MONITORING AND MANAGING RECOVERY OF NOCTURNAL BURROW-NESTING SEABIRD POPULATIONS ON RECENTLY PREDATOR-ERADICATED ALEUTIAN ISLANDS

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by

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ABSTRACT

Few quantitative data exist measuring nocturnal burrow-nesting seabirds that were heavily affected by predator introductions in the Aleutian Islands, due to challenges associated with monitoring. I evaluated the feasibility of using automated recording and recognition of call activity as a way to examine restoration. I assessed recording quality and call recognition rate in the windy Aleutian environment, characteristic of remote seabird breeding islands. With only 3% of nights unusable due to wind noise, devices were extremely robust. I used this method to inventory call activity across the western Aleutian Islands and relate patterns to recovery rate. I found that nocturnal seabird activity is positively related to time since eradication, however a number of other factors render recovery rate complicated. In order to encourage re-colonization I performed a series of social attraction experiments. Continued acoustic monitoring and artificial attraction are required to promote population recovery throughout the Aleutian chain.

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Monitoring seabirds with acoustic recording devices is a unique project that is an exciting prospect for future restoration and conservation research, but certainly comes with its fair share of frustrations! Thanks to Ian Agranat, the CEO of Wildlife Acoustics for endless hours of help and troubleshooting with Song Scope and Ted Miller who provided me with his bioacoustic wisdom.

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LIST OF ABBREVIATIONS AND SYMBOLS

LESP – Leach’s Storm-petrel

FTSP – Fork-tailed Storm-petrel

ANMU – Ancient Murrelet

CAAU – Cassin’s Auklet

HAST – Hawaii-Aleutian Standard Time

Hr – hours

Min – minutes

Ha – Hectares

Km – Kilometers

M - Meters

AIC – Akaike’s Information Criterion

QAIC – Quasi – Akaike’s Information Criterion

GzLM – Generalized Linear Model

EMM – Estimated Marginal Mean

SD – Standard Deviation

SE – Standard Error

ASL – Above Sea Level

WWII – World War Two

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

1.1.1 *Island Invaders.*

Invasion of alien plants and animals is the most important cause of biodiversity loss in island ecosystems (Atkinson 1989, Moors and Atkinson 1984, Chapuis *et al.* 1994, Vitousek 1990). A biological invasion is defined as the expansion of any organism outside its previous known geographical range, and represents an important evolutionary process (Williamson 1996). However, because of humans, invasion of remote islands by species that could not have dispersed there naturally has become common. Introduced species, especially non-native mammals, have devastating effects on island ecosystem dynamics (Wardle 2002, Parker *et al.* 1999), have altered or destroyed natural island habitat, and have driven local fauna to extirpation or extinction (Blackburn *et al.* 2004). Oceanic islands are home to insular animal communities with high rates of endemism and relatively little diversification, resulting in disproportionate rates of extinction and extirpation caused by introduced species (Courchamp *et. al.* 2003, Aguirre-Munnoz *et al.* 2008). For example, 93% of 129 bird extinctions in the past 500 years have been island species (King 1985, Birdlife International 2000) and island birds constitute 67% of the world bird species currently threatened with extinction (Rauzon 2007). Introduced mammalian predators including foxes (*Alopex lagopus, Vulpes vulpes*), dogs (*Canis familiaris*), feral cats (*Felis catus*) and especially rats (*Rattus* spp.), are the primary driver of population reduction (McChesney and Tershy 1998, Courchamp *et al.* 2003, Aguirre-

Munnoz *et al.* 2008). Over 90% of all islands have been invaded by rats; at least 65 major island groups have been invaded by cats; and cattle, rabbits and hares (Leporidae), goats (*Capra hirca*), sheep (*Ovis aries*), and other grazers have been introduced onto islands for farming (Atkinson 1989, Towns 2006, Jones *et al.* 2008b).

1.1.2 *Seabird Vulnerability to Island Invaders.*

Approximately 30% of seabird species that nest on islands are listed as threatened, and 6% are listed as critically endangered by the IUCN, owing to fisheries by-catch (Lewison *et al.* 2004), human-induced climate change (Smith *et al.* 1999, Croxall *et al.* 2002), changes in prey supply (Boersma and Parrish 1998) and most importantly, the introduction of non-native species (Moors and Atkinson 1984, Atkinson 1989, McChesney and Tershy 1998, Rauzon 2007, Birdlife International 2008). Seabirds spend most of their lives on the open ocean, but must return to land to reproduce. Suitable nesting habitat close to optimal foraging grounds and free from disturbance by terrestrial mammals is therefore of the utmost importance.

Introduced mammals can destroy nesting habitat through trampling and grazing (Cruz and Cruz 1987) however, the greatest threat to seabirds is direct predation and caching of eggs, chicks, and adults (Moors and Atkinson 1984). Seabirds are rendered vulnerable because they have evolved for millennia in the absence of terrestrial predators, leading to adaptations such as flightlessness (Diamond 1981, McNab 1994), lack of fear (Milberg and Tyrberg 1993), and conspicuous ground-nesting habits (Ebbert and Byrd 2002). Furthermore, seabirds are long-lived and have low annual reproductive and recruitment rates (Lack 1968, Warham 1990, 1996), meaning that individuals lost to predation cannot be quickly replaced (Moors and Atkinson 1984, Paulay 1994). When non-native mammals are introduced into island ecosystems, populations of seabirds are severely reduced, and small ground nesting seabirds are often extirpated (McChesney and Tershy 1998) or driven to extinction (e.g., Guadalupe Storm-petrel *Oceanodroma macrodactyla*; Jehl and Everett 1985).

1.1.3 *Island Invaders in the Aleutians.*

The Aleutian Islands have been invaded by many different predators including: Norway Rats (*Rattus norvegicus*), Arctic Foxes (*Alopex lagopus*), House Mice (*Mus musculus*), and ground squirrel (Sciuridae) (Ebbert and Byrd 2002). Foxes were first introduced in the 1750s for the Russian fur trade, but the heyday for fox ranching occurred in the early 20th century by American Enterprises when nearly every habitable island (over 450) was stocked with foxes (Bailey 1993, Ebbert and Byrd 2002, Byrd *et al.* 2005). The highly adaptable Norway Rat has become established on 16 Aleutian Islands due to accidental introductions during military occupation or establishment of fox farms (Ebbert and Byrd 2002). Response has rarely been quantified, but anecdotal evidence indicates that insular seabird populations were decimated after predator introductions (Murie 1959, Bailey 1993, Byrd *et al.* 2005).

1.1.4 *Island Restoration. –*

1.1.4.1 *Eradication of Island Invaders. –*

Efforts to eradicate introduced predators are increasing due to widespread accounts of damage inflicted on island faunas (Jones *et al.* 2008b, Brooke *et al.* 2007, Clout 2001). Eradication technologies were pioneered in New Zealand in the 1970s, and since have become more streamlined and sophisticated with the advent of anti-coagulant toxins and bait-delivery systems, more cost-effective with the development of prioritization schemes, and more realistic on larger islands (Towns and Broome 2003, Clout and Russell 2006, Brooke *et al.* 2007, Baker *et al.* 2007). Eradication success stories are numerous, from the removal of Arctic Foxes in Alaska (Bailey 1983) to feral cats in Mexico (Keitt and Tershy 2003). Twenty-five invasive vertebrate species have been removed from over 775 islands world-wide (Keitt *et al.* 2010). As of 2009, Arctic Foxes have been removed from 34 islands across the Aleutian chain and the first eradication of Norway Rats was recently deemed successful (J.C. Williams pers. comm.).

In some cases, eradication has been beneficial for seabird populations. For example, increases in hatching success and nesting distribution have been observed in Xantus's Murrelet on Ancapa Island (*Synthliboramphus hypoleucus;* Whitworth *et al.* 2005), Shags and Razorbills on Canna Island (*Phalacrocorax aristotelis* and *Alca torda*; Swann 2006), and petrel species on Marion Island (Cooper *et al.* 1995), after eradication of rats and feral cats. In the Aleutian Islands, populations of Black Oystercatcher (*Haematopus bachmani*; Byrd *et al.* 1994) and Pigeon Guillemot (*Cepphus columba*; Byrd *et al.* 1997) have increased 4- to 5-fold after Arctic Fox eradication. However, these types of quantitative accounts are rare, and there are many situations where eradication has not resulted in return or recovery of seabirds (e.g., Common Diving Petrels

Pelecanoides urinatrix on Mana Island, New Zealand 10 years after House Mice eradication; Miskelly and Taylor 2004).

1.1.4.2 *Translocation.*

Translocation involves moving chicks from their natal colony to a new site and hand-rearing them to fledging (Serventy 1989) utilizing a key social behaviour of colonial seabirds: imprinting to hatching site or natal philopatry (Thibault 1993, Ovenden *et al.* 1991). Philopatric seabirds show low levels of dispersal from their natal site, a characteristic thought to have evolved along with social organization and coloniality (Stacey and Lignon 1991). When introduced predators extirpate philopatric seabirds, all chicks that would imprint on and return to that colony are destroyed, resulting in no return after eradication. In this case, seabirds can be translocated to re-establish populations (Parker 2008, Griffith 1989). If chicks are translocated early enough in the imprinting stage, they will recognize the new site as the natal colony and return to breed as adults. Translocation has been used for many avian species to re-establish populations at sites where they were obliterated by introduced predators (e.g., Aleutian Cackling Goose *Branta hutchinsii leucopareia*; Byrd and Springer 1976) or at new sites where the original population is threatened by introduced predators (e.g., Gould's Petrel *Pterodroma leucoptera leucoptera*; Pridell and Carlile 2001).

1.1.4.3 *Social Attraction.*

Many prospecting or pre-breeding colonial seabirds use "public or social information", the auditory, visual, and olfactory cues provided by the presence of breeding conspecifics, as information to signal safe nesting habitat (Ward and Schlossberg 2004, Danchin *et al.* 2004). This strategy evolved due to the patchy nature of food resources and suitable island nesting habitat across the open ocean (Danchin *et al.* 1997, Danchin *et al.* 1998). For seabirds that lack natal philopatry, sampling alternatives across long distances would become costly and energy demanding, making monitoring conspecifics (social information) a more parsimonious method of acquiring information about nest-site quality (Boulinier and Danchin 1997, Nocera *et al.* 2006). At sites where seabird colonies have been extirpated or severely reduced by introduced predators, social cues that signal safe and suitable nesting habitat are destroyed. Therefore, prospecting individuals will no longer consider such places for nesting, and re-colonization will be slow or non-existent after eradication. If the abandoned site is still suitable for nesting, established colonies can be simulated artificially to attract birds (Parker *et al.* 2007, Kress 1997). The use of decoys, mirrors, and playbacks as artificial cues to simulate social information from active colonies is referred to as social attraction (Kress 1998). The goal of social attraction is to encourage enough prospecting-age birds to land among the decoys and playbacks and remain long enough to attract additional birds (Kress 1998). As more birds congregate at the site, potential breeders should have an increased chance of pairing and breeding and eventually colonies will result (Parker *et al.* 2007, Kress 1998).

During the last 30 years, social attraction techniques pioneered by S. Kress have become widely used in island restoration projects (Rauzon 2007, Kress 1997). Social attraction has been used to restore colonies of Atlantic Puffins (*Fratercula arctica*; Kress and Nettleship 1988), Common Murres (*Uria aalge*; Parker *et al.* 2007), Short-tailed Albatross (*Phoebastria albatrus*; Hasegawa and DeGange 1982) and many other seabirds; it has also been used for at least 38 other colonial waterbirds and several species of territorial passerines (Ward and Schlossberg 2004).

1.1.5 *Monitoring Population Recovery after Restoration.*

Large restoration efforts suffer from a common problem: lack of long-term monitoring after eradication (Davis *et al.* 2004). Monitoring seabird population recovery after restoration efforts is essential to determine effectiveness and to refine methods for future projects. However, this becomes expensive and problematic with secretive species or at remote sites characteristic of seabird nesting habitat. Common monitoring techniques of seabird recovery include: boat surveys circumnavigating islands using band or strip transects to record the number of birds of each species observed at sea (Day *et al.* 1978, Tasker *et al.* 1985), and beach counts using nest or burrow-sampling (Gaston *et al.* 1988). For larger surface or cliff nesting species, counts can be done using aerial photographs (Nettleship 1976).

1.2 STUDY SITES

1.2.1 *The Aleutian Islands.*

The Aleutian Islands comprise approximately 150 isolated volcanic islands extending 1,800 km west from the Alaska Peninsula (Gibson and Byrd 2007). Formed by the highest peaks of the submerged Aleutian ridge (Jahncke *et al.* 2005), the islands mark the boundary between the Bering Sea and the Pacific Ocean. The Aleutians have a treeless and homogenous floral composition, characterized by unique Beringial oceanic tundra, and dominated by *Leymus/Umbel* subarctic grassland (Talbot *et al.* 1997, Gibson and Byrd 2007). Due to the lack of native terrestrial predators west of the Fox Islands (Bailey 1993), near absence of modern human settlements, proximity to feeding grounds (Byrd *et al.* 2005), and relatively uniform suitable nesting habitat, the islands are a haven for seabirds (Croll *et al.* 2005). The Aleutian Archipelago holds approximately 10 million breeding seabirds of 26 different species (Byrd *et al.* 2005). The islands are extremely remote, barren, and windswept, with a harsh oceanic climate. So notorious are the gales, wind and rain, and dense fog that early Russian missionaries called the area "the place that God forgot" (Corbett and Swibold 2000). For this reason, it was believed that Alaskan islands were largely undisturbed by modern civilization, especially in comparison with temperate and tropical islands, many of which have been seriously affected by human activity (Bailey 1993). However, from the systematic introduction of Arctic Foxes (*Alopex lagopus*) for the fur trade in the 18th to 20th centuries (Bailey 1993), the accidental introduction of Norway Rats (*Rattus norvegicus*) during military occupation (Major and Jones 2005), and heavy aerial bombing raids during World War II (Daines and McClellan 1987), the Aleutians are far from pristine.

Historical distribution of seabird populations is only known from anecdotes by explorers such as Steller, yet by 1937, when the first surveys of the Aleutians were performed, it was clear that seabirds were in decline on islands used as fox farms (Murie 1959). Soon after WWII in 1949, the first resident manager of the Aleutian Islands

National Wildlife Refuge began a fox eradication program and efforts accelerated after consolidation of the Alaska Maritime NWR in 1980 (Ebbert and Byrd 2002). Furthermore, the first successful rat eradication in the Aleutians occurred at Rat Island in 2008 (Woods *et al.* 2009). This has resulted in a patchwork of islands with, without, and at different stages of recovery from introduced predators, making the Aleutians an ideal large-scale natural experiment to study the recovery of seabirds (Ebbert and Byrd 2002, Croll *et al.* 2005).

1.2.2 *Nizki and Alaid Islands*

Shemya, Nizki and Alaid Islands comprise the Semichi group in the Near Islands among the western-most of the Aleutians (Fig. 1.1). Nizki and Alaid are frequently joined by a sandbar at low tide, allowing access between islands (West 1987, Byrd *et al.* 1994). These small islands are extremely low with rolling hills generally under 60 m. In the 1800s and 1900s Nizki/Alaid had a large and diverse population of breeding birds, including seven endemics and extensive waterfowl (Clark 1910, Murie 1937). Both islands were stocked with Arctic Foxes in 1911 and essentially all nesting bird populations were drastically reduced or extirpated by 1937 (Murie 1937, Murie 1959, Byrd *et al.* 1994). Foxes were removed from Nizki in 1969 and Alaid in 1975, among the first successful eradications executed by the refuge.

1.2.3 *Buldir Island*

Buldir Island is the westernmost of the Rat Islands group and is the most isolated of the Aleutian Islands, providing the only landfall in a 220 km-wide pass (Byrd and Day 1986), located about 100 km from Kiska to the east and 130 km from Semya to the west (Fig. 1.1). Characteristic features include boulder beaches backed by steep cliffs and coastal talus slopes (Byrd and Day 1986). Buldir has never had predators introduced and thus has a large population of breeding seabirds. It is the most diverse seabird colony in the northern hemisphere, with 21 different species, including the largest breeding colony of storm-petrels in the Pacific Ocean and the largest colony of Ancient Murrelets in the Aleutian Islands (Byrd *et al.* 2005).

1.2.4 *Kiska Island*

Kiska is the second largest island in the Rat Islands group, with an active stratovolcano at the northern tip which erupted as recently as September 1990. An explosive eruption in 1962 extruded lava and created a new cinder cone about 30 meters high called Sirius point (Miller *et al.* 1998), subsequently creating extensive new auklet habitat. In contrast to Buldir, Arctic Foxes were introduced in 1835 (Ashbrooke and Walker 1925), Norway Rats were introduced accidentally during military occupation (Deines and McClellan 1987), and during WWII Kiska was occupied by Japanese, American, and Canadian troops and heavily attacked and bombed. Besides large populations of Crested and Least Auklets, few birds currently breed at Kiska (Byrd *et al.* 2005) likely due to predation by Norway Rats.

1.2.5 *Little Sitkin Island*

Little Sitkin is an active stratovolcano (Miller *et al.* 1998) in the Rat Island group of the western Aleutians. Its closest neighbours are Davidof and Khvostof about 10 km to the north-east (Fig. 1.1). Much of the island is lined with steep cliffs, particularly on the eastern and northern shores. Foxes were introduced in 1923, removed in 2000, and little is known about historic seabird colonies. In 1937, Murie (1959) found 8 different species of seabirds in over 45% of fox scat, suggesting that seabirds were heavily predated, but some managed to survive up to 14 years after predator introduction.

1.2.6 *Amatignak Island*

Experimental fieldwork was carried out in Ulva Cove to the east of Amatignak Island. Amatignak is in the Delarof Islands to the west of the Andreanof Islands and directly adjacent to Amchitka Pass (Fig. 1.1). Amatignak's southern tip, Nitrof Point, is the southernmost point in Alaska (Campbell 1995). Amatignak is an ancient, glacially eroded, densely vegetated island with extensive regions of peat bog at low elevations (Jones *et al.* 2008a). The island was stocked with foxes in 1923 and had foxes removed in 1991. Although historic colony size of seabirds pre-dating foxes is unknown, Ulva Cove holds the largest Aleut midden site in the Delarofs Islands (D. Corbett pers. comm.) and seabirds were an important constituent in Aleut diet (Lefevre 1997). The island is thought to hold a current breeding population of 7 species of seabird (USFWS 2004, Byrd *et al.* 2005).

1.2.7 *Kasatochi Island*

Kasatochi is located in the Central Aleutian Islands, separated from its nearest neighbour Atka to the southeast by 20 km and Koniuji (one of the largest active nocturnal seabird colonies in the Aleutians) to the east by 25 km. Kasatochi volcano erupted with little warning on August 7, 2008 and buried the island under up to 30 m of tephra, covering or destroying all breeding and foraging habitat on and around the island (Williams *et al.* IN PRESS). Arctic Foxes were introduced in 1927 and removed in 1984 and since then numbers of several seabird species have increased (Dummond 2006, 2007). Pre-eruption, Kasatochi supported large colonies of auklets Fork-tailed Storm-petrels, and as such was the site of extensive biological surveys (Drummond and Rehder 2005). Because some seabirds, such as Crested Auklets (*Aethia cristatella*), in the geologically active environment of the Aleutians are adapted to rapidly exploit new habitat, depending on the rate of tephra erosion, recovery of many seabirds on Kasatochi should occur quickly (Byrd *et al.* 1980, Williams *et al.* IN PRESS).

1.3 FOCAL SPECIES

1.3.1 *Nocturnal Burrow-nesting Seabirds*

All focal species are strictly nocturnal, foraging offshore during the day and visiting breeding colonies at night during complete darkness (Manuwal 1974, Simons 1981, Watanuki 1986, Gaston 1994a). As such, individuals cannot depend on visual communication and instead have developed conspicuous acoustic and chemical signals for homing, to distinguish between sexes, to interact with mates and rivals, and to attract potential mates (Grubb 1974, Brooke 1986, Brooke 2004). All species have similar diet, feeding on a mix of amphipods, copepods, euphausiids, and myctophid fish (Vermeer *et al.* 1985, Vermeer *et al.* 1988). Adults nest in shallow earthen burrows in well drained soil (Stenhouse and Montevecchi 2000), grass hummock (Byrd and Trapp 1977, Vermeer and Lemon 1986), and occasionally talus slopes and rock crevices (Harris 1974, Boersma *et al.* 1980, Drummond 2006), likely as an adaptation to avoid aerial predators and to insulate eggs and chicks from large temperature fluctuations (McKown 2008). All species have strong nest site and mate fidelity, but none are known to exhibit strong natal philopatry (Manuwal 1974, Gaston 1994b, Huntington *et al.* 1996, Boersma and Silva 2001). Therefore, to prospect for suitable nesting habitat, all species use social attraction cues, auditory and olfactory information provided by breeding conspecifics (Kress 1997). Most importantly to this study, all species were devastated by introduced predators in the Aleutians. On islands invaded by foxes or rats, colonies were extirpated or reduced to small remnant populations on offshore islets and other refugia (Murie 1959, Bailey 1993). Although there is some evidence of recovery (Nelson *et al.* 1992, Willet 1915, Willet 1917), few quantitative studies exist.

1.3.2 *Storm-petrels*

Two species of storm-petrel are known to breed in the Aleutians, Leach's (*Oceanodroma leucorhoa*) and Fork-tailed (*O. furcata*) Storm-petrel, the most abundant and widespread storm-petrels breeding in the North Pacific (Boersma and Groom 1993). These birds live colonially on islands from California to Alaska to northern Asia

(Huntington *et al.* 1996, Boersma and Silva 2001). Population estimates range from 10-15 million Leach's Storm-petrel and 5-10 million Fork-tailed Storm-petrels (Sowls *et al.* 1978). All species have similar breeding biology: age at first breeding between 3-5 years; one egg is laid and incubated by both sexes; egg-laying and hatching are asynchronous; and both the egg and chick can withstand neglect during the long incubation period (Boersma and Wheelwright 1979, Vermeer *et al.* 1988, Warham 1990, 1996). Fork-tailed Storm-petrels feed closer to shore, have higher wing-loading, and have earlier fledging than Leach's Storm-petrel (Vermeer *et al.* 1988). Although subtle differences exist, in the Aleutian Islands, Leach's and Fork-tailed Storm-petrels are closely associated in mixed colonies.

1.3.3 *Small Alcids*

Two species of nocturnal burrow-nesting alcids breed in the Aleutian Islands: Cassin's Auklet (*Ptychoramphus aleuticus*) and Ancient Murrelet (*Synthliboramphus antiquus*). These species share many common characteristics including size, nesting, and diving behaviour (Sowls *et al.* 1978, Manuwal 1974); but differ in their chick rearing strategies (Vermeer and Lemon 1986). Ancient Murrelet chicks are precocial; they are not fed within the burrow and instead depart to sea a few days after hatching accompanied by adults (Sealy 1976, Vermeer *et al.* 1984, Jones *et al.* 1987a). Cassin's Auklets on the other hand feed chicks in burrows for six weeks until the young are fledged (Manuwal 1974, Vermeer 1981). Vermeer *et al.* (1985) found that Ancient Murrelet tend to take larger planktivorous and juvenile fish prey than Cassin's Auklet, but no significant difference in diet was observed. Although these species have sympatric breeding ranges (Sowls *et al.* 1978), and nest in close proximity in the Aleutian Islands, Ancient Murrelets often avoid densely nesting Cassin's Auklets (Vermeer and Lemon 1986).

1.4 THESIS FRAMEWORK

1.4.1 *Purpose*

Gardmark *et al.* (2003) stated that all populations are likely to have experienced or will come to experience reduction, crashes, or extirpations due to natural or human-induced environmental changes. Anthropogenic alteration has spread to all ecosystems on earth's surface and rates of population decline and biodiversity loss are accelerating (Vitousek *et al.* 1997). On the other hand, conservation research is growing, and successful restoration projects are increasing around the globe. With such high rates of population reduction and subsequent management, it is important to understand factors limiting and facilitating population recoveries. However, there is a large knowledge gap in restoration literature quantifying patterns in population recovery. Due to reproductive and social constraints, some animal populations re-bound slowly, if at all. In this case, rather than quantifying slow rates of recovery, management strategies incorporating population enhancing techniques may be needed. There exists now a need to monitor population recovery after restoration efforts and to effectively manage populations that are slow to recover naturally, two objectives that are addressed in this study.

For certain seabird species, quantitative recovery data is lacking due to the difficulty of monitoring populations. Most seabirds nest on remote islands that are difficult and expensive to access, and build nests in locations logistically challenging to measure like cliffs or burrows. Leach's and Fork-tailed storm-petrels, Ancient Murrelets, and Cassin's Auklets are the most challenging seabirds to census in the Aleutian Islands (Boersma and Groom 1993). These species visit breeding grounds (where conventionally, seabirds are the most accessible for monitoring) in the dark, have variable colony attendance depending on weather and light variables (Watanuki 1986, Mougeot and Bretagnolle 2000), and nest in earthen burrows which they occupy at a variable rate (Boersma and Groom 1993). On the other hand, these small seabirds were among the most affected by the introduction of non-native predators in the Aleutian Islands (McChesney and Tershy 1998). Considering the decimation of nocturnal burrow-nesting populations, an ideal measure for the success and value of eradication projects would be to measure their recovery.

1.4.1 *Objectives*

The first objective of this study (Chapter 2) was to assess a new method of monitoring nocturnal burrow-nesting seabirds on remote islands, using passive acoustic recording devices and associated call recognition software. Acoustic recording provides a consistent and standardized method of estimating abundance based on call activity and has been used to monitor secretive species from a range of taxa (Hasselmeyer and Quinn 2000, Swiston and Mennill 2009). Nocturnal seabirds in particular lend themselves to acoustic analysis due to their conspicuous vocal displays, which have been characterized and linked to context (e.g. Procellariidae; Robb *et al.* 2000). The ability of acoustic devices and call recognition software to function in exposed conditions characteristic of the Aleutians and most remote oceanic seabird colony sites was assessed. Activity levels of pre-defined calls were used to construct relative indices of abundance for Leach's and Fork-tailed Storm-petrels, Cassin's Auklet and Ancient Murrelet among Aleutian Islands.

In Chapter **3**, acoustic recordings were used to compare recovery of nocturnal seabirds across the western Aleutian Islands. Relative indices of abundance were compared among islands with differing time periods since predator eradication in order to determine each species' rate of recovery.

Finally, in Chapter **4**, at a site where the recovery rate of nocturnal seabirds was found to be low, olfactory and auditory social attraction cues combined with artificial burrows were used in an attempt to enhance storm-petrel re-colonization.

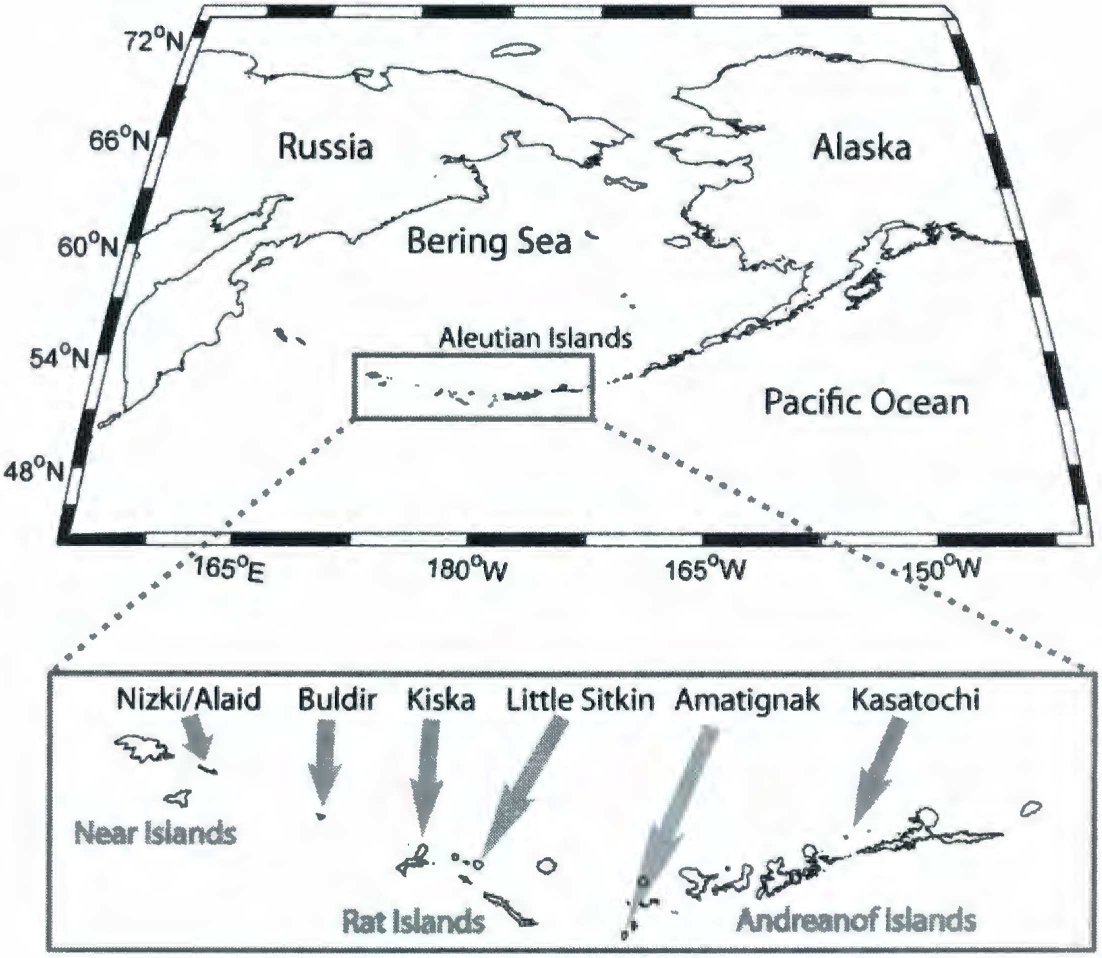

Figure 1.1 Map of the Aleutian Islands, situated between the North Pacific Ocean and the Bering Sea. Inset shows the location of each study site and island group in relation to the Aleutian Archipelago.

