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ORIGINAL PAPER

Application of a non-invasive indexing method 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, we tested a non-invasive technique for measuring inter-annual variation in Norway rat (*Rattus norvegicus*) activity 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 captures/100 trap nights). At Sirius Point, we determined the most effective rat-monitoring method to be a series transects spanning the auklet colony, with detection stations set at 25 m intervals, each including a baited wax block. 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 breeding success 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 qualitatively during 2001–2002 when auklets experienced breeding failure. Our rat activity index protocol is likely applicable to other situations in which introduced rodent numbers needs to be monitored while safeguarding native fauna that could be harmed by snap-trapping.

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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 endemic species and unique ecosystems (Croll et al. 2005; Medina et al. 2014; Mulder et al. 2009). 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 (Gray et al. 2014; Moors 1990). 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 (Colautti and MacIsaac 2004; International Union for the Conservation of Nature 2000). 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 (Harper et al. 2015).

Rats (*Rattus* spp.), including Norway rats (*R. norvegicus*), are widespread introduced species able to survive and thrive in a multitude of environmental conditions. 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). Nevertheless, Towns et al. (2006) underlined the need for more quantitative research documenting rat biology and impacts on native species and ecosystems both before and after rat eradications.

Norway rats were introduced onto Aleutian Islands, Alaska as early as the 1780′s (Black 1984; Brooks 1875), with more introductions during 1941–1946 (Murie 1959), and by 1990 self-maintaining populations were present at least 16 islands (Bailey 1993; Bailey and Kaiser 1993). In Alaska, Norway rats persist as far north as Nome, 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, black, or both) are present on Great Sitkin Island (Ebbert and Byrd 2002; Lack et al. 2013). 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 (Bond et al. 2013; Major et al. 2006, 2007, 2013; Major and Jones 2005) and extirpation of other seabirds from Kiska Island (Buxton et al. 2013; Jones et al. 2008). 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 (Bond et al. 2011), yet no quantitative rat population indexing technique was available to measure the relationship quantitatively.

Measuring relative abundance of introduced 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. Unfortunately, the most 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 Jr. 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, and captures with live traps are equally likely, and would likely result in individuals abandoning any breeding attempt (Piatt et al. 1990), 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 (Blackwell et al. 2002; Quy et al. 1993).

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. For comparative purposes, we measured Norway rat activity away from the auklet colony at 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 introduced 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.

Methods

Fieldwork was conducted at Kiska Island, western Aleutian Islands, Alaska (51°58′N, 177°30′E), an oceanic island with no native land mammals that lies entirely within the Alaska Maritime National Wildlife Refuge. Kiska is 39.8 km long, varies in width from 2.8 to 11 km, and has a total area of 28,177 ha. A large auklet colony occupied in 2001 by >1 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, likely introduced during World 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 introduced Arctic foxes (*Vulpes lagopus*) were eradicated in 1987 (Deines and McClellan 1987a, b). 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 volcanic deposits and all 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.

