ESTIMATING SEABIRD ABUNDANCE:
A CASE STUDY IN KENAI FJORDS NATIONAL PARK, ALASKA

By

JENNIFER CURL, B.S., B.A.

A Thesis Submitted in Partial Fulfillment of the Requirements

For the Degree of

Master of Science

in

Wildlife Biology and Conservation

University of Alaska Fairbanks

May 2018

APPROVED:
Dr. Christa Mulder, Committee Chair
Dr. Joshua Schmidt, Committee Member
Dr. Mark Lindberg, Committee Member
Dr. Kris Hundertmark,
Chair, Department of Biology and Wildlife
Dr. Anupma Prakash,
Interim Dean, College of Natural Science and Mathematics
Dr. Michael Castellini,
Dean of the Graduate School

Abstract

Estimation of breeding seabird population size and trends are integral components of studies or programs seeking to understand how seabird populations respond to changes in marine or coastal environments, to identify threatened or declining species, and to inform management actions and decisions. In Chapter 1, I conduct a review of the challenges, considerations, tools, and methods involved in efforts to estimate and monitor breeding seabird abundance. I discuss challenges in terms of two broad categories: 1) seabird life history, behavior, and breeding environments, and 2) challenges inherent to survey methods and logistics. I introduce methods and tools used to access seabird colonies, detect birds, and design methods to collect and analyze count or abundance data.

The focus of Chapter 2 is to find effective methods to estimate the breeding abundance of glaucous-winged gulls (*Larus glaucescens*) in Kenai Fjords National Park (KEFJ), Alaska, which has been designated as an Important Bird Area (IBA) for this species. There are numerous inherent challenges in this effort, as *L. glaucescens* breeds in widespread colonies on vertical cliff faces of the fjords and associated islands, and their nests are not visually detectable from boat-based surveys. I conducted and compared field counts to replicated photographic counts, and found enough variability between replicates for both count methods to preclude calculation of precise abundance estimates using counts alone. I then developed a more intensive method of analyzing images using a modified mark-resight (MR) approach to identify all potential nest locations, and I took advantage of both attendance and behavioral data collected from repeat photographs to estimate what proportion of them have a high probability of containing nests. I quantified two potential survey error rates and their effects on the results of our modified MR approach. Finally, I considered temporal and environmental factors likely to affect both repeated counts and the results of my modified MR approach. I found that: 1) the modified MR approach provided a better approximation of breeding abundance than simple field counts and addressed variability between replicate surveys; 2) low misidentification survey error rates had a negligible effect on the results; and 3) general patterns of attendance of birds at colonies were influenced by different factors than the attendance patterns at locations that were likely nests. I recommend similar methods for other colonial or cliff-nesting bird species, species that have variable attendance, or species that make nests that are hard to see. These methods may also be helpful in areas that are remote or infrequently visited or where time in the field is a limiting factor in how much data can be collected.

Table of Contents

List of Figures

List of Tables

List of Appendices

Page

Acknowledgements

I would like to acknowledge and thank my committee members, Dr. Mark Lindberg and Dr. Joshua Schmidt for seeing me through a process that was longer than average. Special thanks to my advisor, Dr. Christa Mulder, for her patience at doing the impossible task of mentoring a student through a project that focused on an area outside of her expertise. I would also like to thank Dr. Ronald Barry for many hours, meetings, and scones along the way to finishing my analysis and becoming a generally more quantitative human. Thanks to the rest of the statistics department – Dr. Margaret Short, Dr. Julie McIntyre, and Dr. Scott Goddard for always making time to answer any questions I had along the way, and encouraging me to be a student of statistics, despite not being the most mathematically talented student to start. I would also like to thank Dr. Todd Brinkman, Dr. Michael Harris, Dr. Pat Doak, and Dr. Greg Breed for all of the advice and teaching opportunities I was afforded as a teaching assistant. Thank you to all of the staff at Kenai Fjords National Park, especially Laura Phillips, for helping me accomplish my fieldwork and making it possible to spend so much time in a breathtakingly beautiful, remote, and special place. Thank you also to Heather Renner at the Alaska National Maritime Wildlife Refuge for all the encouragement and understanding.

Finishing this degree would not have been possible without help from all of the funding sources, departments, and other supporting staff that exist in and around the University of Alaska Fairbanks that help move students along. I would like to especially thank Carol Piser, Pauline Thomas, Dr. Denise Kind, and Mat Ashby in the Department of Biology. I would also like to thank former graduate student coordinator Jessica Armstrong for the tea, advice, and help navigating deadlines, forms and all the other stuff. Thank you to the graduate school staff who took the time anytime I walked in to answer questions and offer invaluable assistance with

completing all of the forms and coursework requirements for both of my concurrent degrees. Thank you to Dr. Susan Sugai and Barb Harmeister at the UAF Center for Global Change for giving students the opportunity to write proposals, receive feedback, and compete for their own funding, and for doing it with kindness.

On a more personal note, I am a first generation graduate student, and was not aware of many of the challenges I would face along the way. Thank you to all of the graduate students who I have gotten to share the journey with. There are too many to name, but especially Megan Boldenow and Alexis Will (without whom I may not have finished), Natura Richardson, Kelly Sivy, Katie Rubin, Roy Churchwell, Jennifer Questel, Brian Robinson, Alyse Thurber, Stephany Jeffers, and Heather McFarland, you were all my adopted lab-mates. To my parents, the amount of unconditional support I get from you always takes me a little aback. And to my aunts and uncles who made time to root for me and watch my defense from afar, I could feel the love from thousands of miles away. Thank you to my adopted Smith family who feeds me and lets me in on family functions and projects; it is especially comforting to have family nearby. And to Justin, whose patience and endurance never cease to amaze me, I cannot wait to see what the two of us can do when we are not in school. I would not have made it through the toughest endeavor of my life without an infinite number of snuggles from Justin and our adventure pup Giroux, especially through the long, cold, dark days of winter.

