

**Acoustic recorders reveal the impact of invasive
rats on nocturnal burrow-nesting seabirds in
Haida Gwaii**

by

Luke Robin Halpin

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Approval

Name: Luke R. Halpin
Degree: Master of Resource Management
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Title of Project: *Acoustic recorders reveal the impact of invasive rats on nocturnal burrow-nesting seabirds in Haida Gwaii.*
Examining Committee: **Chair:** Carolyn Duckham
MRM Alumnus, Ph.D. Candidate

Dr Ken Lertzman
Senior Supervisor
Professor

Dr. David B. Lank
Supervisor
University Research Associate and
Adjunct Professor

Dr. Carita Bergman
Supervisor
Terrestrial Ecologist, Parks Canada
Agency

Date Defended/Approved: April 17, 2014

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Abstract

Haida Gwaii supports 1.5 million nesting seabirds, including 50% of the global Ancient Murrelet population and significant nesting populations of several other seabird species. Invasive rats pose a significant threat to the conservation of these populations. In 2010, Gwaii Haanas National Park Reserve and Haida Heritage Site initiated the Night Birds Returning project with the goal of eradicating invasive rats on a number of islands. I used automated acoustic recording units (ARUs) to explore seabird presence and relative abundance of Ancient Murrelets *Synthliboramphus antiquus*, Cassin's Auklets *Ptychoramphus aleuticus*, Fork-tailed Storm-Petrels *Oceanodroma furcata* and Leach's Storm-Petrels *Oceanodroma leucorhoa* on rat-infested and rat-free islands in Gwaii Haanas, during the main breeding season. I assessed the effect of rat presence using two measures derived from acoustic data, relative abundance and attendance period. Relative abundance was higher on rat-free islands, compared to rat-infested islands, but was still less than half that of rat-free islands. Attendance periods were also longer and vocal activity more regular on rat-free islands. My results showed a statistically significant negative effect of rat presence on detections of Ancient Murrelets ($p = 0.01$) and Fork-tailed Storm-Petrels ($p = 0.03$), but the effect was not significant for Cassin's Auklets ($p = 0.31$) and Leach's Storm-Petrels ($p = 0.47$). That rats had not extirpated all seabirds from these islands came as a surprise. Indeed, data suggest that breeding may in fact be occurring, though whether this results in successful fledging still remains unknown. On a positive note, my results suggest that seabird recovery may occur more rapidly following rat eradication on these islands, compared to islands where the species of interest are extirpated.

Keywords: Seabird recovery; acoustic monitoring; bioacoustics; murrelet; storm-petrel; auklet; invasive species, Gwaii Haanas; Haida Gwaii; rat

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Table of Contents

Approval.....	ii
Partial Copyright Licence.....	iii
Ethics Statement.....	iv
Abstract.....	v
Acknowledgements.....	vi
Table of Contents.....	vii
List of Tables.....	ix
List of Figures.....	x
1. Introduction	1
1.1. Invasive Mammal Eradications on Seabird Islands: Global Perspective	2
1.2. Native Seabirds and Introduced Mammals in Haida Gwaii.....	3
1.3. Invasive Mammal Eradication in Haida Gwaii	5
1.4. Automated acoustic monitoring of seabirds on islands.....	6
1.5. Nesting Habits of Nocturnal Seabirds in Gwaii Haanas.....	9
1.5.1. Nesting Habitat of Ancient Murrelets.....	9
1.5.2. Nesting Habitat of Cassin’s Auklets	10
1.5.3. Nesting Habitat of Fork-tailed and Leach’s Storm-Petrels.....	10
1.6. Breeding Phenology of Nocturnal Seabirds in Gwaii Haanas.....	11
1.6.1. Breeding Phenology of the Ancient Murrelet.....	11
1.6.2. Breeding Phenology of the Cassin’s Auklet	11
1.6.3. Breeding Phenology of the Fork-tailed Storm-Petrel	12
1.6.4. Breeding Phenology of the Leach’s Storm-Petrel.....	12
2. Research Objectives and Questions	13
2.1. Objectives.....	13
2.2. Research Questions	14
2.2.1. Does seabird abundance differ with respect to rat presence in Gwaii Haanas?	14
2.2.2. Does seabird attendance differ with respect to rat presence or absence?.....	14
3. Methods.....	15
3.1. Study Area.....	16
3.2. Acoustic Recorder Configuration	19
3.3. Acoustic Recorder Deployment Protocol.....	20
3.4. Site Selection	20
3.4.1. Temporal Allocation of ARU Sampling Effort	23
3.5. Measuring Seabird Presence: Bioacoustic Data Capture.....	26
3.6. Research Metrics and Statistical Analyses	29
3.6.1. Attendance period	29

3.6.2.	Relative abundance	29
3.7.	Statistical analyses	30
4.	Results	31
4.1.	Effects of time of night on seabird vocal activity	31
4.2.	Seabird attendance periods	33
4.2.1.	Length of Ancient Murrelet attendance period	34
4.2.2.	Length of Cassin's Auklet attendance period	34
4.2.3.	Length of Fork-tailed Storm-Petrel attendance period	34
4.2.4.	Length of Leach's Storm-Petrel attendance period	35
4.3.	Effects of Rats on Seabird Relative Abundance in Gwaii Haanas	41
4.3.1.	Ancient Murrelet	43
4.3.2.	Cassin's Auklet	45
4.3.3.	Fork-tailed Storm-Petrel	47
4.3.4.	Leach's Storm-Petrel	49
5.	Discussion	53
5.1.	Effect of Rat Presence on Seabird Detections	53
5.2.	Limitations of the Study	54
5.3.	Interannual Variability in Alcid Relative Abundance	55
5.4.	Seabird Attendance Periods and Relative Abundance	56
5.4.1.	Ancient Murrelet	56
5.4.2.	Cassin's Auklet	57
5.4.3.	Fork-tailed Storm-Petrels	57
5.4.4.	Leach's Storm-Petrels	58
5.5.	Recovery of Nocturnal Seabirds on Arichika and Bischof Islands	58
6.	Conclusions	61
7.	References	63
Appendix A.	Dates, locations and duration of acoustic recording units in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2010 and 2011, to detect nocturnal seabirds	73
Appendix B.	Locations of Songmeter recording interval sites at rat-infested islands (Arichika Island and Bischof Islands group) in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2010	76
Appendix C.	Locations of Songmeter recording interval sites at rat-infested islands (Arichika Island and Bischof Islands group) in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2011	77
Appendix D.	Locations of Songmeter recording interval sites at control islands (Hotspring Islets, Ramsay Island, Alder Island) in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2011	78

List of Tables

Table 1. Acoustic recording survey effort on islands in Gwaii Haanas 2010-2011.....	15
Table 2. Historic population estimates for burrow-nesting seabirds on islands selected for acoustic monitoring in Gwaii Haanas.	21
Table 3. Spatial allocation of sampling effort.	22
Table 4. Temporal allocation of sampling effort at rat-infested and rat-free islands in Gwaii Haanas.	25
Table 5. Length of attendance periods on rat-infested compared to rat-free islands in Gwaii Haanas.	40
Table 6. Relative abundance of nocturnal seabirds in Gwaii Haanas in 2010 and 2011. Means are expressed with standard error.....	42
Table 7. Mean proportion of seabird presence detections per night on rat-infested and rat-free islands in Gwaii Haanas (2011 only) with means compared using a t-test assuming equal variances.	52

List of Figures

- Figure 1. Location of study area in Haida Gwaii archipelago. Acoustic recorders were placed on Arichika Island, Bischof Islands group, Alder Island and islet, Ramsay Island and Hotspring Islets..... 17
- Figure 2. Spectrogram images of seabird species' vocalizations in Gwaii Haanas. (A) Ancient Murrelet, (B) Cassin's Auklet, (C) Fork-tailed Storm-Petrel, (D) Leach's Storm-Petrel. Time (seconds) is on the x axis and frequency (kHz) is on the y axis..... 27
- Figure 3. Mean proportion of recordings per time period per night with detections on rat-free islands for Ancient Murrelet, Cassin's Auklet, Fork-tailed Storm-Petrel and Leach's Storm-Petrel between 12:00 – 03:40 AM..... 32
- Figure 4. Mean proportion of recordings per time period per night with detections on rat-infested islands for Ancient Murrelet, Cassin's Auklet, Fork-tailed Storm-Petrel and Leach's Storm-Petrel between 12:00 – 03:40 AM. Stars indicate a statistically significant difference in means between recording times..... 33
- Figure 5. Length and continuity of Ancient Murrelet attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365..... 36
- Figure 6. Length and continuity of Cassin's Auklet attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365..... 37
- Figure 7. Length and continuity of Fork-tailed Storm-Petrel attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365. 38
- Figure 8. Length and continuity of Leach's Storm-Petrel attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365. 39
- Figure 9. Mean number of recordings per night with Ancient Murrelet detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error..... 43
- Figure 10. Seasonal and spatial pattern of Ancient Murrelet detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading..... 44
- Figure 11. Seasonal and spatial pattern of the mean number of Ancient Murrelet recordings with detections by day and island in 2011. Trend lines use loess smoothing..... 44

Figure 12. Mean number of recordings per night with Cassin’s Auklet detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.....	45
Figure 13. Seasonal and spatial pattern of Cassin’s Auklet detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.....	46
Figure 14. Seasonal and spatial pattern of the mean number of Cassin’s Auklet recordings with detections by day and island in 2011. Trend lines use loess smoothing.....	46
Figure 15. Mean number of recordings per night with Fork-tailed Storm-Petrel detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.	47
Figure 16. Seasonal and spatial pattern of Fork-tailed Storm-Petrel detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.....	48
Figure 17. Seasonal and spatial pattern of the mean number of Fork-tailed Storm-Petrel recordings with detections by day and island in 2011. Trend lines use loess smoothing.	48
Figure 18. Mean number of recordings per night with Leach’s Storm-Petrel detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.	49
Figure 19. Seasonal and spatial pattern of Leach’s Storm-Petrel detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.....	50
Figure 20. Seasonal and spatial pattern of the mean number of Leach’s Storm-Petrel recordings with detections by day and island in 2011. Trend lines use loess smoothing.	50

1. Introduction

The invasion or introduction of non-native species into ecosystems of which they are not historically a component is considered a major driver of adverse effects on biological diversity and ecosystem function (Carlton, 1989; Elton, 1958; Mack et al., 2000). Invasive alien species (IAS hereafter) are well known to cause increased rates of extinction (Blackburn et al., 2009; Jones. et al., 2008; Vitousek, D'Antonio, Loope, & Westbrooks, 1996). In 2005, the IUCN Red List database described causes of extinctions for 170 species. IAS were cited as a cause for the loss of 54% of these, with 20% lost as a direct result of IAS (Clavero & García-Berthou, 2005). Furthermore, IAS are considered the leading cause of extinctions in birds (Clavero & García-Berthou, 2005), since the year 1500 IAS have been implicated in the loss of at least 71 species (BirdLife International, 2008).

Seabirds, in particular, are threatened with the risk of extinction, with almost half of the world's seabird species currently experiencing population decline. IAS, predominantly mammalian, potentially affect 75% of all threatened seabirds (Croxall et al., 2012). Impacts of introduced mammals on seabird populations are well documented (Howald et al., 2007; Jones. et al., 2008; P. M. Moors & Atkinson, 1984; Rauzon, 2008; D. R. Towns et al., 2011). Many seabirds evolved in isolated island ecosystems, which led to a lack of adequate defence mechanisms against such predators. Certain life history features of nocturnal seabirds make them particularly vulnerable to predation by rats and other introduced predators at their breeding sites: slow growth to sexual maturity, low rates of egg production and chicks that are present for long periods in underground burrows or crevice nest sites that are easily accessible to small mammals (Croxall et al., 2012; D. R. Towns et al., 2011).

Rats, *Rattus spp.*, are present on 90% of the world's island archipelagos and are considered the most widespread of introduced mammals (H. Jones, 2010; David R. Towns, Atkinson, & Daugherty, 2006). They have likely been the cause of the greatest number of extinctions on islands and are considered to have had the largest impact on seabirds (P. M. Moors & Atkinson, 1984; David R. Towns et al., 2009, 2006). Rats act primarily at breeding sites, preying on seabirds of varying sizes, from those as small as 27 g to individuals up to 2855 g (Jones et al., 2008), including eggs, chicks and adults (Atkinson, 1985). Indirect impacts of rats in seabird colonies include disturbance, higher mortality rates and nest abandonment (Holly P. Jones, Williamhenry, Howald, Tershy, & Croll, 2006; Jouventin, Bried, & Micol, 2003). Small burrow-nesting seabirds, especially Hydrobatidae (storm-petrels), Alcidae (auks, murrelets and puffins), Pelecanoididae (diving petrels), and some Procellariidae (petrels, shearwaters, fulmarine petrels and prions), are particularly vulnerable due to their small size and largely nocturnal colony behaviour (Atkinson, 1985; Clavero, Brotons, Pons, & Sol, 2009; Jones. et al., 2008).

1.1. Invasive Mammal Eradications on Seabird Islands: Global Perspective

The fundamental objective of IAS eradication on seabird islands is to restore ecological integrity and allow seabird populations to recover to pre-invasion states (Atkinson, 1988; H. Jones, 2010). Invasive mammal eradication can be logistically and economically feasible on isolated island ecosystems (Howald et al., 2007; H. P. Jones et al., 2011; Rauzon, 2008; Taylor, Kaiser, & Drever, 2000). Beginning in the 1960s through to the mid-1980s, conservationists in New Zealand developed techniques and new technologies to improve success of rodent eradications on islands (P. J. Moors, 1985; Taylor & Thomas, 1989, 1993). Since eradication efforts began in 1951, 387 rodent eradication campaigns have occurred worldwide with at least 332 of these campaigns reported successful (Howald et al., 2007).

The first recorded rat eradication took place in 1951 on Rouzic Island in the Sept Îles Archipelago, France, using strychnine poison (Lorvelec & Pascal, 2005). In 1960, rats

were eradicated from Maria Island and David Rocks in New Zealand using warfarin, an anticoagulant poison (Towns & Broome, 2003). Early rodent eradications typically occurred on small islands of only a few hectares in size (e.g. Rouzic Is. [3.3 ha], Maria Is. [1 ha], David Rocks [1 ha]). Later it became evident through such successes that eradication was feasible on larger islands, for example in 1988 on Breaksea Island (170 ha), Fiordland, New Zealand (Taylor & Thomas, 1993), on Langara Island, Haida Gwaii in 1995 (3015 ha) (Kaiser et al., 1997), in 2006 on Hauturu, New Zealand (3,083 ha) (David R. Towns et al., 2006), and in 2011 the Rangitoto-Motutapu Islands (3,880 ha) were declared pest free (New Zealand Department of Conservation, 2011).

1.2. Native Seabirds and Introduced Mammals in Haida Gwaii

Records of introduced predators on the Pacific Northwest coast began to accumulate in 1750, when arctic foxes, *Alopex lagopus*, were introduced to the western Aleutian Islands. From the 1800s to the early 1900s, red foxes, *Vulpes vulpes*, arctic foxes, Norway rats, *Rattus norvegicus*, ground squirrels, *Spermophilus undulates*, and various other rodents were introduced to Alaskan islands (Bailey & Kaiser, 1993). By 1930, approximately 450 islands in Alaska had IAS, at which point the U.S. government began to express concern about declining seabirds (Bailey & Kaiser, 1993).

Haida Gwaii (“*Xaayda Gwaay.yaay*” in the Haida language, Figure 1), is an isolated island archipelago 80 km off the northwest coast of British Columbia, Canada. It is home to more endemic subspecies than anywhere else in Canada and the archipelago has been dubbed “The Canadian Galápagos” (Foster, 1982). More than half of the archipelago’s 1.5 million nesting seabirds, including the federally listed Ancient Murrelet *Synthliboramphus antiquus* (Special Concern, Schedule 1), nest in Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve and Haida Heritage Site (“Gwaii Haanas”) (A. Harfenist, Sloan, & Bartier, 2002). Haida Gwaii supports 50% of the global population of Ancient Murrelets and it is the only nesting location of this species in Canada (Anthony J. Gaston, 1994). Haida Gwaii also supports 21% of the British Columbia storm-petrel

population (Mike Rodway, 1991), and 18% of the global population of Cassin's Auklets (Mike Rodway, 1991).

An agreement between the Government of Canada and the Haida Nation was reached in 1993 to protect Gwaii Haanas. Part of the mandate of Parks Canada Agency (representing the Government of Canada) is to protect and increase ecological integrity in the areas under its management. With this in mind, projects that contribute to ecological restoration receive priority funding.

Ten non-native mammals have been introduced to Haida Gwaii since European contact (T. E. Golumbia, Bland, Moore, & Bartier, 2002). In the 1940s raccoons *Procyon lotor* were introduced to several locations on the east coast of Graham Island as a source of fur for trappers (T. E. Golumbia et al., 2002). With the absence of any natural predator, raccoons quickly spread to most of Graham and Moresby Islands and to other smaller islands that support breeding seabirds (Anne Harfenist, Macdowell, Golumbia, & Schultze, 2000).

Black rats and Norway rats both occur in Haida Gwaii (Bertram & Nagorsen, 1995) and represent a significant threat to seabird conservation. Black rats probably arrived with the first European sailing ships in the 1700s and possibly earlier (T. E. Golumbia et al., 2002; Todd E Golumbia, 2000). By 1901 Norway rats were known to occur locally, but were not confirmed until 1908 when they escaped from a ship beached for repairs (Harrison, 1925). In 1981 Norway rats were confirmed on St. James Island on the southern end of the archipelago (Bertram & Nagorsen, 1995). To date, rats have been recorded on more than 20 islands in the Haida Gwaii archipelago, seven of which support burrow-nesting seabird populations (Bertram and Nagorsen 1995, Parks Canada Agency 2009, C. Bergman, *pers. comm.*). Black rats were identified on Langara Island, in northwestern Haida Gwaii, in 1946, after which they were displaced by Norway rats, identified in 1981 (Bertram & Nagorsen, 1995; T. E. Golumbia et al., 2002). Drever and Harestad (1998) conducted stomach content analyses confirming that Ancient Murrelets formed a large part of Norway rats' diet on Langara Island. Rats were first discovered on the Bischofs and Arichika Islands by Parks Canada in 1992 and 2006 respectively (Parks

Canada Agency, 2009). The only sign of possible continued presence of breeding seabirds that has been documented since the CWS surveys is the presence of an Ancient Murrelet eggshell on Arichika Island in 2008, and on the Bischof Islands group, burrow calls of Fork-tailed Storm-Petrels were heard, also in 2008 (C. Bergman, *pers. comm.*).