Kiska Harbour tracking tunnel activity

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

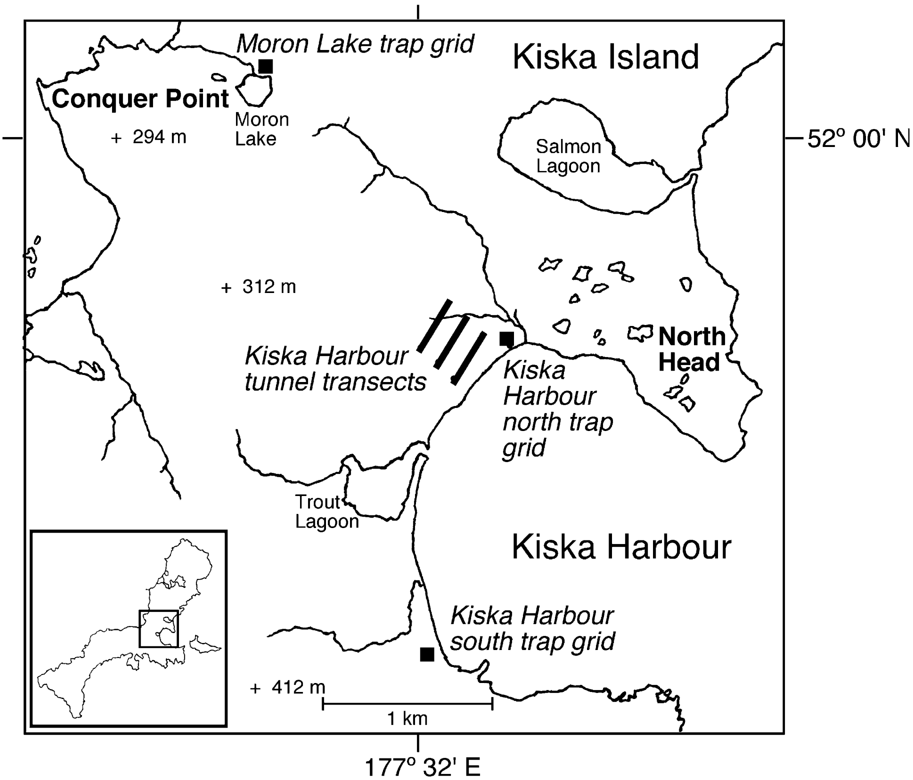

Fig. 1 Location of rat trapping grids and tracking tunnel transects at Kiska Harbour, Kiska Island (*inset* with map location), Aleutian Islands in 2005

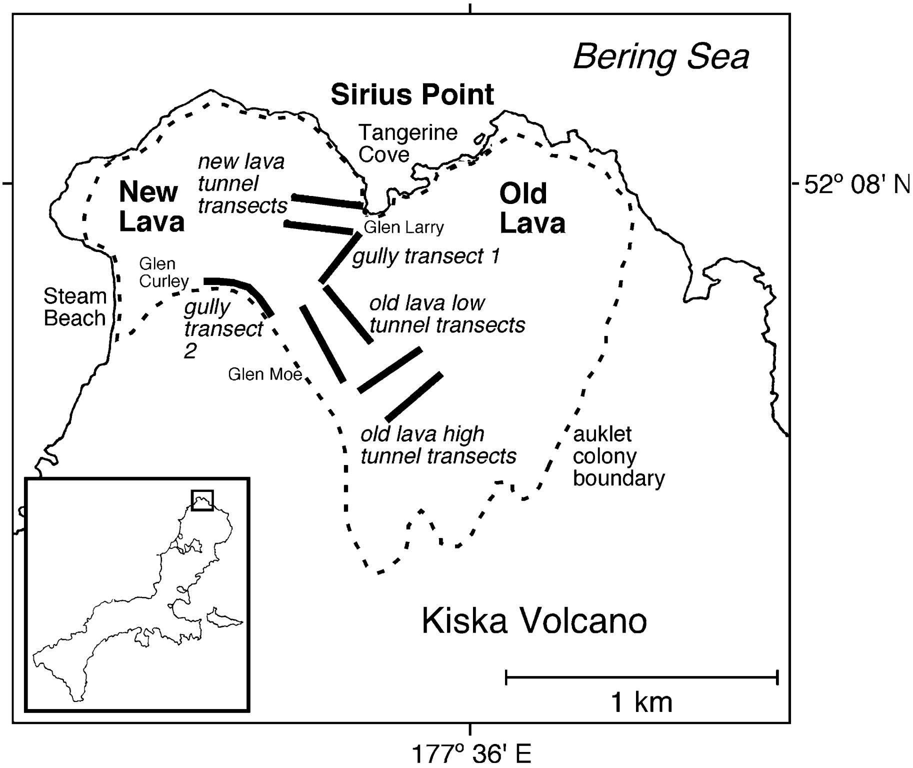

Fig. 2 Location of relative abundance index transects at Sirius Point, Kiska Island (*inset* with map location), Aleutian Islands, Alaska, 2006–2010

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 × 10 × 50 cm, open at each end), and contained 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 2 weeks to reduce the effects of neophobia. Tunnels were then pre-baited with a mixture of peanut butter, honey and oats and left unchecked for an additional 3 days, after which rat activity was measured for two consecutive days. After the first night and again on the second day, rat activity (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 2 weeks and then rat activity measured again (July 15–18, 2005). The index of rat activity was expressed as the percentage of tunnels visited per transect during each of the two-day sets.