Finally, there are always an abundance of people that make it possible to do academic work that never get thanked. To all of the people at UAF, the National Park Service, and all the other agencies and institutions that make it possible for students to grow and learn, we could not do it without all of your hard work. I am sending a large wave of gratitude to all of you.

Chapter 1. Challenges, methods, tools and considerations for monitoring seabird abundance

1.1 INTRODUCTION

Seabirds are sensitive to changes in the environment, both from natural stochasticity and from human activities such as commercial fishing (Tasker et al. 2000), invasive predators (Jones et al. 2008), contaminants (Burger and Gochfeld 2001), oil spills (Irons et al. 2000, Votier et al. 2005), habitat loss or shifts (Boersma et al. 2001; Hazen et al. 2013), and climate change (Gremillet and Boulinier 2009). As such, they are often studied as indicators of biological change such as the abundance and distribution of prey species, bioaccumulation of contaminants, and effects of climate-induced regime shifts in marine ecosystems (Cairns 1988, Burger and Gochfeld 2004, Piatt et al. 2007a, Einoder 2009); seabirds have also been shown to respond to climatic variability, such as patterns or changes in sea-surface temperature, ice conditions, and ocean-driven climate oscillations (Croxall et al. 2002, Jenouvrier et al. 2005; Ballance et al. 2006; Conroy et al. 2015). Responses of seabird populations to these effects vary widely by species, region, and other environmental factors (Schreiber 2001, Sandvik et al. 2005, Byrd et al. 2008).

Seabirds play an important role in marine and intertidal ecosystems as upper trophic level predators that consume a significant portion of marine lower trophic level productivity (Cairns 1988; Brooke 2004, Cury et al. 2011). They alter terrestrial environments through two mechanisms: 1) they transfer nutrients from marine systems to breeding areas on land (through dropping of food, shedding of feathers, deposition of guano, or when eggs, chicks or adults die on land), or 2) they physically disturb the ground due to nesting or burrowing efforts; both influence the structure of soil, plant and invertebrate communities, and coastal and island ecosystems (Polis and Hurd 1996, Ellis 2005, Smith et al. 2011). Seabirds are also of cultural importance for direct harvest of birds and eggs, and more recently as a draw for eco-tourism (Denlinger and Wohl 2001, Zador et al. 2006, Young et al. 2014). For these reasons, seabirds have been the focus of conservation efforts of many agencies and organizations, such as the National Oceanic and Atmospheric Administration (NOAA), the U.S. Fish and Wildlife Service (USFWS), Audubon, BirdLife International, and the Pacific Seabird Group (PSG).

Estimation of breeding seabird population size and detection of trends are integral components of studies or programs trying to discern the impacts of change on seabird population sizes, distinguish between short and long-term effects of change, and make management decisions, such as listing a species as threatened or endangered, removal of invasive predators, protection of habitat, or active restoration efforts (e.g., captive breeding or social attraction efforts) (Croxall et al. 2012). Estimating regional abundance is especially important given the potential for localized variation in environmental conditions, and because populations may respond differently even when exposed to the same conditions in a given region (Croxall et al. 2002, Frederiksen et al. 2004, Sandvik et al. 2005). Information gained from long-term studies of seabird population trends can have significant management implications, leading to decisions such as to eradicate invasive species, protect critical seabird habitat, or improve legislation or enforcement of existing protections (USFWS 2005, Mills et al. 2005, USFWS 2009, Croxall et al. 2012). However, given the variety of life history and behavioral differences between seabird species and the challenges specific to conducting surveys along remote and expansive coastlines, finding effective methods to accurately estimate abundance is not a simple task.

The objectives of this review are to: 1) introduce some of the challenges involved in detecting, counting and estimating the abundance of a variety of seabird species; 2) discuss what methods and approaches are currently available to deal with these challenges; and 3) introduce work conducted in Kenai Fjords National Park motivated by the need to find effective methods to estimate the abundance of marine bird species and respond to challenges inherent to the study/focal species, location, and scale of survey efforts.

1.2 CHALLENGES

Seabirds (members of the orders Sphenisciformes, Procellariiformes, Pelecaniformes, and Charadriiformes (Brooke 2001, Gaston 2004)), are so named because they spend the majority of their time living and foraging in marine ecosystems (Ainley 1980, Schreiber 2001), but nest in places generally accessible to researchers in comparison to most other marine species (Ainley 1980). At first glance, breeding seabirds appear easy to study: they congregate in large groups; individuals and their colonies are generally visible; they nest on land where they can be captured and marked; recapture is often feasible; they are long lived; and they often return, year after year, to the same colonies or breeding areas (Coulson 2001, Piatt et al. 2007b). However, there are a number of seabird behavioral characteristics that can make population monitoring a difficult task. In addition, there are a set of challenges associated with the logistics, costs, and scale of efforts to estimate abundance.

All breeding seabirds move between breeding grounds and marine foraging grounds. Because of this dichotomous lifestyle, seabird abundance can be considered in two distinct ways: 1) abundance of breeding individuals at nest sites or colonies (Walsh et al. 1995, Citta et al. 2007, AMNWR 2017), and 2) abundance of seabirds at sea (Tasker 1984, Ballance 2007, Gall et al. 2017). For this review, I focus on challenges of estimating abundance at breeding colonies, as the methods and issues associated with surveying birds at sea are distinct.

Seabirds are monomorphic, meaning that they are not easily distinguishable from each other without tags or marks of some kind (Kendall et al. 2009); birds do not have distinct enough markings to identify individuals, and males are not distinguishable from females (Gaston 2004). Thus, it can be particularly easy to double count or miss birds during counts. Moreover, seabirds are sensitive to disturbances from predators, humans (including researchers), other colony members (e.g. that are territorial or aggressive), noise, or environmental conditions (e.g. strong wind, rain, heat, etc.) and many species flush easily in large groups from nest sites, exacerbating the problem of knowing which individuals have been counted (Hutchinson 1980, Carney and Sydeman 1999, Parrish et al. 2001, Carey 2009).