The impact of introduced rats in Haida Gwaii has been dramatic. In 1971 on Arichika Island, Summers (1974) estimated 500 breeding pairs of Ancient Murrelets, 500 breeding pairs of Fork-tailed Storm-Petrels, 500 breeding pairs of Cassin's Auklets and approximately 25 breeding pairs of Leach's Storm-Petrels. On Bischof Islands, Summers estimated 500 breeding pairs of Ancient Murrelets and 5,000 breeding pairs of Fork-tailed Storm-Petrels on the Bischofs (Summers, 1974). In 1985, the Canadian Wildlife Service ("CWS") conducted surveys in Haida Gwaii along the east coast of Moresby Island, discovering only two active storm-petrel burrows on the Bischof Islands group (M. Rodway, Lemon, & Kaiser, 1988), and none on Arichika Island, except for a single possible unoccupied storm-petrel burrow. Rodway et al. (1988) suggested that seabird populations may be close to extirpated from Bischof and Arichika. It should be noted that effort during early seabird surveys was minimal and variable, and estimates of variance were not always provided.

1.3. Invasive Mammal Eradication in Haida Gwaii

The CWS successfully organized the first introduced rat eradication project in Haida Gwaii on Langara Island in 1995 (Kaiser et al., 1997); and in 1998 Parks Canada successfully removed rats from St. James Island to protect a small colony of Tufted Puffins (Parks Canada Agency, 2009). Prior to 1950, the Ancient Murrelet population on Langara Island was estimated at 200,000 breeding pairs. By 1988, five of the six burrow-nesting seabirds on Langara had disappeared (e.g. Cassin's Auklet *Ptychoramphus aleuticus*, Fork-tailed Storm-Petrel *Oceanodroma furcata*, Leach's Storm-Petrel *Oceanodroma leucorhoa*, Rhinoceros Auklet *Cerorhinca monocerata*, and Tufted Puffin *Fratercula cirrhata*). The remaining Ancient Murrelet colony size was estimated at 24,000 pairs in

1988 and restricted to a small area in the northwest portion of the island (Bertram & Nagorsen, 1995).

In 1995 Environment Canada instigated the Langara Island Seabird Habitat Recovery Project, which was considered complete by 1996 (Kaiser et al., 1997; Taylor et al., 2000). Nine years later the Ancient Murrelet population on Langara Island, had almost doubled (Regehr, Rodway, Lemon, & Hipfner, 2007). The area of occupancy had also increased and Cassin's Auklets recolonized parts of the island.

In 2009 Parks Canada initiated a project called Night Birds Returning ("*SGiN Xaana Sdiihltl'ixa*" in the Haida language) to eradicate invasive rats on the Bischof Islands group (66.1 ha), Arichika Island (14.6 ha) (Phase 1; bait stations), Murchison Island (425 ha) and Faraday Island (308 ha) (Phase 2; aerial distribution). Rodenticide was placed in bait stations for Phase 1 from August 2011 to April 2014; and distributed aurally for Phase 2 during September 2013. My research is one monitoring component of the Night Birds Returning project. In this work, I focus on assessing the presence and activity of nocturnal seabirds, using acoustic monitoring, on rat-infested (Arichika and Bischof Islands) and rat-free islands (Alder, Hotspring and Ramsay Islands). I use the presence and absence of seabirds in acoustic recordings to explore the effect of rats on seabird detection rates on rat-infested compared to rat-free islands. My principal objective is to examine the timing and relative amount of seabird activity on treatment and control islands, measured by acoustic monitoring prior to the start of Phase 1 rat eradication efforts. These data comprise part of a dataset with a Before-After-Control-Impact (BACI) design, useful to determine the relative success of eradication efforts, and to inform future management decisions for active or passive seabird and ecosystem recovery goals.

1.4. Automated acoustic monitoring of seabirds on islands.

Effective monitoring of seabirds before, during and after predator eradication is helpful to document seabird recovery and inform management decisions and future interventions (Durrett & Mulder, 2011). Post-eradication demographic responses of

seabirds are rarely studied and more research into understanding this is required (Jones et al., 2011; Lavers et al., 2010), including development of criteria and metrics to measure and quantify seabird recovery (Brandes, 2008; Lavers et al., 2010). As Durrett and Mulder (2011) discuss, monitoring allows the degree of restoration success to be evaluated and appropriate responses to be initiated quickly if IAS eradication is not successful. Despite this, studying nocturnal burrow-nesting seabirds on islands is notoriously difficult and expensive due to their inconspicuous nocturnal behaviour, burrow-nesting habits, and colonies typically being located at sites with difficult access. Seabird recovery monitoring can be disruptive to species of interest and sometimes impractical to accomplish where restoration efforts occur over large areas and on inaccessible islands.

Conservation biologists need to find feasible solutions to monitoring challenges when developing plans to assess baseline conditions and recovery goals. Lack of long-term funding, or intermittent funding is often a significant barrier to the inclusion of long-term monitoring in restoration programs (Holly P. Jones & Kress, 2012). Therefore, project budgets for long-term monitoring studies need to be realistic, use sensible timelines and determine measurable goals to evaluate seabird recovery (H. P. Jones et al., 2011; Holly P. Jones & Kress, 2012). Full island ecosystem recovery can take years or decades to emerge; thus monitoring programs also need to consider long time periods to seabird recovery (H. P. Jones et al., 2011; H. Jones, 2010; D. R. Towns, 2009).

One potential solution to the seabird-monitoring dilemma is use of acoustic monitoring technology. Recent advancements in acoustic recording technology have allowed monitoring of various wildlife with minimal field effort and significant reduction the costs associated with conventional monitoring (Brandes, 2008; Farnsworth, 2005; Rempel, Francis, Robinson, & Campbell, 2013). There have been developments and improvements in computer software for bioacoustic analysis, as well as reduced equipment costs and increased portability of acoustic recording units (“ARU”).

An ARU is a digital sound recorder that can be programmed to function on a fully-automated sampling schedule that is predetermined by the user. Users are able to customize a daily recording schedule as well as the digital sampling frequency and the

number of microphones used. ARUs are generally inconspicuous with electronics and batteries contained inside a weatherproof casing. Microphones are also weatherproof and can be attached to various microphone ports on the ARU casing. Digital sound recordings are stored on removable digital storage (usually SD memory cards), and recordings can be saved in a variety of file formats that include details about when and where a recording was made.

ARUs are useful tools for monitoring any species with a uniquely identifiable vocal component to its behavior. Because they require only deployment, minimal servicing, and retrieval, their use can minimize investigator disturbance of seabird colonies (Brandes, 2008). Staff with limited bird identification skills can deploy units in the field; sampling can be kept consistent between and among days, and there is potential to reduce observer effects through consistent interpretation of data (Hobson, Rempel, Greenwood, Turnbull, & Wilgenburg, 2002; Rempel et al., 2013). Along with acoustic recording technology, there have been developments in computer software that facilitate processing of acoustic information. This includes computer programs such as Raven Pro (Bioacoustics Research Program, 2011), Song Scope (Wildlife Acoustics Inc, 2009) and Xbat (Figueroa, 2012).

ARUs can produce very large volumes of acoustic data. While it is often impossible to quantify the number of calling individuals in large acoustic datasets, they can provide information on presence or absence and indices of relative abundance can be developed (Brandes, 2008). Researchers have applied bioacoustic monitoring to a wide range of fauna including birds, mammals, insects, amphibians and even fish (Charif & Pitzrick, 2008; Oswald, Au, & Duennebie, 2011; Riede, 1998; Speares, Holt, & Johnston, 2010). Nocturnal seabirds are ideal candidates for bioacoustic monitoring because most species exhibit highly conspicuous vocal behavior at their colonies (I. L. Jones, Falls, & Gaston, 1989; Seneviratne, Jones, & Miller, 2009). Furthermore, vocal activities of nocturnal seabird species that occur in Haida Gwaii have been well-documented and are associated with specific types of behaviour (I. L. Jones et al., 1989; Seneviratne et al., 2009; Simons, 1981; Taoka, Sato, Kamada, & Okumura, 1989).

The use of acoustic technology to monitor birds is expanding. For example, Goyette (2011) used ARUs and Xbat software to detect nocturnal tropical birds. Borker et al. (2014) used Xbat to detect Forster's Tern (*Sterna forsteri*) calls and compared mean call rates with mean active nest counts to correlate acoustic activity with relative abundance. Goh (2011) used Xbat to estimate relative abundance of Cory's Shearwaters (*Calonectris diomedea*) in the Azores. Oppel et al. (2014) used vocal activity (mean number of calls per minute) of Cory's Shearwaters to examine the relationship between call rates and nest density. In the Aleutian Islands, Alaska, Buxton and Jones (2012; 2013) used ARUs to assess the status and activity of nocturnal seabirds in their colonies. They automatically detected seabird vocalizations using Song Scope software (Wildlife Acoustics Inc, 2009) and quantified the mean number of individual seabird call detections per night for various species, using these metrics as indices of activity and relative abundance.

1.5. Nesting Habits of Nocturnal Seabirds in Gwaii Haanas

1.5.1. Nesting Habitat of Ancient Murrelets

Ancient Murrelets tend to excavate nest burrows and cavities in soft soil, under tree roots, in shallow holes under grassy tussocks, beneath fallen logs and sometimes in underlying rock cavities (A. J. Gaston, 1992). Mature forested areas (typical of Gwaii Haanas islands) are preferred, but where forest is absent Ancient Murrelets will choose densely vegetated areas that are not waterlogged. Usually they prefer areas with a steep slope gradient, but many large colonies do exist in relatively flat areas (A. J. Gaston, 1992). Burrows are usually curved with entrances of approximately 8 – 14 cm in diameter, and birds generally do not defecate at the burrow entrance and sometimes conceal burrow entrances in vegetation, so that burrows appear unused (A. J. Gaston, 1994; K. Vermeer & Lemon, 1986).

1.5.2. Nesting Habitat of Cassin's Auklets

Cassin's Auklets often occupy the same islands as Ancient Murrelets and the two species may overlap near the forest edge (e.g. Frederick Island, Gwaii Haanas), but avoid forest interior, preferring to nest within 100m of shore (A. Harfenist et al., 2002; K. Vermeer & Lemon, 1986). Similar to Ancient Murrelets, they occupy burrows in soft soil substrate as well as rock cavities and chambers beneath fallen logs. Burrow sizes are similar to the Ancient Murrelet. Active burrows are often evident by the presence of guano at the burrow entrance and a strong fishy odour. In Haida Gwaii Cassin's Auklets tend to nest under mature Sitka spruce *Picea sitchensis* and western hemlock *Tsuga heterophylla* in tree roots, stumps, beneath fallen logs and in burrows and grassy tussocks (D. Ainley, Manuwal, Adams, & Thoresen, 2011; K. Vermeer & Lemon, 1986).

1.5.3. Nesting Habitat of Fork-tailed and Leach's Storm-Petrels

Fork-tailed and Leach's Storm-Petrels in Gwaii Haanas both nest under Sitka spruce in tree roots, beneath fallen logs, and to a lesser extent in open grassy areas (Kees Vermeer, Devito, & Rankin, 1988). As such, they frequently occur in conjunction with one another to the extent that some surveys in Haida Gwaii have failed to determine the proportion of each species (A. Harfenist et al., 2002). Storm-petrel burrows are generally smaller than those of Ancient Murrelets and Cassin's Auklets, and active burrows have a typical petrel odour that is easily identifiable by experienced seabird biologists. Storm-petrels will nest both inland on islands and on the coast. The burrows of each species are similar in size at around 9-10 cm in diameter (Boersma, Wheelwright, Nerini, & Wheelwright, 1980), but Fork-tailed Storm-Petrels tend to construct nests in tree roots whereas Leach's Storm-Petrels have a tendency to construct burrows in more open habitat (Kees Vermeer et al., 1988). Both species are reported to frequently nest amongst Cassin's Auklet colonies, but less frequently in Ancient Murrelet colonies (M. Rodway et al., 1988).

1.6. Breeding Phenology of Nocturnal Seabirds in Gwaii Haanas

To determine ARU deployment dates, I studied the previously published breeding phenology of the study species to ensure that ARU deployments coincided with their breeding period in Haida Gwaii. Because the study species are known to be highly vocal during colony attendance, I assume that, if they are present on land at recording sites within a 100 m radius of ARUs, then they are highly detectable.

1.6.1. Breeding Phenology of the Ancient Murrelet

Ancient Murrelets first come ashore to nest sites 2 – 3 weeks before egg-laying begins. Non-breeding birds also visit colonies during the incubation period. On Limestone Island, Haida Gwaii the median date of clutch completion was 17 Apr to 9 May over a 22-year period (Gaston and Akiko 2010). The earliest chick departure was constant over 17 seasons occurring between 7 – 12 May; the median chick departure date varied by 9 days between 19 – 27 May, with the date of the last departure occurring by 22 June (A J Gaston & Akiko, 2010). Ancient Murrelet mean incubation period was 32.7 days at Reef Island, BC, and most chicks fledge within 48 hours of hatching (A. J. Gaston, 1992).

1.6.2. Breeding Phenology of the Cassin's Auklet

In British Columbia, Cassin's Auklet egg laying begins as early as mid- to late March and extends to mid-May on Triangle Island (Hipfner, Charleton, & Davies, 2004), but typically occurs in mid-April (K. Vermeer, 1987). In Haida Gwaii numbers of Cassin's Auklets begin to increase in March (A. Harfenist et al., 2002). Timing of breeding is strongly dependent on ocean conditions and events (e.g. El Niño/La Niña); Cassin's Auklet mean incubation period on the Farallon Islands, CA was 39 days (D. G. Ainley & Boekelheide, 1990). Most Cassin's Auklet chicks in British Columbia fledge by the end of July (A. J. Gaston & Jones, 1998; K. Vermeer, 1981).

1.6.3. Breeding Phenology of the Fork-tailed Storm-Petrel

Northern populations of Fork-tailed Storm-Petrels arrive at colony sites by late March – early April (Boersma et al. 1980). In Alaska, Boersma and Parrish (1998) observed highly variable laying dates of up to 2 months within and among breeding seasons. In British Columbia peak hatching occurred between the end of May – early June, but late records occur in the second week of August (Kees Vermeer et al., 1988). In Haida Gwaii Fork-tailed Storm-Petrels breed, and can be seen at colony sites, between April – September (A. Harfenist et al., 2002). Their incubation period varies more than any other procellariiform, but the mean incubation period on Amatuli Island, AK was 49.8 days (Boersma et al., 1980).

1.6.4. Breeding Phenology of the Leach's Storm-Petrel

In British Columbia, Leach's Storm-Petrel hatching occurs in late July and August (mean hatching date August 9) on Petrel Island, with chick fledging occurring in late September (Kees Vermeer et al., 1988). In Haida Gwaii significant numbers of Leach's Storm-Petrel breed between June – November (A. Harfenist et al., 2002). Vermeer et al. (1988) found that most Leach's Storm-Petrels hatched 53 and fledged 60 days later than Fork-tailed Storm-Petrels. The mean incubation period was 43.3 days on Great Island, NF (Huntington, Butler, & Mauck, 1996).

2. Research Objectives and Questions

2.1. Objectives

My objectives in this study are to:

(1) Investigate the seasonal patterns of nocturnal seabird presence in relation to the presence or absence of rats on Arichika Island, Bischof Islands group, Alder Island, Ramsay Island and the Hotspring Islets in Gwaii Haanas.

(2) Provide guidance with respect to efficient timing of future data collection and analysis techniques of ARU data for the four major nocturnal seabird species present: Ancient Murrelets, Cassin's Auklets, Fork-tailed Storm-Petrels and Leach's Storm-Petrels.

(3) Determine the length of time during which nocturnal seabird species are present at terrestrial breeding sites on rat-infested compared to rat-free islands to infer whether some degree of breeding activity occurs on rat-infested islands.

(4) Develop an index of relative abundance to assess the amount of seabird activity on rat-infested compared to rat-free islands during periods of occupancy.

I intend for this study to provide baseline information about the distribution and relative abundance of nocturnal seabirds on Gwaii Haanas islands that may undergo rat-eradication treatment, and for my automated acoustic monitoring method to help evaluate nocturnal seabird recovery in the future.

2.2. Research Questions

2.2.1. Does seabird abundance differ with respect to rat presence in Gwaii Haanas?

I predicted that relative abundance of seabirds on rat-infested islands would be significantly lower than on rat-free islands; or that nocturnal seabirds are entirely absent on rat-infested islands due to the effect of rats as predators. If rat disturbance affects breeding activity, then I expected to see partial colony abandonment (e.g. a reduction in breeding population size) and therefore fewer detections at those sites. I expected that, on rat-infested islands, seabirds might exist at remnant population sizes and/or exhibit reduced breeding activity at the colony. Therefore I predicted less vocal activity, possibly because of rat disturbance. I predicted that, if birds are present on rat-infested islands, relative abundance (defined in section 3.8) would increase following rat eradication (to be measured in future).

2.2.2. Does seabird attendance differ with respect to rat presence or absence?

On islands where invasive predators are absent, I expect that the length of the attendance period (defined in section 3.8) is typical of undisturbed conditions and breeding activities (e.g. colony attendance, courtship behaviour, egg laying, incubation, chick rearing and fledging) span the full extent of the known breeding phenology of each of the four study species. Under these conditions the length of the attendance period is unaffected (i.e. not shortened) by predation or predator disturbance. On islands where invasive rats are present, I expect that the length of the attendance period may be altered: for example, it may be shortened when adults, chicks and/or eggs are predated on by rats, which may cause breeding activities to cease earlier than at undisturbed islands. Furthermore, at study sites with greater relative abundance, I expected there to be more nights with detections during the attendance period, because of individuals attending nest sites at different times.

3. Methods

I used ARUs (Songmeter SM2 model, Wildlife Acoustics Inc., Concord, MA) to record 10-minute on-off periods through the night on five islands in Gwaii Haanas, including two with and three without rats (Table 1). Recordings were made at two rat-infested islands in 2010 and 2011; the Bischof Islands group, consisting of six small islands close together, and Arichika Island. For rat-free control islands, recording sites in 2011 included three additional islands: Alder Island (including its small islet), Ramsay Island and Hotspring Island (two islets close together). In 2010, I deployed ARUs from 17 April to 31 August; and in 2011, I deployed ARUs from 5 April to 7 September. Given the limitations in the number of recording devices available, I moved ARUs monthly to sample broadly across the islands, and to target various species that differ in their nesting habitat requirements.

Island	Rats	Year	Start Recording	End Recording	Total Recording Hours	Total Recording Nights
Arichika	Yes	2010	17 April	31 August	272	136
Bischof	Yes	2010	15 April	31 August	276	138
Arichika	Yes	2011	05 April	01 September	298	149
Bischof	Yes	2011	07 April	01 September	294	147
Alder	No	2011	05 April	03 September	302	151
Ramsay	No	2011	07 April	31 May	108	54
Hotspring	No	2011	01 June	07 September	196	98

Table 1. Acoustic recording survey effort on islands in Gwaii Haanas 2010-2011.