CO-AUTHORSHIP STATEMENT:

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CHAPTER TWO

MONITORING NOCTURNAL SEABIRDS USING AUTOMATED ACOUSTIC RECORDING DEVICES: APPLICATIONS FOR ISLAND RESTORATION

ABSTRACT

Nocturnal burrow-nesting seabirds breeding on isolated oceanic islands pose challenges to conventional monitoring techniques, resulting in their frequent exclusion from population studies. These birds have been devastated by non-native predator introductions on islands worldwide. After predators are eradicated, recovery has been poorly quantified; yet evidence suggests that some seabirds have been slow to return. We evaluated the feasibility of using automated acoustic recorders and associated call recognition software to examine nocturnal seabird recovery after removal of introduced Arctic Foxes (*Alopex lagopus*) in the Aleutian Archipelago, Alaska by comparing call abundance among islands. We deployed a total of 13 acoustic recorders: four on Nizki/Alaid from which foxes were removed in 1969 and 1975 respectively, four on Amatignak which had foxes removed in 1991, four on Little Sitkin which had foxes removed in 2000, and one on Buldir, a predator free seabird colony. Despite frequent gales and precipitation, only 2.9% of 2,230 hours of nocturnal recordings from May to August of 2008 and 2009 were unusable due to wind noise. Recording quality and call recognition model success were highest (83% of recordings clear of background noise obstruction, 65% of calls identified) when recording devices were placed at sites offering some wind protection. We detected high levels of vocal activity of Fork-tailed

(*Oceanodroma furcata*) and Leach's Storm-petrels (*O. leucorhoa*), and both activity and successful breeding of Ancient Murrelets (*Synthliboramphus antiquus*) on islands thought to be abandoned due to fox predation. Overall, acoustic monitoring provided an opportunity to quantify vocal behaviour of difficult-to-measure populations of seabird species in varying states of recovery on isolated islands.

Key Words: *Aleutian Islands, bioacoustics, nocturnal seabirds, population recovery, vocalizations*

2.1 INTRODUCTION

There is a current need for protocols and consistent methods to monitor avian population recovery at remote sites where introduced predator eradication efforts have made advances in the past few decades (e.g., rats *Rattus spp.*: Clout 2001, feral cats *Felis catus*: Nogales *et al.* 2004). Conservation biology literature is replete with studies that outline the destructive effects of introduced predators on colonial seabirds and other island avifauna (Rauzon 2007, Jones *et al.* 2008b). Nevertheless, eradication techniques have become more affordable and efficient. Removal of predators will have potentially large benefits to depleted avian populations, yet patterns and rate of recovery after eradication have gone largely unstudied, and development of monitoring techniques needs more attention.

In the Aleutian Islands, Alaska, beginning in the 18th century, non-native Arctic Foxes (*Alopex lagopus*) were introduced to over 450 islands for fur farming (Bailey 1993, Croll *et al* .2005). Although the effects were not carefully quantified, it is clear that foxes eliminated or reduced native Aleutian avifauna, especially surface- and burrow-nesting colonial seabirds (Murie 1959, Bailey 1993, Byrd *et al.* 1994, Byrd *et al.* 2005). In the late 1940s, an Arctic Fox eradication program began across the Aleutians to restore seabird populations, and by the 1990s an intensive program was underway (Ebbert 2000, Ebbert and Byrd 2002). Foxes had been removed from 34 Aleutian Islands as of April 2009 (J.C. Williams pers. comm.), resulting in a patchwork of islands with, without, and at different stages of recovery from introduced predators (Ebbert 2000). Research suggests that avian populations are recovering after non-native fox removal; however, not all species have returned, the reasons for which are poorly understood (Byrd *et al.* 1994, Williams *et al.* 2003). The Aleutian archipelago thus provides an opportunity to study re-colonization patterns of seabirds adversely affected by fox farming.

Nocturnal burrow-nesting seabird species were among the most affected by fox predation, and entire colonies were often extirpated on islands used as fox farms (Bailey, 1993). Fork-tailed Storm-petrels (*Oceanodroma furcata*), Leach's Storm-petrels (*O. leucorhoa*), and small alcids such as Ancient Murrelets (*Synthliboramphus antiquus*) and Cassin's Auklets (*Ptychoramphus aleuticus*) suffered intense predation by Arctic Foxes due to the accessibility of their breeding sites, small size, and lack of behavioural adaptations to terrestrial predators (Atkinson 1985, McChesney and Tershey 1998). Furthermore, due to lack of social facilitation (Podolsky and Kress 1989) and reproductive constraints (one egg per breeding season: Warham 1996) populations are often slow to return after introduced predators are eradicated.

Nocturnal burrowing-nesting seabird colonies are noisy places (Brooke 1986) and frequent conspicuous night-time vocalizations are characteristic of all Aleutian breeding sites. Vocalizations are considered to take on greater significance and replace visual displays due to the lack of light during social interactions (Brooke 1978). Vocal repertoires of many nocturnal species, including all Aleutian species, have been characterized and linked to behaviour (Simons 1981, Taoka *et al.* 1988, Jones *et al.* 1989, Seneviratne *et al.* 2009). Call functions include mate attraction, burrow territoriality, nest-site prospecting and other social signalling (Danchin *et al.* 1998, Doliguez *et al.* 2003). Young nocturnal burrow-nesters also use sound cues associated with the presence of breeding conspecifics or "social information" to signal safe nesting habitat (Warham 1996). In other words, prospecting individuals use vocalizations associated with active colonies when deciding where to breed.

Limited opportunistic survey work in the Aleutians has confirmed the scarcity of nocturnal burrow-nesting seabirds on islands used as fox farms (Murie 1959, Bailey 1993, Byrd *et al.* 2005). However, such day-time vessel and beach surveys are inherently problematic, because detection rate of nocturnal seabirds is likely to be low. Both the nocturnal and burrow nesting habits of these species make them difficult to be seen and counted. Furthermore, most sites in the Aleutian Islands are remote and logistically difficult to reach, and islands are visited opportunistically and infrequently, for a day to a week at a time. We therefore address the need for a cost-effective and consistent method of monitoring nocturnal seabird recovery on remote islands using audio recording, targeting nocturnal vocal activity as an indicator of status and relative abundance.

Recording technology is advancing rapidly, with weatherproof, digital, multichannel recording devices with lengthy battery life available for general use. Automated acoustic recording systems have been used for a diverse array of taxa (e.g., anurans: Peterson and Dorcas 1994, cetaceans: Marques *et al.* 2009, woodpeckers: Swiston and Mennill 2009) and difficult applications, for example, high species richness in tropical habitats (Haselmayer and Quinn 2000). Acoustic recording is also useful for species that are secretive (e.g., nocturnal: Mills 2006); have a wide array of spatial distribution due to flocking, lekking, or coloniality; or whose activity from day to day is highly variable, leading to variance in census results (Karr 1981). Acoustic recording devices detect rare species and vocal behaviour, facilitate simultaneous recording at multiple sites, and can be deployed at remote or logistically problematic sites for entire seasons to capture variation in nightly or daily vocal activity. Recognition software can then be used to measure long-term trends in vocal activity represented in large volumes of recording data (Staiger 2004, Peterson and Dorcas 1994). This recording system is especially advantageous for nocturnal species due to their conspicuous and contextual night-time vocalizations. However, passive recording also has its challenges: recordings of individuals can be obscured by wind noise, multiple individuals calling at the same time in dense colonies interfere with detection, and some species' vocalizations can be highly variable and structurally complex, making recognition difficult (Agranat 2009).

In summary, the objectives of our study were to: 1) test the ability of an automated recording device to make informative recordings in a harsh, windy, wet environment characteristic of the Aleutian Islands; 2) test whether call-recognition software was able to identify a variety of seabird species of interest within digital recordings with varying background noise, numbers of birds present, and interference within and between species; 3) develop methods of processing recordings to provide a comparative index of abundance of nocturnal seabirds on four islands in the western Aleutians; and 4) generally, to consider how these methods can be applied to the current need for protocols to monitor nocturnal seabird recovery.

2.2 METHODS

2.2.1 *Autonomous Recording Device*

We used Song Meters (Wildlife Acoustics Inc. model SM1), a programmable, weatherproof, battery-operated, autonomous recording unit (ARU) with a built in data logger composed of two 16 GB memory card slots. In 2008 we used firmware version 1.5.0 and in 2009 all Song Meters were updated to firmware version 1.7.0. Gain on both left and right channel microphones was set to the default of +42.0 dB with a sensitivity of -35dBV/pa. Most seabird calls are below 7-8 kHz; therefore, Song Meters were set to a sample rate of 16 kHz in stereo. At a sample rate of 16 kHz in stereo, the available 32 GB of memory and predicted battery life of 100 hr allowed for about 32 nights at 3hr/night of recording. Each Song Meter was therefore programmed to record in 15 min on/off cycles from approximate dusk (00:30 - Hawaii-Aleutian Standard Time) to approximate dawn (06:15 HAST), and batteries were changed once every 30 days. In 2009, we were unable to retrieve Song Meters from Nizki/Alaid Islands in order to change the batteries; this Song Meter was programmed to record in 15 min increments from only 01:30 to 04:30, which was the peak activity time of nocturnal seabirds in 2008.

2.2.2 *Study Area*

We placed nine Song Meters in 2008 and nine in 2009 on four islands in the western Aleutian Islands, Alaska from May-August. Four Song Meters were placed each on Amatignak, Little Sitkin, and Nizki/Alaid, all relatively small islands lacking established field camps, and one Song Meter was placed on Buldir Island (Appendix A, Fig. 2.1). Amatignak is an ancient, glacially eroded island from which Arctic Foxes were eradicated in 1991. Little Sitkin is a geologically younger island from which Arctic Foxes were eradicated in 2000. Nizki and Alaid Islands are low islands with gentle terrain, joined by a sandbar that washes out periodically (West 1987). Foxes were removed in 1975 from Alaid and 1969 from Nizki (Byrd *et al.* 1994). Buldir was a control site, as it has dense colonies of nocturnal burrow-nesting seabirds and never had foxes introduced. All islands have habitat and climate characteristic of the western Aleutians: a treeless windswept landscape dominated by subarctic grass and scrub ecosystem (Byrd *et al.* 2005). Characteristic weather included steady winds in excess of 30 km/h, frequent fog and rain, average summer temperature of 7.7 °C, and frequent violent wind and rain storms.

2.2.3 *Deployment Protocol*

In the field, Song Meters were placed according to criteria that included: proximity to shoreline (50 – 150 m, close enough to appropriate seabird habitat, far enough to avoid surf noise); elevation (<400 m); suitability of habitat for burrow-nesting and other colonial seabirds; and shelter from wind. Song Meters were mounted on 1-meter wooden stakes that were placed in the ground on vegetated headlands near the four cardinal points of each island (Fig. 2.1). A large volcano blocked passage to the east side of Little Sitkin Island; the Song Meter here was instead placed to the northwest of the island (Fig. 2.1). In 2008 Song Meters were placed on Amatignak, Little Sitkin, and Buldir Islands from mid-June to early August (Appendix A). In 2009 Song Meters were placed on Nizki/Alaid instead of Little Sitkin throughout June and July, and the five other Song Meters were placed in the same locations as 2008 on Amatignak and Buldir from late May to early August. After retrieving Song Meters from Amatignak and Little Sitkin in 2008, we calculated the average recording quality for each site, observed characteristics of sites with the best quality, and in 2009, placed Nizki/Alaid Song Meters at sites with similar features.

2.2.4 *Processing of Recordings*

Recording files (.wav) were uploaded for review using recognition software Song Scope 2.3 (Wildlife Acoustics Inc.). Recording quality was evaluated and categorized based on visual scans of spectrograms. We scored each night on a scale from 1 to 5 based on the amount of continuous broad band 'white noise' or wind noise that obstructed the spectrograms. Categories for wind obstruction were: 1 - no background noise; 2 - light noise that obscured low frequencies (0.1 – 2.0 kHz); 3 – bouts of noise completely obscuring (0.1 – 8.0 kHz) 1-5% of the recording time span; 4 - 5-50% of recording span completely obscured by noise. Recordings with more than 50% of their duration having all frequencies obscured were considered unusable or category 5. In order to assess the Song Meters' performance with known wind velocity, category assignments were compared with historical wind and rain data taken from the National Data Buoy Center (NDBC) of the National Oceanographic and Atmospheric Administration (NOAA), including wind speed in m/s and wind direction. Song Meter recording qualities on Amatignak and Little Sitkin were compared with data from the closest weather buoy, south of Amchitka Island (weather buoy 46071 located at 51.16 °N, 179.00 °E, approximately 100 km from both islands) and recording qualities on Nizki/Alaid were compared to data from a weather buoy in the south-west Bering Sea (weather buoy 46070 located at 55.00 °N, 175.28 °E, approximately 250 km from Nizki/Alaid).

We then built recognition models using Song Scope, to search lengthy field recordings for calls of interest. Song Scope allows classification algorithms to be built based on Hidden Markov Models (HMM) that will identify different classes of calls (Agranat 2009). Recognition models were built using a set of typical examples of each different species' different call types as training data. Vocalizations of interest included Leach's Storm-petrel Purr and Chuckle calls (Taoka *et al.* 1988), Fork-tailed Storm-petrel flight and single-syllable male calls (Simons 1981), and Ancient Murrelet Chirrup call and Song (Jones *et al.* 1989).

For Leach's Storm-petrel Chuckle call, Fork-tailed Storm-petrel flight call and Ancient Murrelet Chirrup call models, first a basic recognition model was built using training data from 3-4 high quality reference recordings. Storm-petrel reference recordings were obtained from Buldir and Egg Islands in 2006 using a Sony TCD-D10PROII Digital Audio Tape recorder or Fostex FR-2 solid-state recorder with Senheiser MKH 70 or MKH 816 directional microphones (see Seneviratne *et al.* 2009). Ancient Murrelet reference recordings were obtained from McPherson Point on Langara Island in 2006 using a recorder with Senheiser directional microphones (Chirrup recordings by H.Major; archived at Macaulay Library, Cornell Laboratory of Ornithology, Ithaca, New York). Using these basic models, field recordings from Amatignak, Nizki/Alaid, and Little Sitkin Song Meters were scanned for loud, clear, and typical calls, which were selected ("annotated" in Song Scope terminology) and saved. After about a dozen loud calls from field recordings with minimal background noise (no background wind, wave noise, or overlapping calls of other species) were annotated, a comprehensive recognition model was built for each call incorporating both reference recordings and annotations from Song Meter recordings as training data. We used model parameters optimal for each level of background noise, amount of interference by other species, and average energy of calls. Parameters included: frequency minimum, frequency range, sample rate, Fast Fourier Transform (FFT) window size, dynamic range, maximum syllable duration, maximum syllable gap, maximum song duration, maximum Hidden Markov Model (HMM) states and HMM feature vector size (Appendix B). To set parameters appropriately, a random group of field recordings were chosen and reviewed in the split waveform and spectrogram view in Song Scope. Calls of varying quality were identified in the spectrogram view and parameters adjusted so that the strongest signal was visible in the log scale of the waveform view.

To evaluate model success, Song Scope recognition models reviewed each night of batched recordings to identify the call type of interest. Identified calls were then checked visually (by an observer) to remove false positives or background noise incorrectly identified as a call. Spectrograms were viewed at a frequency range of 1000-7000 Hz, had a Fourier transform size of 256, a sample rate of 16000 Hz, and a "Background Noise-reduction" feature setting of 1s. An average false positive rate was calculated by subtracting the correctly identified calls (as determined by an observer) from the total number of identified sounds picked up by the recognition model on each night (including background noise). This gave the number of calls incorrectly identified by the recognition model, which was then divided by the total number of calls correctly identified. Recordings were also scanned visually to search for false negatives or calls skipped by recognition models. False negative calls were identified visually using the default settings of Song Scope's relative intensity signal power levels on a logarithmic scale in the spectrogram. Calls whose frequency components were fully visible in the -65 to -60db range were noted. We did not note barely audible calls as false negatives because calls are never identified by recognizers below a certain energy level. A false negative rate was then calculated by dividing the number calls missed by recognition models by the total calls seen during the visual scan (total calls actually present in the recordings).

Recognition models could not be used at certain sites, for example at North Bight, Buldir (see Results). Instead, we counted calls on 16 random nights, by visually scanning spectrograms. Fork-tailed Storm-petrel flight calls and Leach's Storm-petrel Chuckle calls, which were especially abundant, were analyzed by subtracting periods of silence from a constant call rate. Both calls last for approximately 1 second each; resulting in a constant call rate of 900 (60 * 15 for each 15 minute recording period), minus any intermittent periods with no calling.

To determine the number of nights a Song Meter would have to record in order to capture nightly variation in call activity (minimum device nights in a season), we graphed cumulative means for each of the most common call types (Leach's and Fork-tailed Storm-petrel Chuckle and flight call and Ancient Murrelet Chirrup call), at each site on Amatignak Island (the only island with two years of data). We used a random numbers table to select two nights (from a total of 92, 116, 95, and 106 nights at each site on Amatignak, see Appendix A), took an average between numbers of calls on these nights, and repeated this process 200 times (representing 200 nights or approximately 7 months of recordings), summing the cumulative means. We then observed on each graph, the number of units it took for random means to stabilize around the true mean (Figure 2.5).

2.2.5 *Identifying and indexing species*

To characterize each island's nocturnal seabird activity, we used a hierarchical classification scheme based on the frequency of each call type identified by the recognizers and noted during visual scans of recordings. We first identified simply whether the following calls were present or absent: Leach's Storm-petrel Chuckle, Purr, and Screech call; Fork-tailed Storm-petrel flight and three-syllable male call; Ancient Murrelet chick call, Chirrup, and Song; and Cassin's Auklet kreer-er and kut-reeah call. We then calculated the percentage of nights each call was noted throughout the total recording period, the total number of calls noted throughout all recordings, and the mean number of calls per night ± standard error, and maximum calls per night (Table 2.2).

2.2.6 *Statistical Analysis*

Recording quality score was compared with wind speed and wind direction data using a generalized linear model (GzLM) with wind speed, wind direction, their interaction, year, and Song Meter site as the explanatory variables. An Ordinal GzLM with a logistic link was run in SPSS 16.0 (SPSS 2008), and we assessed the χ^2/df values to check for over-dispersion. False negative rates were compared among sites and recording qualities using a binomial GzLM with a log link. False negative calls, scored as a 1, and correctly identified calls, scored as a 0, formed the response variable, while Song Meter location and recording quality were explanatory variables.

2.3 RESULTS

In 2008, a total of 876 hr of recordings (459 hr from Amatignak Island, 240 hr from Little Sitkin Island, and 177 hr from Buldir) were collected. In 2009, a total of 1354 hr of recordings (768 hr from Amatignak Island, 427 hr from Nizki/Alaid, and 159 hr from Buldir) were collected (Table 1).

2.3.1 *Recording Quality*

In 2008, only one night of 324 was considered unusable due to strong wind noise blocking out the frequency range where seabird calls are found for >50% of the night. In 2009, 24 nights of 553 were considered unusable due to strong wind noise. In total, only 25 nights of 877 or 2.9% were considered unusable due to wind noise obstruction.

Wind speed had a significant negative relationship with recording quality across Song Meters and islands ($G = 20.044$ df = 1 $P << 0.001$). As recording quality worsened from a score of 1 to 5 (clear to unusable), mean wind speed per night increased from a gentle breeze 4.3 ± 0.2 m/s to a moderate gale force 13.7 ± 3.4 m/s (mean ± SE) on the Beaufort scale (Fig. 2.2). On the other hand, wind direction, the interaction between wind speed and wind direction, and year had no significant effect on recording quality (all $P \geq 0.248$). Recording quality differed significantly among Song Meter sites and islands ($G = 27.049$ df = 7 $P = 0.043$ and $G = 9.021$ df = 2 $P = 0.011$) so each Song Meter on each island was analyzed separately for effect of wind speed and direction (Table 2.1). Overall, Little Sitkin had the best average recording quality, followed closely by Nizki/Alaid.

Recording quality of Song Meters on Little Sitkin in 2008 was affected by wind speed, wind direction, and the interaction between wind speed and wind direction (all $P << 0$). Recording quality did not differ significantly between sites. However, recordings were higher quality and had the highest percentage of nights with clear recordings (recording quality score 1) at the north-west and west Song Meter sites (Table 2.1).

On Nizki/Alaid, both wind speed and wind direction were highly significant when the interaction term was eliminated from the model (*P* << 0.000). As recording quality worsened from clear to unusable, wind speed increased from 4.87 ± 0.38 to 17.1 ± 6.47 (mean ± SE)(Fig 2.2). Song Meter site also had a significant effect on recording quality. The northern and western sites on Nizki/Alaid had the poorest recording quality scores and highest percentage of nights with poor recordings, while the eastern and southern sites had the best recording quality scores and the highest percentage of nights with clear recordings (Table 2.1).

On Amatignak, in 2008 and 2009, recording quality was significantly affected by wind speed ($G = 53.40$ df = 1 $P << 0.001$). As recording quality worsened from clear to unusable, average wind speed increased from 3.88 ± 0.14 m/s to 9.91 ± 0.73 m/s (mean ± SE)(Fig 2.2). There was also a difference in recording quality between Song Meter sites. Overall, the southern Song Meter had the highest recording quality and percentage of nights with clear recordings, while the western Song Meter had the lowest recording quality and highest percentage of nights with unusable recordings (Table 2.1).

On Amatignak, recording quality had a different pattern between sites in 2009 versus 2008. Although not significant ($G = 2.431$ df = 1 $P = 0.119$), there was a slight increase in recording quality from 2.33 ± 1.18 (mean ± SE) in 2008 to 2.47 ± 1.27 in 2009 and a significant increase in wind speed (G = 9356.649 df = 1 p << 0.00) from 4.85 ± 1.89 m/s in 2008 to 5.94 ± 2.84 m/s in 2009. In 2008 the northern Song Meter had the best average recording quality (1.81 ± 0.22) and high percentage of nights with clear recordings, while the southern Song Meter had the worst average recording quality (2.69

± 0.24) and high percentage of nights with obscured recordings. In 2009 the opposite pattern was observed: the northern Song Meter had the poorest average recording quality (2.74 ± 0.19) and the highest percentage of nights with near unusable recordings, while the southern Song Meter had the best average recording quality (2.07 ± 0.17) and highest percentage of nights with clear recordings.

2.3.2 *Recognition Model Quality*

Successful recognition models were built for Leach's Storm-petrel Chuckle calls, Fork-tailed Storm-petrel flight calls, and Ancient Murrelet Chirrup calls. Two models were built for Leach's Storm-petrel Chuckle calls and Fork-tailed Storm-petrel flight calls – for low and high background noise situations respectively (Appendix B). Models were built for Purr and Screech calls of Leach's Storm-petrel, single-syllable male calls of Fork-tailed Storm-petrel, and Ancient Murrelet Song respectively; however, not enough of these call types were present throughout recordings to make recognition models efficient, due to high levels of false positives and negatives. These calls types were instead identified manually and noted during visual scans of recordings.

False positive rates were very high across all recording types and model types. False positive rates were highest when the average call activity was low for all species. All three sites on each island with the lowest level of calling activity (Little Sitkin - west, Amatignak – south, Nizki/Alaid – north) had the highest rate of false positives. However, false positives are easily identified and removed using Song Scope software; therefore, these rates were not considered a relevant measure of model success.

Overall, false negative rates were significantly affected by recording quality, species, site, and year (all p << 0.00). As recording quality worsened from 1 (clear recordings) to 5 (unusable recordings) false negative rate went from very low (0.29 ± 0.01) to very high (0.54 ± 0.02). Therefore, as recording quality worsened, calls went from being identified on average 71% of the time to on average 46 % of the time (Fig. 2.3).

Leach's Storm-petrel Chuckle call, Fork-tailed Storm-petrel flight call, and Ancient Murrelet Chirrup call recognition models successfully identified an average of 67% (false negative rate 0.67 ± 0.003), 69% (0.69 ± 0.005), and 56% (0.56 ± 0.006) respectively, of the total number of calls observed in the recordings. However, false negative rates differed for each species between islands and sites. For example, Ancient Murrelet Chirrup call recognizers had a minimum false negative rate of 0.22 ± 0.03 at the northern Song Meter on Amatignak and a maximum false negative rate of 1 at the south site on Nizki/Alaid (Table 2.3). In general, as the number of calls at each site increased, false negative rates decreased (Fig. 2.4); or rather, at sites with low activity the number of calls missed by recognizers was much higher.

When all three species call recognizers were pooled, the northern Song Meter on Amatignak and the eastern Song Meter on Nizki/Alaid had the lowest false negative rates while the northern site on Little Sitkin had the highest false negative rate (Table 2.1). Overall, Little Sitkin had the highest false negative rates while Nizki/Alaid had the lowest.

We were unable to analyze recordings from the Song Meter at North Bight on Buldir Island using Song Scope recognition models. Recordings were of equal quality to those on Amatignak, Little Sitkin and Nizki/Alaid; however, the density of overlapping calls made analysis with recognition software problematic. Models recognized calls that were clear and close to the Song Meter, but constant background interference from other birds made these clear calls rare. We were unable to analyze the number of Fork-tailed Storm-petrel flight calls at the west Song Meter on Amatignak for the same reasons. Constant overlapping calls from 0130h – 0430h meant that the recognizers could not pick out individual calls. However, we were instead able to visually identify and count the presence/absence and relative abundance of nocturnal seabird calls.

2.3.3 *Minimum Song Meter Recording Period*

Comparing cumulative random mean values to true mean values to find the minimum time period Song Meters would have to record to capture nightly variation was both species and site specific (Fig. 2.5). The number of units it took to reach an asymptote (actual mean) by adding up random mean values was mostly dependent on level of call activity. For Leach's Storm-petrel Chuckle calls, sites with moderate levels of call activity (north: 80.4± 14.6 and east: 97.1 ± 9.2, mean calls/night ± SE) did not reach an asymptote after 200 units, whereas graphs of the sites with very low or very high levels of call activity (south: 6.7 ± 1.3 and west: 187.2 ± 23.9) reached an asymptote after 95 and 75 units respectively (Fig. 2.5). At sites with low levels of activity, Song Meters would have to record for about 95 nights or 3 months; sites with high levels of activity for

75 nights or 2.5 months; and at sites with moderate levels of call activity for over 200 nights or 6 months to capture nightly variation in Leach's Storm-petrel Chuckle call activity. For Ancient Murrelet Chirrup calls graphs of sites with moderate to high levels of call activity (north: 7.4 ± 1.7 east: 69.3 ± 7.6) did not reach and asymptote after 200 units, whereas graphs of sites with very low levels of call activity (south: 0.3 ± 0.1 and west: 4.9 ± 0.8) reached an asymptote after 95 and 75 units or approximately 3 and 2.5 months respectively. Finally, Fork-tailed Storm-petrel Flight calls reached an asymptote before 200 units (100 units or approximately 3.3 months) only at the north site, which had a moderate level of activity (4.6 ± 0.7). We were not able to measure the site with the highest level of activity (west) due to extremely high density of overlapping calls.