Kiska Harbour snap-trap indexing

To obtain a one-time index of rat density at Kiska for comparison to other islands, sixteen snap traps (Victor Professional Expanded Trigger Rat Trap) in a 4 × 4 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 peanut butter, honey, and oats for at least 2 days before being set for 8 days. Rat activity at each trap was recorded each morning: bait gone, trap sprung, rat body, blood, rat droppings and movement of the trap. Each trap was then sprung, cleaned, and re-baited for the next night's activity. An index of activity for each grid was calculated per 100 corrected trap nights (CTN) (Nelson and Clark 1973). We also tested whether capture rates in snap-traps varied by location using a binary logistic regression. 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

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 a tracking tunnel, chew stick (a 15 cm long by 1 cm diameter hardwood dowel saturated in vegetable oil placed inside tunnels), and a 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 tunnels) spaced 25 m apart.

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). 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. Two replicate 6-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) (Bond et al. 2011). Using a generalized linear

Table 1 Location of eight Norway rat relative abundance-indexing tunnel transects at Sirius Point, Kiska Island in 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

model with Poisson error function, 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 (Table 2).

We compared the rat relative abundance estimates to measures of auklet productivity made concurrently (Bond et al. 2011; Major et al. 2006).

Results

Kiska Harbour tracking tunnel activity

Rat activity was highest in transect line TA (detections at 100 % of stations, low elevation, near the shoreline), intermediate in TB (detections at 80 % of stations, moderate elevation)

Table 2 Norway rat activity at three indicators at ten stations set on eight transect lines at Sirius Point, Kiska Island, Aleutian Islands, Alaska in 2006

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

w wax block, *c* chew stick, *t* tracking tunnel and lowest in line TC (detections at 60 % of stations, high elevation; Table 3); there was a significant difference in rat activity among transects (Wald $\chi^2 = 7.51$, $p = 0.023$), but not period (Wald $\chi^2 = 1.42$, $p = 0.23$), or day (Wald $\chi^2 = 0.95$, $p = 0.33$).

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

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 CTN. Kiska Harbour North (18 traps sprung, 9 captures) had a capture index of 7.86 captures/100 CTN, Kiska Harbour South (7 traps sprung, 11 captures) 9.2 captures/100 CTN, and Moron Lake (5 traps sprung, 10 captures) 8.26 captures/100 CTN, 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 2.8× greater at Kiska Harbour North than at Kiska Harbour South and were 4× 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

In 2006, 93 % of all detections (n = 23 cases) included chewing of the wax block (Table 4).

During 2006–2010, we found significant differences among years (Wald $\chi^2_4 = 39.31$, $p < 0.001$); there were significantly more detections in 2006 than 2008 or 2009, which in turn had more detections than 2007 or 2010 (Table 4). 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 $\chi^2_4 = 51.18$, $p < 0.001$); there were more detections in the Gully plot than on New Lava or Old Lava Low; Old Lava High had the fewest detections. There were significantly more rat detections in July (auklet chick-rearing period) than in June (auklet incubation period; Wald $\chi^2_1 = 15.62$, $p < 0.001$). Comparing relationships between our index of rat abundance and hatching, fledging or overall reproductive success for Least Auklets, all relationships were not statistically significant (all $p > 0.37$, all $r < 0.25$).

Table 3 Number of traps with Norway rat activity at Kiska Harbour in 2005

Transect	July 4	July 5	Total	July 17	July 18	Total
TA	10	10	10	9	10	10
TB	5	7	7	7	9	9
TC	0	5	5	6	7	7

Transects consisted of 10 traps each, and were repeated twice

Table 4 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 (hits 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

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 where rats had better access to denser shoreline vegetation and the marine resources of the intertidal zone. 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 (8.2 captures/100 CTN 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), and significantly higher than 3.26 captures/100 CTN on Stewart Island, New Zealand (Harper et al. 2005). At both Langara and Stewart islands, capture rates were significantly different among habitat types. 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. Incorporating trapping grids in other habitat types would also improve existing data on the distribution of Norway rats at Kiska Island. However, 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. Wire mesh covers can exclude passerine birds and scavengers from traps, but such coverings would likely be ineffective at excluding auklets.