3.1. Study Area

The study area (Figure 1) is located to the east of central Moresby Island in the southern portion of the Haida Gwaii archipelago. The study islands are situated in Juan Perez Sound in Hecate Strait, with the Bischof Islands group (Photo 1) to the southwest of Lyell Island, and Ramsay Island and Hotspring Islets to the southeast of Lyell. Arichika Island, Alder Island and Alder Islet are located to the northeast of Huxley Island in the southern portion of Juan Perez Sound (52°31'N, 131°26'W) (Photo 2). Arichika Island has steeper slope gradients than Bischof and rises higher above the water. Bischof Islands are flatter and with large areas of the intertidal zone exposed at low tide with exposed rocks and islets.

The habitat on these low-elevation islands falls within the coastal western hemlock biogeoclimatic zone (subzone: CWHwh1; Meidinger and Pojar 1991). These densely vegetated and heavily forested islands are dominated by large stands typical of the Wet Hypermaritime subzone of the Coastal Western Hemlock zone (CWHwh): western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), redcedar (*Thuja plicata*) and to a lesser extent yellow-cedar (*Callitropsis nootkatensis*). Bryophytes including step moss (*Hylocomium splendens*), lanky moss (*Rhytidiadelphus loreus*), and large leafy moss (*Rhizomnium glabrescens*) dominate the understory. Herb and shrub layers are dominated by salal (*Gaultheria shallon*) and deer fern (*Blechnum spicant*), but are often sparse due to browsing by introduced Sitka Black-tailed Deer (*Odocoileus hemionus sitkensis*). Climate in the CWHwh1 is generally mild. Winters are wet with little snowfall and summers are generally cool and moist with frequent fog and cloud cover (Meidinger & Pojar, 1991).

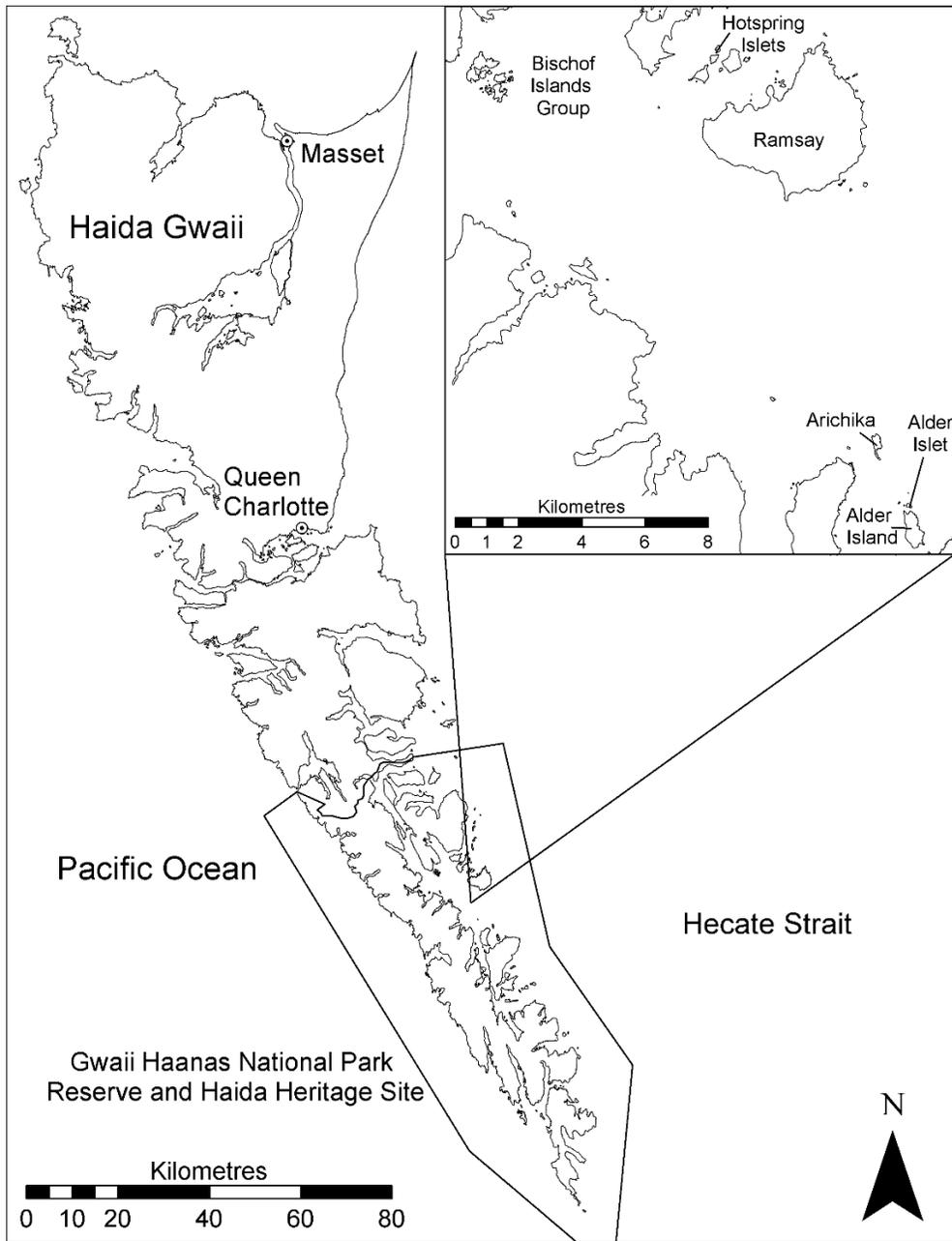


Figure 1. Location of study area in Haida Gwaii archipelago. Acoustic recorders were placed on Arichika Island, Bischof Islands group, Alder Island and islet, Ramsay Island and Hotspring Islets.



Photo 1. Bischof Islands with Beresford Inlet and Lyell Island in the background to the north, Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve and Haida Heritage Site. ©A.S. Wright, Parks Canada, www.cold-coast.com 2013.



Photo 2. Arichika Island with Ramsay Island in the background to the north, Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve and Haida Heritage Site. ©A.S. Wright, Parks Canada, www.cold-coast.com 2013.

3.2. Acoustic Recorder Configuration

I configured ARUs to record on a single channel at 24KHz with one NEMA 4X weatherproof omnidirectional microphone, with a sensitivity of -36 ± 4 dB, frequency response 20Hz-20KHz, signal-to-noise ratio >62 dB. Each ARU was fitted with two SDHC class-6 memory cards (32GB & 16GB, Kingston Technology Company Inc.) to store recorded sound files. I programmed Songmeters to record twelve alternations of 10 minute recordings followed by a 10 minute off period from 10:00 PM to 04:00 AM PDT each night, for a total of three hours cumulative recorded time per night. Due to the large volume of acoustic data, I focused data capture on recordings made in the period between 12:00 AM and 03:40 AM. This time period appeared to be the most active period each night for nocturnal seabirds in the region.

I programmed Songmeters to record at 24 KHz, well above the frequency range necessary to digitize vocalizations of Gwaii Haanas nocturnal seabirds for bioacoustic analysis. I recorded at this sample rate to take into account the Nyquist frequency, which must be more than twice as high as the highest frequency recorded (Charif, Waack, & Strickman, 2010). This avoids aliasing distortion due to recording at inadequate sample rates. Ancient Murrelets vocalize at a peak of 10KHz (Jones et al., 1989), while Cassin's Auklets vocalize at below 6KHz (Seneviratne et al. 2009). Fork-tailed Storm-Petrels vocalize at under 8KHz (Simons, 1981) and Leach's Storm-Petrels vocalize at below 10 KHz (Ainley, 1980; Taoka, Sato, Kamada, & Okumura, 1989). I sampled at a much higher frequency than necessary for nocturnal seabirds, which generally vocalize below 10 KHz, so that an additional 40 minutes of daily early morning songbird data (songbirds vocalize at higher frequencies than most seabirds) could be recorded and digitized for future bioacoustic analysis (an additional monitoring component of Night Birds Returning).

ARUs are generally considered capable of recording nocturnal seabird calls from distances of 50 – 100 m radius from the unit depending on environmental conditions, tone

and amplitude of sound (Buxton & Jones, 2012; Buxton et al., 2013; Hobson et al., 2002; Hutto & Stutzman, 2009). Rempel et al. (2013) found the rate of decline with distance to be greater for higher tones (e.g. within the frequency range of 5000 – 7000 Hz), and some songbird vocalizations broadcast at 80 dB were barely detectable or undetectable by human ear at 100 m distance, and were generally not visible in spectrograms.

3.3. Acoustic Recorder Deployment Protocol

I secured each ARU to a plywood board (30 x 30 cm) and screwed it to a tree (≤ 25 cm diameter where possible) as high as possible to avoid damage by browsing deer. At deployment sites, I positioned the ARUs at a minimum of 50 – 75 m from the shoreline to reduce noise disturbance from wind and waves. I placed each ARU at least 100 m from other deployment sites to avoid recording overlap between ARUs and to maximise spatial coverage of potential seabird nesting area. I was not able to predetermine all ARU deployment locations before arriving in the field because it was not always possible to know habitat characteristics in advance. Where I was unable to predetermine sampling locations, I attempted to deploy the units in suitable seabird nesting habitat (see section 3.4 Site Selection).

3.4. Site Selection

Prior to site selection, I reviewed available literature (Pattison, 2010; M. Rodway et al., 1988; Mike Rodway, 1991; Summers, 1974) and field notes from previous surveys (M.J.F. Lemon *pers. comm.*) that reported population estimates and colony locations for historic burrow-nesting seabird populations in Gwaii Haanas. These data helped inform site selection on treatment and control islands (Table 2).

Location	Ancient Murrelet	Cassin's Auklet	Fork-Tailed Storm-Petrel	Leach's Storm-Petrel
Alder Island	4,000 (1971) ¹ ; 14,388 (1985) ^{2,c}	300 (1971) ¹ , 928(1985) ^{2,a}	0 (1971) ¹	0
Alder Islet	0	928 (1985) ^{2,a}	25 (1971) ¹ , 60 (1985) ^{2,b}	60 (1985) ^{2, b}
Arichika Island	500+(1971) ¹ ; 0 (1985) ²	500 (1971) ¹ , 0 (1985) ²	500 (1971) ¹ , 0 (1985) ²	25+ (1971) ¹ , 0 (1985) ²
Bischof Island Group	500 (1971) ¹ ; 300 (1977) ³ ; 0 (1985) ²	0	5,000 (1971) ¹ ; 50 (1985) ^{2,d}	50 (1985) ^{2, d}
Hotspring Island Group	6 (1986) ^{2,f}	400 (1971) ¹ ; 10 (1986) ^{2, g}	450 (1986) ^{2, e}	450 (1986) ^{2, e}
Ramsay Island	18,161 (1984) ²	12,887 (1984) ²	0	0

Table 2. Historic population estimates for burrow-nesting seabirds on islands selected for acoustic monitoring in Gwaii Haanas.

¹Summers, K (1974); ²Rodway et al. (1988); ³British Columbia Provincial Museum (1977). ^aPopulation estimate for Alder Island and Alder Islet; ^bEstimate does not distinguish between Leach's and Fork-Tailed Storm-Petrel. ^cIncludes Alder Islet, a much smaller area of habitat. ^dEstimate does not distinguish between Leach's and Fork-Tailed Storm-Petrel. ^eRefers to the north, south and west islets in the Hotspring Islands chain, but surveyors were unable to determine the percentage of each storm-petrel species. ^fAppears to refer to the main, largest of the islands in the Hotspring Islands chain; ^gRefers to the islets northeast of Hotspring Island main.

In both 2010 and 2011, I positioned early season ARU deployments (April through May) in areas where Ancient Murrelets and Cassin’s Auklets have been recorded in the past, or in suitable habitat (e.g. Summers 1974; Rodway et al. 1988; M.J.F. Lemon, *pers. comm.*). I positioned late season deployments (June and July) in areas where Fork-tailed Storm-Petrels and Leach’s Storm-Petrels had been observed historically, or in suitable habitat (e.g. Summers 1974; Rodway et al. 1988; M.J.F. Lemon, *pers. comm.*). Although Fork-tailed Storm-Petrel breeding chronology is highly variable (Boersma et al., 1980), Vermeer et al. (1988) state that July is the best month to survey both Leach’s and Fork-tailed Storm-Petrels because they frequently occur in mixed colonies, with both species nesting in July.

I collected data from a total of 54 recording sites over the two sampling seasons across the five islands (Appendix A): Bischof Islands group and Arichika Island (both rat-infested), Alder, Ramsay and Hotspring Islands (all rat-free controls). In 2010 and 2011, I selected 46 seabird recording sites on Bischof Islands group and Arichika Island (Appendix A, B, C). In 2011, I monitored an additional eight control sites across three rat-free islands (Table 3; Appendix D). In 2010, a maximum of six ARUs were active during any single deployment period, and in 2011 a maximum of eight. ARUs were moved around the islands monthly to increase spatial coverage. There were no control sites in 2010 due to a lack of available ARUs. I selected seabird recording interval sites, where possible, in areas where breeding alcids and storm-petrels were previously surveyed and recorded.

Presence of Rats	Number of Islands Sampled	Number of Sites 2010	Number of Sites 2011	Total Number of Sites
Rats	2	22	24	46
No Rats	3	0	8	8

Table 3. Spatial allocation of sampling effort.

For Ancient Murrelet and Cassin's Auklet control sites (2011 only), I deployed ARUs at active colonies (1) on Alder Island (M. Rodway et al., 1988) and (2) on Ramsay Island (M. Rodway et al., 1988). For Fork-tailed Storm-Petrel and Leach's Storm-Petrel control sites I deployed ARUs (1) at two sites on Alder Islet (M. Rodway et al., 1988), and (2) at two Islets in very close proximity to one another at the northeast corner of the Hotspring Island chain (M. Rodway et al., 1988).

3.4.1. Temporal Allocation of ARU Sampling Effort

Early ARU deployments (April-June) were intended to target likely alcid breeding sites, whereas sites deployed in late June onwards were intended to target likely breeding sites for storm-petrels. The final ARU deployments of the season were left in the field from July to September (Table 4). The length of seabird presence per recording site was not used as a response variable because recorders were not deployed at recording sites for long enough to cover the entire duration of the breeding season.

Hotspring Island was sampled only later in the year for storm-petrels. Thus the recording period there did not cover the core breeding season for early-breeding alcids. Ramsay Island was sampled early in the year and therefore it did not cover the core breeding season for storm-petrel species. In statistical analyses, I truncated data for each seabird group such that sample effort matched equal time periods between rat-infested and rat-free islands. For Ancient Murrelet, Cassin's Auklet and Fork-Tailed Storm-Petrel, equal survey effort for most of the breeding season was allocated only on Alder Island as a control and the two rat-infested islands: Bischof Islands and Arichika Island. Each recording site covered only a portion of the main period of breeding for each species. Consequently, attendance period for each species is calculated at the island level, not at the 'site' level because ARUs did not record at each recording site for the full duration of the seabird breeding season.

The end of the attendance period for Ancient Murrelet and Cassin's Auklet was encompassed by the length of the recording period, but Fork-tailed and Leach's Storm-Petrel in 2011 were still being detected on control islands in early September, when

recording concluded. I used the last night of recording on Hotspring Island to calculate the end of the attendance period for Fork-tailed and Leach's Storm-Petrels under control conditions because the recording period on Hotspring Island was slightly longer than on Alder Island, and Fork-tailed Storm-Petrels were detected until the end of the Hotspring Island recording period. The length of the attendance period on rat-free islands was defined from activity on Alder Island only for Ancient Murrelet, Cassin's Auklet, and Fork-tailed Storm-Petrel. In my analyses, I measure seabird attendance in 2010 from mid April to the end of August, and in 2011 from early April to early September. The seabird species I assess probably come to their breeding sites before the start and after the end of recording. Therefore I did not measure the total time that birds were present on land.

Island	Year	Number of ARU Deployments	Start Recording	End Recording	Total Recording Nights	Total Nights
Arichika	2010	1	17-Apr	14-May	27	27
Arichika	2010	2	28-May	27-Jun	60	30
Arichika	2010	1	28-Jun	27-Jul	29	29
Arichika	2010	2	28-Jul	31-Aug	68	34
Arichika	2011	2	05-Apr	30-Apr	50	25
Arichika	2011	2	01-May	30-May	58	29
Arichika	2011	2	31-May	01-Jul	62	31
Arichika	2011	2	02-Jul	01-Sep	122	61
Bischof	2010	4	15-Apr	28-May	172	43
Bischof	2010	4	29-May	26-Jun	112	28
Bischof	2010	4	27-Jun	25-Jul	112	28
Bischof	2010	4	26-Jul	31-Aug	144	36
Bischof	2011	4	07-Apr	03-May	104	26
Bischof	2011	4	04-May	29-May	100	25
Bischof	2011	4	30-May	30-Jun	124	31
Bischof	2011	4	01-Jul	01-Sep	248	62
Alder	2011	1	05-Apr	30-Apr	25	25
Alder	2011	1	01-May	28-May	27	27
Alder Islet	2011	1	29-May	30-Jun	32	32
Alder Islet	2011	1	01-Jul	03-Sep	64	64
Hotspring	2011	1	01-Jun	05-Jul	34	34
Hotspring	2011	1	06-Jul	07-Sep	63	63
Ramsay	2011	1	07-Apr	30-Apr	23	23
Ramsay	2011	1	01-May	31-May	30	30

Table 4. Temporal allocation of sampling effort at rat-infested and rat-free islands in Gwaii Haanas.

3.5. Measuring Seabird Presence: Bioacoustic Data Capture

Before I began to process the sound recordings, I studied the vocal repertoire of Ancient Murrelet (I. L. Jones et al., 1989), Cassin's Auklet (Seneviratne et al., 2009), Fork-tailed Storm-Petrel (Simons, 1981) and Leach's Storm-Petrel (Taoka et al., 1989) to become fully aware of the range of their vocal behavior. I also obtained sample recordings for each of these species as true reference sounds from the Macaulay Library of Sound (Cornell Lab of Ornithology, Ithaca, NY; MLS catalogue numbers: 132011, 132012, 132029, 136440, 137870, 137874, 137876, 8326, 8330, 111096 and 136564).

I used Raven Pro (Bioacoustics Research Program, 2011) to generate a spectrogram of each ten-minute recording, which I then visually scanned to detect and identify nocturnal seabird calls (Signal rate = 24000Hz; Fast Fourier transform (FFT) = 2048; window size = 5 seconds). If seabird species vocalizations were not identifiable visually (e.g. due to a low signal-to-noise ratio), I selected and listened to them in their entirety. If the sound was still unidentifiable then these sounds were not logged as records.

I define a detection as the first vocalization located in a sound recording that is positively identified to have been made by each of the four study species (e.g. Ancient Murrelet, Cassin's Auklet, Fork-tailed and Leach's storm-petrels; Figure 2). Because it was necessary to only record presence or absence, subsequent vocalizations of a species already identified within a 10-minute recording were ignored.