Most seabirds aggregate in colonies during the breeding season, which means they gather and nest in large groups (Clode 1993, Coulson 2001), making most species easy to locate. Characteristics of coloniality – including colony size, colony location, access to prey, nesting habitat quality, inter-colony structure (or connectivity of multiple colonies across a region), colony composition (e.g. the proportion of breeders to non-breeders, or multiple species colonies), and whether a species exhibits breeding synchrony across a colony or region – can all influence the results of efforts to count or census seabirds.

Colonies have variable sizes, structures, densities, and general characteristics (Coulson 2001, Kildaw et al. 2005, Jovani et al. 2015). The range of many seabird species is geographically large and colonies can be of varying sizes, even when colonies are relatively close together (Ainley et al. 2003, Chilvers et al. 2015). A few seabird species are non-colonial, such as marbled (*Brachyramphus marmoratus*) and Kittlitz's (*Brachyramphus brevirostris)* murrelets; thus individual pairs have to be located in order to count, capture or otherwise monitor these species (De Santo and Nelson 1995). At the other end of the spectrum are species that nest in such large groups that they are difficult to census accurately even if they are easy to detect, such as large Northern gannet (*Morus bassanus*) colonies in the Atlantic (~50,000 individuals at some colonies, Wanless et al. 2005).

Seabirds nest in a variety of habitat types (Byrd et al. 2005, Smith et al. 2011); some nest on open ground (Barbraud and Gelinaud 2005, Jackson et al. 2005), some in crevices and burrows (Richardson 1961, Hunter et al. 1982, Piatt et al. 1990), some only on steep cliff faces and ledges (Lloyd 1975, Gaston et al. 2006), some in specialized locations such as high elevation scree or tundra, or the branches of old growth trees (De Santo and Nelson 1995). While it may be simple to identify a nest or colony location, it may not be possible to get a count that represents the true number of birds at a colony or across a region if nesting adults spend most of their time in a crevice or burrow (Jones 1992, Renner et al. 2011). In addition, many seabirds that nest on vertical cliff faces (on ledges, or in crevices or burrows) can also be difficult to observe from either the water or a vantage point on land because of perspective, rock features (i.e. contours, caves, or patches of vegetation hiding nests or birds), and cliff height (Walsh et al. 1995, Bibby 2000).

Breeding phenology of seabirds has a major influence on the appropriate timing for surveys of abundance. For most species, the most consistent attendance of breeding birds at nest sites occurs after eggs are laid, during the incubation period (Johnson and Krohn 2001, Hamer et al. 2001). Most seabirds are synchronous within colonies, but there are some species that exhibit some degree of asynchrony, or a gradient in timing of when transitions between phenological stages occur (Hamer et al. 2001, Murphy et al. 1984). For asynchronous species, abundance is particularly difficult to estimate because nests are constantly being added and lost at either end of the incubation period, in addition to nests lost to predation or disturbance, making underestimation of the total population size likely (Williams et al. 2011).

Attendance, or the total number of birds present at a colony, is often not limited to breeding pairs – colonies can house immature or juvenile birds, birds that have bred before but are not breeding in a given season (intermittent breeders), or birds that have attempted breeding but failed before chicks hatch and fledge (Klomp and Furness 1990, Calladine 1997, Henson et al. 2004, Crespin et al. 2006). The immature phase for seabird species can be multiple years in length, meaning it takes young birds a long time to be recruited into the breeding population, and immature individuals may intermix with breeding adults on colonies for many seasons before they mature. Seabirds are relatively long-lived and have fairly low fecundity coupled with high adult survival (Schreiber and Burger 2001, Gaston 2004). Mature adult seabirds can also forego breeding efforts in response to poor environmental or physical conditions, which can result in highly variable annual reproductive success, confounding efforts to determine trends in abundance without compiling more than a decade of yearly abundance estimates (Chastel et al. 1995, Erikstad et al 1998).

Many seabird species also show within-season and within-day variability in nest attendance (Klomp and Furness 1990, Piatt et al. 1990, Thayer et al. 1999, Harding et al. 2005). This varies by species and can be correlated with a number of factors, including photoperiod (Hatch and Hatch 1989), weather (Oswald et al. 2008), circadian rhythms (Huffeldt et al. 2016), predator avoidance (Keitt et al. 2004), foraging effort (Weimerskirch 1998), day within the season (Gaston et al. 2006), patterns in sun or moonlight (Rodriguez et al. 2016), or tidal height (Henson et al. 2004). Variability in birds attending a colony can exist because immature or intermittent breeders exhibit distinctly different behaviors than breeding birds, making it difficult to identify the general drivers of attendance patterns for a colony as a whole without distinguishing these groups from one another (Hatch and Hatch 1989, Klomp and Furness 1990, Henson et al. 2004).

Surveys of abundance also pose many logistical challenges. Seabirds often nest in locations that are isolated and remote, which has advantages both for foraging and predator avoidance, depending on the location and species (Hamer et al. 2001, Coulson 2001). Remote islands and coastlines can be difficult and expensive to get to, and require a disproportionate amount of resources to access colonies for relatively few surveys (Brooke 2001, Smith et al. 2011, Oppel et al. 2014). Additionally, severe marine weather and seas can be formidable barriers to conducting surveys that optimize ideal periods of the breeding season (Walsh et al. 1995, Citta et al. 2007, AMNWR 2017).

The scale of surveys is often dependent upon the structure of colonies: how far apart, how large, how many, the geographic range, and the inter-colony connectivity or exhibiting a metapopulation structure (Coulson 2001, Ainley et al. 2003, Oro 2003, Jones et al. 2011). Seabird colonies have varied structures across landscapes. Trade-offs exists between the scale of survey efforts and the density of information that can be collected at any one colony, which often determines which colonies are monitored and how intensively (Bibby 2000, Mills et al. 2005, USFWS 2009). Surveys often fall into one of two categories: large-scale infrequent one-time surveys or censuses (Angehr and Kushlan 2007), or smaller scale or local surveys at a single colony or colony complex that are intensive and often involve collecting information in addition to count data (Thayer et al. 1999, Cannell et al. 2011). The latter also allows for more intensive efforts to monitor population parameters beyond just general abundance (e.g. productivity, adult survival, diet, physiological or morphometric data), but may miss large patterns in abundance over time that occur beyond the local scale (Jones et al. 2011).