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 auklets. Annual measurement of rat abundance at Sirius Point using snap-traps was never considered, as Least Auklets (mean mass: 85 g) 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) worked adequately at Kiska Harbour but were more labor intensive to check and maintain and judged imperfect due to the 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 tracking tunnels set in identical locations each year avoided the pitfall of differential habitat effects on rat activity at tunnels (Blackwell et al. 2002). Nevertheless, comparisons in rat relative abundance indices among our Sirius Point plots were not likely affected as micro-habitat was very similar among plots, although the geological lava formations varied somewhat along and among transects. We set transects to cover representative areas of a substantial proportion of the auklet colony at Sirius Point (Fig. 2), 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 numbers, and tests of their efficacy are sparse (Blackwell et al. 2002). We controlled for the activity effect by counting one or more hits 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. (2002) finding of less of a 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 (Boonstra and Krebs 2012; Madsen et al. 2006). Conditions at Kiska varied among years, especially in snowfall, rainfall and spring temperatures that likely affected 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). For this reason, in future it will be important to quantify annual variation in rat numbers in relation to other variables within this environment. Unfortunately, our measurements during 2006–2010 (n = 5 years only) did not coincide with either abundant rats (from observations of rat sign across the colony site as well as our transect results) or auklet breeding failure (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 (Fig. 2). 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. Finally, a longer data series on rat relative abundance at Sirius Point, Kiska, could be helpful for developing a predictive model for rat irruptions in the Aleutians that would be useful for management of breeding seabirds, and for planning of rat eradication.

Non-invasive rat monitoring is likely to be important both before (Lavers et al. 2010) and after (Taylor et al. 2000) eradication operation components of island restoration projects. Before eradication is contemplated, this may be especially important at islands where rats are normally scarce but have periodic ecologically damaging outbreaks for example at Kiska (Major et al. 2006) and Shemya (Taylor and Brooks 1995) islands in the Aleutians. After eradication measures have been implemented and are believed successful, some studies have shown gradual recovery of native avifauna (Buxton et al. 2013; Lavers et al. 2010), so careful non-invasive monitoring is essential to detect any surviving rats. Our method would be most applicable to non-forested islands at all latitudes, but likely less applicable to tropical islands with trees and native (e.g., land crabs) or non-native (e.g., ants) scavengers present due to interference with the baited wax blocks (Cuthbert et al. 2012). Nevertheless, given the need to avoid non-target mortality of birds and other animals vulnerable to snap traps (especially relict threatened populations persisting on rat-infested islands), 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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References

Bailey EP (1993) Introduction of foxes to Alaskan islands—history, effects on avifauna, and eradication. Fish and Wildlife Service Resource Publication 183, Washington

Bailey EP, Kaiser GW (1993) Impacts of introduced predators on nesting seabirds in the northeast Pacific. In: Vermeer K, Briggs KT, Morgan KH, Siegel-Causey D (eds) The status, ecology, and conservation of marine birds in the North Pacific. Canadian Wildlife Service Special Publication, Ottawa, pp 218–226

Bertram DF (1995) The roles of introduced rats and commercial fishing in the decline of Ancient Murrelets on Langara Island, British Columbia. Conserv Biol 9:865–872

Black LT (1984) Atka: An ethnohistory of the Western Aleutians. Alaska history No. 24. The Limestone Press, Kingston

Blackwell GL, Potter MA, McLennan JA (2002) Rodent density indices from tracking tunnels, snap-traps and Fenn traps: do they tell the same story? N Z J Ecol 26:43–51

Bond AL, Jones IL, Sydeman WJ, Minobe S, Major HL, Williams JC, Byrd GV (2011) Reproductive success of planktivorous seabirds in the North Pacific is related to ocean climate on decadal scales. Mar Ecol Prog Ser 424:205–218