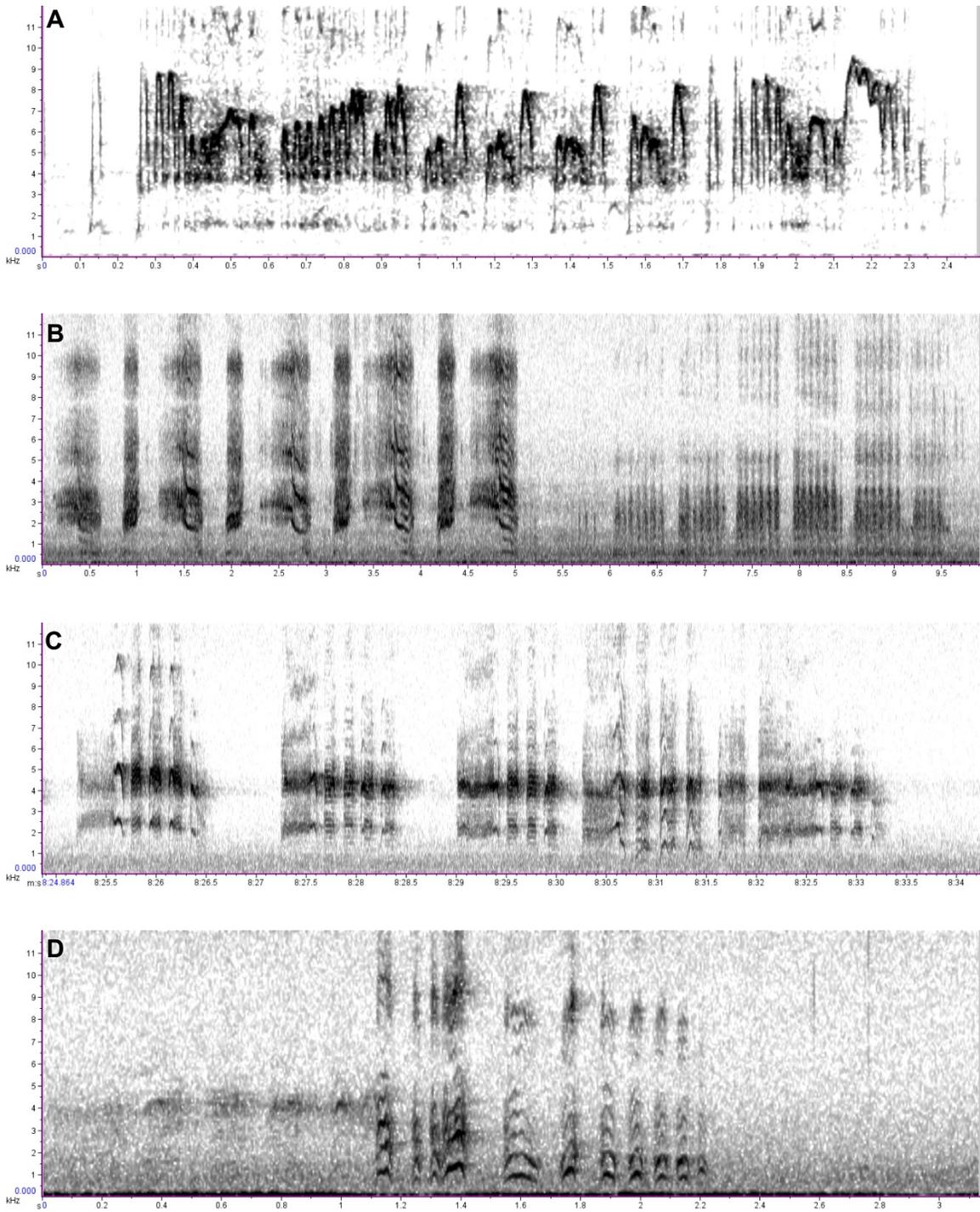


Figure 2. Spectrogram images of seabird species' vocalizations in Gwaii Haanas. (A) Ancient Murrelet, (B) Cassin's Auklet, (C) Fork-tailed Storm-Petrel, (D) Leach's Storm-Petrel. Time (seconds) is on the x axis and frequency (kHz) is on the y axis.

Each data record also contained the time, date and island location (site identification, latitude, longitude). Species presence was categorical (1 = present with non-overlapping calls; 2 = present with overlapping calls, or 0 = absent). “Present with overlapping calls” refers to a positive species’ detection where call density is high and conspecific calls overlap. “Present with non-overlapping calls” refers to a positive detection where no conspecific call overlapping occurs and where call density is relatively low. However, despite coding presence with one of three classes, I later transformed the database to reflect either presence (1) or absence (0). My intention of classifying positive detections as overlapping and non-overlapping was to assess the amount of seabird activity within acoustic recordings. However, the mean number of recordings per night (see section 3.8) with detections proved sufficient to answer questions related relative abundance and the effect of rat presence on seabird detections. Consequently, I only used the two class (present/absent) system in my data analyses.

Heavy rain, windstorms, wave sounds or other acoustic disturbance obscured some sound recordings. I coded the quality of each sound recording based on the amount of precipitation and general background noise. I classified precipitation as 0 = no precipitation; 1 = light precipitation; 2 = moderate-heavy precipitation; 3 = heavy precipitation that obscures >50% of the recording (e.g. Buxton and Jones (2012) considered recordings with >50% obscured sound as unusable). Second, I recorded background noise that was not from precipitation as 0 = no background noise; 1 = some noise; 2 = moderate noise; 3 = loud noise obscuring >50% of the recording. Background noise can include wind, waves, tidal ebb and flow. In my analyses I did not include recordings with a noise value of 3, where precipitation and/or rain obscured more than 50% of the spectrogram.

To assist Parks Canada with its broader avian monitoring objectives, I recorded the presence of all other bird species, including those of special interest such as the endemic Haida Gwaii Northern Saw-whet Owl (*Aegolius acadicus brooksi*), Bald Eagle (*Haliaeetus leucocephalus*), Black Oystercatcher (*Haematopus bachmani*), Common Loon (*Gavia immer*), Marbled Murrelet (*Brachyramphus marmoratus*) and Sooty Grouse

(*Dendragapus fuliginosus*). These data were provided to Parks Canada for future analyses.

3.6. Research Metrics and Statistical Analyses

3.6.1. Attendance period

For the purposes of this study, I defined attendance period as the period of time during which study species were detected at monitoring sites. Because ARUs were not deployed in time to capture arrival for some island-species combinations, this contrasts with the definition in the literature, where attendance is the complete duration of seabirds attending their terrestrial nest sites and engage in their full range of breeding activities. I estimate attendance period as the number of days between first and last detections within the projected breeding season at the island level. I also report the total number of days with seabird detections within the attendance period, since this may vary with colony size

3.6.2. Relative abundance

My second measure was an index of relative abundance. I defined relative abundance as the mean number of ten-minute recordings made each night containing at least one detection of the species of interest. I report these means with standard error over the course of the monitoring period. I compared relative abundance for each seabird species (Ancient Murrelet, Cassin's Auklet, Fork-tailed Storm-Petrel and Leach's Storm-Petrel) on rat-free and rat-infested islands.

I truncated data for calculation and comparison of relative abundances to match equal sample effort as much as possible. Ancient Murrelet and Cassin's Auklet data are truncated to April 17 – May 31 in 2010 and April 7 – May 31 in 2011. Fork-tailed Storm-Petrel data are truncated to April 17 – August 31 in both 2010 and 2011. Leach's Storm-Petrel data are truncated to June 1 – August 31 in 2010 and 2011. I truncated Fork-tailed Storm-Petrel detection data to include most of the available data from both years because

their breeding dates are highly variable (e.g. Boersma et al. 1980). I expected relative abundances to be significantly higher on rat-free islands due to the absence of rat predation. I did not compare relative abundances for alcids on Hotspring Island, nor for storm-petrels on Ramsay Island because those islands were not surveyed at suitable times to assess breeding activities of these seabird groups.

3.7. Statistical analyses

I compiled data and produced summary graphs in Microsoft Excel, and performed statistical analyses using R, version 3.0.1 (R Core Team, 2013) and SAS version 9.4. I used contingency chi-square tests to test whether seabird activity varied through the night for each species. To examine trends in seabird presence over the season, I used R (library: ggplot2) to (1) plot the mean number of recordings with detections for each species, each night for all available data to display seasonal detection patterns and; (2) logit-transform and plot the binomial presence or absence data and calculate the empirical probability of detection for each species on each island. The probabilities are represented by the proportion of recordings per night with detections. I added trend lines to these plots with 95% confidence interval bands and loess smoothing.

I used *t*-tests to test for statistically significant differences between detections of nocturnal seabirds on rat-free compared to rat-infested islands. In these *t*-tests, I compared the log-transformed mean proportion of recordings per night with seabird detections using data from all available recorders on each island, each night. I compared only data that were sampled over the same time period. I therefore truncated data to match equal temporal sample effort between islands for alcid species to include day 97 – 151 (April 7 – 31 May) and for storm-petrel species to include day 152 – 244 (June 1 – September 1). For these analyses, I used data collected in 2011 only because recorders were not deployed on control islands in 2010. Differences in means with a *p* value of <0.05 were considered significantly different

4. Results

I manually processed 22,980 ten-minute recordings (1,890 cumulative survey nights). Of these, 2,114 (9%) were not included in analyses due to high background noise (inclement weather conditions). ARUs failed at two locations on Arichika Island in 2010 (15 May – 27 May). I detected Ancient Murrelets on a total of 56 and 4 nights on Arichika and Bischof Islands respectively, in 2011 (Table 5). In 2010, I detected Ancient Murrelets on a total of 17 and 2 nights on Arichika and Bischof Islands respectively. On Alder Island (no rats), Ancient Murrelets were present in 2011 on 72 nights. I detected Cassin's Auklets on Arichika and Bischof Islands for a total of 67 and 23 nights respectively, in 2011. In 2010, I detected Cassin's Auklets on Arichika and Bischof Islands on a total of 13 and 1 nights respectively. This compares to 82 nights of Cassin's Auklet detections on Alder Island, in 2011. I detected Fork-tailed Storm-Petrels on Arichika and Bischof Islands on a total of 10 and 16 nights respectively, in 2011. In 2010, I detected Fork-tailed Storm-Petrels on Arichika and Bischof Islands on 12 and 51 nights respectively. On Alder Island in 2011, they were detected on 99 nights. I detected Leach's Storm-Petrels on Arichika and Bischof Islands on 70 and 1 nights respectively, in 2011. In 2010, Leach's Storm-Petrels were detected on Arichika and Bischof Islands on 62 and 4 nights respectively. On Alder Island in 2011, Leach's Storm-Petrels were detected on 93 nights.

4.1. Effects of time of night on seabird vocal activity

I detected Ancient Murrelets on rat-free islands in approximately 90% of all recording periods per night. On rat-infested islands Ancient Murrelets were detected most frequently at 1:20 AM (Figure 3). I detected Cassin's Auklets most frequently on rat-free islands at 3:20 AM and 2:20 AM on rat-infested islands. I detected Fork-tailed Storm-Petrels most frequently at 1:20 AM on rat-free islands, and 2:40 AM on rat-infested islands. Leach's Storm-Petrel was detected most frequently on rat-free islands between 3:00 AM – 3:20 AM, but at 2:40 AM on rat-infested islands.

Nightly patterns of detections differed with respect to rat presence for Cassin’s Auklet and Fork-tailed Storm-Petrel (Figure 4). For Cassin’s Auklet, the mean proportion of detections on rat-infested islands were higher than expected for 12:00 AM (mean=0.41, SE=0.14, $X^2(11, N=4535) = 8.90, p = 0.003$), 12:20 AM (mean=0.35, SE=0.14, $X^2(11, N=4535) = 6.30, p = 0.01$), 12:40 AM (mean=0.37, SE=0.14, $X^2(11, N=4535) = 6.99, p = 0.008$) and 2:20 AM (mean=0.29, SE=0.13, $X^2(11, N=4535) = 4.81, p = 0.028$).

For Fork-Tailed Storm-Petrel detections were higher than expected for 1:40 AM (mean=0.56, SE=0.26, $X^2(11, N=8073) = 4.89, p = 0.03$), 2:00 AM (mean=0.88, SE=0.21, $X^2(11, N=8073) = 17.77, p < .0001$), 2:20 AM (mean=1.07, SE=0.19, $X^2(11, N=8073) = 31.17, p < .0001$), 2:40 AM (mean=1.3, SE=0.17, $X^2(11, N=8073) = 58.00, p < .0001$), 3:00 AM (mean=1.3, SE=0.18, $X^2(11, N=8073) = 53.94, p < .0001$) and 3:20 AM (mean=1.37, SE=0.19, $X^2(11, N=8073) = 50.95, p < .0001$).

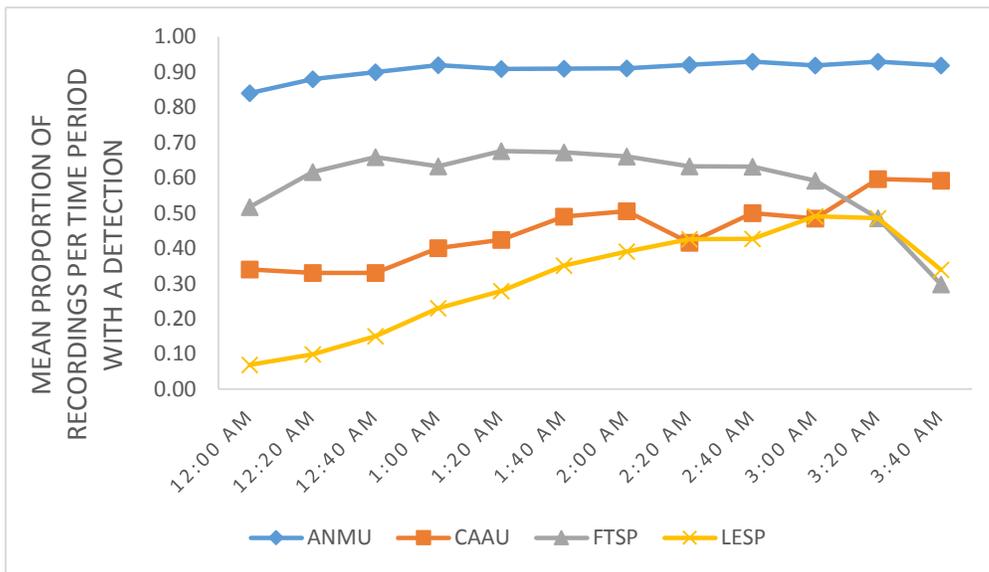


Figure 3. Mean proportion of recordings per time period per night with detections on rat-free islands for Ancient Murrelet, Cassin’s Auklet, Fork-tailed Storm-Petrel and Leach’s Storm-Petrel between 12:00 – 03:40 AM.

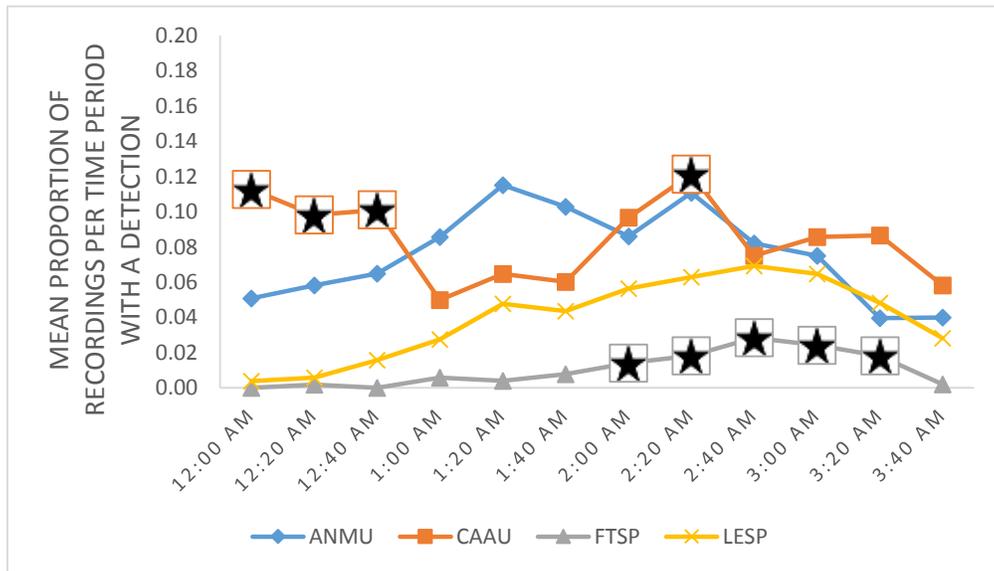


Figure 4. Mean proportion of recordings per time period per night with detections on rat-infested islands for Ancient Murrelet, Cassin’s Auklet, Fork-tailed Storm-Petrel and Leach’s Storm-Petrel between 12:00 – 03:40 AM. Stars indicate a statistically significant difference in means between recording times.

4.2. Seabird attendance periods

Detections of all species except Leach’s Storm-Petrel began at the start of ARU deployments on April 15 in 2010 and April 5 in 2011. I did not detect Leach’s Storm-Petrels until May 7 in 2010 (Arichika Island) and May 16 in 2011 (Arichika Island). The latest sound recording each year was on August 31 in 2010 and September 6 in 2011. I did not detect Leach’s Storm-Petrels until May 29 on Alder Islet. The length of time during which seabirds were detected was generally longer on rat-free sites for most species (Table 5).

4.2.1. Length of Ancient Murrelet attendance period

I detected Ancient Murrelets on both rat-free and rat-infested islands, and the attendance period for Ancient Murrelet in 2011 was similar on treatment and control islands (Figure 5). For example, it was 80 days (72 nights of detections) on rat-free Alder compared to 78 days (56 nights with detections) on rat-infested Arichika. Despite only two days difference in length of attendance period for these islands, Ancient Murrelets were detected on many fewer nights on Arichika (Table 5), suggesting that they were less abundant there. Very few Ancient Murrelet detections were observed in both years on Bischof Islands group, suggesting that although they were present, they were not breeding on the Bischofs.

4.2.2. Length of Cassin's Auklet attendance period

I detected Cassin's Auklets on both rat-free and rat-infested islands. On rat-free Alder island attendance spanned 113 days with 82 nights of detections, continuing to the end of July, but with a period of absence toward the end of the attendance period (Figure 6). On rat-infested Arichika, attendance in 2011 spanned only 82 days with 67 nights of detections (Table 5). Cassin's Auklet was detected on only one night in 2010 on Bischof, but for 23 nights on Bischof in 2011.

4.2.3. Length of Fork-tailed Storm-Petrel attendance period.

I detected Fork-tailed Storm-Petrels on both rat-free and rat-infested islands (Figure 7). Attendance on rat-free Alder Island spanned 153 days with 99 nights of detections. In contrast, attendance on rat-infested Bischof spanned 77 days with 51 nights of detections in 2010, and 75 days with 16 nights of detections in 2011. On Arichika Island, attendance period spanned 16 days with 12 nights of detections in 2010, and 72 days with 10 nights of detections in 2011 (Table 5).