1.3 METHODS AND TOOLS

The challenges outlined in Part 1 often shape what kind of counting and analytical methods are applicable in what places, at what scales, and for which species. In addition, specific challenges are posed by what logistics and resources are available. These include how difficult it is to get to colonies, what environmental conditions are like (weather or sea state), how far apart colonies are, and the scale of efforts, which is usually defined by either: 1) the mission of an agency, organization or project and what resources are limiting (whether it be financial, staff, equipment, or time), or 2) a specific area defined by ecological boundaries (e.g. an island, archipelago, or species range).

1.3.1 Access to colonies

Surveys are often determined by how colonies are accessed (Hutchinson 1980, Barber-Meyer et al. 2007, Barbraud et al. 2014, McClelland et al. 2016). Colony access can be from the ground (including by foot, by trails or roads, and from either above or below colonies located on cliffs (Oppel et al. 2014)), from boats (Kildaw et al. 2005), by air (Johnson and Krohn 2001), or some combination of the three (Chilvers et al. 2015). One factor driving what technique is used is the type of nesting surface used by each species of interest; whether they nest on flat or mostly horizontal surfaces such as low lying atolls in the Hawaiian archipelago (Citta et al. 2007), on steep cliffs as on Arctic coastlines (Gaston et al. 2006), or some of both as in islands in the south of New Zealand (Chilvers et al. 2015). Nesting surface is particularly important in determining from what perspective birds and nests are the most visible and detectable to researchers. Another factor that interacts with how colonies are accessed is the scale that survey efforts target to cover, and the cost of each mode of access.

Surveys on foot or by road are possible when a colony or colonies are within a small area, especially when research is conducted on a single small island (Vermeer 1963; Hunter et al. 1982; Thayer et al. 1999; Saenz et al. 2006; Slater and Byrd 2009). However, when colonies are farther apart, on remote islands, on rugged or inaccessible coastlines, located across large regions, or when birds are particularly sensitive to disturbance, access may be best accomplished by boat or aerial vehicle (i.e. plane, helicopter or UAV (unmanned aerial vehicle)) (Bailey 1977; Byrd et al. 2005; Gilchrist and Mallory 2005; McClelland et al. 2016). Many studies have also employed multiple methods of access to colonies (i.e. both boat-based and aerial surveys, or both ground and aerial surveys) to maximize data collection efforts, to test and compare a variety of survey methods, or to minimize investigator disturbance (Hutchinson 1980, Carey 2009, Chilvers et al. 2015).

1.3.2 Detections

Seabirds are detected visually, aurally, or sometimes through touch or smell of nesting spaces to test if nest burrows or crevices are occupied. Technology, especially in digital recordings of images or sounds, has rapidly developed over the past several decades (Burger and Schaffer 2008, Groom et al. 2013, Borker et al. 2014). Spotting scopes, binoculars, and cameras are all tools that assist in visually detecting birds or nests from a distance, and detections with the naked eye are not usually possible unless observers are walking through a colony. Observer counts are among the most common surveys for breeding seabird abundance (Walsh et al. 1995, Bibby 2000, Sutherland 2004, AMNWR 2017). Large colonies can take a great deal of time to survey, and devices that allow magnification of birds far away are helpful in allowing a wider area to be considered for choosing an ideal observation point, thus making surveys less intrusive or disruptive to nesting birds (Walsh et al. 1995, Bibby 2000, Sutherland et al. 2004).

Cameras can aid in visual detections, especially with the advances and prevalence of high resolution digital imagery. Images create a permanent record of observations that can be analyzed out of the field, when researchers are in a comfortable and stable environment (Hutchinson 1980). Imagery is improving with digital advances, and continuously used in new ways to aid with surveys of abundance or occupancy, such as burrow cameras (Markwell 1997), time lapse functions (Huffeldt and Merkel 2013), radar (Major 2016), infrared cameras (Hamilton et al. 1998) and high resolution videography (Thaxton and Burton 2009). Collecting images has also made the use of aerial vehicles to access colonies more practical – it is far easier and more efficient to take high quality images and cover large areas from a plane or helicopter than it is to physically count and record birds (Dolbeer et al. 1997, Johnson and Krohn 2001, Naughton et al. 2007, Groom et al. 2013). In addition, researchers are using cameras on unmanned or remotely operated aerial vehicles, such as satellites, kites and drones with increasing frequency (Egevang et al. 2003, Barber-Meyer et al. 2007, Ratcliffe et al. 2015, Delord et al. 2015, McClelland et al. 2016).

Aural detections have long been used to locate seabirds that either nest in crevices or burrows, or that are nocturnal and attend nests at night (Monteiro et al. 1999, Keitt et al. 2005). Recently, the development of passive, weather-proof digital recorders and new software has resulted in easier analysis of spectrograms, the physical image created by recording aural detections, to estimate the relative abundance of seabirds (individuals are not generally distinguishable, but large scale changes in call frequency or intensity can indicate changes in abundance), especially in monitoring the recovery of colonies after the removal of invasive predators (Buxton and Jones 2012, Buxton et al. 2013, Borker et al. 2014, Oppel et al. 2014). Passive acoustic recording is especially useful for far flung colonies where consistent, intensive surveys may not be an option, where species take a tremendous amount of effort to detect visually, or for species that are rare or sensitive to disturbance (Shonfield and Bayne 2017).

1.3.3 Sampling and analytical methods

Counting birds seems intuitively simple. However, there are a surprising number of ways to count seabirds at a colony (Bibby 2000). Entities that can be counted include: nests, nest starts, burrows/crevices/ledges that have signs of occupancy, eggs, hatches, chicks, fledges, immature birds, non-breeding birds, breeding birds, adults, flocks of birds that flush from colonies, and birds on land, on the water, or flying. In addition, density can be derived if colony area is known, but can be variable within colonies for many species (Walsh et al. 1995). Methods for counting seabirds vary by species, scale, and resources (Walsh et al. 1995, Bibby 2000, Sutherland et al. 2004, Citta et al. 2007, Naughton et al. 2007, AMNWR 2017). Below I outline types of study design, analytical methods, tools and factors to consider when estimating seabird abundance.

