Application of a non-invasive indexing methodology for introduced Norway rats, *Rattus norvegicus*, in the Aleutian Islands, Alaska

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ABSTRACT

Island restoration projects that address invasive species issues require measures of invader populations before eradication or control efforts begin, especially for cryptic species such as introduced rodents. To address this need, a non-invasive technique for measuring inter-annual variation in Norway rat (*Rattus norvegicus*) activity was tested at Kiska Island, Aleutian Islands, Alaska, during 2005-2010. Snap-trapping could not be used at a large mixed colony of small seabirds (auklets, *Aethia* spp.) at Sirius Point, Kiska, due to the certainty of bird mortality. Away from the colony site at Kiska Harbour, in June 2005, we used snap-traps to measure capture rates, and found a similar corrected trap index (8.5 captures /100 trap nights) to that recorded pre-eradication at Langara Island, British Columbia (8.2). At Sirius Point, we determined the most effective rat-monitoring method to be baited wax blocks in plastic tunnels set on a series of transects spanning the auklet colony (tracking tunnels and chew sticks were less effective). Rat detections varied nearly 100-fold among years, suggesting high inter-annual variability in the rat population. We found no statistically significant relationship between our rat index and auklet productivity at Sirius Point with our small sample of years (n = 5, 2006-2010). Nevertheless, we believe rat numbers were much lower at Sirius Point during 2006-2010 than observed anecdotally during 2001-2002 when auklets experienced breeding failure. Our rat activity index protocol is likely applicable to other situations in which introduced rodent numbers need to be monitored while safeguarding native fauna that could be harmed by snap-trapping.

Key words: Norway rat, *Rattus norvegicus*, relative abundance, monitoring, seabird, auklet, Kiska Island, Aleutian Islands, restoration

INTRODUCTION

Quantifying the distribution, abundance and population variability of introduced (alien) species is fundamental to understanding their effects on the ecology and viability of native populations, particularly at remote oceanic islands that characteristically have high endemism. After a relatively slow colonization period, introduced small mammals may become abundant and widespread (i.e., invasive) in new environments and pose a threat to native species and ecosystems (Innes 2005). Alternatively, alien species may establish themselves at low population levels and either remain scarce (i.e., non-invasive) or periodically irrupt to potentially threatening abundances. There is confusion in the conservation biology literature and popular media about the terms 'invasive' and 'alien' species, these often being used interchangeably (Colautti and MacIsaac 2004). A more useful practice may be to use 'invasive' to refer to any newly established species that are an agent of change and threaten pre-existing biodiversity, with 'alien' referring to any species occurring outside their natural range due to human transport (e.g., IUCN 1999; Colautti and MacIsaac 2004). Therefore, species may be alien and invasive (urgent conservation concern) or alien but not invasive (less conservation concern; Jones 2013). Key steps in introduced species management may be to establish 'invasiveness' by obtaining baseline population estimates and measuring population variability by implementing quantitative monitoring, both to aid the design and increase the effectiveness of conservation and management actions.

Rats (*Rattus* spp.), including Norway rats (*R. norvegicus*), are widespread introduced species able to survive and thrive in a multitude of environmental conditions (Jones *et al.* 2008; Ruedas 2008). This remarkable adaptability makes rats a major threat to insular endemic species, biodiversity and ecosystem health worldwide. Introduced rat destruction of insular avifauna has been well documented (Jones *et al.* 2008). For example, at Langara Island (Haida Gwaii, British Columbia, Canada) introduced Norway rats were implicated in a severe decline of breeding ancient murrelets (*Synthliboramphus antiques*) until rats were eradicated during 1994-1996 (Bertram 1995; Taylor *et al.* 2000). At Kure Atoll, Northwestern Hawaiian Islands, Polynesian rats (*Rattus exulans*) had severe negative effects on native seabirds until their eradication during 1993-1995 (Howald *et al.* 2007). At Palmyra Atoll, Line Islands, black rats (*Rattus rattus*) devastated seabird populations and other native ecosystem components until their eradication in 2011 (Flint 1999; Engeman *et al.* 2013). Nevertheless, Towns *et al.* (2006) argued for more quantitative research documenting rat biology and impacts on native species and ecosystems both before and after rat eradications.

Norway rats were first introduced onto Aleutian Islands, Alaska as early as the 1780's (Brooks 1876; Black 1984), and subsequent introductions occurred during 1941-1946 (Murie 1959). Despite Alaska's remoteness, vast geographic expanse and lack of studies, by 1990 self-maintaining populations were documented on at least 16 Alaskan islands (Bailey and Kaiser 1993). In Alaska, Norway rats persist as far north as Nome (64° N), with high mortality in marginal winter conditions offset by a high rate of reproduction during the summer (Schiller 1956). In the central and western Aleutians, Norway rats persist at Attu, Kiska, Amchitka, Adak and Atka Islands (Ebbert and Byrd 2002), and were successfully eradicated from Rat (Hawadak) Island in 2008 (Buckelew *et al.* 2011). Black rats are present at Shemya Island (Taylor and Brooks 1995) and rats (either Norway or black or both) are present on Great Sitkin Island (Ebbert and Byrd 2002; Lack 2012). At Kiska Island, Norway rats introduced during the 1940s are ubiquitous at low elevations, appear to vary widely in population size from year to year, and are implicated in mortality and breeding failure of auklets (*Aethia* spp.) at a large mixed colony at Sirius Point (Major and Jones 2005; Major *et al.* 2006; Major *et al.* 2007; Major *et al.* 2013; Bond *et al.* 2013), and extirpation of other seabirds from Kiska Island (Jones *et al.* 2008; Buxton *et al.* 2013). Least auklets (*Aethia pusilla*) experienced near complete breeding failure in 2001 and 2002 (the lowest breeding success ever recorded for this species) when rats appeared to be abundant at Sirius Point (Major *et al.* 2006). Auklets had normal reproductive success in other years when rats appeared to be scarce, yet no quantitative rat population indexing technique was available to measure the relationship rigorously (Major and Jones 2005; Major et al. 2006; Bond et al. 2013).