4.2.4. Length of Leach's Storm-Petrel attendance period.

Leach's Storm-Petrel attendance on rat-free Alder Island, in 2011, was 97 days with 93 nights of detections. In 2011, on Arichika Island, attendance spanned 105 days with 70 nights of detections; in 2010 the period spanned 108 days with 62 nights of detections (Table 5). Colony attendance appeared more intermittent on Arichika than rat-free Alder Island (Figure 8).

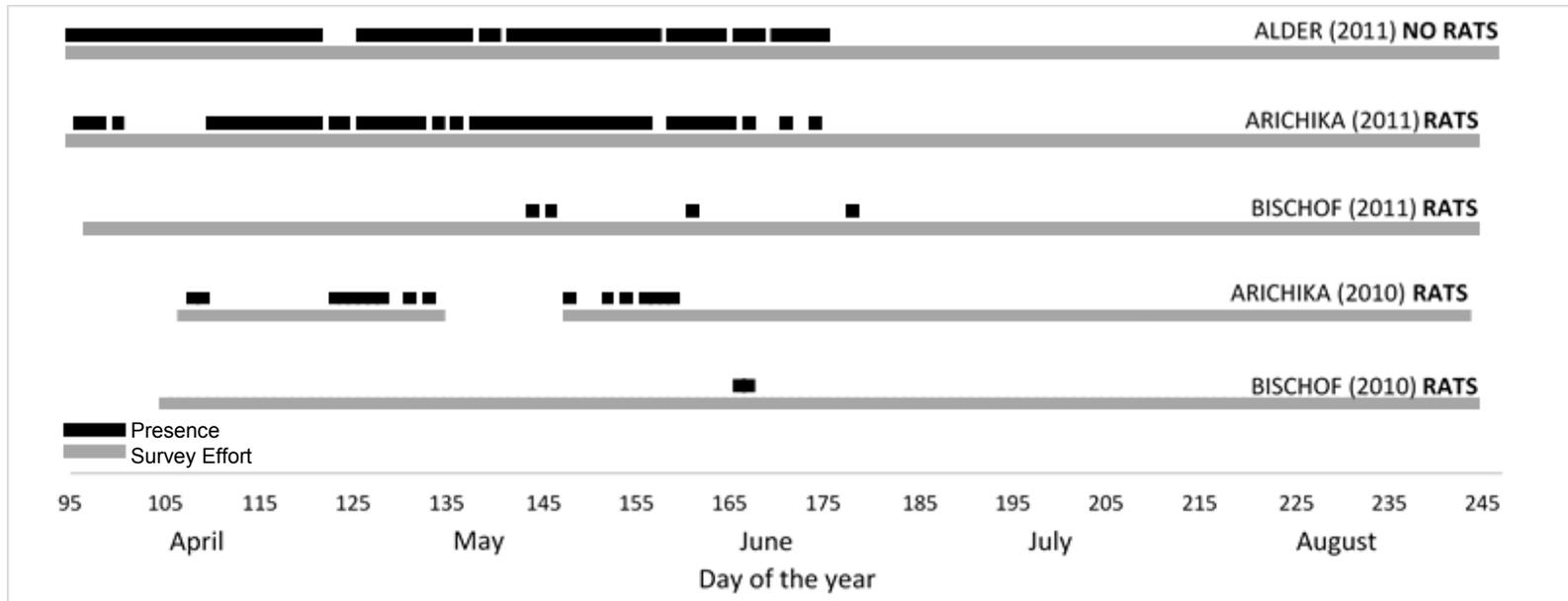


Figure 5. Length and continuity of Ancient Murrelet attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365.

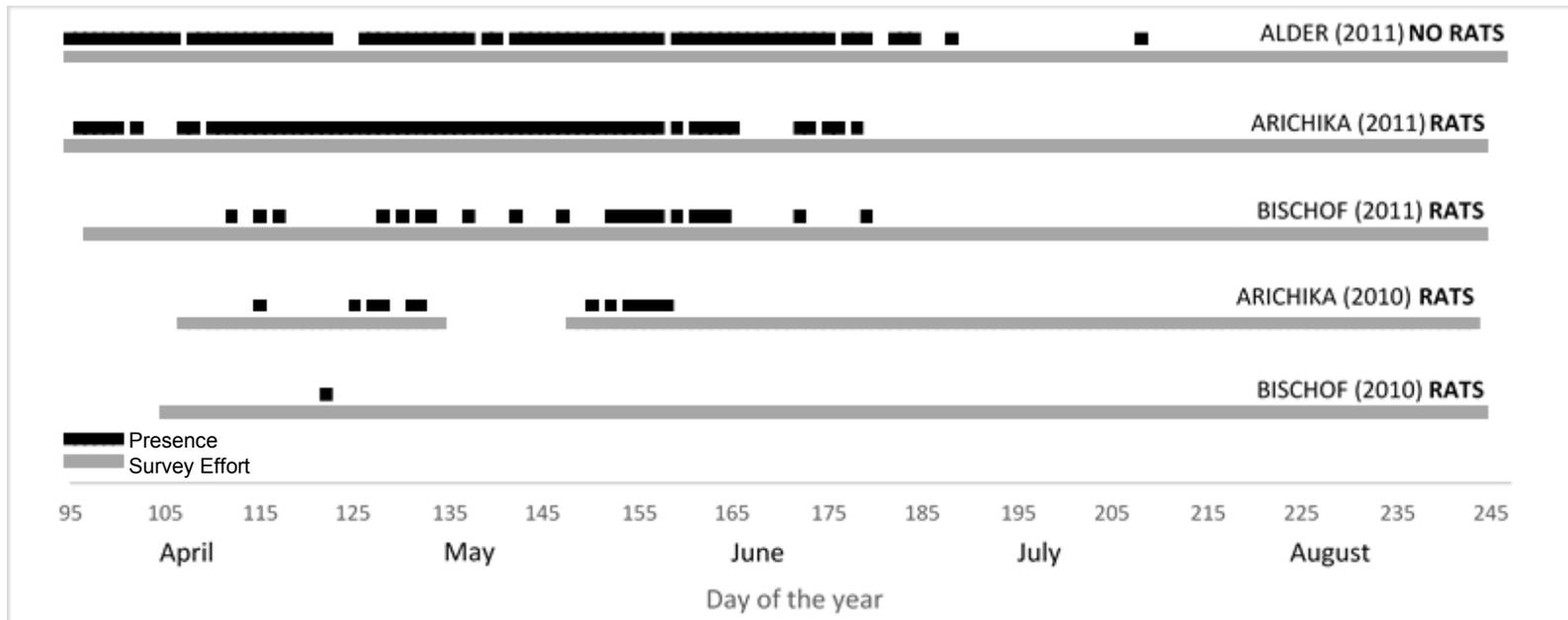


Figure 6. Length and continuity of Cassin's Auklet attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365.

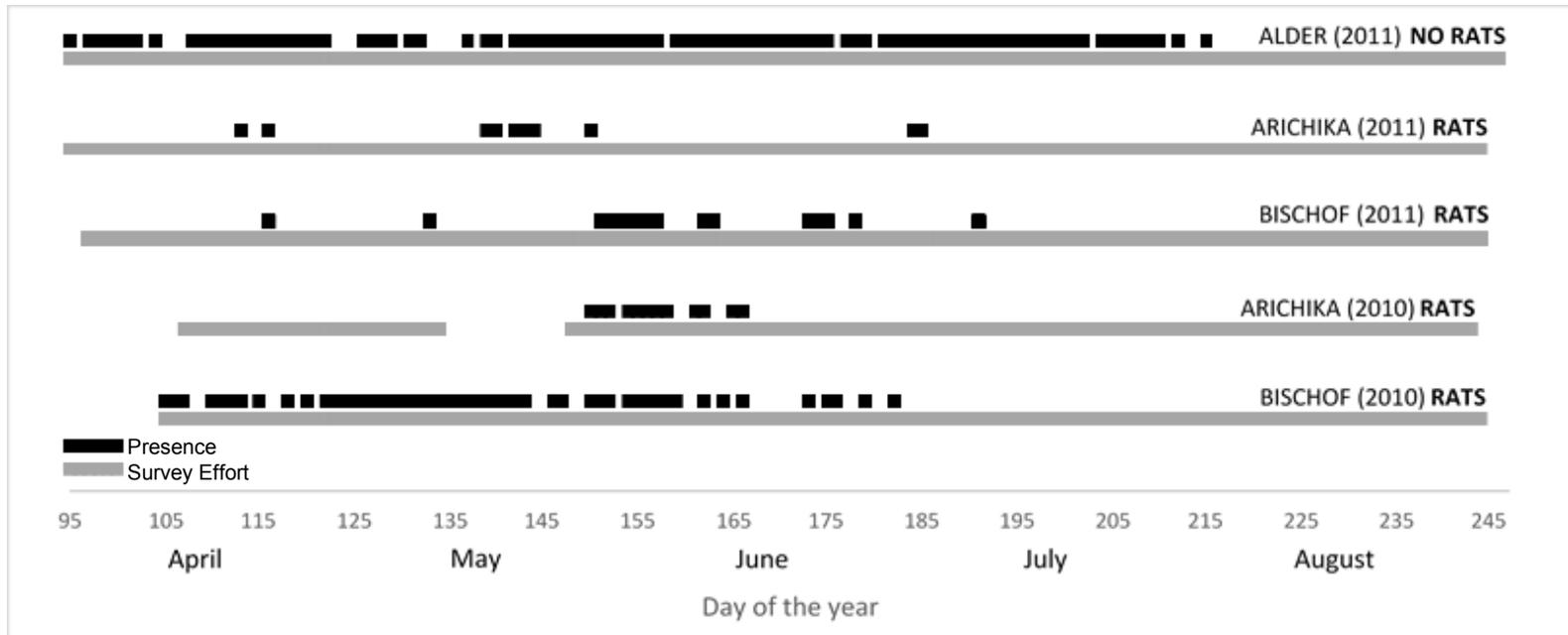


Figure 7. Length and continuity of Fork-tailed Storm-Petrel attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365.

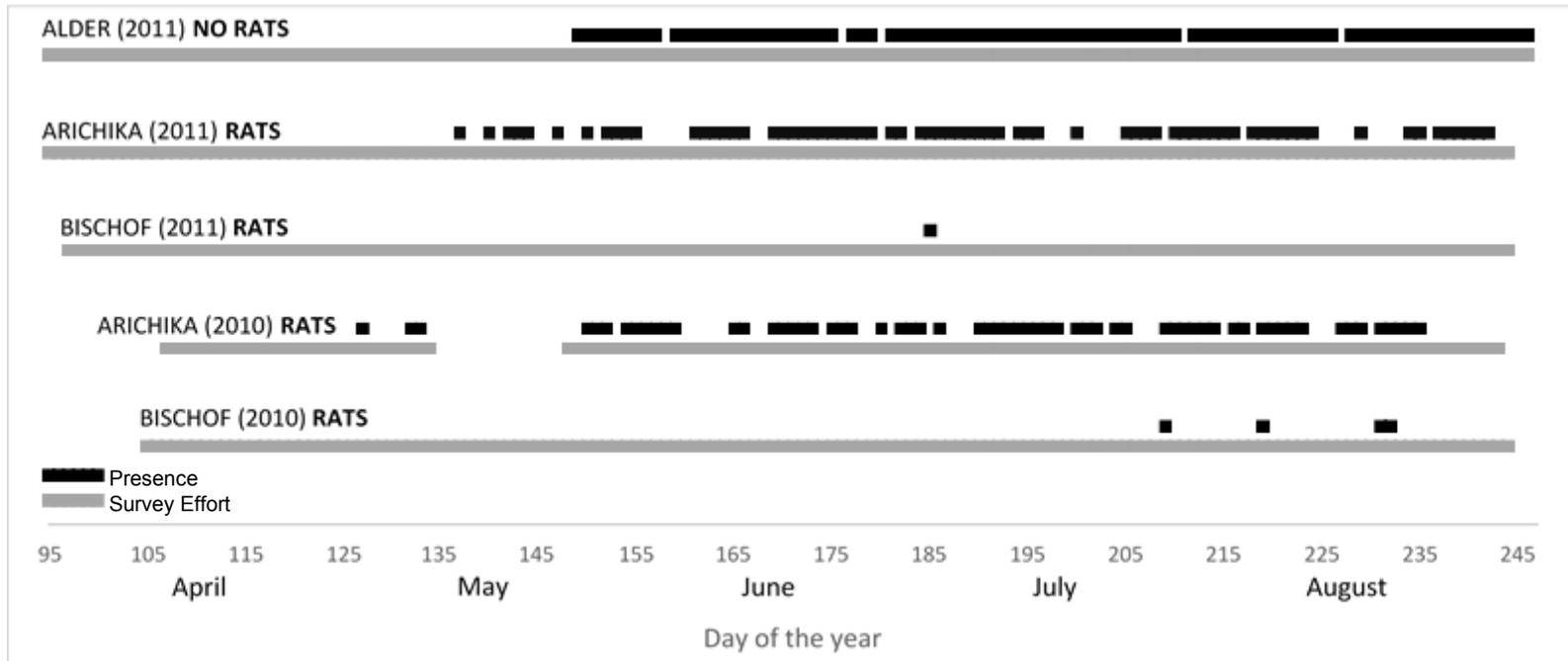


Figure 8. Length and continuity of Leach's Storm-Petrel attendance period. The grey line indicates the survey effort and black line indicates presence. Day of the year is Julian day from 0 – 365.

 Alder (2011)	First Detection	Last Detection	Length of Time (days)	Number of nights with a positive detection	Total survey nights
Ancient Murrelet	05-April	24-June	80	72	151
Cassin's Auklet	05-April	27-July	113	82	151
Fork-tailed Storm-Petrel	05-April	05-September	153	99	150
Leach's Storm-Petrel	29-May	03-September	97	93	150
 Arichika 2010*	First Detection	Last Detection	Length of Time (days)	Number of nights with a positive detection	Total survey nights
Ancient Murrelet	18-April	08-June	51	17	136
Cassin's Auklet	25-April	07-June	43	13	136
Fork-tailed Storm-Petrel	30-May	15-June	16	12	136
Leach's Storm-Petrel	07-May	23-August	108	62	136

*No recordings were made between 15 May – 27 May due to failed ARUs.

 Arichika (2011)	First Detection	Last Detection	Length of Time (days)	Number of nights with a positive detection	Total survey nights
Ancient Murrelet	06-April	23-June	78	56	149
Cassin's Auklet	06-April	27-June	82	67	149
Fork-tailed Storm-Petrel	23-April	04-July	72	10	149
Leach's Storm-Petrel	16-May	30-August	105	70	149

 Bischof 2010	First Detection	Last Detection	Length of Time (days)	Number of nights with a positive detection	Total survey nights
Ancient Murrelet	15-June	16-June	2	2	138
Cassin's Auklet	2-May	2-May	1	1	138
Fork-tailed Storm-Petrel	15-April	01-July	77	51	138
Leach's Storm-Petrel	28-July	20-August	23	4	138

 Bischof 2011	First Detection	Last Detection	Length of Time (days)	Number of nights with a positive detection	Total survey nights
Ancient Murrelet	24-May	27-June	34	4	147
Cassin's Auklet	22-April	28-June	67	23	147
Fork-tailed Storm-Petrel	26-April	10-July	75	16	147
Leach's Storm-Petrel	4-July	4-July	1	1	147

Table 5. Length of attendance periods on rat-infested compared to rat-free islands in Gwaii Haanas.

4.3. Effects of Rats on Seabird Relative Abundance in Gwaii Haanas.

There are clear seasonal trends in probability of detection for all species (Figures 10, 13, 16, 19). Most notable is the comparison between Alder Island (rat-free) and Arichika Island (rat-infested), for all species. Rat-free Alder Island had the highest detection probabilities for both alcid and storm-petrels, while Hotspring, also rat-free, had the highest for Fork-tailed Storm-Petrels, somewhat higher than Alder (Figures 16 – 17). In contrast, detection probabilities for rat-infested Bischof Island were practically nil for all species. Untransformed data (Figures 11, 14, 17, 20) show similar trends (e.g. Leach's Storm-Petrel on Arichika in 2010 compared to Alder in 2011). However, on rat-infested islands, the total number of nights with detections was always lower than on rat-free islands.

Relative abundance for alcids on rat-free islands ranged between 2.77 – 10.71 (Table 6). This contrasts with only 4.65 for Ancient Murrelet and 4.93 for Cassin's Auklet on rat-infested Arichika Island in 2011 (Table 6). Relative abundance of Cassin's Auklet in 2011 was higher on Arichika than rat-free Ramsay Island. In 2010 alcid abundance was much lower on Arichika than in 2011, at 1.13 for Ancient Murrelet and 0.37 for Cassin's Auklet. Alcid relative abundances were much lower in 2010 than 2011.

Storm-petrel relative abundance on rat-free islands ranged between 0.28 – 8.20 (Table 6). On rat-infested islands, relative abundance was highest for Leach's Storm-Petrel on Arichika Island in 2010 at 2.97 and 2.55 in 2011 (Table 6). Among rat-infested islands, Fork-tailed Storm-Petrel relative abundance was highest in 2010 on the Bischof Islands group at 1.45, but lower on the same island in 2011 at 0.47. Among the two rat-infested islands, relative abundance was lowest on Bischof Island in both years for all species except Fork-tailed Storm-Petrel.

Species	Rat-infested				Rat-free		
	Bischof Island (2010)	Bischof Island (2011)	Arichika Island (2010)	Arichika Island (2011)	Alder Island (2011)	Ramsay Island (2011)	Hotspring Island (2011)
Ancient Murrelet ^a	0.00 ± 0.00	0.06 ± 0.04	1.13 ± 0.41	4.65 ± 0.62	10.58 ± 0.42	10.71 ± 0.40	Not Assessed
Cassin's Auklet ^b	0.02 ± 0.02	0.28 ± 0.10	0.37 ± 0.13	4.93 ± 0.48	7.90 ± 0.54	2.77 ± 0.33	Not Assessed
Fork-tailed Storm-Petrel ^c	1.45 ± 0.21	0.47 ± 0.16	0.22 ± 0.08	0.10 ± 0.03	5.66 ± 0.41	Not Assessed	8.20 ± 0.46
Leach's Storm-Petrel ^d	0.04 ± 0.02	0.01 ± 0.01	2.97 ± 0.39	2.55 ± 0.30	6.93 ± 0.30	Not Assessed	0.28 ± 0.08

Table 6. Relative abundance of nocturnal seabirds in Gwaii Haanas in 2010 and 2011. Means are expressed with standard error.

^{a,b}Ancient Murrelet and Cassin's Auklet data are truncated to April 17 – May 31 in 2010 and April 7 – May 31 in 2011. ^cFork-tailed Storm-Petrel data are truncated to April 17 – August 31 in both 2010 and 2011. ^dLeach's Storm-Petrel data are truncated to June 1 – August 31 in 2010 and 2011.