Surveys for breeding seabird abundance fall into one of two groups. The first is a one-time effort to census every bird or nest within a colony, set of colonies, or region (Bailey 1977, Mitchell et al. 2004). Censuses are often of priority in areas that are not visited or studied consistently or often (Barbraud et al. 1999, Simeone et al. 2003, Robertson et al. 2008), or where smaller sub-populations are more intensively monitored. All other types of surveys involve sampling, where some portion of the total population is counted either as a representative sample of the total colony, or as subunits used to extrapolate to abundance or density for the whole colony (Walsh et al. 1995).

Sampling can take many forms. Colonies can be subdivided into countable areas, including quadrats, plots, or transects. Quadrats, plots, or transects are generally chosen with the overall goal of including an area that is representative of the entire colony (Walsh et al. 1995, Byrd et al. 2008, Barbraud et al. 2014). Further sampling considerations include the number of plots/transects/quadrats; their size and what proportion of the colony they make up; the positions, angles, and mode of access that counts are made from; observer effects (their level of experience and familiarity, and if they remain consistent across surveys and years); and perhaps most importantly, how colonies and quadrats/plots/transects are selected, which should include some element of randomness (Walsh et al. 1995, Williams et al. 2002, Thompson 2002). Moreover, in large networks of colonies, randomness should be considered at a second level from which colonies are selected. Simple random sampling is often described as the most unbiased way to sample the population of interest (Thompson 2002). However, seabird colonies are effectively clusters (meaning they are not spread equally over space but grouped in distinct areas) that have varying densities and edges; colonies can also both expand and contract over time, which makes simple random sampling difficult. Some kind of stratified random sampling is often a suitable alternative, as it still incorporates randomness by choosing samples in predefined categories of colony area (i.e. x number of plots on edges, y number of plots in high density areas, z number in low density areas) (Walsh et al. 1995).

Analytical or statistical approaches are shaped by design and sampling methods. Repeated counts can be analyzed using basic summary statistics, such as the mean or maximum of a series of counts within a plot or colony, with an associated calculation of some measure of variability across the replicates (e.g. standard deviation or variance) (Thompson 2002). Statistical approaches, such as distance sampling, double observer methods, and capture-mark-recapture or mark-resight methods (and their many extensions) (Nichols et al. 2000, Mackenzie et al. 2002, Barbraud et al. 2005), are all used to estimate a total abundance when it is impractical to count all individuals, and have the added benefit of producing an estimate of detection probability, or how often a bird or nest is detected when it is present (or the converse, how often a bird present is missed). Finally, improved computing capacities have made all kinds of statistical estimation more feasible and efficient, including maximum likelihood estimation, numerical integration methods, and Bayesian analyses that incorporate prior distributions and rely on sampling algorithms that use hundreds of thousands of iterations (White et al. 2017, Dey et al. 2017, Liu et al. 2017).

The combinations of factors that affect access, issues of detection and an array of possible statistical analyses have translated to a diversity of individualized approaches to wildlife population abundance estimation (e.g. Williams et al. 2002, Thompson 2002, Lancia et al. 2005, Gaston et al. 2012, Chambert et al. 2012, Sutherland and Dann 2012). While there are some unifying characteristics and considerations in ways to go about estimating seabird abundance, most often, individualized methods need to be developed for each unique project, species, region, or monitoring objective.

1.4 CHALLENGES: A CASE STUDY

Every effort to estimate seabird abundance has a unique set of challenges. Below, I describe difficulties in determining the breeding population size of glaucous-winged gulls (*Larus* *glaucescens*) in Kenai Fjords National Park (KEFJ), and in Ch. 2 our approach to working towards effective survey and analytical methods to address them.

L. glaucescens colonies are most often found on horizontal surfaces throughout much of their breeding range, but in Kenai Fjords, they prefer to nest on large, remote, vertical cliff faces that are difficult to access. The region is made up of small to medium colonies spread across the expanse of the coastline of the park. Colonies require access by boat or air as Kenai Fjords is mostly wilderness with few trails, and the boundary of the park stretches 700 km along the coast of steep and rugged fjords. Weather is generally unpredictable and the ability to fly and boat is often hampered by strong winds, high seas, low clouds and rain, or all of the above.

Added on to the challenging terrain, weather, and access to colonies, *L. glaucescens* adults construct nests that are difficult to visually detect, especially from a boat positioned below colonies. Even in some aerial photos, birds are far more visible than nests, which are small scrapes lined with a bit of vegetation that sometimes are easy to miss even when walking right on top of one. We tested different methods of counting, and used repeat photographs and a modified mark-resight (MR) approach to analyze potential nest sites in order to work towards determining the abundance of birds that are breeding at colonies. In addition, we investigate how temporal and environmental variables affected the count methods we compared, in order to better understand how to adjust survey methods in the future, and work towards the goal of effective monitoring of *L. glaucescens* abundance in the region.

1.5 LITERATURE CITED

Ainley, D. G. (1980). Birds as marine organisms: a review. CalCOFI Rep 21:48-53.

Ainley, D. G., R. G. Ford, E. D. Brown, R. M. Suryan, and D. B. Irons (2003). Prey resources, competition, and geographic structure of kittiwake colonies in Prince William Sound. Ecology 84:709-723.

Alaska Maritime National Wildlife Refuge (2017). Stardardized protocols for annual seabird monitoring camps at Aiktak, Buldir, Chowiet, St. George, St. Lazaria, and St. Paul islands, Cape Lisburne, and select intermittent sites in the Alaska Maritime National Wildlife Refuge in 2017. U.S. Fish and Wildlife Service Report, Homer, AK, USA. AMNWR 2017/07.

Angehr, G. R., and J. A. Kushlan (2007). Seabird and colonial wading bird nesting in the Gulf of Panamá. Waterbirds 30:335-357.