Measuring relative abundance of alien rodents on fragile remote islands with threatened ecosystems requires a technique that reflects the activity and numbers of the alien invaders, while leaving relict populations of native species unharmed. After eradication efforts (e.g., rodenticide application) are complete, it is crucial to clarify whether any target rodents have survived. Commonly used small mammal population monitoring techniques for rats have included live-trapping and snap-trapping that may cause incidental capture and mortality of native species including small birds (Dice 1931; Menkens and Anderson 1988; Waldien *et al.* 2004). At Sirius Point, Kiska Island the dense breeding colony of least and crested (*A. cristatella*) auklets makes incidental captures certain with snap-trapping, indicating the need for an alternative rat-monitoring method (Major *et al.* 2006). Here we evaluated alternative techniques that are non-destructive and do not impact non-target species (Quy *et al.* 1993; Blackwell *et al.* 2002).

Our main objective was to identify the most effective way to monitor inter-annual variability in Norway rat presence at Sirius Point, Kiska Island, Alaska. Three indicator methods - wax blocks, tracking tunnels, and chew sticks - were tested to see if rats were attracted to them, if activity was detectable, and if a combination of one or more methods was most effective. To compare rat activity at Kiska to reports from other similar islands, we measured Norway rat activity away from the auklet colony at a representative site near Kiska Harbour (10 km from Sirius Point) in 2005 using a conventional snap-trapping approach. We aimed to develop a non-invasive protocol applicable generally to similar situations on islands with both threatened native species and alien rodents present. Using the perfected method, we measured baseline levels and variability in Norway rat activity at the auklet colony site at Sirius Point during 2006-2010.

STUDY AREA

Fieldwork was conducted at Kiska Island, western Aleutian Islands, Alaska (51°58′N, 177°30′E), a North Pacific oceanic island with no native land mammals. Kiska lies entirely within the Alaska Maritime National Wildlife Refuge, is 39.8 km long, varies in width from 2.8 – 11 km, and has a total area of 28 177 ha. A large auklet colony occupied in 2001 by >one million least and crested auklets (I.L. Jones unpubl. data), encompassing 1.8 km^2, is situated on two lava domes at the base of Kiska Volcano on the northern tip of the island at Sirius Point (52°07′N 177°35′E). Four other seabirds, Leach's (*Oceanodroma leucorhoa*) and fork-tailed storm-petrels (*O. furcata*), ancient murrelet and Cassin's auklet (*Ptychoramphus aleuticus*) occasionally visit Kiska at night but were extirpated as breeding species (Buxton *et al.* 2013). Norway rats, probably introduced during Word War II at Kiska Harbour (Murie 1959), are most common along shorelines and in some years at the auklet colony site at Sirius Point (Major and Jones 2005; Major *et al.* 2006). Little is known about progress of the invasion of Kiska Island by rats, other than that rat sign was widespread after alien Arctic foxes (*Vulpes lagopus*) were eradicated in 1987 (Deines and McClellan 1987a, b). No other alien rodents have been recorded at Kiska. Our preliminary study site, at Kiska Harbour (51°59’N 177°33’E, no seabird colonies) is surrounded by relatively gentle terrain with low grass-covered hills based on glacially eroded Tertiary volcanic deposits (Coats *et al.* 1961). Our main study site at Sirius Point included four similar habitats all overlain on recent rugged volcanic deposits with densely nesting auklets (Major *et al.* 2006): ‘New Lava’ is a recent (January 1962 – September 1969) lava dome (Miller *et al.* 1998) sparsely vegetated with lichens, ‘Old Lava High’ is a c.150 year old basalt blockfield vegetated with *Carex* spp., *Calamagrostis* spp. and fern, ‘Old Lava Low’ at lower elevation but with similar vegetation to Old Lava High, and ‘Glen Larry’ is a deep gully between the new and old lava fields formed during the 1960s eruption.

METHODS

Kiska Harbour tracking tunnel activity, 2005 - A quantitative relative abundance indexing method based on tracking tunnels (Blackwell *et al.* 2002) to monitor rat activity was tested at Kiska Harbour (central Kiska Island, grassy lowlands) in 2005 (Fig. 1) and implemented at Sirius Point (Fig. 2) during 2006-2010.

< INSERT FIG. 1 ABOUT HERE >

In 2005, we set three 450 m transect lines near Kiska Harbour, each traversing a different elevation range. These were line TA (51°58.805'N 177°32.513'E to 51°59.009'N 177°32.727'E, 11 m elevation; lowest elevation and closest to the sea), line TB (51°58.886'N 177°32.396'E to 51°59.091'N 177°32.615'E, 36 m elevation; middle), and Line TC (51°58.955'N 177°32.260'E to 51°59.157'N 177°32.474'E, 74 m elevation; highest), approximately 200 m apart, each with 10 tracking tunnels 50 m apart (Appendix 1). Tracking tunnels were rectangular black PVC plastic boxes (10 cm by 10 cm by 50 cm, open at each end) containing a white paper strip covering the ‘floor’ of the tunnel, with a centrally placed ink square saturated in red ink, to record foot prints as rats traversed the tunnel. On June 15, 2005 the tracking tunnels were placed and left unbaited for two weeks to reduce the effects of neophobia. Tunnels were then baited with a mixture of peanut butter, honey and oats and left unchecked for an additional three days, rebaited, after which rat activity was indexed for two consecutive days (checked at mid-day). After the first night and again on the second day, rat activity (as bait gone, ink tracks, scratches, droppings, chewing) was recorded and ink cards with evidence of rat activity were replaced with fresh cards. In order to test for repeatability and/or habituation, tunnels were left in position unchecked for two weeks and then run again (July 15-18, 2005) to measure rat activity using the same methodology as described above. The index of rat activity was expressed as the percentage of tunnels visited per line during each of the two-day sets.