Species Indexed and Identified

Leach's Storm-petrel Chuckle call were the most common call, present at all 13 sites, followed by Fork-tailed Storm-petrel flight calls which were present at all sites except to the north of Nizki/Alaid (Table 2.2). Ancient Murrelet chick calls and Cassin's Auklet Kreer-er call were the least common calls among sites. Chick calls were present at the eastern site on Amatignak and Buldir, while kreer-er calls were present only at Buldir.

Little Sitkin had the lowest call richness, only flight calls of storm-petrels were present. The western site on Amatignak Island had the highest call richness after the active colony of Buldir, all call types except Cassin's Auklet kreer-er call were recorded.

Although some call types were present throughout many sites, they were not present on many nights. For example, Fork-tailed Storm-petrel flight calls were present at 10 out of 12 sites, but on average calls were recorded on only 25.2 ± 9.3% of nights.

A total of 12666 and 11963 (not including the western site) Leach's Storm-petrel flight calls were recorded on Amatignak in 2008 and 2009, 2329 were recorded on Nizki/Alaid, and 252 recorded on Little Sitkin. On Amatignak in 2008, Leach's Storm-petrel Purr calls were recorded only at the eastern, western, and northern Song Meter. In 2009, Purr calls were recorded at all sites on Amatignak (Table 2.2).

A total of 1373 and 4386 Fork-tailed Storm-petrel flight calls were recorded on Amatignak Island (not including the Western Song Meter) in 2008 and 2009, 1455 were recorded on Nizki/Alaid, and only 39 were recorded on Little Sitkin. At the western Song Meter on Amatignak, which was not analyzed using recognition models; we manually counted flight calls on 16 nights in 2009 and found a total of 9328 calls. Single-syllable male calls were numerous at the eastern and western sites on Amatignak; and were recorded occasionally at the northern, southern, and north-western sites on Little Sitkin and the southern and western sites on Nizki/Alaid (Table 2.2).

A total of 3891 and 5227 Ancient Murrelet Chirrup calls were recorded by Song Meters on Amatignak in 2008 and 2009 respectively. The majority of these calls (91% in 2008 and 77% in 2009) were recorded at the eastern site, where 1025 Songs and 266 chick calls were noted between years. Chick departures, which included adults and chicks calling sequentially, were recorded on 25 separate nights in 2008 and 51 nights in

2009 on the eastern Song Meter. Only Ancient Murrelet Chirrup calls were recorded at Nizki/Alaid, while no Ancient Murrelets were recorded at Little Sitkin (Table 2.2).

Average number of calls of each type recorded per night and the maximum number of calls recorded per night followed similar patterns to the total number of calls heard throughout the season (Table 2.2).

2.4 DISCUSSION:

We assessed the use of automated acoustic recording devices and associated recognition software as a new technique to monitor nocturnal burrow-nesting seabirds on recently fox eradicated Aleutian Islands. During the summer seasons of 2008 and 2009, both the recording devices (Song Meter) and recognition software (Song Scope) successfully collected and analyzed recordings in the windy precipitous environment characteristic of the Aleutians and many other isolated oceanic islands. We identified limitations of this approach and future ways to alleviate these limitations.

Wind noise is known to be the most significant challenge when collecting field recordings (Agranat 2009). With only 2.9% of the total recording time found to be completely unusable due to wind generated background noise throughout 2008 and 2009, our automated recording devices proved to be extremely robust. For 2008 and 2009 there were 11 gale warnings (forecasted wind > 17.5 m/s, NOAA marine forecast) and wind speed was greater than 12 m/s for 16% of recording nights. Nevertheless, Song Meters collected suitable recordings on 97% of nights, suggesting that these devices could function usefully in harsh island habitats used by burrow-nesting seabirds.

However, wind speed and in some cases wind direction negatively affected recording quality. Recording quality of Song Meters placed on Amatignak and Nizki/Alaid were negatively affected by wind speed. As wind speed increased from a gentle breeze to a gale force wind on the Beaufort scale, recording quality worsened from clear to un-usable. However, between a gentle breeze and strong breeze, recordings were less than 5 % obscured by wind noise. The recording quality on Little Sitkin Island was affected by an interaction between wind speed and wind direction, which made interpreting the effects of wind speed or wind direction individually problematic, but there was no observed worsening of recording quality with an increase in wind speed. These Song Meters had much fewer device nights than those on Amatignak and Nizki/Alaid, which may account for the lack of a consistent pattern in effect of wind variables on Little Sitkin recording quality.

We identified sites with the best average recording quality including: the north-west site on Little Sitkin, the south site on Nizki/Alaid, and the south site on Amatignak. These sites were among the farthest from the shoreline, eliminating any possibility of wave noise, and adjacent to one or more large grassy slope, which may have provided wind shelter. The southern Song Meter on Amatignak, for example, was in a small stream gully with steep grassy cliffs that ran extremely high (>40 m) from south to north with a small bank offering protection from the shore. In order to obtain maximum recording quality, Song Meter placement in the future can be modeled from these optimal sites.

Song Meters were placed on Nizki/Alaid in 2009 based on criteria of Song Meter sites with the best recording quality in 2008. Nizki/Alaid had similar recording quality to Little Sitkin. However, Nizki/Alaid islands are much more exposed (at the edge of the Near Island group in the Bering Sea) and Song Meters were placed in 2009 when the average wind speed was higher than 2008. We conclude that although recording quality is almost equal to Little Sitkin, it may in fact be better due to adverse weather conditions in the Near Islands. The strategic placement of these Song Meters was successful, as we achieved almost equal recording quality to the best average quality in 2008, at an island and in a year where wind speed was greater.

We found a difference in recording quality at the same sites on Amatignak between 2008 and 2009. Two sites on Amatignak Island, the north and south Song Meters had the best and worst recording quality respectively in 2008. In 2009 this pattern was reversed, suggesting that recording quality will differ depending on the predominant seasonal wind speed and wind direction. Although some sites favour good recording quality, in order to find sites for optimal placement, Song Meters should be tested in a variety conditions. However, all of our Song Meters had a suitable average recording quality; therefore, we conclude that our placement protocol produced viable and useful recordings.

Recording quality significant affected false negative rates of call recognition models. As recording quality worsened, recognition models went from identifying 71%

to 46 % of calls present. A decline from over 70% to under 50% recognition rate is not trivial for studies interested in temporal patterns of vocalizations. For call models to have the highest success at identifying calls of interest, the number of un-obscured recordings should be maximized, further stressing the importance of appropriate Song Meter placement. Song Meters placed on Nizki/Alaid in 2009 (according to characteristics of the best Song Meters in 2008), resulted in the best average call recognition rate and a relatively high recording quality. Appropriate placement of Song Meters will therefore maximize recognition model success.

Successful recognition models were built for the most commonly heard calls of Leach's Storm-petrels, Fork-tailed storm-petrels, and Ancient Murrelets. Call recognition models had an adequate false negative rate, on average over 50% of calls were correctly identified (Table 2.1). The most successful recognizer was the Fork-tailed Storm-petrel flight call model, which identified over 69% of flight calls present throughout recordings. The flight call is a loud, high energy, broadband screech call that can range between three to five syllables (Simons 1981). This call is distinctive and high energy, with frequencies in each syllable that span from low frequency fundamentals (1 kHz) to high frequency harmonics (8 kHz), often overpowering background noise or other species calls. Song Scope software operates by recognizing both the shape and energy of each sound. If structural aspects of the vocalization are lost to background noise, calls become more difficult to decipher and recognize. Therefore, the high energy and large frequency range of the flight call make it an excellent candidate for recognition models. The least successful recognizer was the Ancient Murrelet Chirrup call model, which identified fewer than 55% of calls throughout recordings. The Chirrup is a high frequency trill between 3 and 7 kHz, and lasts for about 0.5 seconds (Jones *et al.* 1989). High frequency calls dissipate energy in the air more rapidly than sounds in lower frequencies and hence die out more quickly (Wilson 2000). If Chirrup calls are vocalized at longer distances from the Song Meter, aspects of the call may be dissipating in the air, destroying the structural integrity of the call and making it harder for a model to recognize. Furthermore, Jones *et al.* (1989) found that aspects of the Chirrup call are extremely variable, and can be incorporated into more complex displays, such as Song. The variable properties of the Ancient Murrelet Chirrup call made building suitable "all encompassing" recognition models challenging.

Recognition model success was most affected by the amount of call activity at each site. False negative and positive rates were significantly higher at sites where there were very low numbers or very high numbers of calls per night. Sites on Little Sitkin had the highest false negative rates, approximately double that on other islands; these sites also had the lowest number of calls throughout the season, about 38 and 3 times less than Amatignak and Nizki/Alaid respectively. On Amatignak, the two highest false negative rates were at the southern site, with the fewest number of total calls, and the western site with the largest number of calls (Table 2.2). Furthermore, we did not run recognition models on rare calls (Leach's Storm-petrel Purr and Screech call, Fork-tailed Storm-petrel single-syllable male call, or Ancient Murrelet chick call and Song) or extremely abundant calls (Fork-tailed Storm-petrels at western Amatignak) because it was more time consuming to tease out false positives and search for false negatives, rather than to search for calls visually within spectrograms. We conclude that when calls of interest are rare (<5 calls/ night) or extremely abundant (> 250 calls/ night), due to elevated levels of false positives and negatives it may be more advantageous to look for calls manually rather than use recognition models. Other studies using automated methods of identifying target sounds have come to similar conclusions. Swinston and Menhill (2009) conclude that although automated scanning provides a fast alternative, scanning visual representations of recordings manually is a better method for studies involving birds with low or very high vocalization rates.

High density Fork-tailed Storm-petrel flight calls (>250 calls/night) at Amatignak's western Song Meter and all calls at Buldir's Song Meter (>500 calls/night) could not be analyzed using recognition models. When too many birds with calls at overlapping frequencies are vocalizing at the same time, the recognition models are unable to discern individual calls obscured among the interfering noise. Considering the seabird colony at Buldir Island has an estimated 10,000 Ancient Murrelets, 3,000,000 storm-petrels, 300 Cassin's Auklets, and 30,000 Whiskered Auklets (Byrd *et al.* 2005), counting each individual call at night is an impossible task, even for a human observer.

We looked at how many nights Song Meters would have to record in order to capture the actual mean number of calls per night (defined as mean between 2008 and 2009). Each site (with differing call activity) and species took a different number of units to reach an asymptote at the sample mean, suggesting that the minimum number of nights Song Meters must record depends on call type and activity level. Both Leach's Storm-petrel Chuckle and Ancient Murrelet Chirrup call reached an asymptote after 95 units (about 3 months) at sites with low levels of call activity. However, Fork-tailed Storm-petrel flight call reached an asymptote after 75 units (2.5 months) at sites with moderate levels of activity. We conclude that Song Meters should record for a minimum of 2.5 months (1 summer season) in order to capture nightly variation in nocturnal seabird activity.

Calls identified by recognition models confirmed species presence/absence and provided an opportunity to compare the relative abundance of three nocturnal seabirds between Little Sitkin, Amatignak, and Buldir islands. Recordings indicate that Amatignak Island, which had foxes removed nine years prior to Little Sitkin Island, is likely in a more advanced stage of seabird recovery. 49 times more Leach's Storm-petrel flight calls and 73 times more Fork-tailed Storm-petrel flight calls (not including call activity at the very busy site to the west of Amatignak) were recorded on Amatignak than Little Sitkin, while Ancient Murrelet and Cassin's Auklet calls were only present on Amatignak. We also recorded much higher levels of mate advertizing calls on Amatignak, and occasionally the presence of territorial calls and chick calls. On the other hand, recordings also indicate that Amatignak is at a more advanced state of recovery than Nizki/Alaid which had foxes removed over 16 years prior. This strange pattern of call activity across islands cannot be explained by the number of years since fox eradication. Factors affecting nocturnal seabird recovery after introduced predators are eradicated are currently unknown, and further research should analyze more islands, with varying times since eradication.

Song Meters recorded vocalizations linked to behaviour of nocturnal seabirds that is usually overlooked by conventional monitoring techniques. In a study by Byrd *et al.* (2005) examining seabird populations across the Aleutian Islands using data obtained from conventional monitoring techniques (boat and opportunistic beach surveys), no breeding populations of storm-petrels or Ancient Murrelets were detected on Amatignak Island. Using acoustic recording devices, we detected high numbers of Leach's Storm-petrel Purr and Screech calls and Fork-tailed Storm-petrel male calls, associated with attracting a mate to a burrow, courtship within a burrow, and territorial behaviour around a burrow (Simons 1981, Taoka 1988, Huntington *et al.* 1996). Although these vocalizations do not confirm breeding of storm-petrels, they strongly suggest that prospecting or resident birds are advertising for potential mates and protecting burrows. At the high calling rate we observed, this may also suggest that small sub-colonies are forming or already exist. For example, at the western site on Amatignak, the site with the highest density of all types of storm-petrel vocalizations, grubbing revealed newly excavated burrows and individuals in burrows with brood patches (RTB pers. observation). We also recorded several Ancient Murrelet chick departures on the east side of Amatignak Island, confirming the presence of a small breeding population.

Nocturnal seabirds were excluded from Byrd *et al.* 2005 study likely due to the fact that most boat and beach surveys were performed during the day, which excludes accurate monitoring of nocturnal seabird activity (Bailey 1978). Five of the 26 seabird species that breed in the Aleutian Islands are nocturnal, including two species of storm-petrel, Cassin's Auklet, Ancient Murrelet, and Whiskered Auklet, all of which would be inaccurately measured by such daytime surveys. Furthermore, beach surveys are often brief, lasting only a few days on islands that are visited infrequently (Byrd *et al.* 2005). High variability in number of nightly calls of each species (from zero Leach's Storm-petrel Chuckle calls to over 500 with Purr calls on the same Song Meter) indicates that population figures of opportunistic surveys would be extremely skewed (Bailey 1978). We therefore conclude that Song Meters can act as a powerful, affordable tool, complementing conventional monitoring techniques as a source of information to census and monitor nocturnal seabird populations on remote islands.

Further work will be required to relate call activity to population numbers. It was not possible to separate individual callers; therefore, here we evaluated relative population status based on presence/absence and abundance of raw call counts to compare activity among islands. Additional approaches to be evaluated include: density functions, correcting for recording quality, and relating call frequency to known colony size (Borker *et al.* 2010). Advanced work should address the feasibility of quantifying numbers of individuals present based on the unique features of each bird's call. The calls of nocturnal seabirds characteristically show extreme individual stereotypy (e.g., Ancient Murrelet Chirrups, Jones *et al.* 1989; Leach's Storm-petrel chatter calls, Robb *et al.* 2008), that is apparent at the resolution of our recordings. As techniques become more refined and processing methods more efficient, it may be possible for analysis to achieve indexing at the individual level by recognition of stereotypical characteristics of each individual's call.

Nocturnal seabirds on Amatignak, Little Sitkin, and Nizki/Alaid were at a completely unknown stage of recovery. Using acoustic recorders we shed some light on which nocturnal birds were present, and using the known context of each call type we attempted to interpret activity at each site. Whether numbers and diversity of nocturnal seabirds will recover to pre-introduced predator conditions is unknown. Our results indicate that these islands are recovering, because seabirds that were certainly excluded by foxes are now breeding. However the rate of re-colonization and the mechanisms behind it have, until now, gone unstudied. When introduced predators are eliminated, it provides an excellent opportunity to study patterns in re-colonization of affected populations; knowledge that is essential to island conservation strategies. Conventional monitoring techniques may not be sufficient to examine these recovery patterns, especially considering nocturnal and other secretive species characteristic of the Aleutian Islands. As recording technology and automated recognition software advances, acoustic monitoring can play an important role in studies of post-eradication island restoration on hard-to-reach islands.

Table 2.1 Mean recording quality (from 1 – clear to 5 – unusable), false negative rate (calls skipped by recognition models as determined by visual scans of spectrograms made by a human observer), and percentage of nights with each recording quality at each site on each island.

				% nights recording quality				
Island	Site	Mean recording quality ± SE	Mean false negative rate ± SE	1	2	3	4	5
Nizki/Alaid		2.16 ±0.08	0.32 ± 0.01					
	N	2.46 ± 0.17[A]	0.34 ± 0.05	26.8	35.7	12.5	16.1	8.9
	E	1.92 ± 0.17[A]	0.21 ± 0.02	51.0	29.4	0.0	15.7	3.9
	S	1.80 ± 0.13[A]	0.37 ± 0.01	44.6	39.3	8.9	5.4	1.8
	W	2.45 ± 0.17[A]	0.32 ± 0.01	26.3	38.6	7.0	19.3	8.8
Amatignak		2.42 ± 0.07	0.34 ± 0.01					
	N	2.42 ± 0.16[B]	0.22 ± 0.01	42.5	6.3	25.0	18.8	7.5
	E	2.35 ± 0.11[B]	0.35 ± 0.01	25.2	34.0	22.3	17.5	1.0
	S	2.27 ± 0.14[B]	0.48 ± 0.02	43.9	11.0	20.7	23.2	1.2
	W	2.64 ± 0.13[B]	0.45 ± 0.01	23.3	22.2	25.6	24.4	4.4
Little Sitkin		2.02 ± 0.16	0.60 ± 0.01					
	N	2.23 ± 0.16[C]	0.76 ± 0.03	46.2	7.7	23.1	23.1	n/a
	NW	1.74 ± 0.22[C]	0.51 ± 0.03	63.0	14.8	7.4	14.8	n/a
	S	2.52 ± 0.28[C]	0.6 ± 0.02	33.3	14.3	19.0	33.3	n/a
	W	1.79 ± 0.26[C]	0.44 ± 0.08	50.0	28.6	14.3	7.1	n/a

[A] Differ significantly between sites $G = 14.567$ df = 3 $P = 0.002$,

[B] Differ significantly between sites $G = 7.766$ df = 3 $P = 0.05$

[C] Did not differ significantly between sites $G = 6.659$ df = 3 $P = 0.084$

Table 2.2 Detections and abundances of nocturnal burrow-nesting species vocalizations at four Aleutian Islands during 2008 and 2009. Abundances represented as percent of nights throughout the recording period the vocalization was detected, mean vocalizations detected per night ± standard error, maximum vocalizations per night, and total vocalizations detected throughout the recording period.

		Amatignak				Little Sitkin^{D}				Niz/Al^{C}				Buldir^{C,E}
		N	E	S	W	N	NW	S	W	W	N	S	E	N Bight
LESP Chuckle	% nights present	91.0^{A}	88.0^{A}	54.3^{A}	98.8^{A}	84.6	38.7	31.8	42.9	82.0	57.4	86.9	95.1	100.0
	mean ± SE	73.3 ± 20.3^{A}	96.4 ± 17.2^{A}	7.5 ± 2.0^{A}	236.6 ± 32.4^{A}	7.0 ± 0.4	5.5 ± 1.2	1.4 ± 0.6	2.2 ± 1.3	14.1 ± 2.5	2.0 ± 0.4	13.2 ± 1.3	9.6 ± 1.7	2727.8 ± 295.2
	Max	497^{A}	537^{A}	59.5^{A}	975^{A}	46	84	11	18	91	11	135	59	4916
	total calls	6238^{B}	10773^{B}	659^{B}	23493^{B}	98	175	33	33	832	111	802	584	51828
LESP Burrow	% nights present	10.7^{A}	8.6^{A}	30.7^{A}	40.5^{A}	0	0	0	0	9.8	1.6	19.7	13.1	96.2
	mean ± SE	0.4 ± 0.2^{A}	0.2 ± 0.1^{A}	0.08 ± 0.01^{A}	2.2 ± 0.6^{A}	0	0	0	0	0.2 ± 0.1	0.02 ± 0.01	0.6 ± 0.2	0.5 ± 0.2	231.5 ± 48.4
	Max	9^{A}	3.5^{A}	0.5^{A}	23^{A}	0	0	0	0	5	1	12	8	880
	total calls	40^{B}	17^{B}	1^{B}	247^{B}	0	0	0	0	11	1	9	28	4398
LESP Screech	% nights present	2.5^{A}	0.7^{A}	0^{A}	7.9^{A}	0	0	0	0	0	0	0	0	88.7

	mean ± SE	0.03 ± 0.02^{A}	0.01 ± 0.01^{A}	0	0.3 ± 0.1^{A}	0	0	0	0	0	0	0	0	11.5 ± 2.7
	Max	1^{A}	0.5^{A}	0^{A}	6^{A}	0	0	0	0	0	0	0	0	39
	total calls	4^{B}	1^{B}	0^{B}	40^{B}	0	0	0	0	0	0	0	0	219
FTSP Flight	% nights present	56.4^{A}	57.3^{A}	7.9^{A}	100.0^{C,E}	100.0	16.1	90.9	28.6	47.5	0.0	23.0	4.9	100.0
	mean ± SE	4.6 ± 1.0^{A}	43.9 ± 10.9^{A}	0.1 ± 0.1^{A}	583.0 ± 117.7^{C,E}	7.0 ± 0.4	8.3 ± 2.0	32.2 ± 9.5	0.3 ± 0.1	16.4 ± 4.4	0	7.0 ± 2.8	0.08 ± 0.04	1516.1 ± 172.9
	Max	27.5^{A}	506^{A}	2.5^{A}	1419^{C,E}	14	139	219	1	165	0	129	2	2575
	total calls	445^{B}	5189^{B}	19^{B}	9328^{C,E}	98	265	741	4	1014	0	436	5	28804
FTSP Male	% nights present	9.1^{A}	30.5^{A}	0.8^{A}	92.1^{C}	7.7	6.5	50.0	0	14.8	0	18.0	0	92.5
	mean ± SE	0.1 ± 0.1^{A}	5.6 ± 1.0^{A}	0.03 ± 0.03^{A}	72.4 ± 7.6^{C}	0.1 ± 0.3	0.5 ± 0.5	7.7 ± 9.5	0	0.3 ± 0.1	0	1.0 ± 0.4	0	299.2 ± 70.4
	Max	2.5^{A}	65^{A}	2^{A}	256^{C}	0.07	11	57	0	6	0	22	0	975
	total calls	14^{B}	554^{B}	4^{B}	4342^{C}	1	15	741	0	19	0	63	0	6283
ANMU Chirrup	% nights present	36.8^{A}	69.4^{A}	14.2^{A}	68.8^{A}	0	0	0	0	34.4	4.9	3.3	9.8	92.3
	mean ± SE	1.8 ± 0.6^{A}	70.3 ± 11.4^{A}	0.3 ± 0.1^{A}	5.3 ± 1.2^{A}	0	0	0	0	1.4 ± 0.5	0.1 ± 0.03	0.03 ± 0.02	0.1 ± 0.1	86.4 ± 17.9
	Max	14.5^{A}	318.5^{A}	4^{A}	32.5^{A}	0	0	0	0	27	1	1	2	233
	total calls	141^{B}	7561^{B}	23^{B}	470^{B}	0	0	0	0	84	3	2	7	1468
ANMU Song	% nights present	0.8^{A}	61.3^{A}	0.0^{A}	5.6^{A}	0	0	0	0	0	0	0	0	82.7

	mean ± SE	0.01 ± 0.01^{A}	8.5 ± 1.7^{A}	0^{A}	0.09 ± 0.04^{A}	0	0	0	0	0	0	0	0	15.2 ± 5.0
	Max	0.5^{A}	47.5^{A}	0^{A}	2^{A}	0	0	0	0	0	0	0	0	86
	total calls	1^{B}	919^{B}	0^{B}	12^{B}	0	0	0	0	0	0	0	0	334
ANMU chick	% nights present	16.9^{A}	0^{A}	0^{A}	0.8^{A}	0	0	0	0	0	0	0	0	26.9
	mean ± SE	0^{A}	2.5 ± 0.7^{A}	0^{A}	0.01 ± 0.06^{A}	0	0	0	0	0	0	0	0	5.1 ± 1.2
	Max	0^{A}	22.5^{A}	0^{A}	0.5^{A}	0	0	0	0	0	0	0	0	38
	total calls	0^{B}	266^{B}	0^{B}	1^{B}	0	0	0	0	0	0	0	0	82
CAAU Kreer er	% nights present	8.5^{A}	3.7^{A}	4.0^{A}	5.6^{A}	0	0	0	0	3.3	1.6	1.6	3.3	92.3
	mean ± SE	0.3 ± 0.2^{A}	0.1 ± 0.1^{A}	0.1 ± 0.1^{A}	0.1 ± 0.1^{A}	0	0	0	0	0.03 ± 0.01	0.1 ± 0.1	0.03 ± 0.03	0.1 ± 0.1	90.7 ± 1.9
	Max	6^{A}	1.5^{A}	1^{A}	0.5^{A}	0	0	0	0	1	3	2	2	214
	total calls	41^{B}	7^{B}	6^{B}	8^{B}	0	0	0	0	2	4	2	3	1724

A – mean between 2008 and 2009, B – sum between 2008 and 2009, C – 2009 only, D – 2008 only, E – based on 16 nights of data only

Table 2.3: False negative rates (number of calls missed by call recognition models versus total number of calls present throughout recordings, as determined by a human observer) for each call type at each site on Amatignak Island in 2009.

Call type	Site	False Neg Rate	Total calls	SE
ANMU Chirrup	East	0.441038428	7555	0.006014
FTSP flight	East	0.218893505	5216	0.006115
LESP chuckle	East	0.351269584	10773	0.004962
	TOTAL	0.337067172	23544	0.003219
ANMU Chirrup	North	0.221556886	965	0.032233
FTSP flight	North	0.365333333	461	0.024899
LESP chuckle	North	0.211954993	7146	0.004847
	TOTAL	0.266281738	8572	0.004982
ANMU Chirrup	South	0.45	23	0.114133
FTSP flight	South	0.384615385	19	0.140442
LESP chuckle	South	0.484451718	658	0.020235
	TOTAL	0.439689034	700	0.019925
ANMU Chirrup	West	0.490291262	470	0.024659
FTSP flight	West	*	*	*
LESP chuckle	West	0.448760187	6052	0.00655
	TOTAL	0.469525725	6522	0.006348

*(high numbers of Fork-tailed Storm-petrel calls that could not be measured with recognition models)

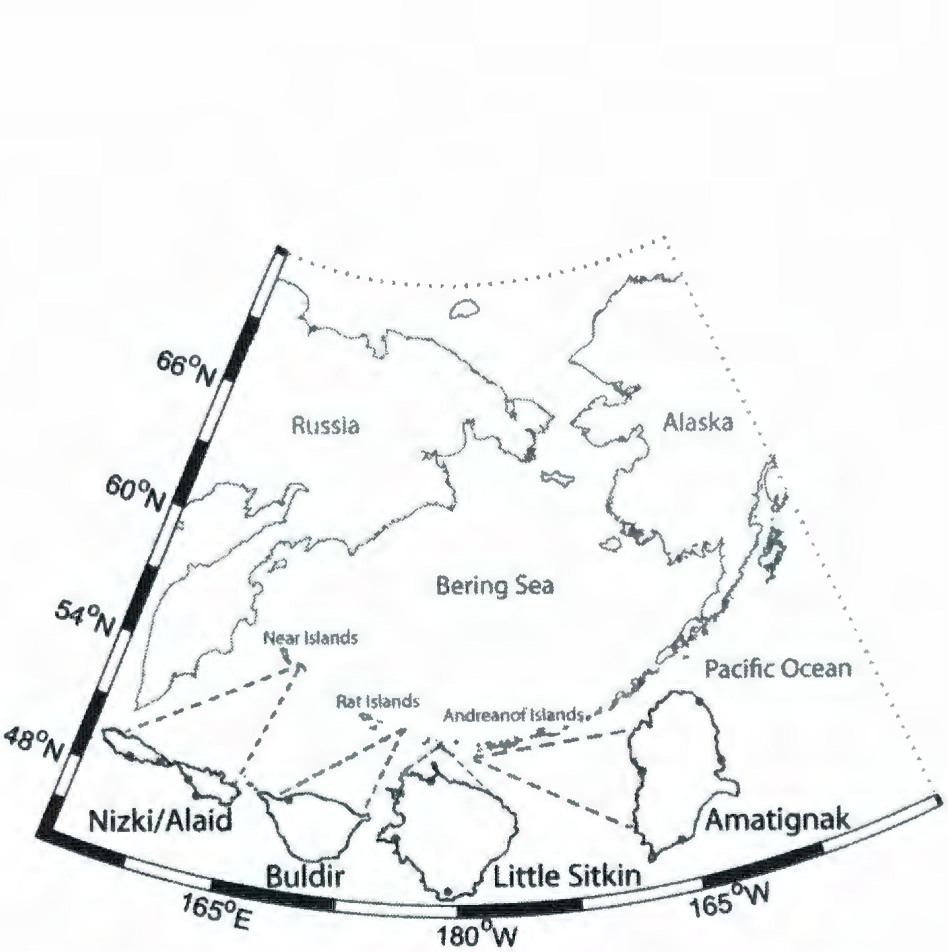


Figure 2.1 Placement of recording devices (Song Meters) across the western Aleutian Islands. Dots represent individual devices. Song Meters were placed on Amatignak, Little Sitkin and Buldir in 2008 and 4 Song Meters were moved from Little Sitkin to Nizki/Alaid in 2009.