Bond AL, Jones IL, Williams JC, Byrd GV (2013) Survival and reproductive success of crested auklets (*Aethia cristatella*) in the presence of introduced Norway rats (*Rattus norvegicus*). Mar Ornithol 41:41–47

Boonstra R, Krebs CJ (2012) Population dynamics of red-backed voles (*Myodes*) in North America. Oecologia 168:601–620

Brooks CW (1875) Report of Japanese vessels wrecked in the north Pacific Ocean, from the earliest records to the present time. Proc Calif Acad Sci 6:50–64

Buckelew SL, Byrd GV, Howald GR, MacLean S, Sheppard J (2011) Preliminary ecosystem response following invasive Norway rat eradication on Rat Island, Aleutian Islands, Alaska. In: Veitch CR, Clout MN, Towns DR (eds) Island Invasives: eradication and management. IUCN, Gland, pp 275–279

Buxton RT, Major HL, Jones IL, Williams JC (2013) Examining patterns in nocturnal seabird activity and recovery across the Western Aleutian Islands, Alaska, using automated acoustic recording. Auk 130:331–341

Coats RR, Nelson WH, Lewis RQ, Powers HA (1961) Geologic reconnaissance of Kiska Island, Aleutian Islands, Alaska. Geol Surv Bull 1028-R:563–582

Colautti RI, MacIsaac HJ (2004) A neutral terminology to define 'invasive' species. Divers Distrib 10:135–141

Croll DA, Maron JL, Estes JA, Danner EM, Byrd GV (2005) Introduced predators transform subarctic islands from grassland to tundra. Science 307:1959–1961

Cuthbert RJ, Brooke MdL, Torr N (2012) Overcoming hermit-crab interference during rodent-baiting operations: a case study from Henderson Island, South Pacific. Wildl Res 39:70–77

Deines FG, McClellan GT (1987a) Post compound 1080 wildlife surveys, Kiska Island, Aleutian Islands, Alaska. Alaska Maritime NWR, Adak

Deines FG, McClellan GT (1987b) Second survey and monitoring of birds and mammals of Kiska Island, June 1986. Alaska Maritime NWR, Adak

Dice LR (1931) Methods of indicating the abundance of mammals. J Mammal 12:376–381

Drever MC (2004) Capture rates of Norway rats (*Rattus norvegicus*) in a seabird colony: a caveat for investigators. Northwest Nat 85:111–117

Drever MC, Harestad AS (1998) Diets of Norway rats, *Rattus norvegicus*, on Langara Island, Queen Charlotte Islands, British Columbia: implications for conservation of breeding seabirds. Can Field Nat 112:676–683

Ebbert SE, Byrd GV (2002) Eradications of invasive species to restore natural biological diversity on Alaska Maritime National Wildlife Refuge. In: Veitch CR, Clout MN (eds) Turning the tide: the eradication of invasive species. IUCN SSC Invasive Species Specialist Group, Cambridge, pp 102–109

Gray MM et al (2014) Demographic history of a recent invasion of house mice on the isolated Island of Gough. Mol Ecol 23:1923–1939

Harper GA, Dickinson KJM, Seddon PJ (2005) Habitat use by three rat species (*Rattus* spp.) on Stewart Island/Rakiura, New Zealand. N Z J Ecol 29:251–260

Harper GA, van Dinther M, Russell JC, Bunbury N (2015) The response of black rats (*Rattus rattus*) to evergreen and seasonally arid habitats: informing eradication planning on a tropical island. Biol Conserv 185:66–74

Hobson KA, Drever MC, Kaiser GW (1999) Norway rats as predators of burrow-nesting seabirds: insights from stable isotope analysis. J Wildl Manag 63:14–25

International Union for the Conservation of Nature (2000) IUCN guidelines for the prevention of biodiversity loss caused by alien invasive species. SSC Invasive Species Specialist Group, Gland

Jones IL (2013) Evolutionary lag of predator avoidance by island seabirds, and what happens when naturally occurring colonists become 'invasive'. Ibis 155:1–3

Jones HP, Tershy B, Zavaleta ES, Croll DA, Keitt BS, Finkelstein ME, Howald GR (2008) Severity of the effects of invasive rats on seabirds: a global review. Conserv Biol 22:16–26