Kiska Harbour snap-trap indexing, 2005 - To obtain a one-time index of rat relative abundance at Kiska for comparison to other islands, 16 snap traps (Victor Professional Expanded Trigger Rat Trap) in a four trap x four trap grid formation, at 20 m spacing between each trap, were established at three locations within 10 m of a shoreline (Kiska

Harbour North centered at 51°58.957'N 177°32.937'E WGS 84, elevation 17 m; Kiska Harbour South 51°57.529'N 177°32.264'E, 25 m elevation; and Moron Lake 52°00.225'N 177°31.071'E, 76 m elevation; Fig. 1) during June 26 - July 4, 2005. Traps were pre-baited with a mixture of oatmeal, honey and peanut butter for at least two days before being set for eight days. Rat activity at each trap was recorded each morning: as bait gone, trap sprung, rat body, blood, rat droppings and movement of the trap. Each trap was then sprung, cleaned, re-baited and re-set for the next night's activity. An index of activity for each grid was calculated per 100 corrected trap nights (Nelson and Clark 1973). We also tested whether capture rates in snap-traps varied by location using a logistic regression (binary logistic regression in Minitab, Biometry[REFERENCES!!!]). Dead rats were dissected on the day of capture and their stomach contents examined to determine presence/absence of expected food types in their diet.

Sirius Point Activity Indexing 2006-2010 - In order to index rat relative abundance at the massive auklet colony site at Sirius Point, we deployed tracking tunnels augmented with wax blocks and chew sticks, during 2006. Eight transects, each with ten stations consisting of 1 tracking tunnel, 1 chew stick (a 15 cm long by 1 cm diameter hardwood dowel saturated in generic vegetable oil; placed inside the tunnel), 1 wax block (a flat cylindrical 25 g block of paraffin wax dyed with red food colouring and smeared with 1 g of peanut butter; placed inside the tunnel) spaced 25 m apart.

< INSERT FIG 2 ABOUT HERE >

The eight transect lines encompassed the four different habitat types (two lines per habitat) within the auklet colony at Sirius Point (Table 1, Fig. 2, Appendix 2).

< INSERT TABLE 1 ABOUT HERE >

For safety considerations the gully transect line was set non-linearly on the winding gully bottom based on a level path. Tunnels were set at the closest available spot for protection from severe weather, within 2 m of the 25 m marker along each line. Ledges, rock crevasses, and caves were chosen in preference to open areas, and obstruction of auklet nest sites was avoided on all transects. Two replicate six-day monitoring trials were carried out: one in mid-June (approximate mid-point of auklet incubation period at Kiska) and one in mid-July of each year (approximate mid-point of auklet chick-rearing period). Using a generalized linear model with Poisson error, we analysed the number of stations on each plot that detected a rat at least once, and examined differences among years (2006-2010) and periods (early and late). Models including three-way and two-way interactions were not significant, so they were removed, and we analyzed main effects only. We made multiple comparisons based on overlapping 95% confidence intervals of model-estimated parameter estimates. Based on the 2006 data (see Results), the rat indexing protocol for 2007-2010 was modified to include only wax blocks smeared with 1 g of peanut butter (placed in the same tracking tunnel boxes) because of their greater frequency of rat detection. We compared the rat relative abundance estimates to measures of auklet productivity made concurrently (Major *et al.* 2006; Bond *et al.* 2011).

RESULTS

Kiska Harbour tracking tunnel activity, 2005 - Rat activity was higher in transect line TA (100% of stations with rat detections, low elevation, near the shoreline), intermediate in TB (mean of 80% of stations with rat detections, moderate elevation) and lowest in line TC (mean of 60% of stations with rat detections, highest elevation (Table 2); there was a significant difference in rat activity among transects (Wald χ^2 [Chi-squared] = 7.51, p = 0.023), but not period (Wald χ^2 [Chi-squared] = 1.42, p = 0.23), or day (Wald χ^2 [Chi-squared] = 0.95, p = 0.33).

< INSERT TABLE 2 ABOUT HERE >

Rats chewed on wax blocks at significantly more stations on transect TA (estimated mean ± SE: 0.97 ± 0.15; 95% CI: 0.71-1.32) than transect TC (0.45 ± 0.11; 95% CI: 0.28-0.71); transect TB did not differ from the other two (0.69 ± 0.13; 95% CI: 0.48-1.01).

Kiska Harbour snap-trap indexing, 2005 - During July 5-18, 2005, 30 rats were trapped over 384 trap nights (128 per grid) from the three grids combined, yielding a corrected trap index (CTI) of 8.46 captures/100 corrected trap nights. Kiska Harbour North (18 traps sprung, nine captures) had a capture index of 7.86, Kiska Harbour South (seven traps sprung, 11 captures) 9.2, and Moron Lake (five traps sprung, ten captures) 8.26, with no significant difference in capture rate among sites (ANOVA $F_{2,45} = 0.09$, P = 0.9). The odds of a false sprung trap were 2.8x greater at Kiska Harbour North than at Kiska Harbour South and were 4x greater than at Moron Lake. False sprung traps provided a measure of bias in the different trapping areas. Rats trapped at the Kiska Harbour grids (near the sea beach) had amphipods (40% prevalence), earthworms (19%) and seaweed (17%) in their stomachs, while those trapped at Moron Lake (inland) had terrestrial vegetation (78%) and insects (33%) predominating.