4.3.1. Ancient Murrelet

Relative abundance of Ancient Murrelets on the Bischof Islands was 0 and 0.06 in 2010 and 2011 respectively (Figure 9, Table 6). However, it was higher on Arichika: 1.13 and 4.65 in 2010 and 2011 respectively, compared to 10.58 on Alder and 10.71 on Ramsay. Detection probabilities were higher on Alder and Ramsay Islands than Arichika and Bischof Islands (Figure 10), while the mean number of recordings with detections per day shows clear seasonal patterns of higher relative abundance on rat-free islands (Figure 11).

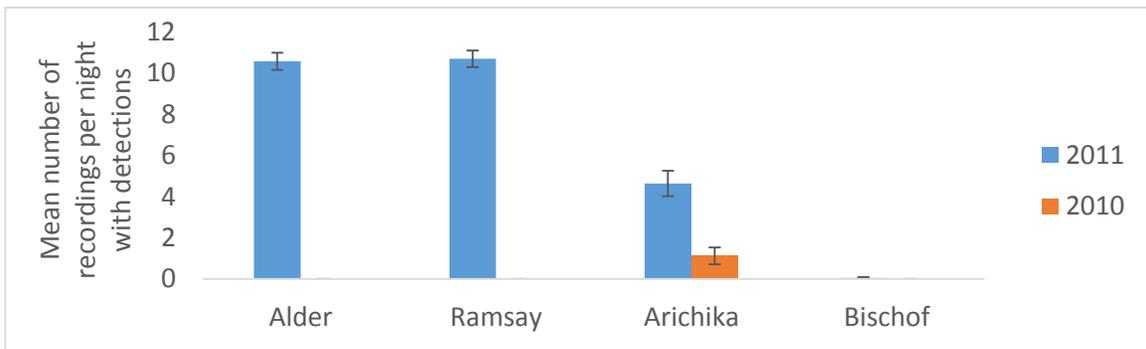


Figure 9. Mean number of recordings per night with Ancient Murrelet detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.

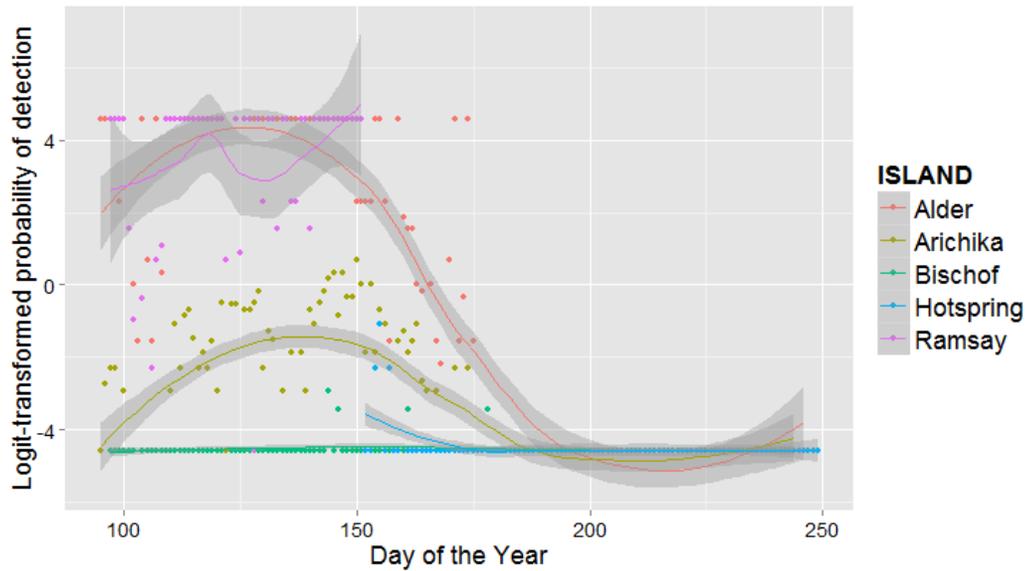


Figure 10. Seasonal and spatial pattern of Ancient Murrelet detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.

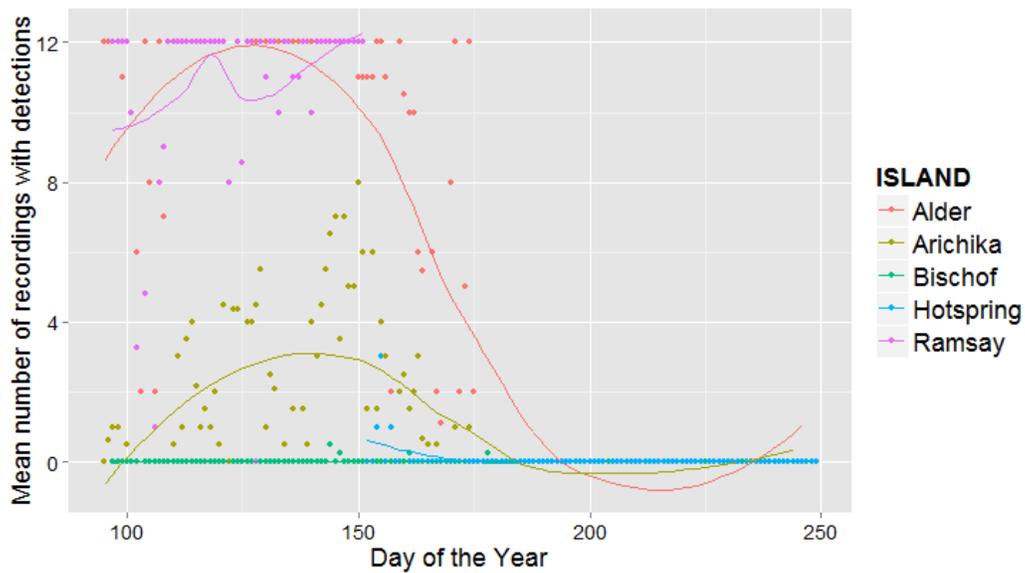


Figure 11. Seasonal and spatial pattern of the mean number of Ancient Murrelet recordings with detections by day and island in 2011. Trend lines use loess smoothing.

4.3.2. Cassin's Auklet

In 2011, relative abundance was higher on Arichika Island (4.93) than rat-free, Ramsay Island (2.77). The highest recorded Cassin's Auklet relative abundance was on rat-free Alder Island in 2011 (7.90). Among the two rat-infested islands, Cassin's Auklet relative abundance was lowest on the Bischof Islands group in 2010 (0.02) and 2011 (0.28, Figure 12, Table 6). On Arichika Island in 2010 it was 0.37. Detection probabilities were higher on Alder Island than Bischof and Arichika Islands, but at some times probability of detection was higher on Arichika Island than rat-free Ramsay Island (Figure 13). The mean number of recordings with detections per day shows clear seasonal patterns of generally higher relative abundance on rat-free islands (Figure 14).

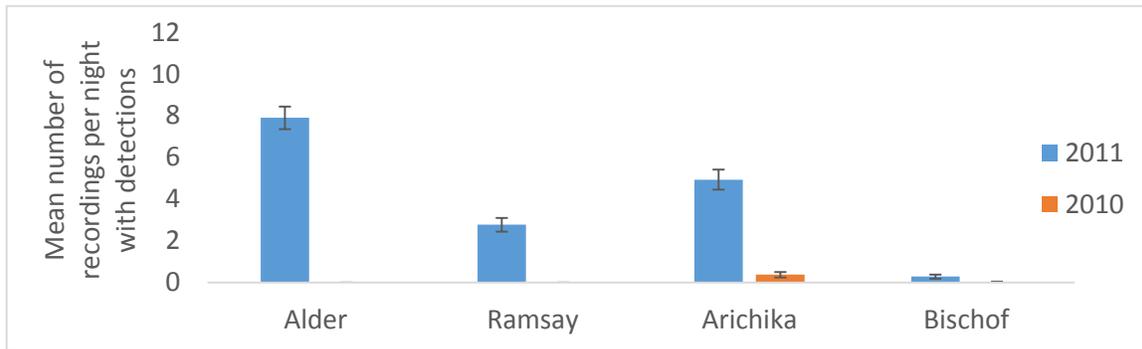


Figure 12. Mean number of recordings per night with Cassin's Auklet detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.

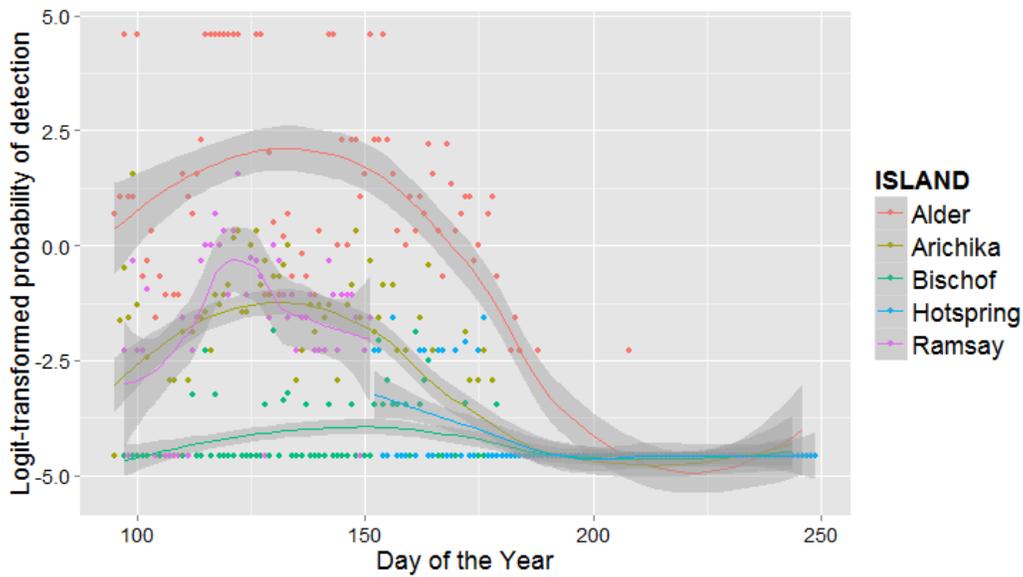


Figure 13. Seasonal and spatial pattern of Cassin's Auklet detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.

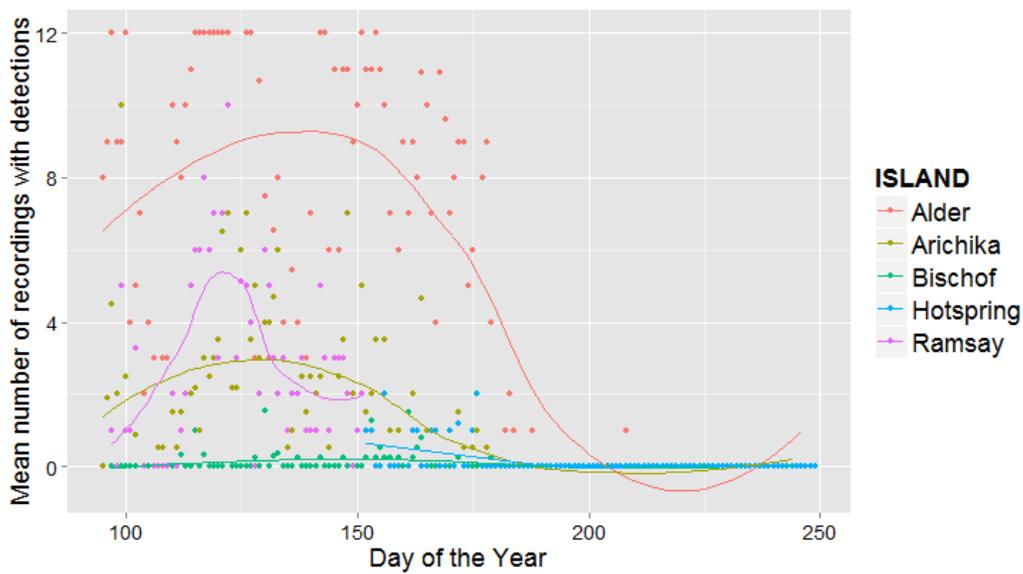


Figure 14. Seasonal and spatial pattern of the mean number of Cassin's Auklet recordings with detections by day and island in 2011. Trend lines use loess smoothing.

4.3.3. Fork-tailed Storm-Petrel

The mean number of recordings per night with Fork-tailed Storm-Petrel detections on rat-infested islands was highest on Bischof during 2010 at 1.45 compared to 0.47 in 2011 (Figure 15). On Arichika Island relative abundance was 0.22 in 2010 and 0.10 in 2011. On Hotspring Island relative abundance was 8.20, and on Alder Island it was 5.66, indicating much higher abundance on the rat-free islands. Detection probabilities were considerably higher on the rat-free islands (Figure 16), while the mean number of recordings with detections per day demonstrates clear seasonal patterns of higher relative abundance on rat-free islands (Figure 17).

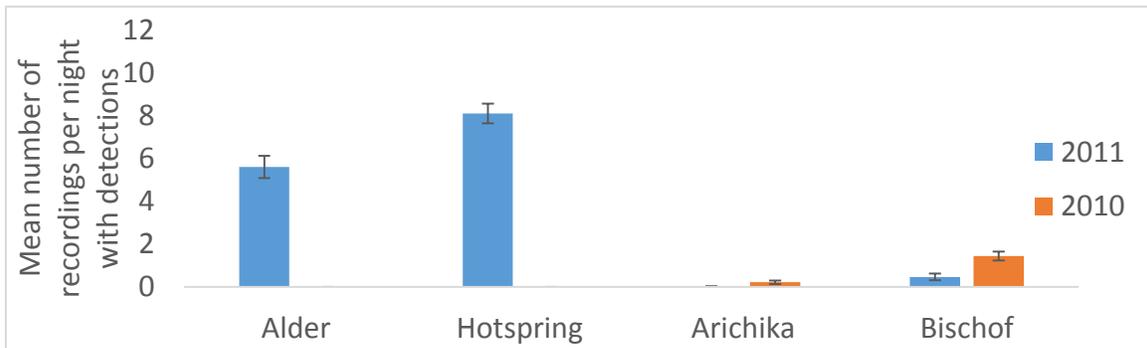


Figure 15. Mean number of recordings per night with Fork-tailed Storm-Petrel detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.

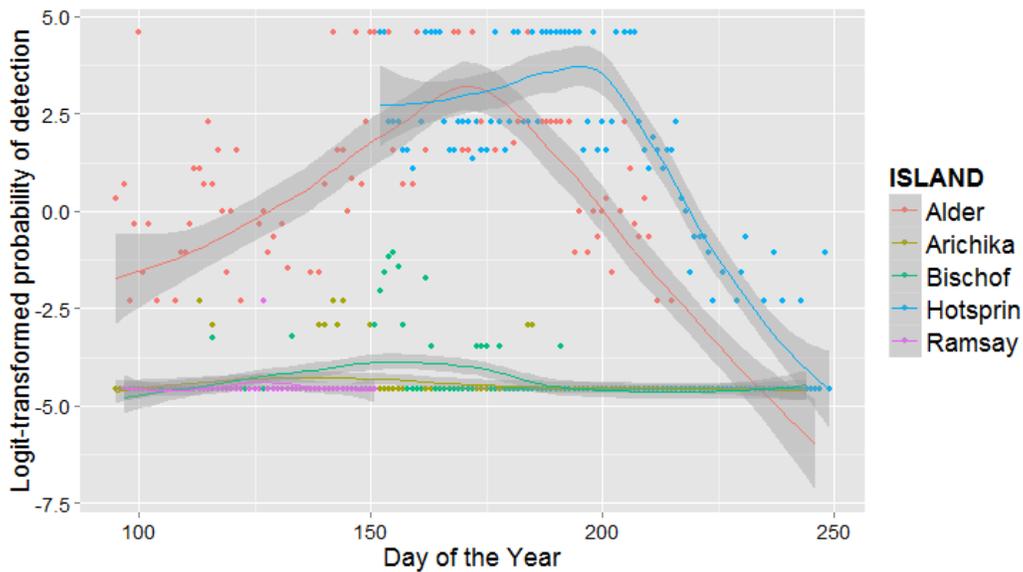


Figure 16. Seasonal and spatial pattern of Fork-tailed Storm-Petrel detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.

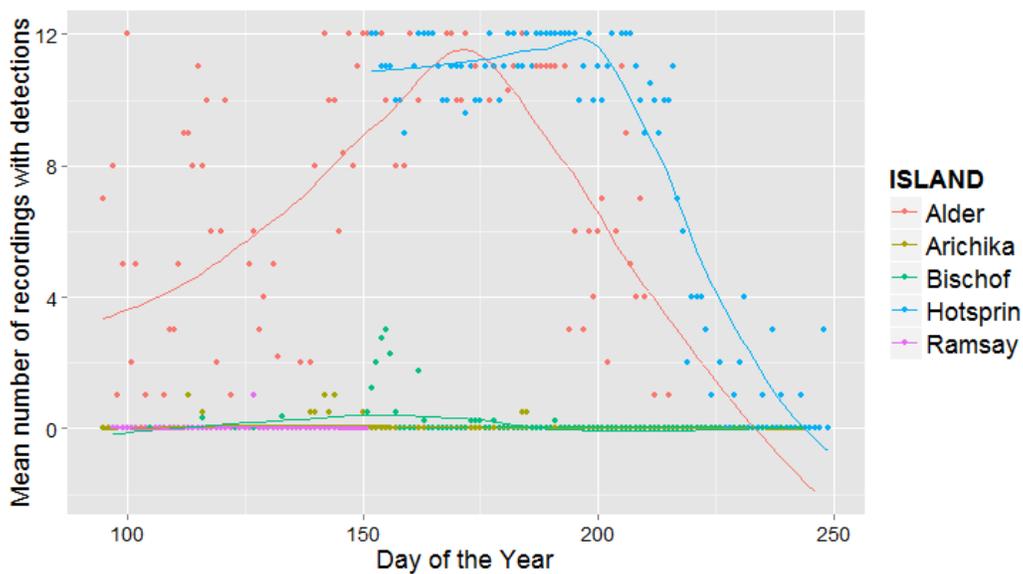


Figure 17. Seasonal and spatial pattern of the mean number of Fork-tailed Storm-Petrel recordings with detections by day and island in 2011. Trend lines use loess smoothing.

4.3.4. Leach's Storm-Petrel

The mean number of recordings per night with Leach's Storm-Petrel detections on rat-infested islands was highest on Arichika Island at 2.97 in 2010 and 2.55 in 2011 (Figure 18). Relative abundance was much higher on Alder Island at 6.93 in 2011. On Bischof relative abundance was 0.04 in 2010 and 0.01 in 2011. On Hotspring Island, relative abundance was 0.28. Detection probabilities were highest on rat-free Alder Island, but higher on rat-infested Arichika Island than rat-free Hotspring Island (Figure 19). The mean number of recordings with detections per day shows clear seasonal patterns of highest relative abundance on Alder Island followed secondly by Arichika Island (Figure 20).