Bailey, E. P. (1977). Distribution and abundance of marine birds and mammals along the south side of the Kenai Peninsula, Alaska. The Murrelet 58:58-72.

Ballance, L. T., R. L. Pitman, and P. C. Fiedler (2006). Oceanographic influences on seabirds and cetaceans of the eastern tropical Pacific: a review. Progress in Oceanography 69:360-390.

Ballance, L. T. (2007). Understanding seabirds at sea: why and how. Marine Ornithology 35:127-135.

Barber-Meyer, S. M., G. L. Kooyman, and P. J. Ponganis (2007). Estimating the relative abundance of emperor penguins at inaccessible colonies using satellite imagery. Polar Biology 30:1565-1570.

Barbraud, C., K. Delord, T. Micol, and P. Jouventin (1999). First census of breeding seabirds between Cap Bienvenue (Terre Adélie) and Moyes Islands (King George V Land), Antarctica: new records for Antarctic seabird populations. Polar Biology 21:146-150.

Barbraud, C., and G. Gélinaud (2005). Estimating the sizes of large gull colonies taking into account nest detection probability. Waterbirds 28:53-60.

Barbraud, C., M. Fortin, Y. Charbonnier, K. Delord, H. Gadennne, J.-B. Thiebot, and G. Gélinaud (2014). A comparison of direct and distance sampling methods to estimate abundance of nesting gulls. Ardeola 61:367-377.

Bibby, C. J. (2000). Bird census techniques. Elsevier, London, UK.

Boersma, P. D., J. A. Clark, and N. Hillgarth (2001). Seabird conservation. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Borker, A. L., M. W. McKown, J. T. Ackerman, C. A. Eagles-Smith, B. R. Tershy, and D. A. Croll (2014). Vocal activity as a low cost and scalable index of seabird colony size. Conservation Biology 28:1100-1108.

Brooke, M. d. L. (2001). Seabird systematics and distribution: a review of current knowledge. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Brooke, M. d. L. (2004). The food consumption of the world's seabirds. Proceedings of the Royal Society of London B: Biological Sciences 271:S246-S248.

Burger, J., and M. Gochfeld (2001). Effects of chemicals and pollution on seabirds. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Burger, J., and M. Gochfeld (2004). Marine birds as sentinels of environmental pollution. EcoHealth 1:263-274.

Burger, A. E., and S. A. Shaffer (2008). Perspectives in ornithology application of tracking and data-logging technology in research and conservation of seabirds. The Auk 125:253-264.

Buxton, R. T., and I. L. Jones (2012). Measuring nocturnal seabird activity and status using acoustic recording devices: applications for island restoration. Journal of Field Ornithology 83:47-60.

Buxton, R. T., H. L. Major, I. L. Jones, and J. C. Williams (2013). Examining patterns in nocturnal seabird activity and recovery across the Western Aleutian Islands, Alaska, using automated acoustic recording. The Auk 130:331-341.

Byrd, V. G., H. M. Renner, and M. Renner (2005). Distribution patterns and population trends of breeding seabirds in the Aleutian Islands. Fisheries Oceanography 14:139-159.

Byrd, G. V., J. A. Schmutz, and H. M. Renner (2008). Contrasting population trends of piscivorous seabirds in the Pribilof Islands: a 30-year perspective. Deep Sea Research Part II: Topical Studies in Oceanography 55:1846-1855.

Cairns, D. (1988). Seabirds as indicators of marine food supplies. Biological Oceanography 5:261-271.

Calladine, J., and M. Harris (1997). Intermittent breeding in the herring gull (*Larus argentatus*) and the lesser black-backed gull (*Larus fuscus*). Ibis 139:259-263.

Cannell, B., K. Pollock, S. Bradley, R. Wooller, W. Sherwin, and J. Sinclair (2011). Augmenting mark–recapture with beach counts to estimate the abundance of little penguins on Penguin Island, Western Australia. Wildlife Research 38:491-500.

Carey, M. J. (2009). The effects of investigator disturbance on procellariiform seabirds: a review. New Zealand Journal of Zoology 36:367-377.

Carney, K. M., and W. J. Sydeman (1999). A review of human disturbance effects on nesting colonial waterbirds. Waterbirds 22:68-79.

Chambert, T., D. Pardo, R. Choquet, V. Staszewski, K. D. McCoy, T. Tveraa, and T. Boulinier (2012). Heterogeneity in detection probability along the breeding season in black-legged kittiwakes: implications for sampling design. Journal of Ornithology 152:371-380.

Chastel, O., H. Weimerskirch, and P. Jouventin (1995). Body condition and seabird reproductive performance: a study of three petrel species. Ecology 76:2240-2246.

Chilvers, B., G. Baker, J. Hiscock, P. McClelland, M. Holdsworth, and K. Jensz (2015). Comparison of breeding population survey methods for the Auckland Island shag (*Phalacrocorax colensoi*). Polar Biology 38:1847-1852.

Citta, J., M. H. Reynolds, and N. E. Seavey (2007). Seabird monitoring assessment for Hawaii and the Pacific Islands. Hawai`i Cooperative Studies Unit Technical Report. HSCU-007. University of Hawai`i at Hilo, Hilo, HI, USA.

Clode, D. (1993). Colonially breeding seabirds: Predators or prey? Trends in Ecology & Evolution 8:336-338.

Conroy, J. L., A. F. Collins, J. T. Overpeck, M. B. Bush, J. E. Cole, and D. J. Anderson (2015). A 400-year isotopic record of seabird response to eastern tropical Pacific productivity. Geo: Geography and Environment 2:137-147.

Coulson, J. C. (2001). Colonial breeding in seabirds. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Crespin, L., M. P. Harris, J. D. Lebreton, M. Frederiksen, and S. Wanless (2006). Recruitment to a seabird population depends on environmental factors and on population size. Journal of Animal Ecology 75:228-238.

Croxall, J. P., P. Trathan, and E. Murphy (2002). Environmental change and Antarctic seabird populations. Science 297:1510-1514.