Sirius Point Activity Indexing 2006-2010 - In 2006, considering all 23 cases where there was any detection at a tunnel, 93% included chewing of the wax block (Table 3). We found significant differences in frequency of detection among methods (Wax: 94 detections /480 trap-days = 19.6%; Chew: 29 / 480 = 6.0%; Track: 50 / 480 = 10.4%), with significantly more wax block detections than track or chew stick detections (Wald $\chi 2 = 412.6$, df = 2, $p < 0.0001$).

< INSERT TABLE 3 ABOUT HERE >

During 2006-2010, we found significant differences among years (Wald $\chi^2 = 39.31$, df = 4, $p < 0.0001$); there were significantly more detections in 2006 than 2008 or 2009, which in turn had more detections than 2007 or 2010 (Table 4).

< INSERT TABLE 4 ABOUT HERE >

Stations in the gully transects had the most detections (112), followed distantly by the new lava (30), the low old lava (22) and the high old lava (1), with significant differences among plots (Wald χ^2 **[Chi-squared]** = 51.18, df = 4, $p < 0.0001$). There were significantly more rat detections in July (auklet chick-rearing period) than in June (auklet incubation period; Wald χ^2**[Chi-squared]** = 15.62, df=1, $p < 0.0001$). Comparing relationships between our index of rat abundance and hatching, fledging or overall reproductive success for least auklets (2006 – 97%, 88%, 85%; 2007 - 81%, 72%, 58%; 2008 - 79%, 74%, 59%; 2009 – 91%, 62%, 52%; 2010 – 78%, 78%, 61%; Bond *et al.* 2013), all relationships were insignificant (all $p > 0.37$, all $r < 0.25$).

DISCUSSION

We began our Norway rat study at Kiska Harbour in 2005, on terrain typical of Kiska Island south of the volcano, where nesting seabirds were absent. In this area, both snap traps and tracking tunnels indicated a higher rat relative abundance at lower elevations and near the coastline. Kiska, like other Aleutian Islands, has a shoreline fringe of dense vegetation consisting of tall grasses and herbs (c. 10 m width) with close proximity to the intertidal zone – both rich in food and cover for rats. Consistent with our analysis of stomach contents, previous rat foraging ecology studies in the Aleutian Islands have reported Norway rats feeding on amphipods in the beach wrack and small invertebrates on Fucoid algae (Kurle 2003; Major *et al.* 2007). Our direct observations of extensive rat tracks on beaches (in 2005 and subsequently) underlined the importance of beach habitat to Kiska rats. Our snap-trap capture rates at Kiska Harbour were similar to rates recorded at Langara Island, British Columbia, Canada (8.2 C/100TN at sites without seabirds; Drever 2004) where Norway rat predation was implicated as a major cause in decline of breeding ancient murrelets (Bertram 1995; Drever and Harestad 1998; Hobson *et al.* 1999). At Langara in 1995, trapping also indicated that capture rates were significantly different between coastal and inland sites. Future rat trapping grids at Kiska could be improved by increasing the area trapped and number of traps used, to provide trapping rates more reflective of the entire island, and also providing wire mesh covers for traps to help exclude passerine birds and scavengers, as well as adding a live capture-mark-recapture effort to more directly quantify density. Incorporating trapping grids to other habitat types would also improve existing data on the distribution of Norway rats at Kiska Island. We note that our small-scale grid study in 2005 resulted in non-target bird mortality (one Pacific Wren, *Troglodytes pacificus* and one Lapland Longspur, *Calcarius lapponicus*), indicating that snap-traps, however useful in measuring rat numbers, have an ethical cost. Placement of all snap-traps in wooden boxes or with wire mesh covers would reduce non-target mortality, although wrens were killed by snap-traps set in boxes with small (3 cm diameter) entrances in 2000 (ILJ).

Our greater interest concerned Norway rat abundance (especially inter-year variability in abundance) at Sirius Point, Kiska Island, where rats are present at a colony of >1 million least and crested auklets nesting on lava flows along the north side of Kiska Volcano (Major *et al.* 2006). Annual measurement of rat abundance at Sirius Point using snap-traps was never considered, as least auklets (85 g mass) enter all crevices and holes at the colony site and every snap trap set was expected to kill an auklet, creating both non-target bird mortality and interference with rat capture. As an alternative to snap-trapping, we chose to employ a modification of the tracking tunnel technique widely used in New Zealand (Blackwell *et al.* 2002). We determined that the most successful method tested in 2006, peanut butter flavored wax blocks (used alone in black plastic tunnels), was a simple and inexpensive method to apply in the rugged terrain of the lava flows at Sirius Point, Kiska Island. Tracking tunnels (i.e., with ink and paper) were more labor intensive to maintain and negatively affected by wet conditions. Our simultaneous test of both methods in 2006 revealed that baited wax blocks detected >90% of tracking detections, so we used these alone for our subsequent monitoring. Because our primary interest was in inter-annual variability, our use of wax blocks placed in tunnels set in identical locations each year avoided the pitfall of differential habitat effects on rat activity at tunnels (Blackwell *et al.* 2002). Comparisons in rat relative abundance indices among our Sirius Point plots were probably not affected as micro-habitat was very similar among plots, although the geological lava formations varied along and among transects. We set transects to cover representative areas of a substantial proportion of the auklet colony at Sirius Point, so we assumed that detections would reflect overall conditions. Our aim was to monitor fluctuations in rat populations annually at the seabird colony at Sirius Point, but what exactly did rat activity detected at our tunnels indicate? Blackwell *et al.* (2002) pointed out differences among snap-traps and tracking tunnels in simultaneous measurements. Tracking tunnels are thought to indicate rat 'density' although they likely reflect 'activity' as well as relative abundance, and tests of their efficacy are sparse (Blackwell *et al.* 2002). We controlled for the activity effect by counting one or more rat detections at a particular station as a single detection for a tracking period. Nevertheless, we believed our approach was the best for indexing annual variation in rat relative abundance at our auklet colony site, given the inadvisability of using snap-traps at this location. One concern that remains is Blackwell *et al.'s* (2002) finding a poor correlation between tracking tunnels and other methods at low levels of rat relative abundance (as appeared to be present during 2007-2010). This was offset by our aim to detect peaks in rat abundance such as appeared to occur during 2001-2002, before our rat indexing began, and when auklets failed.