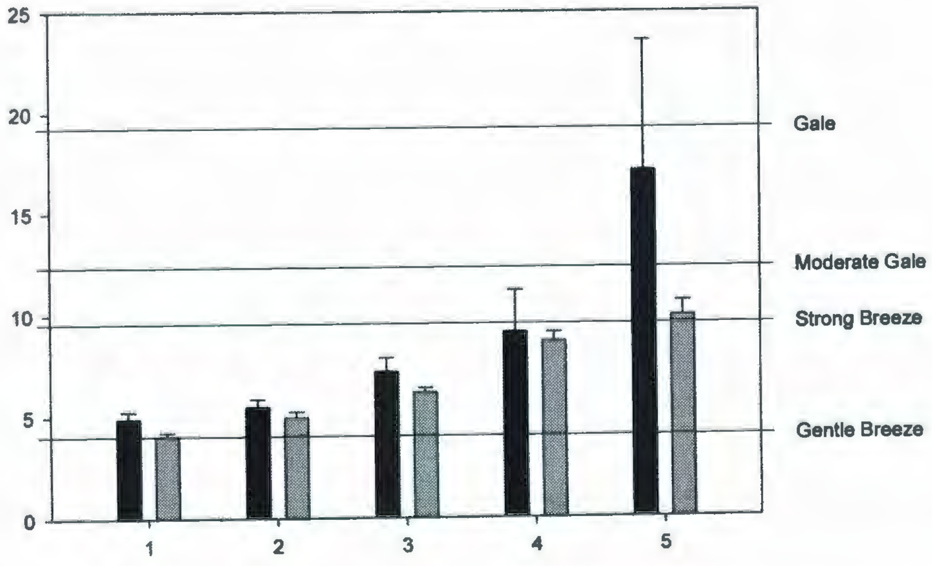


Figure 2.2 Mean recording quality declined as wind velocity increased for Song Meters placed on Amatignak and Nizki/Alaid. Wind speed obtained from NOAA weather buoys. Wind categories (gentle breeze to gale) are measured on the Beaufort scale.

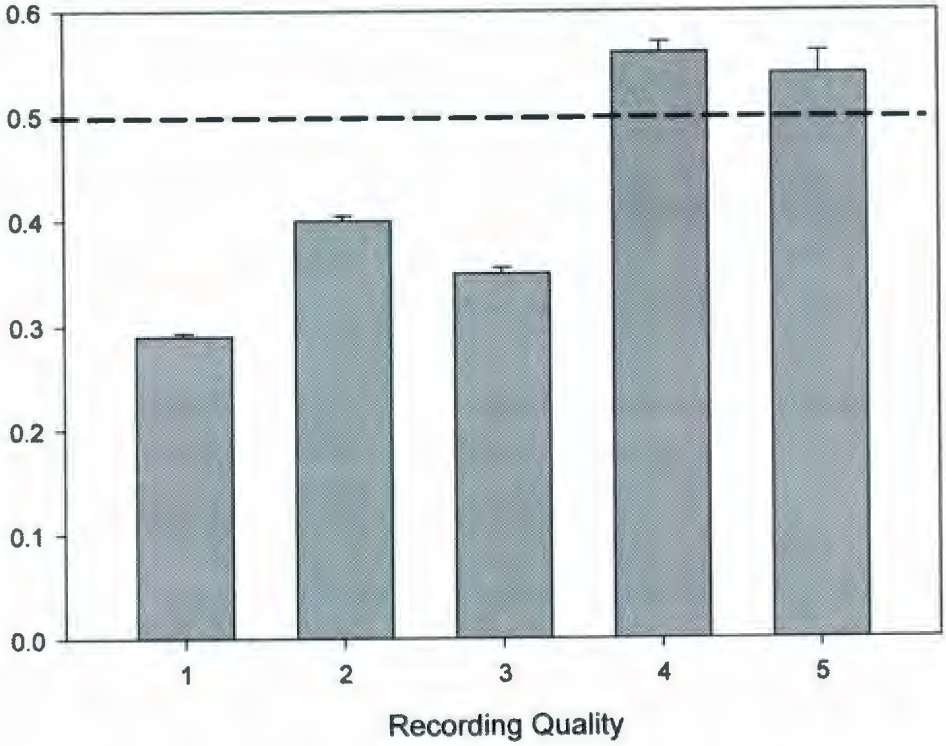


Figure 2.3 False negative rate (the number of calls missed by call recognition models, determined by human visual scans of spectrograms) increases with recording quality. Dashed line indicates 50% of calls identified by the call recognizers.

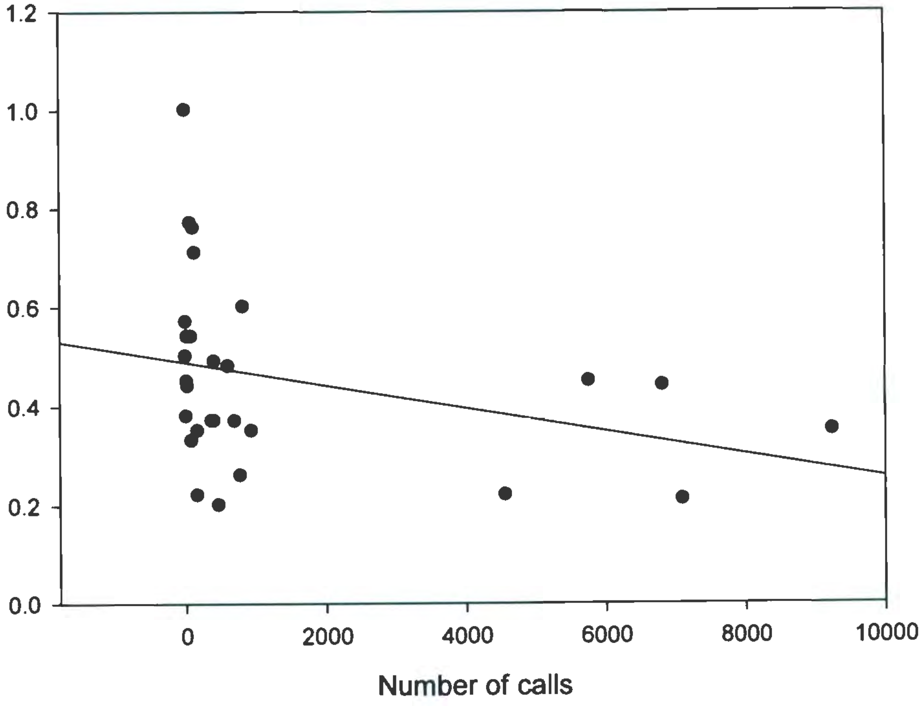


Figure 2.4 False negative rates increase (fewer calls identified by recognition models) as the total number of calls of nocturnal species per night decreases.

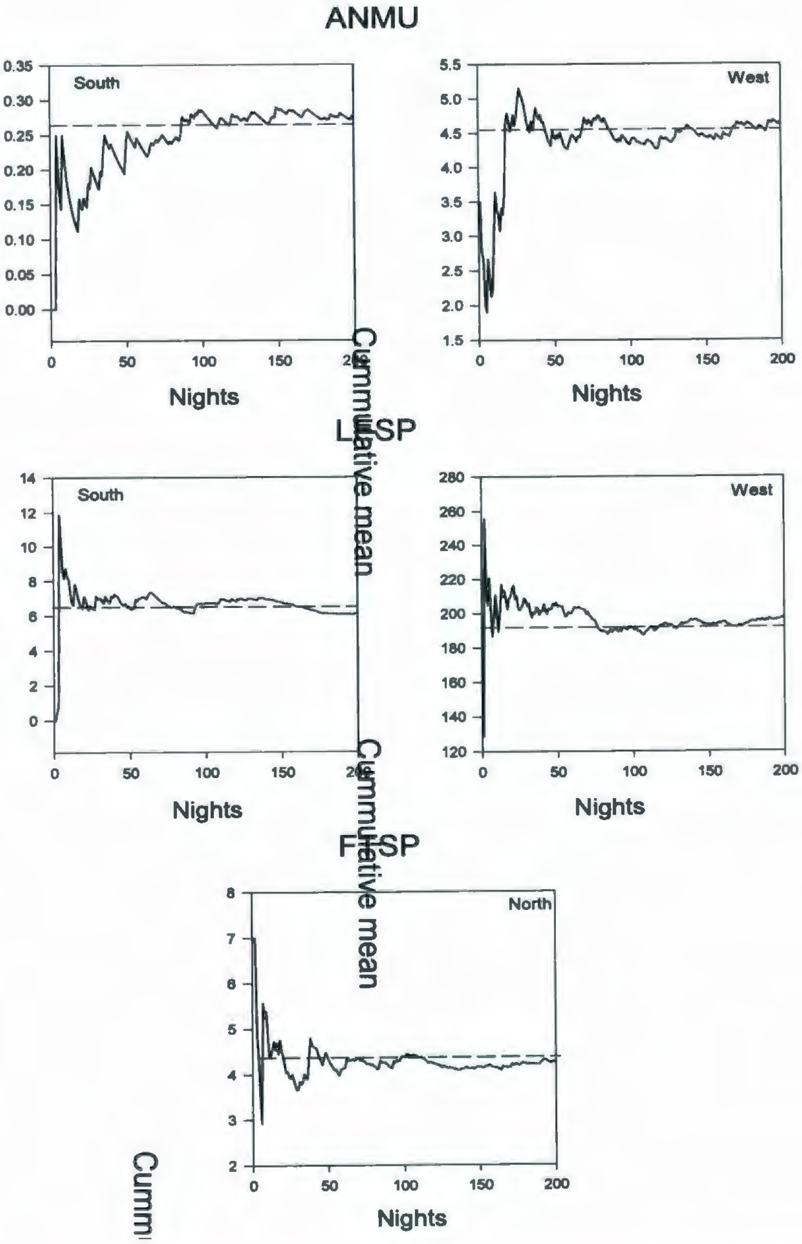


Figure 2.5 Distribution of cumulative means versus the true mean number of calls per night in 2008 and 2009. Only sites where the distribution reached an asymptote at the true mean within 200 nights are shown. Dashed lines indicate true means.

CHAPTER THREE

EVALUATING NOCTURNAL SEABIRD RECOVERY AFTER PREDATOR ERADICATION IN THE WESTERN ALEUTIAN ISLANDS, ALASKA, USING ACOUSTIC MONITORING

ABSTRACT

On oceanic islands, where efforts to eradicate introduced predators have increased over the past few decades, there is an urgent need to identify factors affecting recovery of seabird populations. Introduced mammalian predators have had devastating effects on colonial seabirds and other island avifauna, and removal of these invasive species has potentially large benefits to extirpated or depleted populations. However, the rate and means by which avian populations recover on islands after predator eradication have gone largely unstudied. We used automated acoustic monitoring to study patterns of nocturnal seabird recovery on islands with different time periods since introduced fox and rat eradication in the western Aleutian Archipelago, Alaska. A total of 19 acoustic recorders were deployed on six islands during 2008 and 2009, comparing presence/ absence and call activity of different species. We found low nocturnal call activity at Kiska (9 calls/64 device nights), an island where rats are still present, in contrast to extremely high activity at the pristine colony of Buldir (approximately 95,140/14 device nights). Also, we found increasing levels of call activity, from the lowest on Little Sitkin (foxes removed 2000), to Amatignak (foxes removed 1991), to the highest on Kasatochi (foxes removed 1984, volcanic eruption in 2008), but very low levels on Nizki/Alaid (foxes removed 1975/1969). Using an information-theoretic approach, we found support for multiple factors, such as presence of breeding refugia and number of years since predator removal, as an explanation for recovery of Leach's Storm-petrel (*Oceanodroma leucorhoa*), Fork-tailed Storm-petrel (*O. furcata*), and Ancient Murrelet (*Synthliboramphus antiquus*). Twenty-one other species were detected at our study islands, including 5 Eurasian migrants and 4 species of conservation concern. Overall, our results demonstrated a complicated pattern of recovery of nocturnal seabirds 10-35 years following predator eradication in the Aleutian Islands, with implications for island restoration.

Key words: *Population recovery, nocturnal seabirds, islands, introduced predators*

3.1 INTRODUCTION:

Increasing rates of anthropogenic environmental change have resulted in severe population declines of island avifauna worldwide (Vitousek 1997, Birdlife International 2000). Due to conservation and management efforts, population crashes have been followed by island restoration efforts and in some cases, recovery of native species (Gadmark *et al.* 2003). Thus, understanding factors that limit or facilitate island bird recovery has become a conservation priority (Gadmark *et al.* 2003). Determining ways to consistently monitor the rate and patterns associated with recovery is important, not only to enhance the effectiveness of existing projects (Davis *et al.* 2004), but also to promote innovation of methods for increasingly challenging cases of avian biodiversity restoration.

Nowhere are population declines, followed by restoration efforts, better exemplified than with seabirds nesting on oceanic islands. Islands have suffered disproportionately in terms of extinction due to their unique and vulnerable avifaunal communities (Moors and Atkinson 1984, Atkinson 1985, Aguirre-Munoz *et al.* 2003). Human-introduced mammals, such as feral cats (*Felis catus*), foxes, and especially rats (*Rattus* spp.), are the primary mechanism of avian, especially seabird, population decline (Atkinson 1989, Groomsbridge *et al.* 1992, Howald *et al.* 2007). For this reason, numerous seabird conservation efforts have included attempts to eradicate invasive species from breeding islands (Veitch and Clout 2002). To date, twenty-five invasive vertebrate species have been removed from over 775 islands world-wide (Keitt *et al.* 2010), including large and complex island ecosystems such as Campbell Island, New Zealand (Towns and Broome 2003). In many cases, seabirds locally extirpated by invasive predators have benefited from eradication (e.g. Xantus's Murrelet *Synthliboramphus hypoleucus,* Whitworth *et al.* 2005; Manx Shearwater *Puffinus puffinus*, Lock 2006; Wedge-tailed Shearwater *Puffinus pacificus*, Smith *et al.* 2006). However, the species- and site-specific patterns by which seabirds return and recover have gone largely unstudied. A need now exists to invest in establishing criteria to measure restoration success by monitoring the process of recovery (Reay and Norton 1999, Davis *et al.* 2004).

The Aleutian Islands, Alaska have suffered extensive ecological damage from the introduction of Arctic Foxes (*Alopex lagopus*) for the fur trade and accidental introduction of Norway Rats (*Rattus norvegicus*) during military occupation in World

War II (Murie 1959, Bailey 1993, Ebbert 2000, Major and Jones 2005). Introduced predators have had negative effects on insular seabird populations by consuming large amounts of adults and eggs (Murie 1959, Sekora *et al.* 1979, Byrd *et al.* 2005). By 1937, a drastic decrease or total exclusion of seabirds at colonies on Aleutian Islands used as fox farms was noted (Murie 1959). Also, on the 16 Aleutian Islands where Norway Rats have become established, diversity and number of breeding seabirds are conspicuously low (Bailey 1993). Although all seabird species were affected, it is likely that small, nocturnal, easily-excavated burrow-nesting seabirds, such as storm-petrels (Leach's *Oceanodroma leucorhoa* and Fork-tailed *O. furcata* Storm-petrels) and small alcids (Ancient Murrelets *Synthliboramphus antiquus* and Cassin's Auklets *Ptychoramphus aleuticus*) were the first to disappear after non-native mammalian introductions (Bailey 1993, Hatch 1993).

As the extent of ecological devastation in the Aleutians was realized, a fox eradication program began in 1949 and efforts accelerated after consolidation of the Alaska Maritime NWR in 1980 (Ebbert 2000). The first successful rat eradication in the Aleutians occurred at Rat Island in 2008 (Woods *et al.* 2009). The Aleutians now represent a patchwork of islands with, without, and at different stages of recovery from introduced predators (Ebbert and Byrd 2002). Although not documented quantitatively, evidence suggests an increase in avian populations 4- to 5-fold after predator removal (e.g. Black Oystercatcher *Haematopus bachmani*, Byrd *et al.* 1994; Pigeon Guillemot *Cepphus Columba*, Byrd *et al.* 1997). Nevertheless, there is little evidence of seabird re-establishment on islands where they were completely extirpated, and few post-eradication surveys of nocturnal burrow-nesting populations. More quantitative post-eradication studies are needed, especially regarding the most affected seabird group: nocturnal burrow-nesters.

The Aleutians provide a unique opportunity for large-scale natural experiments to study the recovery of seabirds post-eradication for several reasons (Croll *et al.* 2005): their homogenous floral, faunal, and weather patterns; lack of human settlements and associated disturbance; many small islands for sampling; and the widespread historical introduction and patchwork of eradication of rats and foxes (Kurle *et al.* 2008). However, monitoring seabirds throughout the islands also poses challenges. Most sites are logistically difficult and expensive to reach. Also, seabird species most affected by introduced foxes and rats live in burrows and are active above ground only at night. Measuring populations of nocturnal burrow-nesting seabirds at Aleutian breeding sites, although important, is not feasible using conventional techniques.

Here we used a novel approach to monitor nocturnal burrow-nesting seabird recovery in the Aleutian Islands: indices of vocal activity collected with automated acoustic recording devices. Bird sound is often the most efficient means for surveying birds, particularly nocturnal species that have conspicuous night-time vocalizations (Brooke 1986, Brandes 2008). Calls are easily quantified and, for all nocturnal Aleutian species, have been described and linked to behaviour (Simons 1981, Taoka 1988, Jones *et al.* 1989, Seneviratne *et al.* 2009). Although measures of population size cannot be deduced from numbers of nightly calls, an index of abundance can be used to compare among sites (Haselmayer and Quinn 2000).

In summary, the objectives of our study were to: 1) use activity indices based on recorded vocalizations to survey the presence/absence of nocturnal burrow-nesting seabirds across the western Aleutians and evaluate patterns of recovery on islands with differing periods following predator eradication; 2) from observed patterns across sites, identify factors important to recovery; 3) examine the diversity of other avifauna recorded and compare recovery rate to that of nocturnal seabirds; and 4) derive from the combined results recommendations for island restoration and seabird population management.

3.2 METHODS

3.2.1 *Study sites*

We assessed call activity of nocturnal seabirds across the western Aleutians with 16 automated acoustic recorders on six different islands: three islands in 2008 (Amatignak, Little Sitkin and Buldir) and five islands in 2009 (Amatignak, Nizki/Alaid, Kasatochi, Kiska, and Buldir) (Appendix A, Fig. 3.1). Islands were selected based on a range of time periods since introduced predator-eradication. All islands have typical Aleutian habitat: treeless, windswept, *Leymus/Umbel* dominated sub-arctic grassland tundra (Byrd *et al.* 1994) and as a whole have a relatively uniform geologic, climatologic, and marine environment (Springer 1991, Croll *et al.* 2005).

For comparative purposes, we placed one automated recording device in areas with dense, active, nocturnal seabird burrows at North Bight, Buldir Island (Appendix A). Unlike most of the Aleutians, Buldir (approximately 6.4 km long and 3.2 km wide, 657 m

Above Sea Level - ASL) has never had predators introduced and thus holds one of largest and most diverse seabird colonies in the northern hemisphere, with 21 species of breeding seabirds (Byrd *et al.* 2005).

Two automated recording devices were placed along the southern coast of Kiska Island (Fig. 3.1, Appendix A), the second largest island in the Rat Islands group, with an active stratovolcano at the northern tip (1221 m). Foxes were introduced in 1835 (Ashbrooke and Walker 1925) and removed in 1987, and Norway Rats were introduced during military occupation in World War II (Deines and McClellan 1987). Murie (1959) found Fork-tailed Storm-petrels in 5.2% of fox droppings in 1937, yet rats were not observed preying on seabirds (auklets at Sirius Point) until after fox eradication in 1988 (AMNWR unpubl. data, Major and Jones 2005). Currently, rats actively predate all seabirds on Kiska Island (Major and Jones 2005).

We placed four automated recording devices at the north, south, west, and northwest headlands on Little Sitkin Island an active stratovolcano (1199 m ASL) in the Rat Island group (Miller *et al.* 1998) (Appendix A). Foxes were introduced 1923, removed in 2000, and little is known about historic nocturnal seabird colony size. Yet, Murrie (1959) found Fork-tailed Storm-petrels in 5.4% of fox droppings in 1937, suggesting remnant populations were still present 14 years after fox introduction.

Four automated recording devices were placed at the cardinal points of Amatignak Island, in the Delarof Islands of the Andreanof Island group (Appendix A). Amatignak (approximately 8 km long by 4 km wide, 515 m ASL), was stocked with foxes in 1923 and had foxes removed in 1991. Similar to Little Sitkin, historic seabird colony size pre-dating foxes is unknown, although Fork-tailed Storm-petrels were found in 13% of fox droppings in 1937 (Murie 1959). Furthermore, the largest Aleut midden site in the Delarofs is found in Ulva Cove on Amatignak (Corbett pers. comm.) and seabirds were an important constituent of Aleut diet (Lefevre *et al.* 1997).

We placed two automated recording devices near a known nocturnal seabird colony site at Troll Talus, Kasatochi Island (Appendix A). Kasatochi is a volcanic caldera located in the central Aleutian Islands, which had foxes introduced in 1927 and removed in 1984 (Bailey 1993). Kasatochi erupted on 7 August, 2008, burying the island under 30 m of tephra, destroying all breeding and foraging habitat on and around the island (Williams *et al.* IN PRESS). Pre-eruption, Kasatochi rose about 316 m ASL, had extensive rocky sloping talus at Troll Talus, and supported a large *Aethia* auklet colony and populations of storm-petrels (Drummond and Larned 2007). Post-eruption (when devices were placed) Kasatochi was covered in a layer of eroding fine ash.

Two automated recording devices were placed on each of Alaid and Nizki Islands on south-facing slopes to the east and west of each island (Appendix A). Nizki/Alaid are joined by a sandbar that washes out occasionally and are relatively low with rolling hills and a maximum elevation of 190 m (West 1987, Byrd *et al.* 1994). Both islands were stocked with foxes in 1911 and represent one of the first successful eradications executed by the refuge - in 1969 on Nizki and 1975 on Alaid. In the 19th century Nizki/Alaid were considered excellent waterfowl breeding islands (Murie 1959); however, after foxes were introduced, essentially all nesting bird populations were reduced drastically or extirpated (Murie 1937, Byrd *et al.* 1994).

3.2.2 *Study Species*

We measured call activity of all nocturnal burrow-nesting species in our recordings: Leach's and Fork-tailed Storm-petrel, Cassin's Auklet, and Ancient Murrelet. All species are widespread around the rim of the North Pacific Ocean and breed in relatively large numbers in the Aleutian Islands (Byrd *et al.* 2005). All are planktivorous and forage offshore in oceanic habitat, have strictly nocturnal activity at breeding colonies characterized by conspicuous and contextual vocalizations, and nest in shallow earthen or grass tussock burrows on sloping vegetated hillsides (Manuwal and Thoresen 1992, Gaston 1994a, Huntington *et al.* 1996, Boersma and Silva 2001).

We noted all three Leach's Storm-petrel call types (Taoka *et al.* 1988 and Huntington *et al.* 1996): Chuckle calls used by adults and prospectors in flight, on the ground and from burrows; Purr calls vocalized inside or from the ground outside burrows, associated with mate advertizing, pair formation, and courtship; and Screech calls used during aggressive encounters associated with burrow defence. We also recognized chick calls based on spectrograms from Naugler and Smith (1992) and Robb *et al.* (2000). We noted two distinct call types of Fork-tailed Storm-petrels: a flight call given by both sexes and a 3-syllable male call used for mate advertizing (Simons 1981). Chick calls have not been described for this species. For Ancient Murrelets, we noted two of the most common adult call types: Chirrups given by both sexes in a variety of contexts, and Song used only by males as an advertising display (Jones *et al.* 1989 and Gaston 1994a). We also recognized chick calls and family departures from Jones *et al.*

(1987 a,b). Finally, we recognized two adult Cassin's auklet calls (Thoresen 1964, Seneviratne *et al.* 2009): the Kreer-er call given by both sexes in flight, and the less common Kut-reearh call, given from a burrow or crevice as an advertisement display.

3.2.3 *Acoustic Hardware*

We measured nocturnal seabird call activity using digital automated acoustic recorders called Song Meters (Wildlife Acoustics Inc.), model SM1, firmware version 1.5.0 in 2008 and version 1.7.0 in 2009. These waterproof autonomous devices were programmed and left to record for the entire summer season (late May – early August). Song Meter settings are outlined in Chapter Two. Song Meters placed on islands where batteries could be changed every 30 days (Amatignak, Little Sitkin, and Buldir) were programmed to record in 15 minute on/off increments from approximate dusk (0030h - Hawaii-Aleutian Standard Time) to approximate dawn (0615h). Song Meters on islands we were unable to visit for the entire season (Nizki/Alaid and Kasatochi) were programmed to record in 15 minute increments from 0130h to 0430h, when nocturnal seabird activity reached its peak (RTB pers. obs.). Song Meters programmed to monitor both nocturnal and diurnal birds (Kiska) recorded in 15 minute increments from 0130h to 0430h and for 30 minutes at approximate dusk and dawn. Devices were nailed to 1 meter plywood posts, which were dug 30 cm into the ground and stabilized with soil or rocks.

We deployed Song Meters according to a protocol that included a trade-off between appropriate burrow-nesting habitat and protection from wind noise. Song Meters were placed in characteristic nocturnal burrow nesting habitat, defined as sloping

Leymus/Umbel dominated grassy headlands (Byrd and Trapp 1977) with well drained soil (Stenhouse and Montevecchi 2000), within 150 m of the shoreline, and under 400 m elevation. Wind shelter was attained by placing Song Meters in gullies or at sites adjacent to slopes or cliffs. In 2009 we placed Song Meters according to characteristics of sites with the best recording quality experienced in 2008 (Chapter 2).

3.2.4 *Measuring Call Activity*

To count calls described above, we reviewed recordings using a combination of automated methods and manual scanning in Song Scope 2.3 (Wildlife Acoustics Inc.).

Recognition models were built using training data from high quality and 2008 Song Meter recordings (Chapter 2), in order to scan recordings with moderate levels of call activity (average of 2-90 calls per night, maximum of 900 calls in a night). To filter false positives, or spurious calls identified by recognizer models, each point was reviewed in the corresponding spectrogram to ensure it was the call of interest. To identify false negatives, or calls that were missed by recognition models, recordings were scanned visually (See Chapter 2 for more detail).

When call activity was very low or very high (average of less than 2 or greater than 100 calls/night), calls were identified by scanning spectrograms visually. Sound spectrograms viewed in Song Scope were limited to a frequency range of 1000-8000 Hz (a range where all nocturnal seabird vocalizations were visible and low-frequency wind noise was excluded), had a Fourier transform size of 256, and a sample rate of 16000 Hz. The “Background Noise-reduction” feature was used at a setting of 1s for recordings that were ≤ 25% obstructed by broadband wind noise and disabled for recordings 25-50% obstructed, where high energy calls were often confused with high energy wind gusts and excluded from spectrograms. Recordings more than 50% obscured by wind noise were not analyzed, due to obstruction of seabird call frequencies not allowing for a reliable estimate of call activity.

At sites with high call density, instead of counting individual calls, which would be impossible given the frequency of overlapping calls, a visual percent cover of each 15 minute spectrogram was taken. Fork-tailed Storm-petrel flight calls are approximately 1.2 seconds and Leach's Storm-petrel Chuckle calls 1 second in duration. Each 15 minute recording period was multiplied by 50 (60 sec/1.2 calls per sec) for a total of 750 Fork-tailed Storm-petrels calls, or 60 (60 sec/1 call per sec) for a total of 900 Leach's Storm-petrel calls. Periods of silence were then subtracted from these totals. Due to high numbers of call activity, only 14 random nights were measured at Buldir, Kasatochi, and the west site on Amatignak (Fork-tailed Storm-petrels only).

Each call was classified as present or absent at a site. Also, we report mean calls per night ± standard error, total, and maximum calls pooled over the whole recording period. These values were used to compare activity between sites.

We also noted and attempted to identify other calls recorded at Amatignak, Little Sitkin, Nizki/Alaid, and Kiska, sites where nocturnal seabirds activity was low enough to distinguish other species calls. Unusual species calls observed during visual scans were saved and uploaded to: http://www.mun.ca/serg/Aleutian_unid_birdcalls.html in order for experts to identify unknown calls. Most calls were identified using Birds of North

America accounts and example calls from the Cornell Macaulay Library. Important calls were then further analyzed using Raven Pro 1.3 software (Cornell Lab of Ornithology) where accurate spectrograms could be amplified and made to scale.