Kurle CM (2003) Description of the rocky intertidal communities and Norway rat behavior on Rat Island, Alaska in 2003. Alaska Maritime National Wildlife Refuge, Homer

Lack JB, Hamilton MJ, Braun JK, Mares MA, Van Den Bussche R (2013) Comparative phylogeography of invasive *Rattus rattus* and *Rattus norvegicus* in the U.S. reveals distinct colonization histories and dispersal. Biol Invasions 15:1067–1084

Lavers JL, Wilcox C, Donlan CJ (2010) Bird demographic responses to predator removal programs. Biol Invasions 12:3839–3859

Madsen T, Ujvari B, Shine R, Olsson M (2006) Rain, rats and pythons: climate-driven population dynamics of predators and prey in tropical Australia. Austral Ecol 31:30–37

Major HL, Jones IL (2005) Distribution, biology and prey selection of the introduced Norway rat *Rattus norvegicus* at Kiska Island, Aleutian Islands, Alaska. Pac Conserv Biol 11:105–113

Major HL, Jones IL, Byrd GV, Williams JC (2006) Assessing the effects of introduced Norway rats (*Rattus norvegicus*) on survival and productivity of Least Auklets (*Aethia pusilla*). Auk 123:681–694

Major HL, Jones IL, Charette MR, Diamond AW (2007) Variations in the diet of introduced Norway rats (*Rattus norvegicus*) inferred using stable isotope analysis. J Zool (Lond) 271:463–468

Major HL, Bond AL, Jones IL, Eggleston CJ (2013) The stability of a seabird population affected by an introduced predator. Avian Conserv Ecol 8:2. http://www.ace-eco.org/vol8/iss1/art2/

Medina F, Bonnaud E, Vidal E, Nogales M (2014) Underlying impacts of invasive cats on islands: not only a question of predation. Biodivers Conserv 23:327–342

Menkens GE Jr, Anderson SH (1988) Estimation of small mammal population size. Ecology 69:1952–1959

Miller TP, McGrimsey RG, Richter DH, Riehle JR, Nye CJ, Yount ME, Dumoulin JA (1998) Catalogue of the historically active volcanoes of Alaska. Open file report 98-582. U.S. Geological Survey, Anchorage

Moors PJ (1990) Norway rat. In: King CM (ed) The handbook of New Zealand mammals. Oxford University Press, Auckland, pp 192–206

Mulder CPH et al (2009) Direct and indirect effects of rats: does rat eradication restore ecosystem functioning of New Zealand seabird islands? Biol Invasions 11:1671–1688

Murie OJ (1959) Fauna of the Aleutian Islands and Alaska peninsula. N Am Fauna 61:1–364

Nelson L, Clark FW (1973) Correction for sprung traps in catch/effort calculations of trapping results. J Mammal 54:295–298

Piatt JF, Roberts BD, Lidster WW, Wells JL, Hatch SA (1990) Effects of human disturbance on breeding least and crested auklets at St. Lawrence Island, Alaska. Auk 107:342–350

Quy RJ, Cowan DP, Swinney T (1993) Tracking as an activity index to measure gross changes in Norway rat populations. Wildl Soc Bull 21:122–127

Schiller EL (1956) Ecology and health of *Rattus* at Nome, Alaska. J Mammal 37:181–188

Taylor RH, Brooks JE (1995) A survey of Shemya rodents. Project report. U. S. Fish and Wildlife Service Legacy Project 1244. Alaska Maritime National Wildlife Refuge, Homer

Taylor RH, Kaiser GW, Drever MC (2000) Eradication of Norway rats for recovery of seabird habitat on Langara Island, British Columbia. Restor Ecol 8:151–160

Towns DR, Atkinson IAE, Daugherty CH (2006) Have the harmful effects of introduced rats on islands been exaggerated? Biol Invasions 8:863–891

Waldien DL, Cooley MM, Weikel J, Hayes JP, Maguire CC, Manning T, Maier TJ (2004) Incidental captures of birds in small-mammal traps: a cautionary note for interdisciplinary studies. Wildl Soc Bull 32:1260–1268