Many rodents have extreme inter-annual population fluctuations in response to climate and food-supply factors (Madsen *et al.* 2006; Boonstra and Krebs 2011). Conditions at Kiska Island varied among years, especially in snowfall, rainfall and spring temperatures that affected primary productivity that rats depend on, which in turn might affect parts of the ecosystem that rats are dependent on. We believed these factors might affect Norway rat productivity. This possibility is consistent with anecdotal observations of fluctuating rat abundance at Kiska among different years (1996-2010, many observers, personal observations; Major and Jones 2005; Major et al. 2006; Bond et al. 2013). For this reason, in future it will be important to quantify annual variation in rat numbers in relation to other environmental variables at Kiska. Unfortunately, our measurements during 2006-2010 (n = 5 years only) did not coincide with either abundant rats or auklet breeding failure, as both occurred concurrently in 2001-2002 (Major *et al.* 2006). For example, rat sign was abundant near the high transects in 2001 and a rat cache of 38 least auklets was found in that area on 2 June 2001 (Major and Jones 2005), yet during 2006-2010 we recorded only a single detection on either of the high tunnel transects (Table 4). We believe our wax block monitoring protocol will provide a method to further explore this issue on Kiska and also other islands where rats and seabirds persist together in the same habitat. In particular, our most urgent need for Kiska is to measure the frequency of the apparently occasional years with abundant rats (such as 2001-2002, when auklets suffered breeding failure) – a key variable for a rigorous population viability model for least and crested auklets at the Sirius Point colony (Major *et al.* 2013), but a challenging proposition given the remoteness and harsh environment of this location. A longer data series on rat relative abundance at Sirius Point, Kiska, could be helpful for developing a predictive model for rat irruptions on Aleutian islands that would be useful for management of auklets and other affected seabirds and for planning of rat eradication or control.

Non-invasive monitoring of rats is likely to be important both before (Lavers *et al.* 2010) and after (Taylor *et al.* 2000) eradication has been attempted as a component of island restoration projects. Before eradication is contemplated, this will be important at islands where rats are normally scarce but have periodic irruptions for example at Kiska (Major *et al.* 2006) and Shemya (Taylor and Brooks 1995) Islands in the Aleutians. After a rat eradication operation is carried out some studies have shown gradual recovery of native avifauna (Lavers *et al.* 2010; Buxton *et al.* 2013), so careful non-invasive monitoring is essential to detect surviving rats. Our method would be most applicable to islands at all latitudes, but likely less applicable to tropical islands with native (e.g., land crabs) or non-native (e.g., ants) scavengers due to interference with the baited wax blocks. Nevertheless, given the need to avoid non-target mortality of birds (e.g., storm-petrels) and other fauna vulnerable to snap traps (especially relict threatened populations), variations on our methodology are likely applicable to other systems, keeping in mind the caveats outlined by Blackwell *et al.* (2002).

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Table 1 Location of eight Norway rat relative abundance-indexing tunnel transects at Sirius Point, Kiska Island, Aleutian Islands, Alaska during 2006-2010.

Transect	Start location	End Location	Mean elevation (m)
New Lava 1	52°7.962′N 177°35.687′E	52°7.972′N 177°35.496′E	51
New Lava 2	52°7.908′N 177°35.659′E	52°7.908′N 177°35.659′E	59
Gully 1	52°7.903′N 177°35.679′E	52°7.820′N 177°35.570′E	42
Gully 2	52°7.766′N 177°35.397′E	52°7.820′N 177°35.244′E	46
Old Lava Low 1	52°7.768′N 177°35.517′E	52°7.672′N 177°35.629′E	89
Old Lava Low 2	52°7.800′N 177°35.589′E	52°7.708′N 177°35.711′E	88
Old Lava High 1	52°7.622′N 177°35.686′E	52°7.690′N 177°35.848′E	122
Old Lava High 2	52°7.568′N 177°35.770′E	52°7.643′N 177°35.913′E	137

Table 2 Frequency of rat detections (number of stations out of 10 with activity) at three Norway rat relative abundance-indexing transects at Kiska Harbour, Kiska Island, Aleutian Islands, Alaska during 2005.

Transect	July 4	July 5	early totals	July 17	July 18	late totals
TA	10	10	10	9	10	10
TB	5	7	7	7	9	9
TC	0	5	5	6	7	7

Table 3 Norway rat activity (count of detections) on three indicators at ten stations set on eight transect lines at Sirius Point, Kiska Island, Aleutian Islands, Alaska in 2006.

	June										July									
	13			14			15			Total	13			14			15			Total
Treatment	w[1]	c[1]	t[1]	w	c	t	w	c	t		w	c	t	w	c	t	w	c	t	
New 1	1	1	0	3	0	0	2	0	0	7	2	2	0	5	3	0	5	2	0	19
New 2	0	0	1	0	0	0	0	0	1	2	0	0	0	0	0	1	3	0	1	5
Gully 1	3	0	0	2	0	1	2	0	1	9	7	1	6	7	4	7	8	7	9	56
Gully 2	3	2	0	1	0	0	2	0	0	8	8	1	0	9	1	3	7	1	6	36
Low 1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	2	1	0	1	7
Low 2	0	0	0	0	0	0	0	0	0	0	4	2	3	3	1	3	3	1	4	24
High 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
High 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[1] w: wax block, c: chew stick, t: tracking tunnel – placed together at each station.