Croxall, J. P., S. H. Butchart, B. Lascelles, A. J. Stattersfield, B. Sullivan, A. Symes, and P. Taylor (2012). Seabird conservation status, threats and priority actions: a global assessment. Bird Conservation International 22:1-34.

Cury, P. M., I. L. Boyd, S. Bonhommeau, T. Anker-Nilssen, R. J. Crawford, R. W. Furness, J. A. Mills, E. J. Murphy, H. Österblom, and M. Paleczny (2011). Global seabird response to forage fish depletion—one-third for the birds. Science 334:1703-1706.

De Santo, T. L., and S. K. Nelson (1995). Comparative reproductive ecology of the auks (Family Alcidae) with emphasis on the Marbled Murrelet. In The ecology and conservation of the Marbled Murrelet in North America: an interagency scientific evaluation (C. J. Ralph, G. L. Hunt, Jr., M. G. Raphael, and J. F. Piatt, Editors). United States Department Agriculture Forest Service General Technical Report PSW-GTR-152.

Delord, K., G. Roudaut, C. Guinet, C. Barbraud, S. Bertrand, and H. Weimerskirch (2015). Kite aerial photography: a low-cost method for monitoring seabird colonies. Journal of Field Ornithology 86:173-179.

Denlinger, L., and K. Wohl (2001). Seabird harvest regimes in the circumpolar nations. Conservation of Arctic Flora and Fauna (CAFF). Conservation of Arctic Flora and Fauna (CAFF) Technical Report No. 9. CAFF International Secretariat, Circumpolar Seabird Working Group (CSWG), Akureyri, Iceland.

Dey, S., M. Delampady, R. Parameshwaran, N. S. Kumar, A. Srivathsa, and K. U. Karanth (2017). Bayesian methods for estimating animal abundance at large spatial scales using data from multiple sources. Journal of Agricultural, Biological and Environmental Statistics, 22:111-139.

Dolbeer, R. A., J. L. Belant, and G. E. Bernhardt (1997). Aerial photography techniques to estimate populations of laughing gull nests in Jamaica Bay, New York, 1992-1995. Colonial Waterbirds 20:8-13.

Egevang, C., D. Boertmann, A. Mosbech, and M. P. Tamstorf (2003). Estimating colony area and population size of little auks (*Alle alle*) at Northumberland Island using aerial images. Polar Biology 26:8-13.

Einoder, L. D. (2009). A review of the use of seabirds as indicators in fisheries and ecosystem management. Fisheries Research 95:6-13.

Ellis, J. C. (2005). Marine birds on land: a review of plant biomass, species richness, and community composition in seabird colonies. Plant Ecology 181:227-241.

Erikstad, K. E., P. Fauchald, T. Tveraa, and H. Steen (1998). On the cost of reproduction in long-lived birds: the influence of environmental variability. Ecology 79:1781-1788.

Frederiksen, M., M. P. Harris, F. Daunt, P. Rothery, and S. Wanless (2004). Scale-dependent climate signals drive breeding phenology of three seabird species. Global Change Biology 10:1214-1221.

Gall, A. E., T. C. Morgan, R. H. Day, and K. J. Kuletz (2017). Ecological shift from piscivorous to planktivorous seabirds in the Chukchi Sea, 1975–2012. Polar Biology 40:61-78.

Gaston, A. J. (2004). Seabirds: a natural history. Yale University Press, New Haven, CT, USA.

Gaston, A. J., M. L. Mallory, H. G. Gilchrist, and K. O'Donovan (2006). Status, trends and attendance patterns of the Northern Fulmar (*Fulmarus glacialis*) in Nunavut, Canada. Arctic 59:165-178.

Gaston, A. J., M. L. Mallory, and H. G. Gilchrist (2012). Populations and trends of Canadian Arctic seabirds. Polar Biology 35:1221-1232.

Gilchrist, H. G., and M. L. Mallory (2005). Declines in abundance and distribution of the ivory gull (*Pagophila eburnea*) in Arctic Canada. Biological Conservation 121:303-309.

Grémillet, D., and T. Boulinier (2009). Spatial ecology and conservation of seabirds facing global climate change: a review. Marine Ecology Progress Series 391:121-137.

Groom, G., M. Stjernholm, R. D. Nielsen, A. Fleetwood, and I. K. Petersen (2013). Remote sensing image data and automated analysis to describe marine bird distributions and abundances. Ecological Informatics 14:2-8.

Hamer, K. C., E. Schreiber, and J. Burger (2002). Breeding biology, life histories, and life history-environment interactions in seabirds. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Hamilton, S., J. de Cruz, C. Hunter, H. Moller, and D. Fletcher (1998). An infrared scope for assessing sooty shearwater burrow occupancy. Conservation Advisory Science Notes No 187. Department of Conservation, Wellington, New Zealand.

Harding, A., J. Piatt, G. Byrd, S. A. Hatch, N. Konyukhov, E. Golubova, and J. Williams (2005). Variability in colony attendance of crevice-nesting horned puffins: implications for population monitoring. Journal of Wildlife Management 69:1279-1296.

Hatch, S. A., and M. A. Hatch (1989). Attendance patterns of murres at breeding sites: implications for monitoring. The Journal of Wildlife Management 53:483-493.

Hazen, E. L., S. Jorgensen, R. R. Rykaczewski, S. J. Bograd, D. G. Foley, I. D. Jonsen, S. A. Shaffer, J. P. Dunne, D. P. Costa, and L. B. Crowder (2013). Predicted habitat shifts of Pacific top predators in a changing climate. Nature Climate Change 3:234-238.

Henson, S. M., J. L. Hayward, C. M. Burden, C. J. Logan, and J. G. Galusha (2004). Predicting dynamics of aggregate loafing behavior in glaucous-winged gulls (*Larus glaucescens*) at a Washington colony. The Auk 121:380-390.

Huffeldt, N. P., and F. R. Merkel (2013). Remote time-lapse photography as a monitoring tool for colonial breeding seabirds: a case study using thick-billed murres (*Uria lomvia*). Waterbirds 36:330-341.