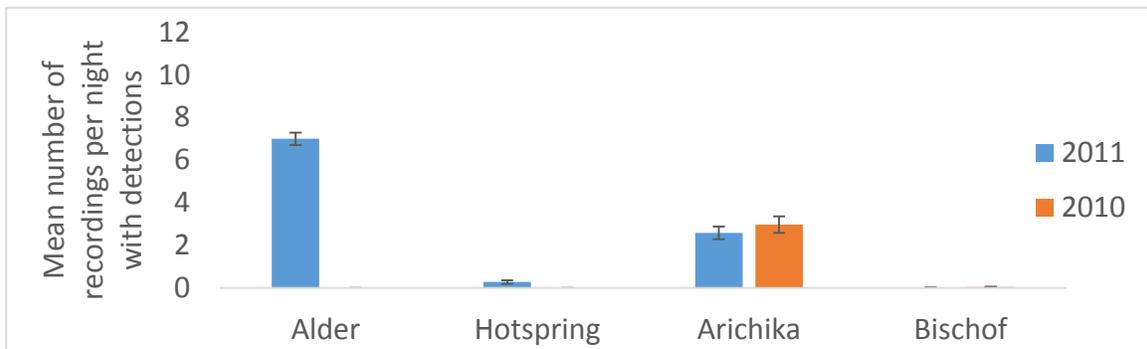


Figure 18. Mean number of recordings per night with Leach's Storm-Petrel detections on islands in Gwaii Haanas in 2010 and 2011. Bars indicate standard error.

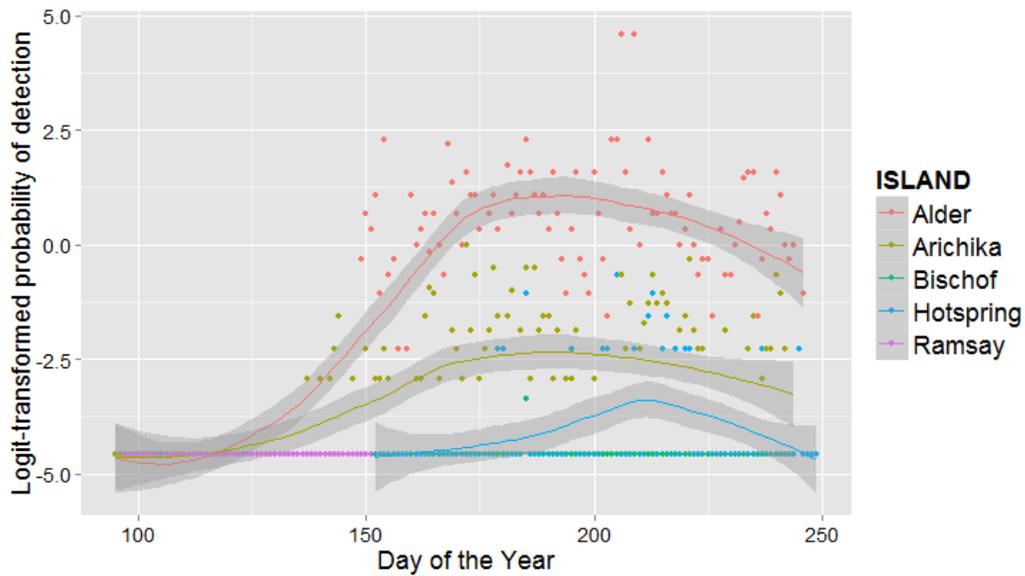


Figure 19. Seasonal and spatial pattern of Leach's Storm-Petrel detections by island in 2011. Data points (many obscured due to overlap) indicate logit-transformed probability of detection out of 12 recordings per day. Trend lines use loess smoothing with 95% confidence interval bands indicated by shading.

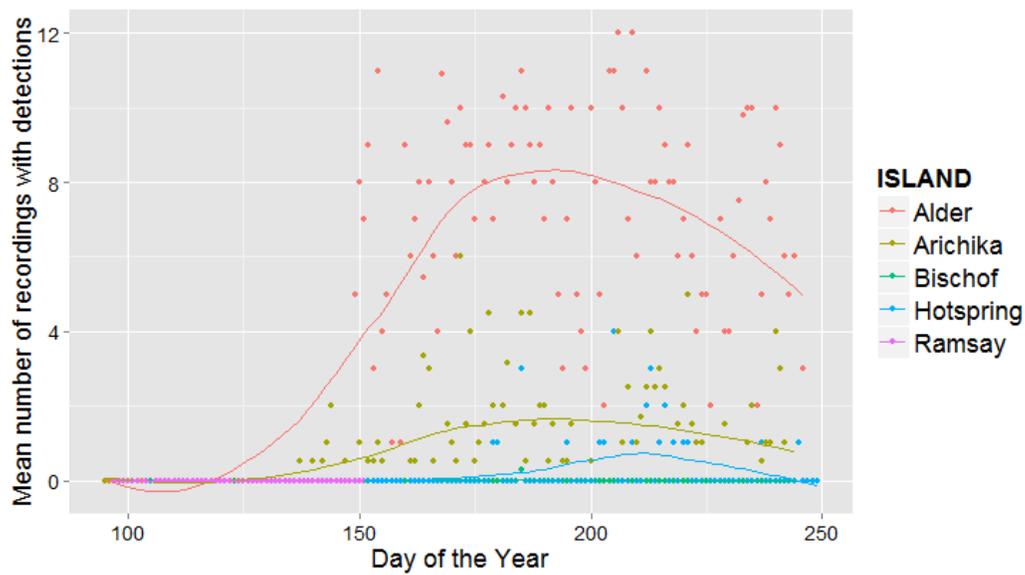


Figure 20. Seasonal and spatial pattern of the mean number of Leach's Storm-Petrel recordings with detections by day and island in 2011. Trend lines use loess smoothing.

Although the sample size in terms of number of islands is small, I tested for statistical differences in relative abundance between rat-free and rat-infested islands (Table 7). I restricted these analyses to comparable recording periods during the active parts of the seasons (see 3.9 Statistical Analyses). Ancient Murrelet and Fork-tailed Storm-Petrels were more likely to be detected on rat-free islands (Table 7).

There was a significant difference in the mean proportion of recordings per night with Ancient Murrelet detections on rat-infested (mean=0.01, SD 0.14, $n = 2$) compared to rat-free (mean=0.91, SD=0.01, $n = 2$) islands; $t(2)=8.17$, $p=0.01$. There was also a significant difference in the mean proportion of recordings per night with Fork-tailed Storm-Petrel detections on rat-infested (mean=0.01, SD=0.01, $n = 2$) compared to rat-free (mean=0.59, SD=0.14, $n = 2$) islands; $t(2)=5.69$, $p=0.03$.

Although the mean values for rat-free islands were higher, there was no statistically significant difference in the mean proportion of Cassin's Auklet detections on rat-infested (mean=0.12, SD=0.16, $n = 2$) compared to rat-free (mean=0.45, SD=0.31, $n = 2$) islands; $t(2)=1.36$, $p=0.31$. There was also no significant difference for Leach's Storm-Petrel detections on rat-infested (mean=0.05, SD=0.08, $n = 2$) compared to rat-free (mean=0.31, SD=0.41, $n = 2$) islands; $t(2)=0.88$, $p=0.47$.

Species	n	Rats	Mean	95% CL Mean		Std. Dev	DF	t Value	Pr > t
Ancient Murrelet	2	NO	0.91	0.82	0.99	0.01	2	8.17	0.01
	2	YES	0.10	-1.15	1.35	0.14			
Cassin's Auklet	2	NO	0.45	-2.33	3.24	0.31	2	1.36	0.31
	2	YES	0.12	-1.30	1.54	0.16			
Fork-tailed Storm-Petrel	2	NO	0.59	-0.71	1.89	0.14	2	5.69	0.03
	2	YES	0.01	-0.07	0.09	0.01			
Leach's Storm-Petrel	2	NO	0.31	-3.37	3.99	0.41	2	0.88	0.47
	2	YES	0.05	-0.63	0.74	0.08			

Table 7. Mean proportion of seabird presence detections per night on rat-infested and rat-free islands in Gwaii Haanas (2011 only) with means compared using a t-test assuming equal variances.

5. Discussion

Given historical survey information (e.g. Summers 1974, Rodway et al. 1988, Rodway 1991) I expected that seabirds were most likely extirpated from Arichika and Bischof Islands. In contrast to this prediction, results of all my measures (attendance, the number of nights with detections and relative abundance) showed that nocturnal seabirds were still present on rat-infested Arichika and Bischof islands. However, despite their continued presence, all measures were considerably reduced on rat-infested islands. While these measures are only indices of relative abundance, I assume that they do correlate with absolute abundance. It does appear that these highly reduced populations on rat-infested Arichika and Bischof islands may still be attempting to breed: the length of attendance shows extended presence of some species throughout the main breeding periods. In many cases the period of attendance on rat-infested islands is long enough for breeding activities to occur.

5.1. Effect of Rat Presence on Seabird Detections

There was a statistically significant negative effect of rats on relative abundance of Ancient Murrelet and Fork-tailed Storm-Petrel. Despite these differences, my results are encouraging for future recovery of nocturnal seabirds on Gwaii Haanas islands. Using acoustic monitoring, I demonstrated that nocturnal seabirds are present to some degree and use potential breeding habitat on rat-infested islands. The lack of significant effect of rat presence on Cassin's Auklet detections arises because Ramsay Island (rat-free) and Arichika Island (rat-infested) appeared to have similar abundances. The effect of rat presence on Leach's Storm-Petrel detections was not significant because abundance was low on Hotspring Island (rat-free) whereas on rat-infested Arichika Island it was relatively high.

Topographical differences between Arichika and Bischof could play a part in determining availability of alternative prey sources for rats. Whereas the perimeter of Arichika has many steep cliffs and rocks, often with no shoreline, Bischof's topography is relatively flat with many accessible beaches and intertidal zones exposed at low tide. Rat populations could be sustained by accessibility to intertidal marine life as prey sources. Furthermore, the steep rocky cliffs of Arichika Island may provide some refugia for species that tend to nest in rocky crevices close to shore (e.g. Cassin's Auklets). None of these factors were tested in my analyses, but marine amphipods have been confirmed as rat prey in stomach content analyses (Kurle, Croll, & Tershy, 2008) and Buxton et al. (2013) identified refugia from predators as a variable that may increase probability of seabird recovery. A larger rat population throughout the year on Bischof Island could explain lower seabird abundance there.

The large volume of data I collected to assess nocturnal seabird presence represents a considerable amount of time committed to processing sounds and capturing seabird vocal information. The same or similar statistical results on the effect of rats on seabird encounter probabilities could be achieved with a reduced amount of acoustic recordings. For example, by truncating the data that I used for the *t*-tests to reduced periods where islands received equal temporal survey effort for each seabird group (e.g. alcid and storm-petrels), the effect of rat presence on bird detections was significant despite testing this reduced amount of data. The seasonal and time of night representation of seabird detections in Gwaii Haanas indicate periods of maximal seabird presence. This information will allow for more cost-effective survey effort during future years with similar statistical power with respect to probable rates of detection.

5.2. Limitations of the Study

The study exhibited some sampling bias toward rat-infested islands because I deployed more ARUs on rat infested islands. Further, sampling bias arose due to unequal spatial and temporal deployment of ARUs. Despite these biases, there were still clear seasonal patterns of the effect of rats on seabird detections between rat-infested and rat-

free islands. Additionally, attendance periods are likely underrepresented for each species. It is likely that the attendance periods for all or some species extend to before the start of recording (especially for alcids and Fork-tailed Storm-Petrels) or beyond the conclusion of recording (especially for storm-petrels).

Various factors limit the amount of information acoustic recordings can provide. In this work I used phenological detection data on each island to infer the likelihood of breeding activity by each species, but there were many questions I could not answer about the activities of nocturnal seabirds. Firstly, it is not possible to determine population size, or the number of birds present in a given acoustic recording. Secondly, acoustic data does not always provide information about nesting success. It is not possible to distinguish individual birds, the age of birds, or to determine whether adults successfully incubated and hatched eggs or fledged chicks. In theory, chick calls may be detectable (e.g. Simons 1981, Taoka et al. 1989, Gaston 1992, Naugler and Smith 1992, Seneviratne et al. 2009), but this was not assessed in this study. It is also unclear whether some of the birds recorded on Bischof and Arichika were adults or subadults prospecting for nest sites.

5.3. Interannual Variability in Alcid Relative Abundance

Ancient Murrelet and particularly Cassin's Auklet had lower relative abundances in 2010. This may be explained by a severe El Niño event along the west coast of British Columbia (DFO, 2011). On Triangle Island, off the coast of northern Vancouver Island, Cassin's Auklet growth rates in 2010 were the lowest they had been in 15 years (DFO, 2011); this was attributed to the late arrival of spring weather. Cassin's Auklet is a zooplanktonivorous species (K. Vermeer, 1981) and the timing of its egg laying and hatching generally coincides with zooplankton productivity, which was significantly reduced due to the El Niño event. El Niño events have been related to colony abandonment and reproductive failure in zooplanktonivorous auklets in the North Pacific in 1983, 1997 and 2005 (Sydeman et al., 2006).

5.4. Seabird Attendance Periods and Relative Abundance

Long attendance periods and high relative abundance measures on Arichika Island imply that Ancient Murrelet, Cassin's Auklet and Leach's Storm-Petrel could be initiating nesting there. This may also be true for Fork-tailed Storm-Petrels on the Bischof Islands. That nightly detections were more continuous, and the total number of nights with detections were higher on control islands suggests that reproduction on rat infested islands may not have been successful, or alternatively it may be reduced.

Rat-infested Arichika Island had higher relative abundance for Cassin's Auklet than rat-free Ramsay Island. It is possible that the area where I deployed ARUs on Ramsay Island had less suitable habitat for Cassin's Auklet than on Arichika Island, but this was not examined. Arichika also had higher relative abundance of Leach's Storm-Petrel than Hotspring Island. There also may be some differences in habitat characteristics on Hotspring Island that favor Fork-tailed Storm-Petrels, but again this was not examined.

On rat-infested Bischof, the low number of detections of Ancient Murrelet, Cassin's Auklet and Leach's Storm-Petrel that was apparent during both 2010 and 2011 suggest that breeding attempts were almost certainly absent. In contrast, results from rat-infested Arichika Island suggest that both Ancient Murrelet, Cassin's Auklet and Leach's Storm-Petrel are almost certainly attempting to breed there, with some possible chick fledging success.

5.4.1. Ancient Murrelet

In 2011, the length of the Ancient Murrelet attendance period on Arichika was 78 days, with 56 nights of detections. On rat-free Alder Island the period was 80 days with 72 nights of detections. Gaston (1992) recorded a mean Ancient Murrelet incubation period of 32.7 days on nearby Reef Island. Ancient Murrelet chicks are precocial and most chicks depart nest burrows to the ocean, where they are reared, within approximately 48 hours after hatching (A. J. Gaston, 1992). This indicates that birds were present long enough on Arichika Island for incubation and chick fledging to potentially occur.

5.4.2. Cassin's Auklet

Cassin's Auklet attendance period on Arichika in 2011 was 82 days with 69 days of detections. On Alder the period was 113 days with 82 nights of detections, but the attendance period appeared to be longer because of some late Cassin's Auklet presence that was preceded by a period of absence of approximately 20 days. These late birds may have been non-breeding nest site prospectors, or late fledging juveniles. Due to the long period of presence on rat-infested Arichika, it is likely that Cassin's Auklet successfully reared at least some young. The mean incubation period for Cassin's Auklets on the Farallon Islands was 39 days (D. G. Ainley & Boekelheide, 1990) and is known to be similar in British Columbia where most Cassin's Auklets fledge by the end of July (K. Vermeer, 1981). This indicates that birds were possibly present on Arichika for sufficient length of time for adults to incubate eggs and rear chicks.

5.4.3. Fork-tailed Storm-Petrels

Fork-tailed Storm-Petrels possibly attempted egg laying and incubation on Bischof in 2010, but are unlikely to have successfully reared chicks given their short period of presence. Mean incubation periods on Amatuli Island, AK were 49.8 days with a nestling period of 59.5 days (Boersma et al., 1980). Fork-tailed Storm-Petrels were present on Bischof for a total of 51 nights in 2010 and 16 nights in 2011. This suggests that some incubation may have occurred in 2010. It is possible that rat predation on eggs or chicks could have caused premature colony abandonment. Fork-tailed Storm-Petrels are known for their highly variable laying dates and the ability of their egg embryos to withstand periods of neglect (e.g. Boersma and Parish 1998). This could explain why relative abundance appeared high early in the year on Alder Island and later on Hotspring because different colonies could be breeding asynchronously. Despite the likelihood that Fork-tailed Storm-Petrels may have attempted to breed on Bischof in 2010, relative abundance, even at its highest on Bischof, was still less than half that of control islands.

5.4.4. Leach's Storm-Petrels

On Bischof Islands, encounter probabilities and relative abundance for Leach's Storm-Petrels were extremely low, which implies that the island almost certainly lacks a breeding population there. Despite the longer period of Leach's Storm-Petrel presence on rat-infested islands, relative abundance was half that of rat-free Alder Island. The long attendance on Arichika Island implies that this species is likely attempting to breed and possibly rearing some chicks on the island. The mean incubation period was recorded at 43.3 days with a nestling period of 48 days on Great Island, NF (Huntington et al., 1996), indicating that the species was present for long enough to rear chicks. Despite this, the lower relative abundance and relatively broken, discontinuous colony suggests that absolute abundance is likely much lower on rat-infested Arichika compared to rat-free Alder.

5.5. Recovery of Nocturnal Seabirds on Arichika and Bischof Islands

Extirpations of nesting seabird colonies on rat-infested islands are well documented (e.g. Moors and Atkinson 1984, Atkinson 1988, Towns et al. 2006, 2009, Jones. et al. 2008), so presence of burrow-nesting seabirds on rat-infested islands in Gwaii Haanas is surprising. The close proximity of treatment islands to those without rats (Alder, Hotspring and Ramsay Islands) provides source populations of seabirds that may recolonize Arichika and Bischof Islands. In an analysis of seabird recovery after predator eradication, Buxton et al. (2014) found that distance to a source population (within 25 km) was an influential factor in seabird recovery after predator eradication. Bischof and Arichika Islands are within this distance of rat-free islands with breeding populations of all species assessed in this study.

My results imply that seabird recovery could successfully occur passively, i.e. with minimal or no management intervention (other than rat-eradication), assuming no other factors limit seabird populations on these islands. However, as Buxton et al. (2014) emphasize, monitoring efforts should continue post-predator eradication until seabird

responses to eradication are better understood. It is possible that Bischof and Arichika islands act as high-mortality population sinks in a metapopulation (Pulliam, 1988) that are populated with seabird offspring from nearby rat-free islands. For example, Bischof and Arichika Islands could have high seabird immigration from populations on nearby rat-free islands, but mortality could be high, and emigration low or non-existent.