Table 4. Inter-annual variation in Norway rat activity indicated by wax blocks at transects (two each) set in four habitats in the auklet colony at Sirius Point, Kiska Island, Aleutian Islands, Alaska during 2006-2010 (rat detections by tunnel, no repeats counted).

Year	Plot	June	July	**All**
2006	all	13	33	**46**
	new	4	8	12
	gully	8	18	26
	low	1	7	8
	high	0	0	0
2007	all	0	0	**1**
	new	0	0	0
	gully	0	1	1
	low	0	0	0
	high	0	0	0
2008	all	7	18	**25**
	new	0	6	6
	gully	7	12	19
	low	0	0	0
	high	0	0	0
2009	all	5	16	**21**
	new	0	0	0
	gully	2	13	15
	low	3	3	6
	high	0	0	0
2010	all	3	0	**3**
	new	1	0	1
	gully	1	0	1
	low	0	0	0
	high	1	0	1

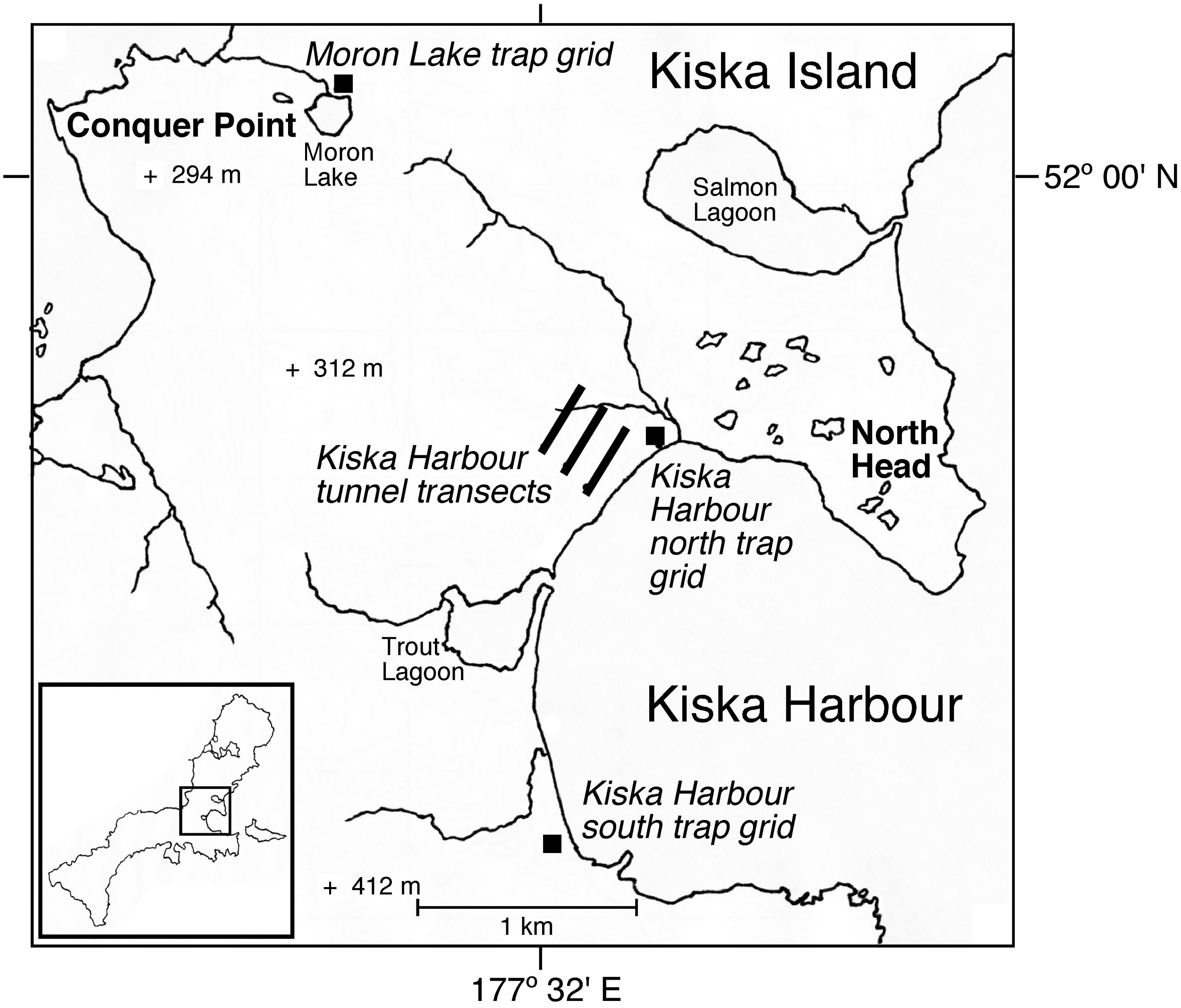

Fig. 1 Location of rat trapping grids and tracking tunnel transects at Kiska Harbour, Kiska Island (inset with map location), Aleutian Islands in 2005.