3.2.5 *Variables Affecting Recovery.* –

To evaluate how call activity relates to patterns in seabird recovery after removal of introduced predators, nightly frequency of flight calls of the most common species (Leach's Storm-petrel, Fork-tailed Storm-petrel, and Ancient Murrelet) were compared to six factors (Table 3.4).

1) Years since predator eradication, with fox eradication dates from Bailey (1993), between 0 on Kiska, 9 on Little Sitkin, 18 on Amatignak, 25 on Kasatochi, 34 on Nizki/Alaid and an arbitrarily chosen 1000 on Buldir (approximate time since last catastrophic volcanic eruption). Factors that affect historical rate of predation and subsequent extinction such as 2) presence of talus, cliff, or offshore island breeding site refugia (within 500 meters of Song Meter site) and 3) island size (from AMNWR Unpubl. data). Factors that affect current seabird distribution and determine suitability of nesting habitat; 4) dispersal distance from a large predator-free source colony such as Buldir or Chagulak for Kasatochi, or smaller subcolonies (data from Byrd *et al.* 2005) obtained by measuring from the center of one island to the other on a map (to the nearest km); 5) marine habitat (oceanic habitat in the Rat and Andreanof Islands versus shelf habitat in the Near Islands, Springer *et al.* 1996); and 6) social facilitation, or cues

provided by the activity of conspecific and heterospecific species, as measured by each Song Meter (Kress 1997).

We also included two factors that affect call activity on a nightly basis: 1) light intensity, as most nocturnal seabirds are less active on bright nights (Watanuki 1986), defined as the four moon phases (data from USNO) and 2) weather variables, such as wind speed and wind direction, which are known to interact and affect colony attendance by adult and prospecting individuals (Major *et al.* IN PREP). Data obtained from NOAA weather buoy 46071 located at 51.16 °N, 179.00 °E and 46070 located at 55.00 °N, 175.28 °E.

3.2.6 *Statistical Analysis*

We compared calls/night among islands and sites using a negative binomial GzLM with a log link in SPSS version 16.0 (SPSS 2008). Separate models for each 9 call types were run, resulting in a total of 9 models. Although we obtained meaningful p-values from this analysis, due to quasi-complete separation in the data (entire islands or sites with 0s, e.g. Kiska) we could not examine parameter estimates. Instead, we examined presence/absence and abundance tables (Table 3.1-3.3) and calculations of standard error. We then used a negative binomial GzLM with a log link in order to compare calls/night between years (2008 and 2009) on Amatignak.

To evaluate the relationship of call activity to various factors relating to recovery, (Table 3.4) we used a series of models in an information theoretic framework. A set of 15 *a priori* models was constructed for the most common calls (using only data from

2009) with the most biologically relevant combinations of 11 variables (Table 3.5). Models were ranked using Akaike's Information Criterion corrected for small sample sizes and overdispersed data ($QAIC_c$), and support for each model was evaluated using the difference between each candidate model's $QAIC_c$ and the lowest $QAIC_c$ to produce a $\Delta QAIC_c$ score. Models with $\Delta QAIC_c < 2$ had substantial support, while those with 4-7 had less support, and when $\Delta QAIC_c > 10$, there was no support for the model. $QAIC_c$ weights were then calculated and used to evaluate model likelihood (Burnham and Anderson 1998). In order to examine each variables effect on call activity in the most parsimonious model, we used parameter estimates (continuous variables) or estimated marginal means (categorical variables) and their corresponding 95% confidence intervals.

3.3 RESULTS

We recorded on 292 nights in 2008 and 673 recording nights in 2009, for a total of 2,520 recording hours on 965 nights (Appendix A). We recorded a total of 206,502 nocturnal burrow-nesting species calls (including only 14 nights of analysis of call activity from Buildir and Kasatochi). Of these, 100,697 were Leach's Storm-petrel calls (95,681 Chuckle, 4752 Purr, and 264 Screech), 90,788 were Fork-tailed Storm-petrel calls (77,707 flight and 13,081 male), 13,220 were Ancient Murrelet calls (11,400 Chirrup, 1471 Song, and 349 chick), and 1797 were Cassin's Auklet kreer-er calls. Of these total calls, 9 were recorded on Kiska, 2,204 on Little Sitkin, 4,022 on Nizki/Alaid, 34,263 on Kasatochi (14 days of data only), 95,140 on Buldir (14 days of data only), and 70,864 from Amatignak (2008 and 2009).

3.3.1 *Nocturnal Call Activity*

Overall, the three most common nocturnal burrow-nesting species calls throughout recordings were Leach's Storm-petrel Chuckle calls (present at 16/16 or 100% of sites), Fork-tailed Storm-petrel flight calls (13/16 or 81% of sites), and Ancient Murrelet Chirrup calls (11/16 or 69% of sites). The least common nocturnal species calls were Ancient Murrelet chick calls, present only at Buldir and the western site on Amatignak, and Cassin's Auklet Kut-reearh calls, present only at Buldir. Due to low representation across sites, Kut-reearh calls were excluded from further analysis. Cassin's Auklet calls had the lowest presence throughout sites. Kreer-er calls were present only on Amatignak and Buldir and we recorded no Kut-I-er calls, another known vocal display (Seneviratne *et al.* 2009). The lowest richness of calls present was at Kiska, with only Leach's Storm-petrel Chuckle call, and Ancient Murrelet Chirrup calls at Bukhti Point. Aside from the active colony on Buldir, the site with the highest diversity of calls present was the east of Amatignak where all call types, aside from Cassin's Auklet Kut-reearh, were present (Fig. 3.2).

The average nightly call activity of all 9 call types differed significantly among islands (all $P << 0.001$) and between sites (all $P << 0.001$).

Leach's Storm-petrel Chuckle calls were the only call type recorded at all sites on all islands, but abundance of calls varied significantly. For example, although calls were present at Kiska and Buldir, there were over 30,000 more calls per night at North Bight, Buldir then on both sites on Kiska (Table 3.1). Aside from Buldir, Chuckle calls were most abundant on Amatignak Island (Table 3.1). Chuckle calls were also present at all sites on Little Sitkin and Nizki/Alaid; however, the average number of calls per night was low (Table 3.1). Chuckle call activity was lowest on Kasatochi. Other Leach's Storm-petrel calls, such as Purr and Screech calls, were much less numerous and specific to certain sites. These calls were present where Chuckle call activity was high, for example at the western site on Amatignak (Fig. 3.2). We recorded frequent Leach's Storm-petrel chick begging calls at Buldir, and on two occasions at the western site of Amatignak.

Fork-tailed Storm-petrel flight calls were the second most numerous call type. Fork-tailed Storm-petrel flight calls were present throughout most recordings, except those on Kiska and at one site on Nizki/Alaid (Table 3.2). Average flight calls/night was highest on Kasatochi, followed by Buldir, and western Amatignak (Fig. 3.2, Table 3.2). Relatively high numbers of flight calls were also recorded at the eastern site on Amatignak, the southern site on Little Sitkin, and the western site on Nizki/Alaid. Male call activity was highest on Buldir, followed by Kasatochi, and western Amatignak. No male calls were recorded on Kiska, the northern site on Nizki/Alaid, or the western site on Little Sitkin, which had the least amount of flight call activity (Table 3.2).

High levels of Ancient Murrelet Chirrup call activity were recorded at Kasatochi, western Amatignak, and Buldir (Table 3.3). Sites with high levels of Chirrup call activity also had high numbers of Songs. We recorded low levels of Song at the northern site on Amatignak, where levels of Chirrup calls were also low. At sites with high levels of Chirrup calls and Songs (Buldir and western Amatignak), family departures or sequences of chick and Chirrup calls were recorded. No chick calls were recorded at Kasatochi

Island, despite high levels of Chirrup calls and Song. No Ancient Murrelet calls were recorded on Little Sitkin, while only one call was recorded on Kiska.

3.3.2 *AIC Analysis*

The best supported model from our candidate set explaining Leach's Storm-petrel Chuckle call activity included all variables except Ancient Murrelet Chirrup call and Fork-tailed Storm-petrel flight call abundance. This model received 56.2 % of the total weight among models, indicating substantial support. This model was about 2.4 times more likely than the global model and 3.1 times more likely than a model excluding all other species calls (Table 3.5). There was a significant effect of all variables on rate of calling in the most parsimonious model, except distance from source colony and Purr call activity (Appendix C). Years since predator eradication and distance to Buldir had slight positive effects on call activity, while island size had a slight negative effect on call activity. There was less call activity on nights with a full moon and when offshore islands and cliffs were present, there were higher amounts of call activity (Appendix C). Finally, there was more call activity when sites were close to shelf habitat, however, confidence intervals on the estimated marginal means overlapped with the oceanic habitat (Appendix C).

The best supported model explaining Fork-tailed Storm-petrel flight call activity was the global model with 66.1 % of the total weight among models, and was 4.5 and 5.3 times more likely than the two other models that received weight or support (Table 3.5). There was a significant effect of all variables on calling rate in the global model: years since predator eradication, distance to Buldir, and island size had negative effects on call activity, while Chirrup, Chuckle, and male calls and distance to source had a slight positive effect on call activity. There was more call activity when talus slopes or cliffs and offshore islands were present, less call activity when no refugia were present, and more activity when sites were close to oceanic habitat (Appendix C). Finally, similar to Leach's Storm-petrel Chuckle calls, there was less call activity on nights with a full moon.

Similar to Leach's Storm-petrel Chuckle call activity, the Ancient Murrelet Chirrup call model with the most support included all variables except Leach's Storm-petrel Chuckle calls and Fork-tailed Storm-petrel flight calls with 60.4 % of the total weight among models and was 1.5 times more likely than the global model. All variables in the most parsimonious model had a significant effect on call rate, except distance to Buldir (Appendix C). All continuous variables, including years since predator eradication, distance to source, and island size and Song activity had positive effects on call activity. Estimated marginal means could not be constructed due to maximum step-halvings reached in the model producing inflated values. However, it appeared as though there was more activity at sites with cliffs present, and at sites close to oceanic habitat.

3.3.3 *Other Species Recorded.* –

We recorded 22 other species (Table 3.6). Species such as Rock Sandpiper (*Calidris ptilocnemis*) and Glaucous-winged Gull (*Larus glaucescens*) were recorded at all sites. Lapland Longspur (*Calcarius lapponicus*) and Aleutian Cackling Goose (*Branta hutchinsii leucopareia*) were also recorded across most sites, although Lapland

Longspurs were not heard at Nizki/Alaid, due to the strictly nocturnal nature of the recording schedule. Eurasian migrant species such as Wood Sandpiper (*Tringa glareola*) and the Siberian Ruby-throat (*Luscinia calliope*) were recorded only on Amatignak Island. Song Meters at Nizki/Alaid recorded the highest number of species mainly in the Scolopacid and Anatid families, followed by Amatignak, Kiska, and Little Sitkin.

3.4 DISCUSSION

To address a lack of data examining seabird recovery, we investigated patterns of nocturnal burrow-nesting seabird re-colonization after eradication of foxes in the western Aleutian Islands. Overall we found considerable evidence of recovery of affected species at multiple islands, with time elapsed after removal of introduced predators related to recovery rate. However, we found additional island and species characteristics that also contributed to patterns of re-colonization.

As expected, there were striking differences in call activity between pristine islands (Buldir) and islands with introduced predators still present today (Kiska). At the nocturnal seabird colony on Buldir, there were extreme levels of vocal activity of all species, including calls used in mate advertising and by chicks. At Kiska, only nine calls of 2 species were recorded over 64 device nights of monitoring. Low activity was expected, as Kiska has been occupied for over 170 years by introduced predators, from fox introductions in the early 19th century, to accidental rat introductions in the 1940's. Rats are well known to have extirpated colonies of small seabird species worldwide (Gaston 1994b, Towns 2006, Jones *et al.* 2008b), and are likely responsible for the current scarcity of nocturnal seabird activity on Kiska. Although we recognize that two Song Meters only cover a small area of the immensely large island of Kiska, other accounts (Byrd *et al.* 2005, USFWS reports) confirm the virtual absence of breeding nocturnal seabirds. The only known sign of such species was from a rat prey cache at Sirius Point on the northern end of Kiska. (7 Fork-tailed Storm-petrel, 122 Least Auklets and a nest with rat pups; Major and Jones 2002). This was the last account of small nocturnal species at Sirius point, and at present storm-petrel call accounts are rare. We conclude, from the amount of call activity recorded on our Song Meters and anecdotal accounts, that few nocturnal burrow-nesting seabird species nest on Kiska Island, likely due to historic fox predation and current rat predation. Further research should focus on placement of recording devices at Sirius Point, where accounts of storm-petrel activity exist.

Comparing calls between Little Sitkin, Amatignak, and Kasatochi (foxes removed in 2000, 1991, and 1984 respectively), a positive pattern emerged between number of years since predator eradication and call activity and number of different call types (Fig 3.2). Presumably, nocturnal seabird activity increases the longer the recovery period from fox predation, as re-colonization occurs over time. Call activity and richness were relatively low on Little Sitkin: no Ancient Murrelet calls or Leach's Storm-petrel purr and screech calls were recorded. Call activity and call types present were much greater at sites on Amatignak, which had 9 years longer to recover from fox predation than Little Sitkin (Bailey 1993). Not only were flight calls extremely numerous but mate advertizing burrow calls, territorial calls, and at some sites chick calls were also recorded.

Call activity of Fork-tailed Storm-petrel and Ancient Murrelet was much higher at Kasatochi Island, with numbers often comparable to the pristine colony of Buldir. Kasatochi had foxes removed 7 years earlier than Amatignak. Extremely high levels of mate advertizing calls were also recorded at Kasatochi, but there was a lack of chick calls. This is likely due to the volcanic eruption that occurred during the previous season and destroyed breeding habitat at Troll Talus, covering the entire site with a thick layer of tephra (Williams *et al.* IN PRESS). Many of the breeding and prospecting adults present pre-eruption survived and returned to Kasatochi, but due to the destruction of nesting habitat, were unable to reproduce. However, activity in 2009 suggested the presence of pre-eruption populations were at a more advanced stage of recovery than at Amatignak.

However, opposite to this positive trend between years since predator eradication and call activity, Nizki/Alaid, with foxes removed in 1975, had approximately the same call activity and diversity as Little Sitkin which had foxes removed 25 years later. Also, when we compared the activity level of the three main call types (Flight, Chuckle, and Chirrup) to years since eradication (Appendix C) in the AIC analysis, results were not straightforward and differed between species. Chirrup and Chuckle call activity had a positive relationship with years since eradication; yet Fork-tailed Storm-petrel flight call activity had a negative relationship. This suggests that mechanisms responsible for current nocturnal seabird activity and re-colonization are more complicated than simply being explained by time since predator eradication. Indeed, seabird re-colonization at a predator-free island is a product of many factors: presence and suitability of breeding habitat, the dispersal distance from the nearest viable colony site, historical escape from predation (presence of refugia, island size), and social facilitation (Stephenson and Irons 2003).

We found, among all species, more activity at sites where refugia were present within 500 meters. Seabirds breed on sloping talus, steep cliffs and offshore islet refuges to avoid predation (Murie 1959, Larson 1960, Lack 1968, Birkhead and Nettleship 1995) and after predators are removed, remnant populations provide pioneering individuals to re-colonize the island. At islands without such refugia, no individuals remain to immediately re-colonize following predator eradication and recovery is delayed until prospectors arrive from distant source populations. At Nizki/Alaid, low lying islands lacking refugia, we found little sign of recovery. In contrast, at the western site on Amatignak with steep cliffs and offshore islet refugia, we confirmed breeding of Ancient Murrelet and Leach's Storm-petrel, indicating an advance stage of recovery. Preference of refugia type was species specific. For example, Leach's Storm-petrel were most numerous at sites with nearby off-shore islets and steep cliffs (western Amatignak), while Fork-tailed storm-petrel were most numerous near talus (Kasatochi pre-eruption) that likely provided refuge from foxes. This may explain why Fork-tailed Storm-petrels recovered so quickly on Kasatochi, while Leach's Storm-petrel have not. The latter species nest only soil burrows while Fork-tailed Storm-petrels occassionally use rocky crevaces (Harris 1974, Drummond 2007), allowing them to take refuge from foxes in rock talus.

The use of, and fast recovery close to refugia has important conservation implications. For example, a small population of Ancient Murrelets (approximately 175 individuals – Byrd *et al.* 2005) is believed to persist at Little Kiska Island near Kiska Harbor. If predation pressure by rats were removed from the larger island of Kiska, this sub-colony could provide individuals to re-colonize the main island.

We found that island size was included in top models explaining patterns in call activity for all three species, suggesting that island size plays a role in nocturnal seabird recovery. According to the theory of island biogeography, extirpation is more likely on small islands, and therefore post-eradication re-colonization may take longer (MacArthur and Wilson 1967). Seabirds are less likely to re-colonize smaller islands (such as Nizki/Alaid), due to higher chances of complete extirpation from these islands when predators are introduced.

We found that distance from large predator-free source colonies (Buldir and Chagulak) and closest small sub-colonies (Gareloi, Rat, Agattu, and Koniuji - Byrd *et al.* 2005) were included in the most parsimonious models for all three species. None of the nocturnal species tested are known to exhibit natal philopatry (Gaston 1994, Huntington *et al.* 1996, Boersma and Silva 2001) so individuals are free to evaluate other islands for breeding, therefore, dispersal is expected play a major role in distribution. Dispersal distance and rate is unknown for nocturnal burrow-nesting species, but is likely affecting recovery rate.

Social facilitation, or habitat selection based on information obtained from conspecifics or ecologically similar heterospecifics, also affected the recovery rate of some nocturnal species (Kress 1997, Monkkonen and Forsman 2002, Ward and Schlossberg 2004). Fork-tailed Storm-petrel flight calls were positively related to both

Ancient Murrelet Chirrup calls and Leach's Storm-petrel Chuckle calls, meaning that activity of Fork-tailed Storm-petrels was high at sites where activity of other species was also high. Yet this trend was not observed in the two other species tested. Although social facilitation is important and contributes to rate of recovery, it is clearly species specific.

Finally, proximity of foraging areas is one of the main determinants of seabird breeding habitat and distribution (Lack 1968, Furness and Birkhead 1984, Birkhead and Nettleship 1995). Although the majority of the Aleutian Island marine habitat is relatively uniform, the Near Islands represent the only exception, as they sit on a shelf which results in a coastal type habitat (Springer *et al.* 1996). Marine habitat (oceanic versus shelf) was included in all three species most parsimonious models, suggesting its importance in influencing seabird distribution. Fork-tailed Storm-petrel flight call activity was higher at oceanic habitat sites, whereas Leach's Storm-petrel chuckle call activity was slightly higher at shelf habitat sites (although confidence intervals overlapped with oceanic sites). This outlines the subtle differences in foraging strategy between these two species. Wing-loading is significantly less for Leach's than Fork-tailed Storm-petrels, an energy saving device for a species which forages at greater distances from its nesting grounds (Vermeer *et al.* 1988); meaning that Leach's storm-petrels are more adept to fly longer distances from breeding colonies. These differences in marine habitat could affect where colonies are located and prevent certain species (such as Fork-tailed Storm-petrel) from re-colonizing certain sites (such as the Near Islands).

All three nocturnal species had lower call activity on nights during moonlight periods. Storm-petrels and Ancient Murrelets are known to be lunar phobic, or less active on moonlit nights (Watanuki 1986, Jones *et al.* 1990). We also found that the interaction between wind speed and wind direction had negative effects on all three species of nocturnal seabirds call activity. Adverse weather conditions make returning to the colony or prospecting more energetically difficult and result in less site visitation under windy or stormy circumstances (Vermeer *et al.* 1988). Any interpretation of nightly call comparisons across seasons must take into account these significant light and weather factors that affect activity and will detract from actual numbers of calls present at a site. Here again, automated recording devices show their value by allowing simultaneous monitoring at multiple sites, allowing such environmental variable to be controlled for.

Song Meters also recorded other species of conservation concern in the Aleutian Islands. Song Meters on Little Sitkin Island recorded Rock Ptarmigan (*Lagopus mutus townsendi*), a surface-nesting bird that suffered severe population declines after fox introduction in the Aleutian Islands. In the western Aleutians, Rock Ptarmigan are divided into 4 subspecies (*evermanni, townsendi, gabrielson*, and *sanfordi*; Holder *et al.* 2004, Montgomerie and Holder 2008). Small populations restricted to even smaller island ranges make Rock Ptarmigan of particular concern to wildlife biologists (Byrd and Anderson 1993). Song Meters successfully recorded the recovery of this particular subspecies of Rock Ptarmigan in the Rat Islands. Song Meters also detected Aleutian Cackling Goose (*Branta hutchinsii leucopareia*) calls, a species listed as endangered in

1967 due to fox predation, but now recovering due to eradication and translocation efforts. The population rebounded from about 800 in the mid-seventies to 22,000 in 1991, when they were downlisted to threatened (Byrd 1998). However little is known about how Cackling Geese are re-populating or recovering across the entire Aleutian chain. We recorded Cackling Geese on three of four islands, plus a gosling call at Nizki/Alaid (I.L. Jones pers. comm.). These birds may be breeding across the Western Aleutians, and future research should focus on placing Song Meters at possible sites of population expansion. Although Nizki/Alaid had relatively low nocturnal seabird call richness, it had a high number of diurnal species calls, including many sandpipers. Kiska, which had the lowest call activity and richness of nocturnal species, had the third highest diversity of diurnal species (perhaps due to its recording schedule including dusk and dawn), including the presence of Aleutian Cackling Geese. This suggests that factors controlling nocturnal seabird recovery patterns and distribution are not the same for shorebirds, ducks, and other diurnal birds.

We conclude that recovery of nocturnal burrow-nesting seabird populations in the Aleutians is not straightforward. The number of years since predator removal is an important factor in re-colonization, but many other variables contribute to the rate of recovery. Therefore, although eradication of predators is an essential first step in island restoration, it may not directly result in nocturnal seabird recovery. Also, it probably cannot be assumed that all nocturnal seabird species were present historically at all sites or on all islands in the absence of introduced predators, a factor that was not considered in this study. Paleoecological investigations at Aleut midden sites will likely provide the best opportunity to quantify pre-fox and rat distribution of nocturnal seabirds on Aleutian Islands, more of which are needed to evaluate modern recovery patterns. Further Song Meter deployments should expand analysis to other islands across the Aleutians in order to tease out details and important factors impacting recovery. Also, at islands where site characteristics do not allow for fast rates of recovery for nocturnal species, for example on Nizki/Alaid, more extensive management may be required post-eradication. In this case, social attraction techniques or translocation could be used to encourage a faster rate of re-colonization. We suggest further study into the mechanisms of seabird re-colonization in order to facilitate the recovery of historically damaged populations.

Table 3.1: Leach's Storm-petrel detections using automated acoustic recording devices during 2008-2009. Includes mean, maximum, and total calls per night in the western Aleutian Islands.

	Chuckle			Burrow			Screech		
Site	mean ± SE	max	total calls	mean ± SE	max	total calls	mean ± SE	max	total calls
Kasatochi	0.3 ± 0.1	4	14	0.0	0	0	0.0	0	0
Amatignak N									
2008	65.2 ± 21.0	176	1435	0.2 ± 0.2	4	4	0.0	0	0
2009	81.4 ± 19.7	818	4803	0.6 ± 0.3	14	36	0.1 ± 0.04	2	4
TOTAL	73.3 ± 20.3	497.0	6238.0	0.4 ± 0.2	9.0	40.0	0.0	1.0	4.0
Amatignak E									
2008	93.6 ± 16.9	454	4025	0.1 ± 0.1	2	5	0.0	0	0
2009	99.2 ± 17.5	620	6748	0.2 ± 0.1	5	12	0.0	1	1
TOTAL	96.4 ± 17.2	537.0	10773.0	0.2 ± 0.1	3.5	17.0	0.0	0.5	1.0
Amatignak S									
2008	9.7 ± 2.8	69	309	0.0	0	0	0.0	0	0
2009	5.3 ± 1.3	50	350	0.0	1	1	0.0	0	0
TOTAL	7.5 ± 2.0	59.5	659	0.0	0.5	1	0.0	0	0
Amatignak W									
2008	181.5 ± 26.4	560	5989	0.8 ± 0.2	4	26	0.0	0	0
2009	291.7 ± 38.3	1390	17504	3.7 ± 0.9	42	221	0.7 ± 0.2	12	40
TOTAL	236.6 ± 32.4	975.0	23493.0	2.2 ± 0.6	23.0	247.0	0.3 ± 0.1	6.0	40.0
Little Sitkin N	7.0 ± 0.4	46	98	0.0	0	0	0.0	0	0
Little Sitkin NW	5.5 ± 1.2	84	175	0.0	0	0	0.0	0	0
Little Sitkin S	1.4 ± 0.6	11	33	0.0	0	0	0.0	0	0
Little Sitkin W	2.2 ± 1.3	18	33	0.0	0	0	0.0	0	0
Nizki/Alaid W	14.1 ± 2.5	91	832	0.2 ± 0.1	5	11	0.0	0	0
Nizki/Alaid N	2.0 ± 0.4	11	111	0.0	1	1	0.0	0	0
Nizki/Alaid S	13.2 ± 1.3	135	802	0.6 ± 0.2	12	9	0.0	0	0
Nizki/Alaid E	9.6 ± 1.7	59	584	0.5 ± 0.2	8	28	0.0	0	0
Buldir N. Bight	2727.8 ± 295.2	4916	51828	231.5 ± 48.4	880	4398	11.53 ± 2.7	39	219
Kiska Bukhti Pt	0.15 ± 0.06	1	5	0	0	0	0	0	0
Kiska West	0.10 ± 0.05	2	3	0	0	0	0	0	0

Table 3.2 Fork-tailed Storm-petrel detections, including mean, maximum and total calls, in the western Aleutian Islands, monitored using automated acoustic recording devices during 2008-2009.

		Flight			Male		
Site		mean ± SE	max	total calls	mean ± SE	max	total calls
Kasatochi		2239.9 ± 312.3	4985	31359	74.6 ± 12.7	169	1045
Amatignak N							
	2008	2.8 ± 0.9	17	61	0.03 ± 0.18	1	1
	2009	6.4 ± 1.0	38	384	0.2 ± 0.1	4	13
TOTAL		4.6 ± 1.0	27.5	445.0	0.1 ± 0.1	2.5	14.0
Amatignak E							
	2008	30.1 ± 7.5	213	1269	8.4 ± 1.1	86	361
	2009	57.7 ± 14.4	799	3920	2.9 ± 0.9	44	193
TOTAL		43.9 ± 10.9	506.0	5189.0	5.6 ± 1.0	65.0	554.0
Amatignak S							
	2008	0.0	0	0	0.0	0	0
	2009	0.3 ± 0.1	5	19	0.1 ± 0.1	4	4
TOTAL		0.15 ± 0.1	2.5	19	0.03 ± 0.03	2	4
Amatignak W							
	2008	n/a	n/a	n/a	n/a	n/a	n/a
	2009	583.0 ± 117.7	1419	9328	72.4 ± 7.6	256	4342
TOTAL		583.0 ± 117.7	1419.0	9328.0	72.4 ± 7.6	256.0	4342.0
Little Sitkin N		7.0 ± 0.4	14	98	0.1 ± 0.3	0.07	1
Little Sitkin NW		8.3 ± 2.0	139	265	0.5 ± 0.5	11	15
Little Sitkin S		32.2 ± 9.5	219	741	7.7 ± 9.5	57	741
Little Sitkin W		0.3 ± 0.1	1	4	0.0	0	0
Nizki/Alaid W		16.4 ± 4.4	165	1014	0.3 ± 0.1	6	19
Nizki/Alaid N		0.0	0	0	0.0	0	0
Nizki/Alaid S		7.0 ± 2.8	129	436	1.0 ± 0.4	22	63
Nizki/Alaid E		0.1 ± 0.04	2	5	0.0	0	0
Buldir N. Bight		1516.1 ± 172.9	2575	28804	299.2 ± 70.4	975	6283
Kiska Bukhti Pt		0	0	0	0	0	0
Kiska W		0	0	0	0	0	0

Table 3.3 Ancient Murrelet detections, including mean, maximum and total calls, in the western Aleutian Islands, monitored using automated acoustic recording devices during 2008-2009.