After rat-eradication there are two pathways for seabird recovery to occur: active or passive. Firstly, active intervention involves deliberate actions to manipulate seabird populations through restoration techniques such as social attraction and translocation of chicks. Social attraction employs the use of social cues such as displaying model decoys of birds or acoustic playback of bird calls, the goal of which is to lure birds to a location and encourage colonization (Holly P. Jones & Kress, 2012; Kress, 1983). The presence of conspecifics has been identified as a function of habitat quality for colonial nesting birds (Podolsky & Kress, 1992). Secondly, passive recovery whereby seabird populations are allowed to recover naturally following predator removal (Scott, Wehtje, & Wehtje, 2001). Passive recovery is more feasible when source populations exist nearby, or when translocation is not suitable for the species of interest (e.g. Buxton et al. 2014).

Arichika Island is of particular interest for considering passive seabird recovery in Gwaii Haanas. Despite the presence of rats on Arichika Island, my data demonstrate the strong likelihood of breeding attempts by Ancient Murrelet, Cassin's Auklet and Leach's Storm-Petrel on Arichika. Moreover, the close proximity of high density breeders of these species on Alder Island further facilitates passive recovery. Such is not the case for the Bischof Islands, where active restoration efforts could be useful to expedite alcid recovery due to the current absence of most historically occurring species there with the possible exception of Fork-tailed Storm-Petrel.

Field workers on the Bischofs and Arichika, before and during eradication, found two instances of depredated adult Ancient Murrelets during 2011 on Arichika, and one Ancient Murrelet eggshell that appeared to indicate that the chick hatched successfully in 2008 (C. Bergman *pers. comm.*). Despite this evidence that seabirds may still be present on Arichika and Bischof islands, field workers did not identify a single burrow during their

significant time there. That ARU's are able to detect what appears to be very low densities of nesting seabirds is significant, and their future for monitoring vocal seabirds is encouraging.

6. Conclusions

My results imply that remnant populations of breeding seabirds still exist on rat-infested islands in Gwaii Haanas. Therefore, so long as there are nearby rat-free islands to serve as source populations, seabird recovery on Arichika and the Bischof Islands could occur relatively quickly following rat-eradication relative to islands where rats have completely extirpated seabirds. As well, the close proximity of Arichika and Bischof to source populations (e.g. nearby rat-free islands with breeding seabird populations) may also expedite passive recovery of these populations.

ARUs were a successful tool in investigating and comparing seasonal patterns of seabird presence, providing natural history with respect to the timing of breeding, describing seabird attendance periods, and measuring relative abundance on rat-infested compared to rat-free islands. Despite these successes, further research is needed to develop and improve automatic detection and experimental design, which could save a tremendous amount of time spent on acoustic data capture and make it possible to detect individual calls of seabirds on Gwaii Haanas islands, rather than just presence/absence. It would be useful to then be able to determine whether the number of calls detected can be correlated with estimates of absolute population size for the seabird species that I assessed (e.g. Borker et al. 2014, Opper et al. 2014).

Taking a passive approach to seabird recovery on Arichika Island appears to be a feasible option. However, on Bischof, active restoration methods could be considered to expedite the recovery of Ancient Murrelet, Cassin's Auklet and Leach's Storm-Petrels. Further seabird monitoring should continue to occur so that the responses of nocturnal seabirds to rat-eradication on Arichika and Bischof can be measured and further action can be taken to conserve seabirds in future if recovery does not occur. I recommend that future seabird acoustic monitoring in Gwaii Haanas use a balanced deployment of ARUs between control and treatment islands and over equal time periods. Furthermore, traditional survey methods may also be used in future to measure nesting success as a

component of seabird recovery. The seasonal detection probabilities presented in this study will help to inform timing of these surveys.

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Appendix A.

Dates, locations and duration of acoustic recording units in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2010 and 2011, to detect nocturnal seabirds.

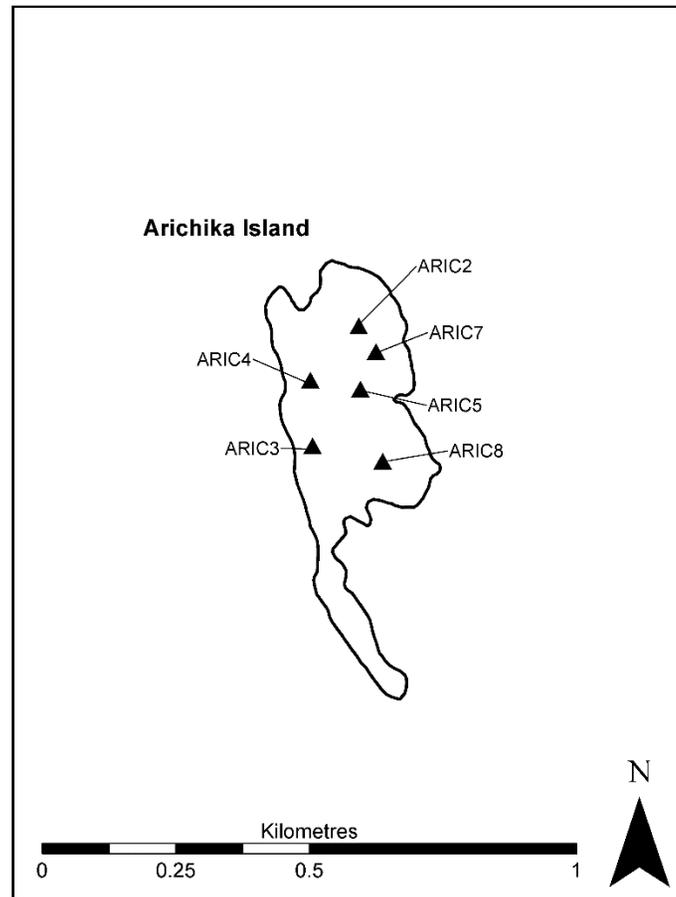
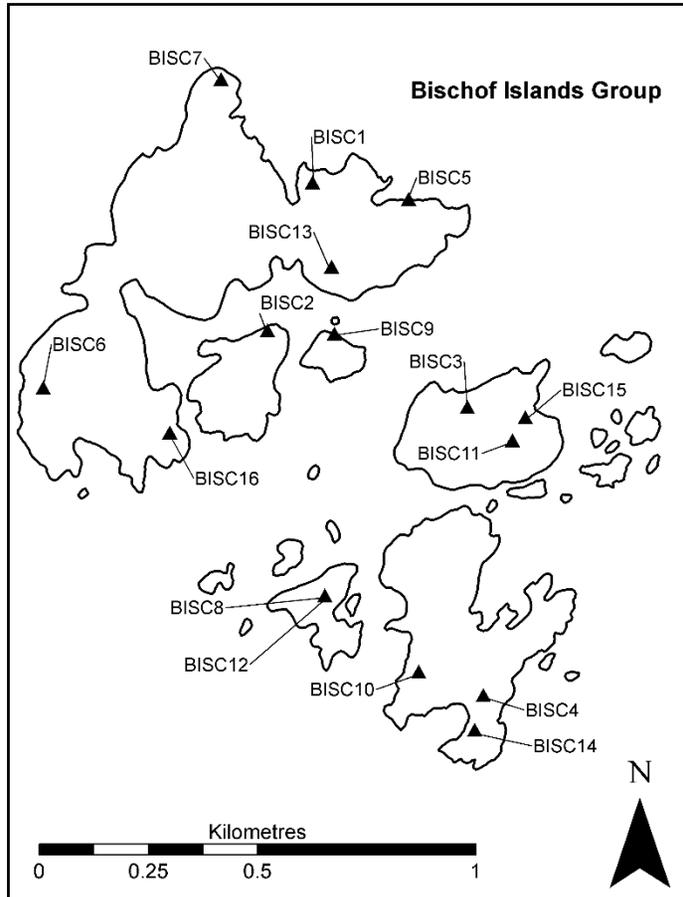
Rats	Island	Recording Interval Site	Year	Recording Start	Recording End	Recording Nights	Recording Hours	Decimal Latitude	Decimal Longitude	Recording site selected for (seabird group)
Yes	Bischof	BISC1	2010	15 April	29 May	44	88	52.58082	-131.56213	Alcids
Yes	Bischof	BISC2	2010	15 April	28 May	43	86	52.57778	-131.56398	Alcids
Yes	Bischof	BISC3	2010	15 April	28 May	43	86	52.57620	-131.55577	Alcids
Yes	Bischof	BISC4	2010	15 April	28 May	43	86	52.57028	-131.55511	Alcids
Yes	Arichika	ARIC2	2010	17 April	14 May	27	54	52.47338	-131.34098	Alcids
Yes	Bischof	BISC5	2010	30 May	26 June	27	54	52.58048	-131.55818	Alcids
Yes	Bischof	BISC6	2010	29 May	27 June	29	58	52.57660	-131.57320	Alcids
Yes	Bischof	BISC7	2010	29 May	26 June	28	56	52.58294	-131.56589	Alcids
Yes	Bischof	BISC8	2010	29 May	26 June	28	56	52.57233	-131.56163	Alcids
Yes	Arichika	ARIC3	2010	28 May	27 June	30	60	52.47137	-131.34254	Alcids
Yes	Arichika	ARIC4	2010	28 May	27 June	30	60	52.47247	-131.34261	Alcids
Yes	Bischof	BISC9	2010	26 June	25 July	29	58	52.57771	-131.56123	Storm-petrels
Yes	Bischof	BISC10	2010	27 June	25 July	28	56	52.57076	-131.55777	Storm-petrels
Yes	Bischof	BISC11	2010	27 June	25 July	28	56	52.57599	-131.55338	Storm-petrels
Yes	Bischof	BISC12	2010	26 June	25 July	29	58	52.57233	-131.56163	Storm-petrels
Yes	Arichika	ARIC5	2010	28 June	27 July	29	58	52.47232	-131.34093	Storm-petrels
Yes	Bischof	BISC13	2010	26 July	31 August	36	72	52.57908	-131.56135	Storm-petrels
Yes	Bischof	BISC14	2010	26 July	31 August	36	72	52.56957	-131.55547	Storm-petrels

Rats	Island	Recording Interval Site	Year	Recording Start	Recording End	Recording Nights	Recording Hours	Decimal Latitude	Decimal Longitude	Recording site selected for (seabird group)
Yes	Bischof	BISC15	2010	26 July	31 August	36	72	52.57552	-131.55392	Storm-petrels
Yes	Bischof	BISC16	2010	26 July	31 August	36	72	52.57568	-131.56800	Storm-petrels
Yes	Arichika	ARIC7	2010	28 July	27 August	30	60	52.47295	-131.34040	Storm-petrels
Yes	Arichika	ARIC8	2010	28 July	31 August	34	68	52.47112	-131.34018	Storm-petrels
Yes	Bischof	BISC17	2011	07 April	17 April	10	20	52.57613	-131.55578	Alcids
Yes	Bischof	BISC18	2011	07 April	03 May	26	52	52.58004	-131.55755	Alcids
Yes	Bischof	BISC19	2011	07 April	03 May	26	52	52.58268	-131.56599	Alcids
Yes	Bischof	BISC20	2011	07 April	03 May	26	52	52.57669	-131.57322	Alcids
Yes	Arichika	ARIC9	2011	05 April	30 April	25	50	52.47352	-131.34088	Alcids
Yes	Arichika	ARIC10	2011	05 April	30 April	25	50	52.47144	-131.34235	Alcids
No	Ramsay	RAMS1	2011	07 April	30 April	23	46	52.56488	-131.42883	Alcids
No	Alder	ALDE1	2011	05 April	30 April	25	50	52.44999	-131.32478	Alcids
Yes	Bischof	BISC21	2011	04 May	29 May	25	50	52.57985	-131.56171	Alcids
Yes	Bischof	BISC22	2011	04 May	29 May	25	50	52.58065	-131.56905	Alcids
Yes	Bischof	BISC23	2011	04 May	29 May	25	50	52.58035	-131.56035	Alcids
Yes	Bischof	BISC24	2011	03 May	29 May	26	52	52.57570	-131.56892	Alcids
Yes	Arichika	ARIC11	2011	01 May	30 May	29	58	52.47241	-131.34245	Alcids
Yes	Arichika	ARIC12	2011	01 May	30 May	29	58	52.47117	-131.34003	Alcids
No	Ramsay	RAMS2	2011	01 May	31 May	30	60	52.56488	-131.42883	Alcids
No	Alder	ALDE2	2011	01 May	28 May	27	54	52.44999	-131.32478	Alcids
Yes	Bischof	BISC25	2011	30 May	30 June	31	62	52.57233	-131.56163	Storm-petrels
Yes	Bischof	BISC26	2011	30 May	30 June	31	62	52.57559	-131.55726	Storm-petrels
Yes	Bischof	BISC27	2011	30 May	30 June	31	62	52.57146	-131.55327	Storm-petrels
Yes	Bischof	BISC28	2011	30 May	30 June	31	62	52.57546	-131.55408	Storm-petrels

Rats	Island	Recording Interval Site	Year	Recording Start	Recording End	Recording Nights	Recording Hours	Decimal Latitude	Decimal Longitude	Recording site selected for (seabird group)
Yes	Arichika	ARIC13	2011	31 May	01 July	31	62	52.47346	-131.34204	Storm-petrels
Yes	Arichika	ARIC14	2011	31 May	01 July	31	62	52.47201	-131.34086	Storm-petrels
No	Hotspring	HOTS1	2011	01 June	05 July	34	68	52.58157	-131.43230	Storm-petrels
No	Alder (Islet)	ALDI1	2011	29 May	30 June	32	64	52.45408	-131.32353	Storm-petrels
Yes	Bischof	BISC29	2011	01 July	01 September	62	124	52.56980	-131.55515	Storm-petrels
Yes	Bischof	BISC30	2011	01 July	26 August	56	112	52.57305	-131.55696	Storm-petrels
Yes	Bischof	BISC31	2011	01 July	29 August	59	118	52.57695	-131.56459	Storm-petrels
Yes	Bischof	BISC32	2011	01 July	31 August	61	122	52.57503	-131.55602	Storm-petrels
Yes	Arichika	ARIC15	2011	02 July	31 August	60	120	52.46857	-131.34135	Storm-petrels
Yes	Arichika	ARIC16	2011	02 July	01 September	61	122	52.47087	-131.34137	Storm-petrels
No	Hotspring	HOTS2	2011	06 July	07 September	63	126	52.58342	-131.43130	Storm-petrels
No	Alder (Islet)	ALDI2	2011	01 July	03 September	64	128	52.45406	-131.32248	Storm-petrels

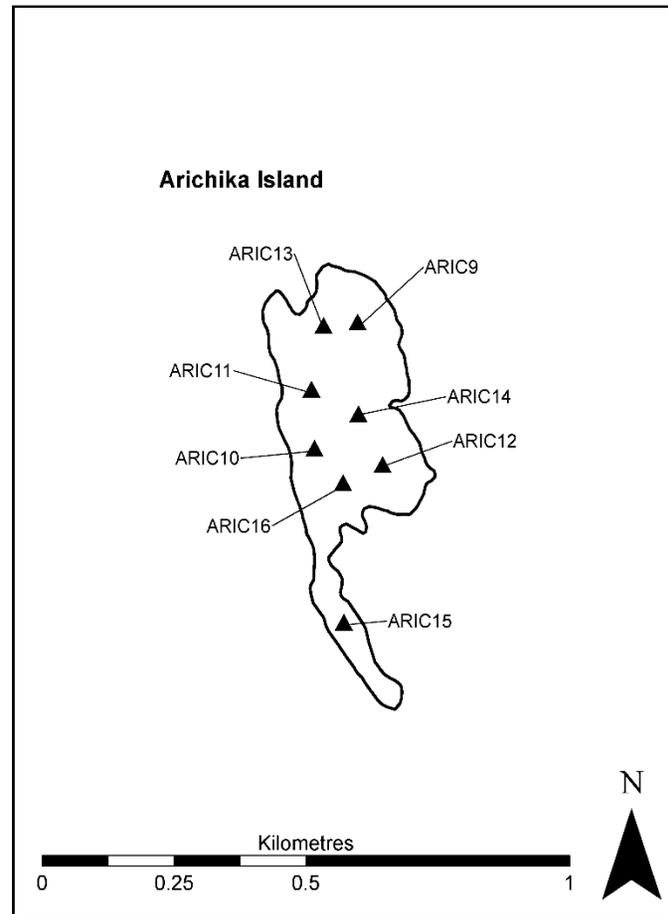
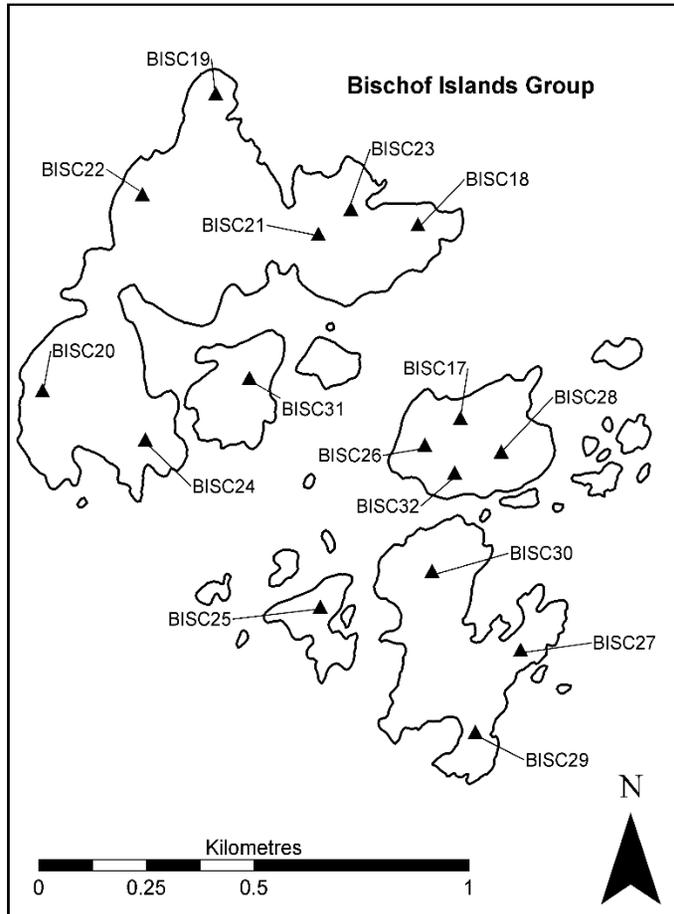
Appendix B.

Locations of Songmeter recording interval sites at rat-infested islands (Arichika Island and Bischof Islands group) in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2010.



Appendix C.

Locations of Songmeter recording interval sites at rat-infested islands (Arichika Island and Bischof Islands group) in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2011.



Appendix D.

Locations of Songmeter recording interval sites at control islands (Hotspring Islets, Ramsay Island, Alder Island) in Gwaii Haanas National Park Reserve and Haida Heritage Site in 2011.