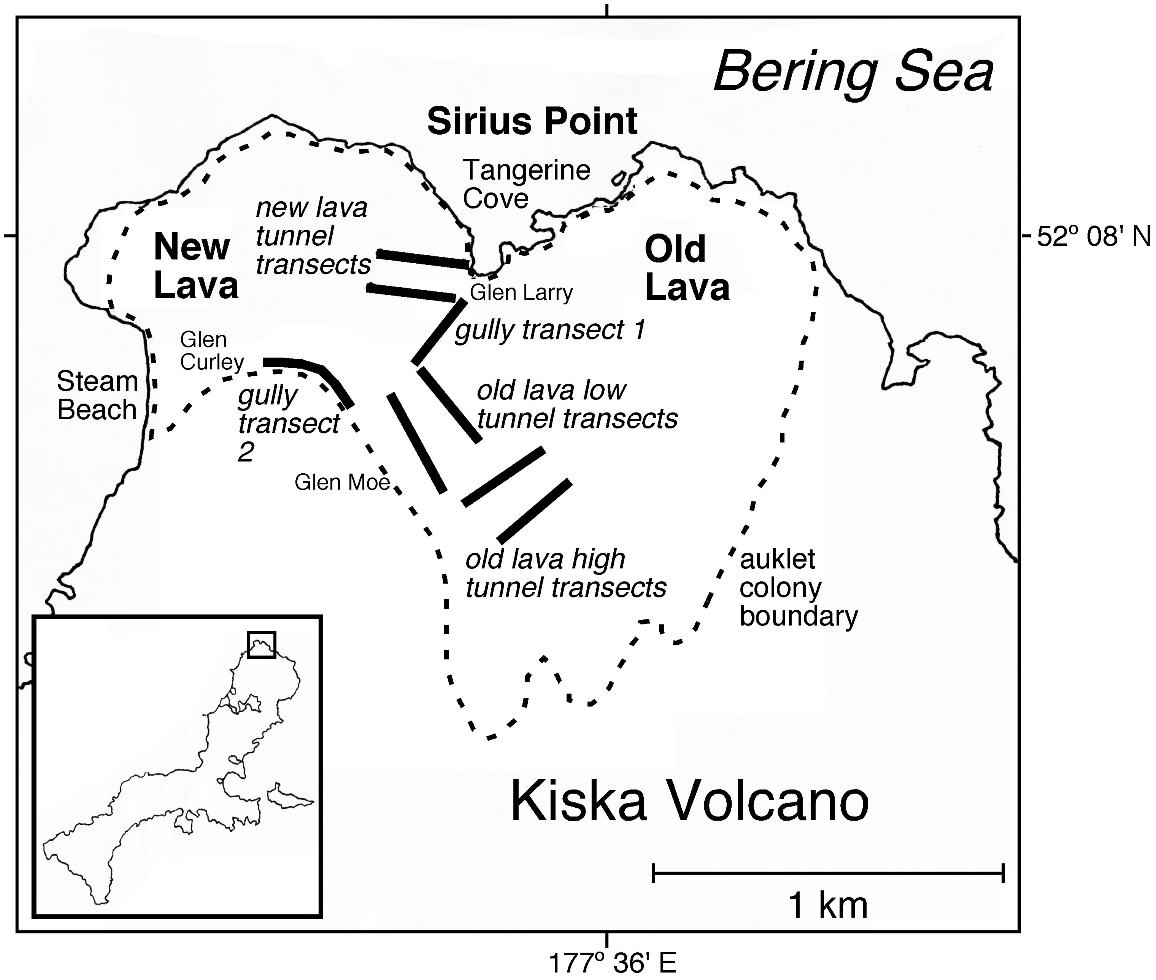

Fig. 2 Location of relative abundance index transects at Sirius Point, Kiska Island (inset with map location), Aleutian Islands, Alaska, 2006-2010.

Appendix 1 (*supplementary material*) Locations (datum WGS 84) of 30 rat relative abundance-indexing tunnel transect stations on three transects at Kiska Harbour, Kiska Island, Aleutian Islands, Alaska, in 2005.

Transect	Station ID	Position	Elevation (m)
A	TA1	51°58.805′N 177°32.513′E	5
A	TA2	51°58.830′N 177°32.528′E	13
A	TA3	51°58.855′N 177°32.552′E	14
A	TA4	51°58.877′N 177°32.580′E	13
A	TA5	51°58.899′N 177°32.607′E	13
A	TA6	51°58.918′N 177°32.636′E	3
A	TA7	51°58.943′N 177°32.652′E	11
A	TA8	51°58.968′N 177°32.673′E	13
A	TA9	51°58.989′N 177°32.703′E	14
A	TA10	51°59.009′N 177°32.727′E	11
B	TB1	51°58.886′N 177°32.396′E	52
B	TB2	51°58.911′N 177°32.422′E	42
B	TB3	51°58.935′N 177°32.443′E	33
B	TB4	51°58.955′N 177°32.473′E	36
B	TB5	51°58.976′N 177°32.497′E	34
B	TB6	51°59.001′N 177°32.515′E	34
B	TB7	51°59.026′N 177°32.535′E	34
B	TB8	51°59.048′N 177°32.559′E	30
B	TB9	51°59.073′N 177°32.581′E	30
B	TB10	51°59.091′N 177°32.615′E	32
C	TC1	51°58.955′N177°32.260′E	103
C	TC2	51°58.978′N 177°32.284′E	97
C	TC3	51°59.000′N 177°32.309′E	91
C	TC4	51°59.023′N 177°32.332′E	87
C	TC5	51°59.045′N 177°32.357′E	77
C	TC6	51°59.068′N 177°32.379′E	68
C	TC7	51°59.090′N 177°32.407′E	66
C	TC8	51°59.114′N 177°32.421′E	59
C	TC9	51°59.138′N 177°32.445′E	52
C	TC10	51°59.157′N 177°32.474′E	45

Appendix 2 (*supplementary material*) Locations (datum WGS 84) of 80 rat relative abundance-indexing tunnel transect stations on eight transects in four habitats at during 2006-2010 at Sirius Point, Kiska Island, Aleutian Islands, Alaska.