	ANMU chirrup			ANMU song			ANMU chick		
Site	mean ± SE	max	total calls	mean ± SE	max	total calls	mean ± SE	max	total calls
Kasatochi	109.3 ± 35.8	429	1640	5.9 ± 2.4	53	205	0.0	0	0
Amatignak N									
2008	2.1 ± 0.8	13	47	0.0	0	0	0.0	0	0
2009	1.5 ± 0.4	16	94	0.02 ± 0.02	1	1	0.0	0	0
TOTAL	1.8 ± 0.6	14.5	141.0	0.0	0.5	1.0	0.0	0.0	0.0
Amatignak E									
2008	82.6 ± 15.8	436	3553	9.9 ± 2.2	49	427	3.1 ± 1.0	29	133
2009	58.1 ± 7.1	201	4008	7.13 ± 1.2	46	492	1.9 ± 0.5	16	133
TOTAL	70.3 ± 11.4	318.5	7561.0	8.5 ± 1.7	47.5	919.0	2.5 ± 0.7	22.5	266.0
Amatignak S									
2008	0.3 ± 0.2	5	11	0.0	0	0	0.0	0	0
2009	0.2 ± 0.1	3	12	0.0	0	0	0.0	0	0
TOTAL	0.3 ± 0.1	4	23	0.0	0	0	0.0	0	0
Amatignak W									
2008	7.1 ± 1.6	42	233	0.0	0	0	0.0	0	0
2009	3.6 ± 0.8	23	237	0.2 ± 0.1	4	12	0.0	1	1
TOTAL	5.3 ± 1.2	32.5	470.0	0.09 ± 0.04	2.0	12.0	0.0	0.5	1.0
Little Sitkin N	0.0	0	0	0.0	0	0	0.0	0	0
Little Sitkin NW	0.0	0	0	0.0	0	0	0.0	0	0
Little Sitkin S	0.0	0	0	0.0	0	0	0.0	0	0
Little Sitkin W	0.0	0	0	0.0	0	0	0.0	0	0
Nizki/Alaid W	1.4 ± 0.5	27	84	0.0	0	0	0.0	0	0
Nizki/Alaid N	0.1 ± 0.03	1	3	0.0	0	0	0.0	0	0
Nizki/Alaid S	0.03 ± 0.02	1	2	0.0	0	0	0.0	0	0
Nizki/Alaid E	0.1 ± 0.05	2	7	0.0	0	0	0.0	0	0
Buldir N. Bight	86.4 ± 17.9	233	1468	15.2 ± 5.04	86	334	5.13 ± 1.22	38	82
Kiska Bukhti Pt	0.03 ± 0.03	1	1	0	0	0	0	0	0
Kiska West	0	0	0	0	0	0	0	0	0

Table 3.4 Variables used to explain flight call activity of three nocturnal species (Leach's Storm-petrel, Fork-tailed Storm-petrel, and Ancient Murrelet) in AIC analysis.

Variable	Description
YrsPred	Years since predators removed (from 0 on Kiska to 1000 on Buldir)
Ref	Presence of refugia from introduced predators (scored as 0 – no refugia, 1 – talus slopes, 2 – steep cliffs, 3 – offshore islets, 4 – cliffs and offshore islets)
IS	Island size (in hectares)
DistB	Distance to closest large colony (Buldir, or Chagulak for Kasatochi)
DistS	Distance to nearest sub-colony (Byrd *et al.* 2005)
Food	Type of marine habitat (scored as SH – shelf or OC – oceanic)
LESP, FTSP, ANMU	Frequency of Leach's Storm-petrel Chuckle, Fork-tailed Storm-petrel flight call, and Ancient Murrelet Chirrup calls per night.
LESPp, FTSPm, ANMUs	Frequency of Leach's Storm-petrel Purr, Fork-tailed Storm-petrel male call, Ancient Murrelet Song per night.
WS*WD	The interactive effect of wind speed and wind direction. Wind speed pooled into 4 categories: north, south, east, and west.
Moon	Moon cycle divided into 4 categories (0 new, 1 first quarter, 2 third quarter, 3 full), scored from 2 days before to 2 days after each phase.

Table 3.5 Candidate model sets of three different species (Leach's and Fork-tailed Storm-petrel and Ancient Murrelet) call activity in relation to 11 different recovery related variables.

Model	K	QAICc	ΔQAICc	wi
LEACH'S STORM-PETREL CHUCKLE CALL				
LESP = YrsPred+WS*WD+Moon+ DistS+DistB+Ref+IS+Food+LESPp	19	1736.934	0	0.56237
LESP = YrsPred+WS*WD+Moon+DistS+ DistB+Ref+IS+Food+FTSP+LESPp+ANMU	21	1738.662	1.728158	0.237005
LESP = YrsPred+WS*WD+Moon+DistS+ DistB+Ref+IS+Food	18	1739.173	2.239371	0.183548
LESP = YrsPred+WS*WD+Moon+DistS+DistB+ Ref+IS+FTSP+LESPp+ANMU	20	1743.942	7.007834	0.016916
LESP = WS*WD+Moon+DistS+DistB+Ref+ IS+FTSP+LESPp+ANMU	19	1754.977	18.04304	6.79E-05
LESP = WS*WD+Moon+DistS+Ref+IS+ Food+FTSP+LESPp+ANMU	19	1755.383	18.44905	5.54E-05
LESP = WS*WD+Moon+DistS+DistB+Ref+IS+ Food+FTSP+LESPp+ANMU	20	1756.083	19.14912	3.91E-05
LESP = YrsPred+WS*WD+Moon+DistS+Ref+IS+ Food+FTSP+LESPp+ANMU	20	1821.733	84.79915	2.17E-19
LESP = YrsPred+Ref+DistS	8	1901.962	165.0279	8.22E-37
LESP = Ref	6	2034.122	297.1879	1.65E-65
LESP = WS*WD+Moon+FTSP+LESPp+ANMU	12	2120.418	383.4844	3E-84
LESP = FTSP+LESPp+ANMU	5	2198.961	462.0267	2.6E-101
LESP = YrsPred	3	2255.717	518.7831	1.3E-113

LESP = WS*WD+Moon	9	2543.09	806.1558	5E-176
intercept	2	2779.855	1042.921	1.9E-227
FORK-TAILED STORM-PETREL FLIGHT CALL				
FTSP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+Food+FTSPm+LESP+ANMU	21	993.7495	0	0.661808
FTSP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+Food	18	996.7569	3.007364	0.147127
FTSP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+Food+FTSPm	19	997.095	3.345434	0.124245
FTSP = WS*WD+Moon+DistS+DistB+Ref+IS+Food+FTSPm+LESP+ANMU	20	998.3359	4.586303	0.066808
FTSP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+FTSPm+LESP+ANMU	20	1015.759	22.00927	1.1E-05
FTSP = WS*WD+Moon+DistS+DistB+Ref+IS+FTSPm+LESP+ANMU	19	1020.624	26.87485	9.66E-07
FTSP = YrsPred+WS*WD+Moon+DistS+Ref+IS+Food+FTSPm+LESP+ANMU	20	1042.319	48.5695	1.88E-11
FTSP = WS*WD+Moon+DistS+Ref+IS+Food+FTSPm+LESP+ANMU	19	1043.93	50.18017	8.4E-12
FTSP = YrsPred+Ref+DistS	8	1208.184	214.4347	1.81E-47
FTSP = Ref	6	1295.214	301.4641	2.28E-66
FTSP = WS*WD+Moon+FTSPm+LESP+ANMU	12	1347.469	353.7193	1.03E-77
FTSP = FTSPm+LESP+ANMU	5	1385.385	391.6356	6E-86
FTSP = YrsPred	3	1888.425	894.6757	3.5E-195

FTSP = WS*WD+Moon	9	1938.71	944.9605	4.2E-206
intercept	2	1982.756	989.0065	1.2E-215
ANCIENT MURRELET CHIRRUP CALL				
LESP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+Food+ANMUs	19	1222.294	0	0.603976
LESP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+Food+FTSP+LESP+ANMUs	21	1223.143	0.848919	0.395074
LESP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+Food	18	1235.458	13.16353	0.000837
LESP = YrsPred+WS*WD+Moon+DistS+Ref+IS+Food+FTSP+LESP+ANMUs	20	1239.46	17.16548	0.000113
LESP = YrsPred+WS*WD+Moon+DistS+DistB+Ref+IS+FTSP+LESP+ANMUs	20	1329.567	107.273	3.07E-24
LESP = WS*WD+Moon+DistS+DistB+Ref+IS+FTSP+LESP+ANMUs	19	1335.689	113.3948	1.44E-25
LESP = WS*WD+Moon+DistS+DistB+Ref+IS+Food+FTSP+LESP+ANMUs	20	1336.741	114.4466	8.5E-26
LESP = WS*WD+Moon+DistS+Ref+IS+Food+FTSP+LESP+ ANMUs	19	1352.094	129.8003	3.94E-29
LESP = YrsPred+Ref+DistS	8	1548.737	326.4428	7.85E-72
LESP = Ref	3	1604.036	381.7415	7.71E-84
LESP = WS*WD+Moon+FTSP+LESP+ANMUs	12	2359.735	1137.441	6.1E-248
LESP = FTSP+LESP+ANMUs	5	2399.688	1177.394	1.3E-256

LESP = WS*WD+Moon	9	3254.004	2031.71	0
LESP = YrsPred	3	3221.24	1998.946	0
intercept	2	3336.15	2113.856	0

Table 3.6 All species detected on four recording devices placed in the western Aleutians.

Family	Species	Island			
		Amatignak	Nizki/ Alaid	Kiska	Little Sitkin
Accipitridae	Bald Eagle *Haliaeetus leucocephalus*	X			
Alcidae	Whiskered Auklet *Aethia pygmaea*	X	X		
Anatidae	Aleutian Cackling Goose *Branta hutchinsii leucopareia*	X	X	X	
	Common Eider *Somateria mollissima*		X		
	Green-winged Teal *Anas crecca*	X	X	X	
	Mallard Duck *Anas platyrhynchos*		X		
Muscicapidae	Siberian Ruby-throat *Luscinia calliope*	X			
Emberizidae	Lapland Longspur *Calcarius lapponicus*	X		X	X
	Song Sparrow *Melospiza melodia*	X	X		
Gaviidae	Common Loon *Gavia immer*		X		
	Red-throated Loon *Gavia stellata*	X			
Haematopodidae	Black Oystercatcher *Haematopus bachmani*	X		X	
Laridae	Glaucous-winged Gull *Larus glaucescens*	X	X	X	X
Charadriidae	Semipalmated Plover *Charadrius semipalmatus*			X	
Phasianidae	Rock Ptarmigan *Lagopus mutus townsendi*		X	X	X

Scolopacidae	Bar-tailed Godwit *Limosa lapponica*		X		
	Common Sandpiper *Actitis hypoleucos*			X	
	Greenshank *Tringa nebularia*		X		
	Rock Sandpiper *Calidris ptilocnemis*	X	X	X	X
	Wandering Tattler *Tringa incana*		X		
	Wood Sandpiper *Tringa glareola*	X			
Troglodytidae	Winter Wren *Troglodytes troglodytes*	X	X		
	Total species	13	14	9	4

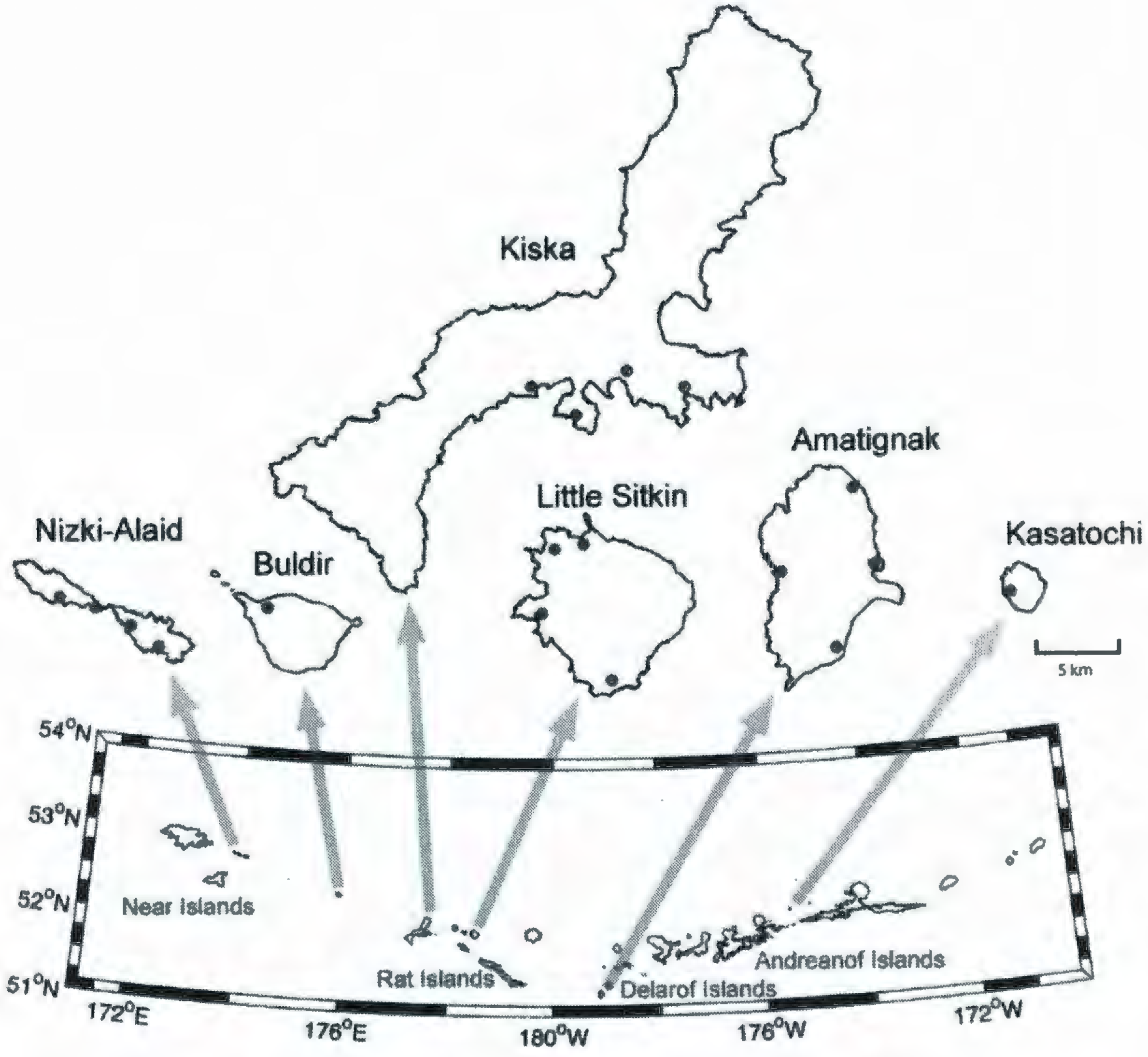


Figure 3.1 Placement of acoustic recording devices (Song Meters) across the western Aleutian Islands. Song Meter sites are indicated by dots.

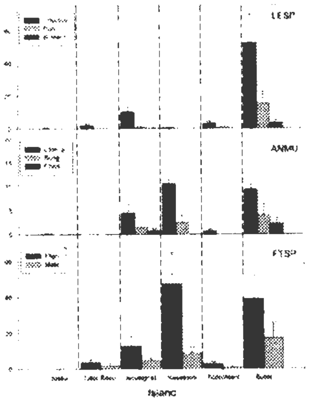


Figure 3.2 Patterns in recovery of nocturnal seabirds in the western Aleutians. Nightly call activity of Leach's Storm-petrel, Ancient Murrelet, and Fork-tailed Storm-petrel on 6 islands. Islands from left to right have increasing time periods since predator eradication (Kiska still has rats present; foxes removed from Little Sitkin in 2000, Amatignak in 1991, Kasatochi in 1984, and Nizki/Alaid in 1969/1975; and Buldir never had introduced predators).

CHAPTER FOUR

AN EXPERIMENTAL STUDY OF SOCIAL ATTRACTION IN TWO SPECIES OF STORM PETREL USING ACOUSTIC AND OLFACTORY CUES

ABSTRACT

The effects of introduced predators on island ecosystems represent one of the most acute threats to seabirds worldwide. Eradicating non-native predators and protecting islands from further anthropogenic disturbance is important, but represents only a first step in restoring extirpated seabird populations. Many seabirds use social information (the visual, auditory, and olfactory presence of breeding conspecifics) when selecting safe nesting habitat. When colonies are extirpated, cues that indicate nesting site quality are lost. We tested various social attraction techniques as a method to encourage re-colonization of Leach's (*Oceanodroma leucorhoa*) and Fork-tailed Storm-petrels (*O. furcata*); two seabirds whose populations were destroyed by introduced fox predation and have been slow to return after eradication in the Aleutian Islands, Alaska. Attraction to conspecific calls was tested by broadcasting playback treatments adjacent to a mist net and attraction to conspecific odor was tested using a t-maze design. We combined these two cues to test whether birds would be more likely to enter and inhabit artificial burrows depending on playback and odor treatment. Both species of storm-petrel were strongly attracted to conspecific and heterospecific call playback; Fork-tailed Storm-petrels were significantly attracted to conspecific odor while Leach's Storm-petrels were repulsed by conspecific odor; and more artificial burrows were entered when combined with odor and playback of both species. We discuss the implications of these results, including the development of protocols to encourage restoration of seabird colonies in the Aleutian Islands after eradication of introduced Arctic Foxes (*Alopex lagopus*) and Norway Rats (*Rattus norvegicus*).

Key words: *Social facilitation, island restoration, storm-petrel, playback, t-maze, odor, artificial burrows*

4.1 INTRODUCTION

Historically, conservation strategies have focussed on habitat protection and management and although this is important and often effective, it may be inadequate in some cases, such as island habitats where colonial seabirds have been extirpated by introduced predators. There is an underlying assumption in avian conservation that, if suitable habitat structure and protection from anthropogenic disturbance can be provided, birds will return ("if you build it, they will come"; Ahlering and Faaborg 2006). For endangered or threatened avian species, safeguarding against biodiversity loss often depends on creation, enhancement, and protection of key habitats. However, this strategy is questioned because it fails to consider basic avian social behaviour that will indefinitely delay some bird's recovery (e.g., colonial species), no matter how suitable the habitat appears to be (Muller *et al.* 1997, Clout 2001, Doliguez *et al*. 2002, Ward and Schlossberg 2004).

There are many examples where eradication of introduced mammals or habitat management through protection from anthropogenic disturbance has not resulted in the return of seabird populations. Common Murres (*Uria aalge*) in California had not returned to breed 10 years after an oil spill and El Niño event extirpated a large colony (Parker *et al.* 2007), Common Diving Petrels (*Pelecanoides urinatrix*) did not return to Mana Island in New Zealand over 10 years after the eradication of House Mice (*Mus musculus*) (Miskelly and Taylor 2004), and nocturnal seabirds have not returned to some Aleutian islands over 40 years since non-native foxes were eradicated (Chapter 3).

We conclude that facilitation of island restoration and recovery of extirpated seabird colonies cannot be limited to habitat management alone, but that social and behavioural factors must also be considered. Island-nesting seabirds are often colonial; strong mate and site fidelity, colony-site philopatry, and gregariousness are basic elements of their behaviour (Greenwood and Harvey 1982, Danchin and Wagner 1997, Parker *et al.* 2007). Young seabirds of philopatric species will simply return to their natal site to breed (Jenouvrier *et al.* 2008), while other dispersing colonial seabirds will assess the quality of existing active colonies rather than quality of nesting habitat, resulting in little pioneering or re-colonizing of unoccupied sites (Danchin *et al.* 1998, Parker *et al.* 2007). These strategies are encompassed in the Public Information or Social Information hypotheses: "a strategy where prospecting or pre-breeding birds use the presence of breeding conspecifics (social information) as information to signal safe nesting habitat" (Ward and Schlossberg 2004). Seabirds, which feed at sea and come to land only to breed, chose a breeding site based on many criteria: absence of predators, topography, substrate, and proximity to feeding grounds (Birkhead and Furness 1985, Stephensen and Irons 2003). Gathering information about resources and sampling alternatives of each small island dispersed across long distances of open ocean would be costly and energy demanding (Boulinier and Danchin 1997, Nocera *et al.* 2006), making monitoring conspecifics (social information) a more parsimonious method of acquiring information about nest-site quality. Social Information, such as the abundance of breeding conspecifics, the presence of chicks, and reproductive success of individuals with similar resource requirements can be used to assess nest-site quality (Valone 2007, Danchin *et al.* 1998, Valone 1989). Prospecting birds can deduce social information from visual, auditory or olfactory cues, such as the visual presence of courting conspecifics or the auditory presence of calls associated with pair bonding.

Storm-petrels (Procellariiformes: Hydrobatidae) are colonial nocturnal burrow-nesting seabirds that are known to use social information, such as the vocalizations of conspecifics, when selecting nesting habitat (Warham 1990). They are also vulnerable to terrestrial predation due to their small size, lack of anti-predator behaviour, low reproductive rates, and ground nesting habits (Atkinson 1985, Warham 1990). Storm-petrels' shallow earthen nesting burrows are easily entered by introduced predators either directly (mice and rats; Jones *et al.* 2008b) or by digging (foxes; Bailey 1993). Unattended chicks are especially vulnerable to predation during the lengthy nestling period, in which they are often left unattended (Warham 1990, Simons 1981). As a consequence of this enhanced vulnerability, the introduction of predatory mammals is a large threat to storm-petrels, and entire colonies or even species have been wiped out (e.g., Guadalupe Storm-petrel *Oceanodroma macrodactyla*; Jehl 1972). When colonies of storm-petrels are extirpated, populations often do not return, due to a combination of social constraints (Podolsky and Kress 1989) and demographic factors (Warham 1990). Thus there is now an urgent need for information regarding cues used in petrels' colony formation behaviour.

Few attempts have been made to attract petrels to new sites using social attraction and few projects have led to the establishment of a breeding colony at a new site (Miskelly and Taylor 2004). However, it is widely known that storm-petrels are attracted to artificial social cues and studies that have attempted to establish new colonies in this way have been successful. Podolsky and Kress (1989) lured Leach's Storm-petrels to abandoned sites in Maine using call playbacks and, within one season, found individuals laying eggs in artificial burrows near speakers. Bolton *et al.* (2004) attracted Madeiran Storm-petrels (*Oceanodroma castro*) using audio cues and similarly found that individuals occupy artificial burrows closer to audio speakers. Grubb (1974) showed that breeding Leach's Storm-petrels navigate to their burrow using olfaction and are attracted to their own nesting material, but olfaction has not been used to date in social attraction experiments.

The Aleutian Islands, Alaska are no exception to the trail of ecological devastation following introductions of mammalian predators on formerly pristine oceanic islands. Most islands were stocked with Arctic Foxes (*Alopex lagopus*) for the fur trade in the 19th and 20th centuries and Norway Rats (*Rattus norvegicus*) were accidentally introduced to several (Ebbert and Byrd 2002). Consequently, the elimination or severe reduction of Leach's (*Oceanodroma leucorhoa*), and Fork-tailed Storm-petrel (*O. furcata*) colonies on islands used as fox farms was noted as early as 1937 (Murie 1959, Bailey 1993, Bailey and Kaiser 1993, Williams *et al.* 1993). Eradication of introduced foxes from Aleutian Islands has been a priority of the Alaska Maritime NWR since the first successful eradication in 1949 (Ebbert and Byrd 2002). Some bird populations have responded positively to fox eradications, although their recovery has rarely been quantified. Storm-petrel rate of re-colonization after fox removal has ranged from relatively fast (less than 15 years for Fork-tailed Storm-petrels on Kasatochi Island; Drummond 2007) to non-existent (Nizki/Alaid Island; Byrd 1994).

In summary, the objectives of our study were to address the following questions: 1) Are storm-petrels attracted to conspecific or heterospecific vocalizations and if so, are non-breeding prospectors or breeding birds more likely to be attracted? 2) Are non-breeding storm-petrels attracted or repelled by conspecific odour? 3) With simultaneous auditory and olfactory cues, is it possible to attract storm-petrels to artificial burrows? and finally, 4) Can social attraction be used as a conservation technique to speed the rate of storm-petrel re-colonization in the Aleutian Islands? The general objective of this study was to consider whether social attraction techniques are suitable for attracting both species of storm-petrel common to the expansive environment of the Aleutian Islands.

4.2 METHODS

4.2.1 *Study area*

We performed field experiments in Ulva Cove at Amatignak Island in the Delarof Islands group of the western Aleutian Islands (Fig. 4.1). Amatignak is an average sized Aleutian island (1433 ha, 8 km north-south and 4 km east-west) situated directly adjacent to Amchitka Pass (97 km east of Amchitka Island). Like most Aleutian Islands Amatignak is treeless, characterized by lush subarctic tundra including patches of grasses (*Leymus sp.*) and Umbelliferae (*Heracleum*, *Angelica*), with hyperoceanic blanket-bogs at low elevations. Amatignak was selected for storm-petrel restoration studies based on its relatively long recovery time period since fox eradication (1991), its resemblance in vegetation and terrain to a large active storm-petrel colony site (Byrd and Trapp 1977), and its similarity in size to other storm-petrel inhabited islands. Although storm-petrels are not known to breed on Amatignak Island (Byrd *et al.* 2005), night-time vocal activity at the experimental site in Ulva Cove was high in 2008-2009 (RTB pers. obs.).

4.2.2 *Playback*

We evaluated Leach's and Fork-tailed Storm-petrel response to conspecific auditory cues using various call playback treatments adjacent to a mist-net. Playback was broadcast between peak hours of storm-petrel activity throughout June and July of 2008 and 2009. Recordings of typical storm-petrel calls for playback were collected from North Bight, Buldir Island in 2006 using a Sony TCD-D10PROII Digital Audio Tape recorder or Fostex FR-2 solid-state recorder with Senheiser MKH 70 or MKH 816 directional microphones (Seneviratne *et al.* 2009) and in 2008 using a Song Meter (Wildlife Acoustics Inc. firmware version 1.5.0 model SM1). A variety of recorded calls were combined and composed into 2 minute medleys using the application Garage Band (Apple Computer Inc.) and uploaded to an iPod shuffle (Apple Computers Inc.). To test response to a variety of sound cues, we used five playback treatments: silent control (no sound), noise control (20 second on/5 second off increments of John Mellencamp's 'Jack and Dianne', Riva Records, 1982), Leach's Storm-petrel playback (a combination of Chuckle and Purr calls, Taoka *et al.* 1988), Fork-tailed Storm-petrel playback (a combination of three-syllable flight and single-syllable male calls, Simons 1981), and finally colony playback (a combination of all calls of both species of storm-petrel). A combination of both call types was used for each species, as Podolsky and Kress (1989) showed a higher hourly capture rate of Leach's Storm-petrel by using both Chuckle and Purr calls. In 2008, playback experiments were run for a total of 15 nights from 26 June – 2 August (each treatment played for 3 nights) and in 2009, experiments were run for a total of 25 nights from 6 June to 26 July (each treatment played for five nights), with separate treatments played on each night according to a randomized schedule.

To evaluate behavioural and vocal response to playback, we recorded storm-petrel captures in an 8 m by 2 m mist net from 0130 h to 0430 h (HAST) each night. Playback from a TOA ER-2230 wireless megaphone was on a 30 minute on/30 minute off schedule, broadcast towards the ocean adjacent to the net. Vocal response was evaluated by an observer who sat 15 m inland of the net counting all call types up to approximately 50 meters. The interspersed 30 min silence periods allowed the observer to evaluate general storm-petrel activity around Ulva Cove (up to 100 meters). Behavioural response (i.e., circling around playback source) was evaluated by counting storm-petrels caught in the net. In 2008, storm-petrels were marked using a spot of quick-dry nail polish on the outer rectrix to detect recaptures. In 2009, storm-petrels were banded with USGS BBL stainless steel bands. All birds were examined for a brood patch. Medial brood patches were scored based on Pyle (2008): a complete lack of feathers on the abdomen was scored as 1 and incomplete feather loss or complete coverage of contour feathers was scored as 0. We recognize the variability and often, unreliability of medial brood patches in ageing long-lived seabirds (McFarlane Tranquilla *et al.* 2003) and the problems associated with linking brood patches to current breeding status. We had no other available methods to age individuals; therefore, we used swollen and vascularised brood patches of breeding birds found in burrows as a reference to score captured storm-petrels (RTB pers. obs.).

To compare the responses of each species of storm-petrel to different playback treatments between years we used a Generalized Linear Model (GzLM) with Poisson error structure and a loglinear link in SPSS version 16.0. By calculating the model means or Estimated Marginal Means and standard error (EMM ± SE), the number of birds in the net (storm-petrel response) could be compared between treatments. To compare the number of birds caught in the net with and without brood patches on conspecific or colony playback nights we used a binomial test (Zar 1999).

