus rattus*) and seabirds on many Mediterranean islands was facilitated by biogeographical factors that created intra-island refuges for seabirds. In particular, the life-history traits of rats may exclude them from areas that do not have sufficient resources to continuously support rat populations, and they may not be able to seasonally occupy areas that are protected by their remoteness or terrain. However, it may be that in some years, environmental conditions are such that rats can survive in higher numbers in the shearwater breeding areas through the winter months, leading to a larger founding population the following year. Variations in some rodent populations appear to be closely linked to climatic events (e.g. Madsen and Shine, 1999) while, particularly in northern latitudes, abundance appears to be linked to population processes that result in multiannual cycles. For example, field vole populations in northern Fennoscandia oscillate in 4-5 year cycles, and the amplitude and cycle period decrease along a north-south gradient (Hanski *et al.*, 2001). Cyclic changes in brown rat populations have not been reported; this may be because systematic long-term data do not exist, or the oscillations are subtle and have therefore gone unnoticed. Alternatively, rats could potentially migrate from areas where they are more abundant, such as the coastal regions and the village, into the shearwater breeding areas, and the rate of this population transfer could vary between years in response to factors such as changes in food availability for example.

Given that there may be areas of the Rum Manx shearwater colonies that have inherently low levels of rat activity; opportunities may exist to further explore the relationship between levels of rat activity and shearwater breeding success without using rodenticides to artificially manipulate rat population levels. One of the aims of a PhD project initiated in 2012 is to carry out more extensive surveys of rat activity on the island, and this could potentially identify more sites where data on levels of rat activity and shearwater breeding success could be collected; possibly using a greater range of levels of rat activity. We do not currently know the frequency with which rat activity reaches the level seen at Clough's Crag in 2013 and the extent to which these or higher levels might occur island-wide, and therefore cannot conclude that there is no overall effect. We can conclude that localised effects probably occur, but we do not know how widespread or frequent these events are, and we have therefore been unable to assess the overall risk level. Further work is required to determine the relationship between brown rat activity levels and Manx shearwater breeding success with an appropriate level of confidence, and a better understanding of the distribution of rats in relation to current and potential Manx shearwater breeding sites would enable a whole-island assessment of the risk from rat predation to be made.

5. CONCLUSIONS

The current study had limited opportunities to artificially manipulate levels of brown rat activity, and therefore limited opportunity to quantify levels of rat predation, because of low levels of rat activity at the study sites during the first three years of the project. However, an increase in rat activity in 2013 provided some indication of a potential relationship between rat activity levels and shearwater breeding success, either by enabling a treatment effect which had not been possible in previous years, or through an inherent difference between sites in their potential to support rat populations. Recommendations for future work therefore include identifying more sites with high levels of rat activity, in order to provide more opportunities for artificially manipulating rat populations, or to enable the collection of data from sites with a wider range of rat activity levels in order to complete the process of identifying the relationship between rat activity and shearwater breeding success with an appropriate level of confidence. Further information is also required on the distribution of rats across the island and changes in levels of activity over different years. Once these parameters have been established it should be possible to generate a risk-based model that could be used to examine the effect of different brown rat management strategies on the long term security of Manx shearwater breeding colonies on the island of Rum.

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