Transect	Station	Position
New Lava 1	TS01	52°7.962′N 177°35.687′E
New Lava 1	TS01-5	52°7.963′N 177°35.666′E
New Lava 1	TS02	52°7.966′N 177°35.646′E
New Lava 1	TS02-5	52°7.966′N 177°35.625′E
New Lava 1	TS03	52°7.968′N 177°35.598′E
New Lava 1	TS03-5	52°7.968′N 177°35.584′E
New Lava 1	TS04	52°7.968′N 177°35.557′E
New Lava 1	TS04-5	52°7.970′N 177°35.541′E
New Lava 1	TS05	52°7.972′N 177°35.519′E
New Lava 1	TS05-5	52°7.972′N 177°35.496′E
New Lava 2	TS71	52°7.908′N 177°35.659′E
New Lava 2	TS72	52°7.906′N 177°35.639′E
New Lava 2	TS73	52°7.904′N 177°35.616′E
New Lava 2	TS74	52°7.902′N 177°35.591′E
New Lava 2	TS75	52°7.910′N 177°35.568′E
New Lava 2	TS76	52°7.905′N 177°35.545′E
New Lava 2	TS77	52°7.908′N 177°35.528′E
New Lava 2	TS78	52°7.909′N 177°35.508′E
New Lava 2	TS79	52°7.911′N 177°35.487′E
New Lava 2	TS80	52°7.908′N 177°35.659′E
Old Lava Low 1	TS11	52°7.768′N 177°35.517′E
Old Lava Low 1	TS12	52°7.761′N 177°35.532′E
Old Lava Low 1	TS13	52°7.753′N 177°35.548′E
Old Lava Low 1	TS14	52°7.740′N 177°35.560′E
Old Lava Low 1	TS15	52°7.730′N 177°35.575′E
Old Lava Low 1	TS16	52°7.718′N 177°35.587′E
Old Lava Low 1	TS17	52°7.707′N 177°35.599′E
Old Lava Low 1	TS18	52°7.696′N 177°35.612′E
Old Lava Low 1	TS19	52°7.686′N 177°35.625′E
Old Lava Low 1	TS20	52°7.672′N 177°35.629′E
Old Lava Low 2	TS41	52°7.800′N 177°35.589′E
Old Lava Low 2	TS42	52°7.789′N 177°35.604′E
Old Lava Low 2	TS43	52°7.778′N 177°35.617′E
Old Lava Low 2	TS44	52°7.767′N 177°35.631′E
Old Lava Low 2	TS45	52°7.759′N 177°35.646′E
Old Lava Low 2	TS46	52°7.749′N 177°35.656′E

Old Lava Low 2	TS47	52º7.738′N 177º35.670′E
Old Lava Low 2	TS48	52º7.730′N 177º35.680′E
Old Lava Low 2	TS49	52º7.719′N 177º35.697′E
Old Lava Low 2	TS50	52º7.708′N 177º35.711′E
Old Lava High 1	TS31	52º7.622′N 177º35.686′E
Old Lava High 1	TS32	52º7.629′N 177º35.705′E
Old Lava High 1	TS33	52º7.636′N 177º35.724′E
Old Lava High 1	TS34	52º7.644′N 177º35.741′E
Old Lava High 1	TS35	52º7.651′N 177º35.761′E
Old Lava High 1	TS36	52º7.659′N 177º35.778′E
Old Lava High 1	TS37	52º7.668′N 177º35.803′E
Old Lava High 1	TS38	52º7.675′N 177º35.814′E
Old Lava High 1	TS39	52º7.681′N 177º35.834′E
Old Lava High 1	TS40	52º7.690′N 177º35.848′E
Old Lava High 2	TS51	52º7.568′N 177º35.770′E
Old Lava High 2	TS52	52º7.577′N 177º35.785′E
Old Lava High 2	TS53	52º7.585′N 177º35.798′E
Old Lava High 2	TS54	52º7.596′N 177º35.820′E
Old Lava High 2	TS55	52º7.604′N 177º35.832′E
Old Lava High 2	TS56	52º7.611′N 177º35.846′E
Old Lava High 2	TS57	52º7.619′N 177º35.864′E
Old Lava High 2	TS58	52º7.626′N 177º35.882′E
Old Lava High 2	TS59	52º7.632′N 177º35.899′E
Old Lava High 2	TS60	52º7.643′N 177º35.913′E
Gully 1	TS21	52º7.903′N 177º35.679′E
Gully 1	TS22	52º7.895′N 177º35.675′E
Gully 1	TS23	52º7.882′N 177º35.654′E
Gully 1	TS24	52º7.871′N 177º35.650′E
Gully 1	TS25	52º7.860′N 177º35.639′E
Gully 1	TS26	52º7.853′N 177º35.622′E
Gully 1	TS27	52º7.840′N 177º35.607′E
Gully 1	TS28	52º7.831′N 177º35.606′E
Gully 1	TS29	52º7.823′N 177º35.590′E
Gully 1	TS30	52º7.820′N 177º35.570′E
Gully 2	TS61	52º7.766′N 177º35.397′E
Gully 2	TS62	52º7.773′N 177º35.378′E
Gully 2	TS63	52º7.781′N 177º35.364′E
Gully 2	TS64	52º7.791′N 177º35.350′E
Gully 2	TS65	52º7.804′N 177º35.343′E
Gully 2	TS66	52º7.813′N 177º35.328′E
Gully 2	TS67	52º7.820′N 177º35.310′E
Gully 2	TS68	52º7.820′N 177º35.289′E

Gully 2	TS69	52º7.819′N 177º35.267′E
Gully 2	TS70	52º7.820′N 177º35.244′E