4.2.3 *T-Maze*

To test for prospecting (non-breeding) storm-petrel response to conspecific odour cues, a T-maze experiment (e.g., Grubb 1974) was conducted from June 12 – 27 July 2009 inside a 4 m by 5 m Weatherport shelter. The test maze was made of 1.5 cm birch plywood and consisted of a clear acrylic top, a removable plastic start box (4 mm corriboard), a 20 cm by 20 cm choice arena, and two removable corriboard boxes containing the scented materials at either end of each 30 cm arm (Fig. 4.2). The 12 cm by 12 cm start box included a clear acrylic top to permit observation of the bird inside, a sliding divider on the maze-facing side, and 1 cm plastic grill opposite, for ventilation. Other boxes containing scented materials were of the same design. The maze floors were lined with removable white corriboard that was washed with 70% methanol and water between trials. Air and odour cues were drawn through the maze, from the arm ends towards the choice area and start box, by a 12 volt battery powered CPU cooling fan (Thermaltake Inc.) set to its minimum of 9 CFM or 243 l min^{-1} (Appendix C).

Experimental subjects (Leach's and Fork-tailed Storm-petrels) were captured using an 8 m by 2 m mist net set up 25 m east of the Weatherport, with attraction via playback of conspecific calls from the TOA ER-2230 wireless megaphone. Captured storm-petrels lacking brood patches were given a 5-7 min acclimation period in the start box prior to experimental trials. At 1 min before trials began, odour cue boxes were inserted into the end of each arm and the fan activated, to draw odour evenly through the maze. After the acclimation period, the start box containing each subject was inserted into the maze and the divider opened. Blind to the location of the scent boxes, an observer (RTB) recorded the following: species (Leach's or Fork-tailed), stress level of the subject (see below), whether or not the bird had to be nudged (poked lightly with a pencil), the amount of time a light was used, the time (min) it took the bird to make a decision, and the bird's final decision (defined as >30 seconds spent in the scent box or arm of the maze). A bird was defined as "stressed" if they were exhibiting any combination of the following behaviour: scratching at the edges of the box, fluttering wings, vocalizing, or pacing. Each bird was given 2 min to move, after which, if it was still in the start box it was nudged. If no reaction was observed the bird was recorded as 'no-choice'. Between each trial each individual had a 5 min rest period while the maze walls were cleaned and control materials replaced. Each bird performed three different odour choice trials: 1) "Stomach oil" - paper towel saturated with regurgitation versus plain paper towel 2) "Feather odour" collected by rubbing 3-5 birds with a paper towel versus plain paper towel and 3) "Nesting material" made by putting 7-10 captured birds in a scent box on top of dry *Leymus* grass for 15 minutes each versus fresh dry *Leymus* grass. These materials were collected before each maze night during the mist-net/playback experiments and kept in a sealed zip-lock bag. The order in which the trials were presented to each bird was randomized, as was the left/right position of the scented materials, to control for the possibility of multiple testing on the same subject influencing selection by learning (Minguez 1997). To control for the possibility of birds orienting to external or internal cues, the orientation of the maze facing north, south, east, or west was randomized for each successive trial. After completing three odour trials, each subject was banded with a USGS BBL stainless steel band and released.

To analyze the effects of factors such as stress, nudging, species, and the use of light, on the birds' ultimate choice between odour and control, we ran a GzLM in SPSS version 16.0 with a binomial error structure and logit link. To examine response to different odour types (different scent trials), we ran a GzLM with a binomial error structure and logit link testing the effects of trial type on the bird's decision. Finally, we used a binomial test to assess choice preference between odour and control (Zar 1999).

4.2.4 *Artificial Burrows*

To assess the possibility of auditory and olfactory cues attracting storm-petrels to artificial burrows, a series of artificial nest site study plots were set up within suitable storm-petrel nesting habitat in Ulva Cove. Two plots were located 50 m apart, on the north face of the valley around Ulva Cove (Plot 2: 51.26045 °N, 179.07993 °W, Plot 3: 51.26074 °N, 179.07878 °W). The substrate of these two plots was dominated by tussocks of *Leymus sp.* (Rye Grass) and *Heracleum lanatum* (Cow Parsnip). One plot was located 800 m away on the south face of the valley (Plot 1: 51.25761 °N, 179.07709 °W) and the substrate was dominated by poorly drained *Lycopodium selago* (Fir Club Moss) and *Leymus sp.* All plots were 5 m by 5 m at an elevation of 15 m above sea level. In 2008, 15 plastic tubes 40 cm long and 10 cm in diameter were placed in grass tussocks or dug into the ground at each plot and in 2009, 5 more tubes were added to each site. At the end of each plastic tube, a small chamber (approximately 15 cm by 15cm) was dug into the soil. The dimensions of the artificial burrows and chambers were based on a mean burrow length of 43 cm and chamber depth of 13 cm of Leach's Storm-petrels nesting on islands in Newfoundland and Maine (Huntington 1996).

Treatments included: 1) "Control" with no sound or manipulation of the burrows; 2) "Playback" where recordings of both species of storm-petrel were broadcast adjacent to the plot; and 3) "Playback and nesting material" where recordings were broadcast and nesting material was placed inside each artificial burrow. One of three treatments was run per night at each consecutive site according to a randomized schedule. Experiments were run for 21 nights in 2008 from 3 July – 6 August and for 34 nights in 2009 from June 6 – July 28. At 0030 h (approximate sunset) a toothpick was placed upright at the entry to each burrow. On "playback" nights, colony recordings (a medley of both storm-petrel species calls) were broadcast on a TOA ER-2230 wireless megaphone from an ipod shuffle from 0030 h to 0500 h. On "playback and nesting material" nights, in addition to broadcasting calls, nesting material from the active storm-petrel colony on Buldir Island was placed in each burrow in 2008 and nesting material from the t-maze experiment was placed in each burrow in 2009. Between 0530 h and 1100 h after each night, burrows were checked for toothpick knockdowns or other signs of activity such as presence of feathers or evidence of digging.

In order to analyze toothpick knockdowns as a function of years, sites, and treatments we ran a GzLM with a Poisson error structure and loglinear link. Data were then broken down by year and a GzLM with a Poisson error structure and loglinear link was run including only treatment as an explanatory variable.

4.3 RESULTS

4.3.1 *Playback*

Both Leach's and Fork-tailed Storm-petrels were strongly attracted to conspecific playback. Within 10-15 min of playback initiation, birds were actively circling and calling. In both species, significantly more birds were caught on conspecific call playback nights (Leach's Storm-petrel, $G = 317.9$, df = 4, $P << 0.001$; Fork-tailed Storm-petrel $G = 105.5$ df = 4 $P << 0.001$). On conspecific playback nights that were especially dark (no moon present and heavy fog) reaction to playback was so dramatic that not only were many birds caught in the net, dozens of birds were circling and calling, bouncing out of the net, and hitting net poles, the banding shed and personnel. There were approximately 22 times more Leach's Storm-petrels caught in the net on Leach's Storm-petrel nights and 16 times more on colony playback nights compared to silent control and noise control nights (Table 4.1). More Leach's Storm-petrels were also caught on Fork-tailed Storm-petrel playback nights versus silent control nights; however, confidence intervals overlapped slightly between Fork-tailed playback nights and noise control nights (Table 4.1). Approximately 11 times more Fork-tailed Storm-petrels were caught on Fork-tailed playback nights and 3 times more on colony playback nights, compared to silent control and noise control nights. Fork-tailed Storm-petrels were not significantly attracted to Leach's Storm-petrel call playback (Table 4.1).

On average, there were fewer Leach's Storm-petrels caught per night in 2009 (0.51 ± 0.07, EMM ± SE) than in 2008 (1.27 ± 0.16) ($G = 113.9 =$ df $= 1$ $P << 0.001$) and more Fork-tailed Storm-petrels per night in 2009 (0.37 ± 0.057, EMM ± SE) than in 2008 (0.18 ± 0.04) ($G = 10.692$ df $= 1$ $P = 0.001$) (Fig. 4.3).

Among 346 Leach's Storm-petrel and 28 Fork-tailed Storm-petrel captures in 2008 there was 1 Leach's Storm-petrel re-capture (retrix marked with nail polish), on 25 July during Leach's Storm-petrel playback. The polish was still slightly wet, suggesting this was a recapture from the same night. Among 228 Leach's Storm-petrel and 97 Fork-tailed Storm-petrel captures in 2009 there were 2 Leach's Storm-petrel re-captures. The first was captured on 7 July during Leach's Storm-petrel playback and the second was captured on 20 July during Colony playback, both birds were recaptured within 35 minutes of initial capture. There were no Fork-tailed Storm-petrel re-captures in 2008 or 2009.

There were significantly more Leach's Storm-petrels caught in the net on conspecific and colony playback nights that lacked brood patches (148 out of 207, $P << 0.001$). On the other hand, significantly more Fork-tailed Storm-petrels caught in the net on conspecific and colony playback nights had brood patches (77 out of 95, $P = 0.000$). There was no evidence of brood patch swelling or vascularization in any individuals caught in the net.

4.3.2 *T-Maze*

No effect of trial type ("nest material" versus "feather odour" versus "stomach oil") on individual choice was observed ($G = 0.879$ df = 2 $P = 0.644$), therefore trials were pooled. When stressed subjects were removed from the analysis, 49 out of 79 (62%) of Fork-tailed Storm-petrel subjects chose to approach conspecific odour (Binomial, $P = 0.04$), and 59 out of 96 (62%) of Leach's Storm-petrel subjects avoided the conspecific odour cue (Binomial, $P = 0.03$; Fig. 4.4). Including all birds (stressed and unstressed subjects), 64 out of 135 Leach's Storm-petrels chose the experimental arm ($P = 1.00$) and 46 out of 87 Fork-tailed Storm-petrels chose the experimental arm ($P = 0.69$).

Leach's Storm-petrels took an average of 17.7 ± 3.4 min each (total mean maze time ± SD) or 2.6 min per trial and Fork-tailed Storm-petrels took an average of 22.1 ± 3.1 min each (total mean maze time ± SD) or 3.7 min per trial. In total, only 3 Leach's

Storm-petrel trials and no Fork-tailed Storm-petrels were recorded as ‘no choice’. 16 Leach’s Storm-petrels and 18 Fork-tailed Storm-petrels had to be nudged in order to start the maze. When the dividing gate was opened these subjects would sit in the start box quietly without moving. For both species, stress level had a significant effect on choice ($G = 6.107$, $df = 1$, $P = 0.013$) and were therefore removed from analysis. No other factors tested, such as use of a light, nudging, trial type, or any interaction terms had any effect on choice ($P > 0.68$).

4.3.3 *Artificial Burrows*

Data were broken down by year and tested for effect of treatment on entry of artificial burrows, as indicated by number of toothpick knockdowns. Number of burrow entries was significantly affected by treatment type in 2009 ($G = 6.418$ $df = 2$ $P = 0.04$) but treatment had no effect in 2008 ($G = 2.954$ $df = 2$ $P = 0.228$). In 2009, when playbacks were broadcast and scented materials placed inside burrows, the average number of burrow entries increased. The average number of toothpick knockdowns increased from 0.18 ± 0.102 (EMM ± SE) on control nights to 0.50 ± 0.22 on playback nights to 1.00 ± 0.38 on playback and nesting material nights. In 2008, knockdowns increased slightly from 1.29 ± 0.43 on control nights to 1.40 ± 0.53 on playback and nesting material nights, but this increase in mean was not significant.

Both year and site also had a significant effect on burrow entries (Year $G = 5.687$ $df = 1$ $P = 0.017$, Site $G = 8.634$ $df = 2$ $P = 0.013$). On average, there were more knockdowns at site 2 (1.13 ± 0.26 EMM ± SE) and less at site 1 (0.23 ± 0.12) and more knockdowns in 2008 (0.83 ± 0.21) than in 2009 (0.37 ± 0.06).

When toothpick knockdowns were checked the morning after both "playback" and "playback and material" nights in 2008, on five separate mornings (out of 9 playback nights and 5 playback and material nights) freshly deposited storm-petrel feathers and feces were observed on the plot. In 2009, evidence of freshly dug burrows (dirt displaced up to 15 cm) was observed, one at plot 2 and one at plot 3. In 2009, on a "playback and material" night, at 0030 h when nesting material was placed inside a burrow on plot 1 an unidentified bird flew out. Except for this one occasion, no evidence was found of storm-petrels inhabiting or taking up daytime residence in artificial burrows.

4.4 DISCUSSION

Pre-breeding storm-petrels in natural surroundings were strongly attracted to playback of conspecific and heterospecific calls, and Fork-tailed Storm-petrels were attracted to conspecific odour in an experimental maze. Attracting individuals to artificial burrows using these auditory and olfactory cues was not as straightforward, with significant results only in the second year of experimental attraction. Social attraction experiments on Amatignak Island were highly successful in attracting pre-breeding and prospecting storm petrels, but recruitment of these individuals as breeders was not achieved in our short-term experiment and deserves more discussion.

Our results show a strong attraction of both Leach's and Fork-tailed Storm-petrels to conspecific call playback, as in other storm-petrel species (Leach's Storm-petrel;

Podolski and Kress 1989, Dark-rumped Storm-petrel *Pterodroma phaeopygia*; Podolsky and Kress 1992, British Storm-petrels *Hydrobates pelagicus*; Furness and Baillie 1981, and Wilson's Storm-petrel *Oceanites oceanicus*; Bretagnole 1989). Furthermore, both species were attracted to colony call playback (recordings of both species) and weakly attracted to heterospecific call playback versus a noise control. Throughout most of their range, from northern California to the Gulf of Alaska and the Aleutian Islands (Boersma and Silva 2001), Fork-tailed Storm-petrel colonies are often mixed with large numbers of Leach's Storm-petrels (Boersma et al 1980, Vermeer et al 1988, and McChesney and Carter 2008). Fork-tailed and Leach's Storm-petrels burrows are often associated with the same type of habitat, well drained soil or hummock (Stenhouse and Montevecchi 2000). Although there are subtle differences throughout the breeding season, the main diet of both storm-petrel species (amphipod *Paracallisoma coecus*) is similar (Vermeer et al 1988). Furthermore, behaviour of both of these species is characterized by frequent loud night-time vocalizations around colonies. Prospecting individuals use these vocalizations as cues when selecting appropriate breeding sites (social information). Given the breeding habitat and food resource similarity between species, social information should be useful between both Leach's and Fork-tailed storm-petrels. Non-breeding or prospecting birds should be able to listen for either conspecific or heterospecific storm-petrels in order to gather information about breeding habitat. Heterospecific attraction is a widely accepted concept in migratory passerine biology (Monkkonen and Forsman 2002), but our study provided the first piece of evidence for its use by colonial seabirds.

Differences in number of storm-petrels caught between years could be due to the difference in start time of the experiment. In 2009, mist-net experiments began in early June and were finished by late July, whereas in 2008 experiments began in late June and were finished by early August. At active storm-petrel colonies, Vermeer *et al.* (1988) found in June and July most activity was dominated by Fork-tailed Storm-petrels, by August however, Leach's Storm-petrels were more commonly caught in the net. This is consistent with our findings that Fork-tailed Storm-petrels were more numerous in 2009 when experiments began and ended earlier in the summer, while Leach's Storm-petrels were more numerous in 2008 when experiments began and ended later in the summer. The increase in 2009 captures may also be due to the fact that there was a cumulative effect of repeating the attraction experiment two years in a row. This cumulative effect was also observed in the artificial burrow experiment, where significantly more birds entered burrows on playback nights in 2009 than 2008.

Most Leach's Storm-petrels attracted to playback of conspecific calls lacked brood patches (non-breeders or prospectors). This is consistent with findings for British Storm-petrels, which showed breeding birds are generally not attracted to sound lures and most birds captured in nets adjacent to playback are second or third year pre-breeders (Fowler *et al.* 1982, Okill and Bolton 2005). Naive birds that have yet to recruit to a breeding population (prospectors) and birds whose nesting attempt was postponed or failed (non-breeders) would require more information about nesting habitat quality than birds that are established breeders. Leach's Storm-petrels have a high rate of nest-site fidelity (Warham 1990); therefore it would serve no function for breeding birds to be attracted to calls of conspecifics, considering they have already established a suitable mate and nesting location. However, we found that a high proportion of Fork-tailed Storm-petrels attracted to conspecific playback had brood patches (breeders). We speculate that many of these birds with de-feathered brood parches were not actually breeding birds. Harris (1964) noted that non-breeding Fork-tailed Storm-petrel individuals that spend time with a mate in a burrow, or individuals that periodically spend days alone in a burrow may also develop brood patches. Pre-breeding birds may acquire brood patches and display vigorously for several years before their first breeding attempt (Warham 1990). Among our captures, no vascularized brood patches were observed in either species, suggesting that none of the birds captured were incubating eggs and all were non-breeders. McFarlane Tranquilla *et al.* (2003) showed that brood patches in some seabirds do not correspond to breeding attempt and often birds with brood patches were not nesters or even putative nesters. Therefore, in the future, other methods of assessing breeding status may be more reliable and may provide more consistent results.

Procellariiformes have a well developed olfactory apparatus and excellent olfactory capabilities, which they use to find productive foraging areas in the open ocean (Warham 1990, Nevitt and Haberman 2003) and as a guidance system in colony and burrow location (Grubb 1974). Storm-petrels have a distinct, strong, and persistent musky odour that is present on their feathers and around their burrows, a smell which may be available as social information. Our results show that non-breeding Fork-tailed Storm-petrels were attracted to conspecific odour including 'nesting material', feather odour, and stomach oil. All odours would be associated with active colonies; where smelly nesting material would signal active burrows, stomach oil would signal adults feeding chicks and detectable musky feather odour would signal a large presence of conspecifics. However, non-breeding Leach's Storm-petrels were significantly repulsed by conspecific odour. Leach's Storm-petrels may have been repulsed by conspecific odour at a more confined level, due to its possible function as a burrow occupancy signal. The reason for such a distinct difference between species is unknown, but may be that Leach's Storm-petrels are more territorial (Screech call used in territorial interactions, Taoka *et al.* 1988) and less likely to enter strange unoccupied burrows (Huntington *et al*. 1996) than Fork-tailed Storm-petrels. This suggests that timid Leach's Storm-petrels use odour as an occupancy signal, while less timid Fork-tailed Storm-petrels use odour as social information when prospecting for safe nesting habitat.

By combining auditory and olfactory cues, we examined the possibility of attracting both species of storm-petrel to enter and inhabit artificial burrows. In the first year of burrow experiments (2008) we found no significant increase in burrow entries between control and experimental treatments. On nights with playback or playback and scent treatments we observed many birds calling and circling and found evidence of birds landing on the plot (feathers and faeces on the plot); however, individuals were not entering burrows. In the second season (2009) we found a significant increase in burrow entries from control to playback to playback and nesting material. An increase in burrow entries from the first to second season suggests that artificial colonization experiments may be cumulative, and in order to encourage burrow use, more time may be required. Delayed breeding is a feature of tubenose reproduction; most storm-petrels recruit into the breeding population at 3 to 5 years old (Huntington *et al.* 1996, Warham 1990) while returning to prospect potential colonies after a year or two at sea (Okill and Bolton 2005). This means that storm-petrels prospecting on Amatignak could have 2 to 4 years before they finally decide to settle and breed. The relationship between prospecting behaviour and recruitment into a breeding population is not well understood (Bradley *et al.* 1999). However, it is clear from the lack of recaptures in our playback experiment there is a large population of pre-breeding birds. Huntington *et al.* (1996) found that during the prospecting period storm-petrels become progressively more faithful to a colony. Therefore, if this social attraction experiment were to continue for another 2 to 4 years, during which prospecting individuals would mature to breeding age, more storm-petrels may inhabit artificial burrows.

On the other hand, Podolsky and Kress (1989) performed a similar experiment in Maine examining Leach's Storm-petrel colonization of artificial burrows using playback, and found dramatic and almost instant results. Within the first year of setting up social attraction experiments, adult storm-petrels occupied and laid eggs in artificial burrows near playback. However, this study focused on only one species of storm-petrel, all experiments were performed on small islands within a close range of active colonies, and the islands were rocky with only small amounts of suitable habitat available. Amatignak is a relatively large island (1433 ha), it is over 360 km east from the active colony on Buldir Island, and there is suitable storm-petrel habitat around the majority of the island. This is a much more diffuse situation than the environment in Maine, in both distance from natal site and large numbers of options for nesting habitat. Furthermore, at many sites on Amatignak there are small sub-colonies of storm-petrels (Chapter 2) and the odds that prospecting individuals will chose a small artificial colony versus a small natural colony are very low (S. Kress pers. comm.).

Storm-petrels were not observed inhabiting burrows and no evidence (feathers or faeces) was found supporting long-term burrow use. This lack of burrow use may have been due to microhabitat. The site with the fewest knockdowns, site 1, had a thick layer of peat with poor drainage, and during heavy rains the chamber at the end of the tube would become wet, or in some cases flood. Stenhouse and Montevecchi (2000) showed that burrow density was highest in areas of Great Island, Newfoundland with a steeper slope and therefore better drained, looser soil (Harris 1974). Call playback and scented materials may have attracted prospectors, but un-suitable microhabitat, especially of site 1, may have deterred them from inhabiting plastic burrows.

Burrows were checked between 0530h and 1100h in the morning, when diurnal songbirds such as Lapland Longspur (*Calcarius lapponicus*) and Song Sparrow (*Melospiza melodia*) are actively singing. Although these passerines would not necessarily inhabit plastic burrows, both species nest throughout *Leymus-Umbel* plant communities, especially near beaches (Byrd and Day 1986). Therefore, they may have set up territories on the plots and occasionally investigated burrows. Males of both passerine species were observed singing around plots when burrows were checked each morning. Considering the small number of knockdowns on most nights, their random pattern between treatments in 2008, and the time at which burrows were checked, some knockdowns may have been caused by diurnal songbirds.

Although it may be possible to attract pre-breeding storm-petrels to abandoned sites in the Aleutians, whether or not social attraction is a suitable method of speeding re-colonization is yet to be determined. Playbacks and scented materials attracted many birds, and after just two seasons encouraged individuals to enter artificial burrows. Considering storm-petrel's late age at first breeding and the large diffuse nature of suitable habitat across the Aleutian Islands, storm-petrel attraction as a conservation tool in the Aleutians may be more cost-effective on a longer time-scale. If this experiment were to continue to a point where all pre-breeding birds reached an age appropriate for recruitment, storm-petrels may have inhabited and bred in artificial burrows. There is now a need for research concerning restoration techniques for petrels, especially in the Aleutian Islands, where storm-petrel populations were decimated by introduced foxes. This study represents a first step working towards producing a protocol by which burrow-nesting seabirds can be restored to their former breeding numbers across the Aleutian chain.

Table 4.1 Estimated Marginal Mean captures of Leach's and Fork-tailed Storm-petrel during five different playback treatments, showing higher captures during conspecific call playback (N control = 20 sec increments of music, S control = silence, Leach's = playback of Chuckle and Purr calls, Fork-tailed = playback of flight and male calls, and Colony = both Leach's and Fork-tailed calls mixed).

				95% Wald Confidence Interval	
Species	Treatment	Mean	SE	Lower	Upper
LESP	Colony	4.81	0.321	4.18	5.44
	Fork-tailed	0.42	0.097	0.23	0.61
	Leach's	6.61	0.381	5.86	7.35
	N Control	0.30	0.079	0.14	0.45
	S Control	0.09	0.043	0.00	0.17
FTSP	Colony	0.43	0.092	0.25	0.61
	Fork-tailed	1.47	0.186	1.10	1.83
	Leach's	0.17	0.058	0.06	0.29
	N Control	0.14	0.052	0.04	0.25
	S Control	0.07	0.037	0.00	0.15

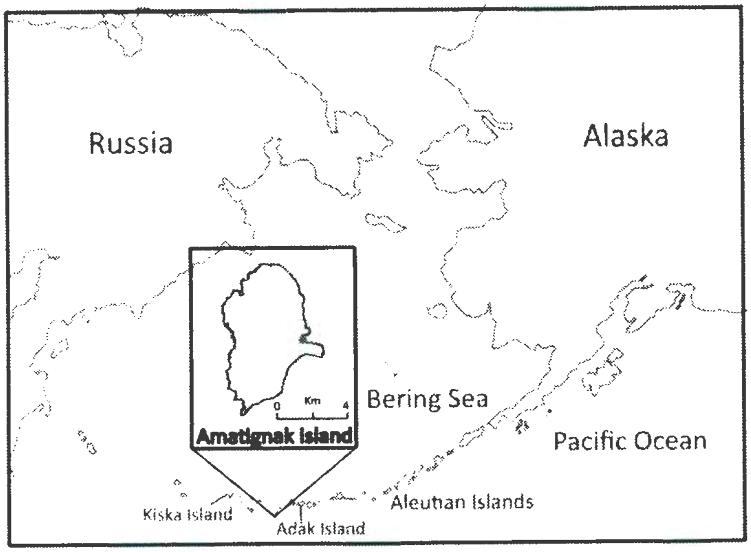


Figure 4.1 Map of experimental site, Ulva Cove (51.27 °N, 179.10 °W), in relation to the Aleutian Archipelago. Ulva Cove is on the east side of Amatignak Island, represented by a dot.

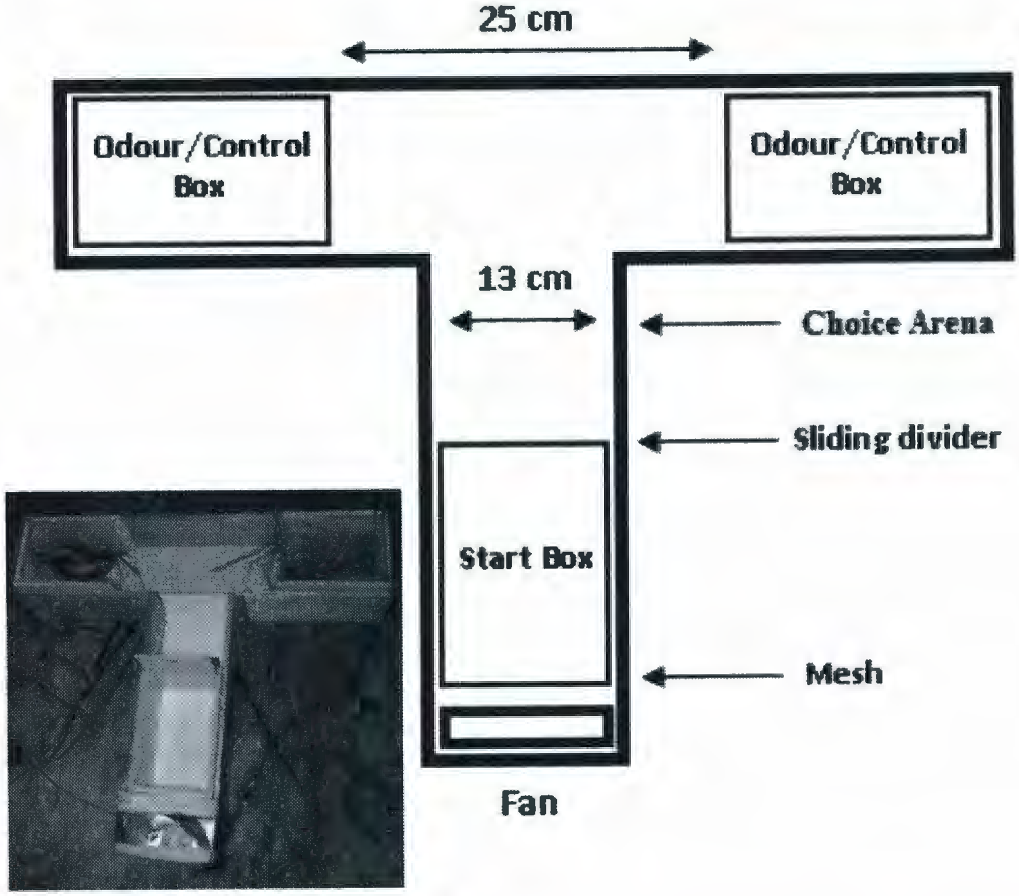


Figure 4.2 T-maze design used to test non-breeding storm-petrel attraction to conspecific odour. Includes three removable plastic 12 cm by 20 cm boxes, each with mesh at one end to allow for air circulation, and a sliding divider at the other to release the bird into the choice arena. (Inset: t-maze set-up in the field)

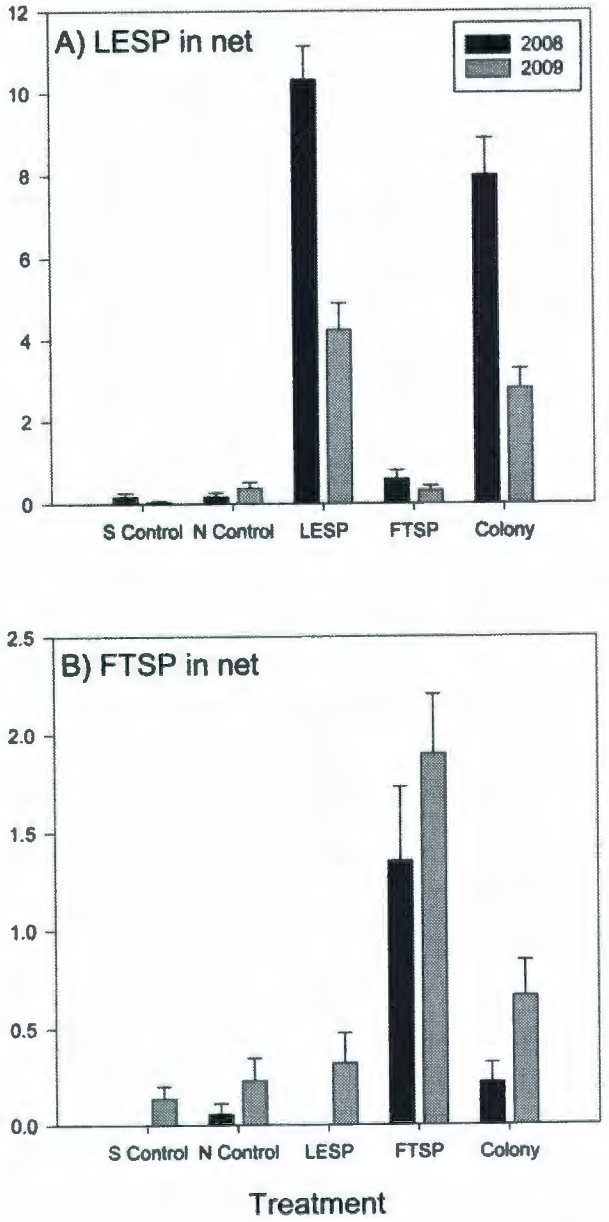


Figure 4.3 Average number of captures in net per night of Leach's (A) and Fork-tailed (B) Storm-petrels during various playback treatments including: S Control (no sound), N Control (20 sec on/5 sec off increments of music), LESP (Chuckle and Purr calls), FTSP (flight and male calls), and Colony (a combination of LESP and FTSP).

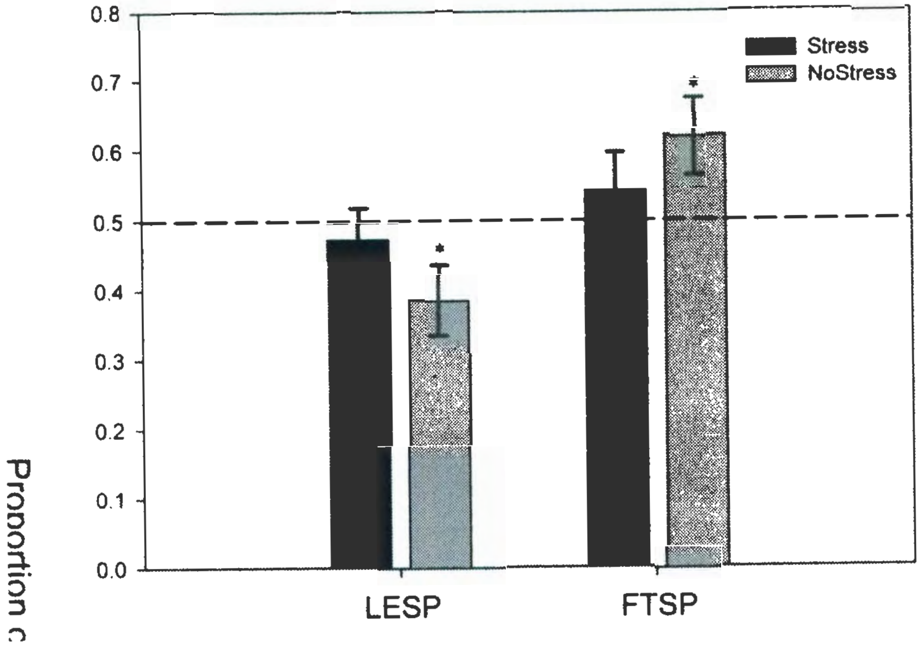


Figure 4.4 Proportion of Leach's and Fork-tailed Storm-petrels that chose scented materials in the t-maze experiment. Black bars show proportion of choices with stressed individuals included, and grey bars with stressed individuals removed. (*) indicate proportions that differ significantly ($P < 0.05$) from 0.5.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

The objectives of my study were to monitor the rate of nocturnal seabird re-colonization in the western Aleutian Islands, Alaska, and at sites where re-colonization was slow, test ways to enhance recovery. This was accomplished in three ways:

1) Assessing a new method to monitor nocturnal burrow-nesting seabirds, which are logistically difficult to census using conventional techniques.

Little is known about recovery of the focal species in this study due to their nocturnal lifestyle and fossorial nesting strategy. I successfully tested a novel technique in the field of seabird ecology: passive acoustic monitoring and automatic call recognition. This unique method can be used to measure and compare species which are misrepresented by conventional monitoring techniques.

Acoustic recorders (Song Meters) were found to be extremely robust, considering the windy precipitous environment of the Aleutian Islands. Although recording quality decreased as wind speed increased, if wind speed was below gale force, the majority of recordings were useful. Remarkably, despite frequent summer gales and strong winds, only 2.9% of all recordings between 2008 and 2009 were deemed unusable. Call recognition models successfully detected the most common nocturnal seabird calls, with a recognition rate well above 50%. However, when calls were infrequent or extremely dense and overlapping, simple visual scans of spectrograms were found to be more efficient. Using acoustic recorders we confirmed breeding of seabirds on islands thought to be abandoned due to fox farming when surveyed using conventional monitoring techniques (boat surveys). Relative indices of abundance were constructed to compare call activity between islands and sites.

Acoustic monitoring provided a cost and time effective way (placing devices to collect data, rather than setting up an expensive field camp for biologists to collect data) to collect large amounts of data that allowed comparison of relative nocturnal seabird abundance and in some cases, confirmed breeding. Limitations of this new monitoring system were recognized: primarily, although acoustic recording provides a comparative index of abundance, it does not give population estimates. The relationship between call activity and population size is currently unknown and caution should be taken not to confuse number of calls with number of individuals. Future research should focus on relating call activity to known population size or identifying individual birds based on differences in call features.

2) Using this new acoustic survey method to compare nocturnal seabird activity in the western Aleutian Islands and relating differences in call activity to patterns and rates of recovery.

Evidence that seabird populations recover after removal of anthropogenic sources of mortality (introduced predators) is often anecdotal. Most research has focused on the negative impacts of introduced mammalian species on seabird populations, such as decreasing hatching success and adult survival, and the likely positive impact eradication will provide. My study differs from anecdotal accounts because I provide quantitative comparisons of seabird recovery. I consider patterns of recovery in four similar species among a series of islands, providing a range of comparisons.

Not surprisingly, very few calls (8 calls throughout the entire recording period) were recorded at Kiska Island which is still inhabited by introduced rats. Activity was slightly higher, but still very low, at Little Sitkin Island, which has only had 9 years to recover from introduced predators. This trend continued with an increase in activity on Amatignak with 18 years since foxes were removed, and Kasatochi with 25 years. However, much less call activity was recorded on Nizki/Alaid, which had foxed removed 16 years previous to Amatignak. This suggests that recovery is complex, and seabird return is not solely dependent on time. Other factors such as island biogeography, presence of refugia from predators, proximity to feeding grounds, and social information, were found to influence call activity and thus recovery of nocturnal seabirds. Recovery rate depends on the interaction between many factors pertaining to island nesting habitat, suggesting that simply eradicating predators may not be sufficient, that more management post-eradication is needed.

This chapter was limited by a lack of historical seabird population data. Seabird distributions pre-dating foxes are unknown in the Aleutian Islands, however paleoecological research examining Aleut midden sites may provide clues in evaluating modern recovery patterns. Future studies should focus on characterizing mechanisms by which seabirds return to breeding sites in order to refine management strategies post-eradication.

3) Attempting to enhance slower rates of recovery using social attraction techniques.

Conservation strategies tend to focus on habitat restoration and protection. This represents an important first step, but does not consider social or reproductive constraints that limit recovery. In this study, at sites where re-colonization of nocturnal seabirds was slow, I tested social attraction techniques in an attempt to speed recovery.

Similar to previous studies, pre-breeding storm-petrels were strongly attracted to conspecific playback cues and interestingly, storm-petrels were also attracted to heterospecific playback cues. Although intuitive, as storm-petrels breed sympatrically in large mixed colonies, heterospecific attraction has never been tested in seabirds. Unique to my study, I tested pre-breeding storm-petrel attraction to conspecific olfactory cues. In an enclosed setting, Fork-tailed Storm-petrels were attracted to conspecific odour, but Leach's Storm-petrels were repulsed, suggesting that olfactory cues may be useful to attract Fork-tailed Storm-petrels but may have the opposite effect on Leach's. A combination of acoustic playbacks and olfactory cues caused storm-petrels to enter artificial burrows, but only during the second year of experiments. Social cues clearly attract pre-breeding seabirds, but more time is needed to enhance re-colonization. Future projects using social attraction with seabirds should span longer than 2 seasons in order to obtain more conclusive results.

From a management perspective my study is practical. The tested techniques can be used with any hard-to-measure seabird in any island system around the globe. Acoustic recorders can be placed on islands before and after eradication to gather information about nocturnal seabirds, and for islands that have low recovery, social attraction can be used. This system represents a cheap and effective island conservation strategy. Considering 52% of nocturnal burrow-nesting petrel species (family Procellariidae) nesting on remote islands are threatened (Birdlife International 2008), innovative conservation and restoration techniques such as these are essential.

APPENDIX A: Specifications of each acoustic recording device (Song Meter) including recording start and end time, number of nights and hours recorded, and coordinates of each site and island between 2008 and 2009.

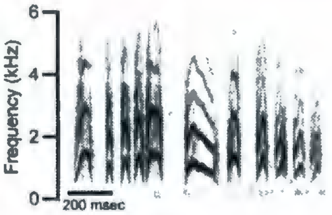
Island	Site	Foxes	Island Size (ha)	Elevation (m)	Coordinates	Year	Recording Start	Recording End	Device Nights	Recording Hours
Kasatochi	Troll Talus	1927-1984	287	316	52.169° N, 175.524° W	2009	16/06/2009	11/08/2009	56	98
Amatignak	North	1923-1991	3453	515	51.293° N, 179.090° W	2008	27/06/2008	29/07/2008	32	96
						2009	04/06/2009	03/08/2009	60	180
						TOTAL			92	276
	East				51.264° N 179.074° W	2008	17/06/2008	04/08/2008	48	144
						2009	28/05/2009	04/08/2009	68	204
						TOTAL			116	348
	South				51.230°N, 179.010° W	2008	16/06/2008	18/07/2008	32	96
						2009	30/05/2009	01/08/2009	63	189
						TOTAL			95	285
	West				51.262° N 179.134° W	2008	15/06/2008	26/07/2008	41	123
						2009	31/05/2009	04/08/2009	65	195
						TOTAL			106	318
Little Sitkin	North	1923-2000	6354	1199	51.975° N, 178.457° E	2008	18/07/2008	31/07/2008	13	39
	North-West				51.955° N, 178.452° E	2008	02/07/2008	02/08/2008	31	93

	South				51.904° N, 178.538° E	2008	10/07/2008	01/08/2008	22	66
	West				51.932° N, 178.453° E	2008	19/07/2008	02/08/2008	14	42
Niz/Al	West	1911-1969/75	1200	190	52.748° N, 173.950° E	2009	31/05/2009	31/07/2009	61	106.75
	North				52.750° N, 173. 898° E	2009	31/05/2009	31/07/2009	61	106.75
	South				52.750° N, 173.928° E	2009	31/05/2009	31/07/2009	61	106.75
	East				52.733° N, 173. 967° E	2009	31/05/2009	31/07/2009	61	106.75
Kiska	Bukh Pt	1835-1987 *rats	28177	1221	51.919° N, 177.461° E	2009	22/06/2009	25/07/2009	33	115.5
	West				51.940° N, 177.430 °E	2009	02/07/2009	02/08/2009	31	108.5
Buldir	N Bight	n/a	2000	657	52.372° N, 175.894 °E	2008	29/05/2008	27/07/2008	59	177
						2009	07/06/2009	30/07/2009	53	159
						TOTAL			112	336

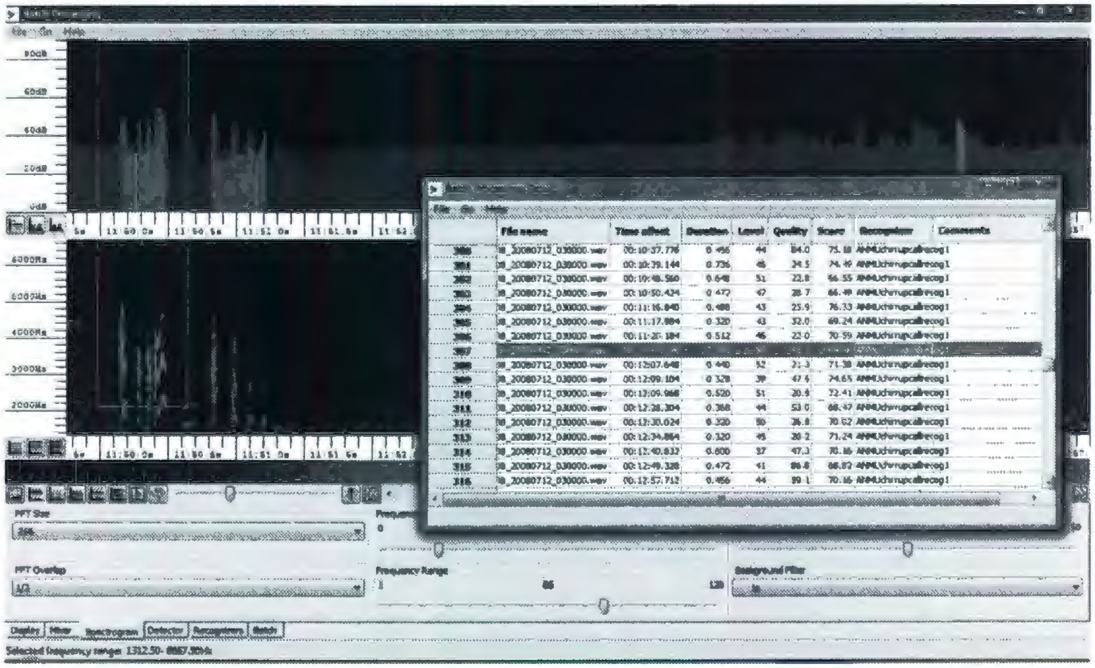
APPENDIX B: Call recognition model specifications in Song Scope.

Spectrogram examples:

Example of high quality reference call (Leach's Storm-petrel Chuckle call, recorded on Buldir Island 2006 using a Sony TCD-D10PROII Digital Audio Tape recorder) used to build a basic recognition model.



Screen capture of Song Scope output of Leach's Storm-petrel Chuckle call recognition model.



Parameters involved in creating recognition models:

Sample Rate: number of audio samples taken per second. A sampling rate of twice the maximum frequency of calls of interest is all that is needed to resolve frequency ranges.

Fast Fourier Transform (FFT): an algorithm that transforms a time domain signal into a frequency domain.

Fast Fourier Transform (FFT) Size/Overlap: adjusts the number of samples (window size) and amount of overlap between samples of the FFT algorithm used to produce spectrograms. Larger FFT sizes will show more frequency resolution at the expense of detail on the time axis and vice versa.

Frequency Minimum/Frequency Range: lowest frequency and range of frequencies displayed on the spectrogram and used in comparing vocalizations. Minimum frequencies should be set as high as possible without clipping the lowest frequency component of vocalizations of interest. Upper frequencies should be limited so as not to include redundant harmonics.

Background Filter: reduces background noise and sharpens vocalization spectrograms by specifying the number of seconds over which to average background noise levels. A filter of one second is recommended.

Max Syllable/Syllable Gap: used to specify the longest syllable and inter-syllable gaps likely to be encountered in the vocalization.

Max Song: used to specify the longest vocalization likely to be encountered

Dynamic Range: cuts off weaker vocalizations in favour of stronger ones as candidates (i.e. eliminating noise). If this value is too low, there will not be enough information to detect important elements of the vocalization and if it is too high, recognizers will be more susceptible to background noise.

Maximum Complexity: limits the size of a recognition model to a specified number of "states". If vocalizations of interest are highly varied, consisting of many syllable types, more complexity may be required.

Maximum Resolution: limits the size of spectral "feature vectors". Vocalizations rich in spectral complexity (broadband calls) may require more resolution. Low quality recordings may require low resolution to match poor spectral resolution.

Recognition model results (in Song Scope):

Cross Training/Total Training: shows the average and standard deviation of the "fit" of excluded annotation ids (calls or 'training data' included when building the model) and of all training data in the final model. A low score may indicate that the generated model may not accurately represent the vocalization.

Model States: the size of the model.

Feature Vector: same as the Max. Resolution.

Syllable Types: the number of different syllable classes used to construct the final model.

State Usage: indicates the average and standard deviation in the number of different states traversed by each vocalization

Mean Symbols: indicates the average and standard deviation of the number of symbols contained within each vocalization

Mean Duration: Indicates the average and standard deviation of the duration of each vocalization

Recognition model specifications (for nocturnal seabirds in the Aleutian Islands):

Leach's Storm-petrel Chatter Call recognizer 1 (for low background noise situations)

Sample rate: 10,000Hz; FFT Size: 256; FFT Overlap: ½

Frequency Min: 10 FFT bins (390 Hz); Frequency Range: 128 (390-5000 Hz)

Background Filter: 1s

Max Syllable: 50 (0.5 sec); Max Syllable Gap: 50 (0.5 sec)

Max Song: 30 (3 sec)

Dynamic Range: 17dB

Maximum Complexity: 48; Maximum Resolution: 4

Recognizer Information –

Cross Training: 75.79% +/- 6.0% Total Training: 75.10 +/- 4.88%

Model States: 27 State Usage: 20 +/- 6

Feature Vector: 4 Mean Symbols: 37 +/- 12

Syllable Types: 9 Mean Duration: 0.97 +/- 0.28s

Total high quality calls used: 2

Total Field annotated calls used (from Buldir Island recordings): 4

Leach's Storm-petrel Chatter Call recognizer 2 (for high background noise situations)

Sample rate: 16,000Hz; FFT Size: 256; FFT Overlap: ½

Frequency Min: 12 FFT bins (750 Hz); Frequency Range: 60 (750-4500 Hz)

Background Filter: 1s

Max Syllable: 50 (0.5 sec); Max Syllable Gap: 34 (0.34 sec)

Max Song: 50 (5 sec)

Dynamic Range: 20dB

Maximum Complexity: 48; Maximum Resolution: 4

Recognizer Information –

Cross Training: 75.56% +/- 4.14% Total Training: 75.48 +/- 3.83%

Model States: 45 State Usage: 27 +/- 8

Feature Vector: 4 Mean Symbols: 63 +/- 14

Syllable Types: 7 Mean Duration: 1.14 +/- 0.22s

Total high quality calls used: 2

Total Field annotated calls used: 15 from the Southern Song Meter, 2 from the Western Song Meter, and 2 from the Northern Song Meter

Ancient Murrelet Chirrup recognizer

Sample rate: 16,000Hz; FFT Size: 256; FFT Overlap: ½

Frequency Min: 45 FFT bins (2812 Hz); Frequency Range: 60 (2812-5938 Hz)

Background Filter: 1s

Max Syllable: 50 (0.5 sec); Max Syllable Gap: 30 (0.3 sec)

Max Song: 30 (3 sec)

Dynamic Range: 18dB

Maximum Complexity: 48; Maximum Resolution: 4

Recognizer Information –

Cross Training: 71.97% +/- 2.63% Total Training: 72.63 +/- 2.36%

Model States: 46 State Usage: 24 +/- 8

Feature Vector: 4 Mean Symbols: 44 +/- 10

Syllable Types: 7 Mean Duration: 0.45 +/- 0.10 s

Total high quality calls used: 5

Total Field annotated calls used: 1 from the Southern Song Meter, 13 from the Eastern Song Meter, and 2 from the Northern Song Meter

Fork-tailed Storm-petrel Flight Call recognizer 1 (for low background noise situations)

Sample rate: 12,000Hz; FFT Size: 256; FFT Overlap: ½

Frequency Min: 30 FFT bins (1406.25 Hz); Frequency Range: 90 (1406.25-5625 Hz)

Background Filter: 1s

Max Syllable: 60 (0.6 sec); Max Syllable Gap: 15 (0.15 sec)

Max Song: 30 (3 sec)

Dynamic Range: 13dB

Maximum Complexity: 48; Maximum Resolution: 4

Recognizer Information –

Cross Training: 76.02% +/- 4.09% Total Training: 75.18 +/- 4.28%

Model States: 42 State Usage: 16 +/- 7

Feature Vector: 4 Mean Symbols: 33 +/- 19

Syllable Types: 8 Mean Duration: 0.85 +/- 0.42 s

Total high quality calls used: 2

Total Field annotated calls used: 3 from the Western Song Meter, 6 from the Eastern Song Meter, and 1 from the Northern Song Meter

Fork-tailed Storm-petrel Flight Call recognizer 2 (for high background noise situations)

Sample rate: 12,000Hz; FFT Size: 256; FFT Overlap: ½

Frequency Min: 45 FFT bins (2812 Hz); Frequency Range: 60 (2812-5938 Hz)

Background Filter: 1s

Max Syllable: 50 (0.5 sec); Max Syllable Gap: 30 (0.3 sec)

Max Song: 30 (3 sec)

Dynamic Range: 18dB

Maximum Complexity: 48; Maximum Resolution: 4

Recognizer Information –

Cross Training: 71.97% +/- 2.63% Total Training: 72.63 +/- 2.36%

Model States: 46 State Usage: 24 +/- 8

Feature Vector: 4 Mean Symbols: 44 +/- 10

Syllable Types: 7 Mean Duration: 0.45 +/- 0.10 s

Total high quality calls used: 5

Total Field annotated calls used: 3 from the Western Song Meter, 6 from the Eastern Song Meter, and 2 from the Northern Song Meter

*all other settings were kept at default

APPENDIX C: Parameter estimates and Estimated Marginal Means for all variables in top AIC models for Leach's Storm-petrel, Fork-tailed Storm-petrel and Ancient Murrelet.

Species	**Parameter**	**β**	**Est. Marg Mean**	**Std. Error**	**Lower 95% C.I.**	**Upper 95% C.I.**	**Wald Chi-Square**	**df**	**Sig.**
LESP	(Intercept)	3.676			2.866	4.485	79.155	1	0.000
	East Winds * WindS	-0.107		0.027	-0.160	-0.055	15.965	1	0.000
	North Winds * WindS				-0.075	-0.028	9.859	1	0.002
	South Winds * WindS	-0.163		0.023	-0.207	-0.118	51.843	1	0.000
	West Winds * WindS	-0.082		0.014	-0.110	-0.055	33.638	1	0.000
	New moon	0.879	15.277	2.999	21.155	9.399	24.290	1	0.000
	Crescent moon	0.855	14.910	2.526	19.861	9.959	34.163	1	0.000
	Gibbous moon	0.616	11.740	1.891	15.446	8.034	18.430	1	0.000
	Full moon	0^a	6.342	1.187	8.668	4.017	.	.	.
	No refugia	-2.801	5.566	0.542	6.629	4.504	88.834	1	0.000
	Talus	-5.648	0.323	0.176	0.669	-0.023	87.103	1	0.000
	Steep cliffs	-1.078	31.165	5.206	41.369	20.961	13.496	1	0.000
	Offshore islets	-0.888	37.707	5.571	48.626	26.789	9.994	1	0.002
	Steep cliffs + Offshore islets	0^a	91.610	26.197	142.955	40.264	.	.	.
	Oceanic habitat	-1.306	5.939	1.068	8.033	3.845	16.942	1	0.000
	Shelf habitat	0^a	21.928	5.613	32.930	10.926	.	.	.
	Distance to Buldir	0.007		0.002	0.002	0.011	7.561	1	0.006
	Distance to source	0.006		0.010	-0.012	0.025	0.465	1	0.495
	Years since eradication	0.006		0.001	0.005	0.008	74.082	1	0.000

	Island size	0.000		0.000	0.000	0.000	13.948	1	0.000
	Purr calls	0.002		0.003	-0.003	0.007	0.921	1	0.337
FTSP									
	(Intercept)	9.15831			8.182	10.134	338.296	1	0.000
	East Winds * WindS	-0.158		0.028	-0.213	-0.103	31.397	1	0.000
	North Winds * WindS				-0.136	-0.086	28.895	1	0.000
	South Winds * WindS	-0.411		0.030	-0.469	-0.352	188.226	1	0.000
	West Winds * WindS	-0.350		0.029	-0.407	-0.293	146.728	1	0.000
	New moon	0.140	30.626	6.530	17.828	43.424	0.507	1	0.476
	Crescent moon	0.628	49.881	9.124	31.999	67.763	14.582	1	0.000
	Gibbous moon	0.972	70.387	11.970	46.925	93.848	38.286	1	0.000
	Full moon	0^a	26.632	5.252	16.338	36.926	.	.	.
	No refugia	-5.861	0.930	0.125	0.684	1.176	299.452	1	0.000
	Talus	2.511	4020.409	1701.393	685.740	7355.078	29.090	1	0.000
	Steep cliffs	-4.228	4.757	0.976	2.845	6.669	187.022	1	0.000
	Offshore islets	-2.778	20.293	3.565	13.307	27.280	85.917	1	0.000
	Steep cliffs + Offshore islets	0^a	326.395	101.477	127.503	525.287	.	.	.
	Oceanic habitat	2.715	159.844	28.213	104.548	215.139	62.066	1	0.000
	Shelf habitat	0^a	10.587	3.022	4.663	16.511	.	.	.
	Distance to Buldir	-0.028		0.002	-0.032	-0.023	131.100	1	0.000
	Distance to source	0.099		0.009	0.081	0.117	117.514	1	0.000
	Years since eradication	-0.006		0.001	-0.008	-0.003	18.114	1	0.000
	Island size	0.000		0.000	0.000	0.000	106.271	1	0.000
	Chuckle calls	0.001		0.000	0.001	0.002	11.464	1	0.001
	Chirrup calls	0.004		0.002	0.001	0.007	6.101	1	0.014
	Male calls	0.005		0.002	0.002	0.009	9.481	1	0.002

ANMU

(Intercept)	-122.73			-151.379	-94.073	70.474	1	0.000
East Winds * WindS	-0.059		0.049	-0.155	0.037	1.446	1	0.229
North Winds * WindS				-0.096	-0.033	9.020	1	0.003
South Winds * WindS	-0.077		0.037	-0.150	-0.004	4.256	1	0.039
West Winds * WindS	-0.117		0.037	-0.189	-0.044	9.990	1	0.002
New moon	1.052	n/a	n/a	n/a	n/a	12.573	1	0.000
Crescent moon	1.299	n/a	n/a	n/a	n/a	24.521	1	0.000
Gibbous moon	0.924	n/a	n/a	n/a	n/a	14.494	1	0.000
Full moon	0[a]	n/a	n/a	n/a	n/a	.	.	.
No refugia	12.689	0.000	0.000	0.000	0.012	49.878	1	0.000
Talus	124.876	0.000	0.000	0.000	0.000	80.848	1	0.000
Steep cliffs	23.147	212.031	135.416	-53.381	477.442	72.926	1	0.000
Offshore islets	12.090	0.003	0.004	-0.004	0.011	116.085	1	0.000
Steep cliffs + Offshore islets	0[a]	0.000	0.000	0.000	0.000	.	.	.
Oceanic habitat	-99.218	n/a	n/a	n/a	n/a	60.131	1	0.000
Shelf habitat	0[a]	n/a	n/a	n/a	n/a	.	.	.
Distance to Buldir	0.049		0.033	-0.016	0.113	2.208	1	0.137
Distance to source	3.242		0.368	2.520	3.963	77.498	1	0.000
Years since eradication	0.211		0.026	0.160	0.261	66.664	1	0.000
Island size	0.001		0.000	0.001	0.002	12.773	1	0.000
Song	0.037		0.009	0.019	0.055	16.034	1	0.000

[a] This parameter is set to 0 because it is redundant.

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