Huffeldt, N. P., and F. R. Merkel (2016). Sex-specific, inverted rhythms of breeding-site attendance in an Arctic seabird. Biology Letters 12: 20160289.

Hunter, I., J. Croxall, and P. Prince (1982). The distribution and abundance of burrowing seabirds at Bird Island, South Georgia: introduction and methods. BAS Bulletins 56:49-67.

Hutchinson, A. E. (1980). Estimating numbers of colonial nesting seabirds: a comparison of techniques. Proceedings of the Colonial Waterbird Group 3:235-244.

Irons, D. B., S. J. Kendall, W. P. Erickson, L. L. McDonald, and B. K. Lance (2000). Nine years after the Exxon Valdez oil spill: effects on marine bird populations in Prince William Sound, Alaska. The Condor 102:723-737.

Jackson, A. L., S. Bearhop, and D. R. Thompson (2005). Shape can influence the rate of colony fragmentation in ground nesting seabirds. Oikos 111:473-478.

Jenouvrier, S., C. Barbraud, B. Cazelles, and H. Weimerskirch (2005). Modelling population dynamics of seabirds: importance of the effects of climate fluctuations on breeding proportions. Oikos 108:511-522.

Johnson, C. M., and W. B. Krohn (2001). The importance of survey timing in monitoring breeding seabird numbers. Waterbirds 24:22-33.

Jones, H. P., B. R. Tershy, E. S. Zavaleta, D. A. Croll, B. S. Keitt, M. E. Finkelstein, and G. R. Howald (2008). Severity of the effects of invasive rats on seabirds: a global review. Conservation Biology 22:16-26.

Jones, J. P. (2011). Monitoring species abundance and distribution at the landscape scale. Journal of Applied Ecology 48: 9-13.

Jones, I. L. (1992). Colony attendance of Least Auklets at St. Paul Island, Alaska: implications for population monitoring. Condor 94:93-100.

Jovani, R., B. Lascelles, L. Z. Garamszegi, R. Mavor, C. B. Thaxter, and D. Oro (2015). Colony size and foraging range in seabirds. Oikos 125:968-974.

Keitt, B. S., B. R. Tershy, and D. A. Croll (2004). Nocturnal behavior reduces predation pressure on black-vented shearwaters (*Puffinus opisthomelas*). Marine Ornithology 32:173-178.

Keitt, B. S. (2005). Status of Xantus's Murrelet and its nesting habitat in Baja California, Mexico. Marine Ornithology 33:105-114.

Kendall, W. L., S. J. Converse, P. F. Doherty, M. B. Naughton, A. Anders, J. E. Hines, and E. Flint (2009). Sampling design considerations for demographic studies: a case of colonial seabirds. Ecological Applications 19:55-68.

Kildaw, D. S., D. B. Irons, D. R. Nysewander, and L. C. Buck (2005). Formation and growth of new seabird colonies: the significance of habitat quality. Marine Ornithology 33:49-58.

Klomp, N., and R. Furness (1990). Variations in numbers of nonbreeding great skuas attending a colony. Ornis Scandinavica 94:270-276.

Lancia, R. A., W. L. Kendall, K. H. Pollock, and J. D. Nichols (2005). Estimating the number of animals in wildlife populations. In Techniques for Wildlife Investigations and Management (C. E. Braun, Editor). Wildlife Society, Patuxtent Wildlife Research Center, Bethesda, MD, USA.

Liu, Y., P. Li, and J. Qin (2017). Maximum empirical likelihood estimation for abundance in a closed population from capture-recapture data. Biometrika 104:527-543.

Lloyd, C. (1975). Timing and frequency of census counts of cliff-nesting auks. Br. Birds 68:507-513.

MacKenzie, D. I., J. D. Nichols, G. B. Lachman, S. Droege, J. Andrew Royle, and C. A. Langtimm (2002). Estimating site occupancy rates when detection probabilities are less than one. Ecology 83:2248-2255.

Major, H. L. (2016). Ancient Murrelet (*Synthliboramphus antiquus)* colony attendance at Langara Island assessed using observer counts and radar in relation to time and environmental conditions. Marine Ornithology 44:233-240.

Markwell, T. (1997). Video camera count of burrow-dwelling fairy prions, sooty shearwaters, and tuatara on Takapourewa (Stephens Island), New Zealand. New Zealand Journal of Zoology 24:231-237.

McClelland, G. T., A. L. Bond, A. Sardana, and T. Glass (2016). Rapid population estimate of a surface-nesting seabird on a remote island using a low-cost unmanned aerial vehicle. Marine Ornithology 44:215-220.

Mills, K. L., M. Naughton, and G. Elliott (2005). Seabird Conservation Planning in the Pacific Region. USDA Forest Service Gen. Tech. Rep. PSW-GTR-191.

Mitchell, P. I., S. F. Newton, N. Ratcliffe, and T. E. Dunn (2004). Seabird populations of Britain and Ireland: results of the seabird 2000 census. T & AD Poyser, London, UK.

Monteiro, L., J. Ramos, J. Pereira, P. Monteiro, R. Feio, D. Thompson, S. Bearhop, R. Furness, M. Laranjo, and G. Hilton (1999). Status and distribution of Fea's petrel, Bulwer's petrel, manx shearwater, little shearwater and band-rumped storm-petrel in the Azores Archipelago. Waterbirds 22:358-366.

Murphy, E. C., R. H. Day, K. L. Oakley, and A. A. Hoover (1984). Dietary changes and poor reproductive performance in Glaucous-winged Gulls. The Auk 101:532-541.

Naughton, M. B., D. S. Pitkin, R. W. Lowe, K. J. So, and C. S. Strong (2007). Catalog of Oregon Seabird Colonies. U.S. Department of the Interior, Fish and Wildlife Service, Washington D.C., USA. FWS/BTP-R1009-2007.

Nichols, J. D., J. E. Hines, J. R. Sauer, F. W. Fallon, J. E. Fallon, and P. J. Heglund (2000). A double-observer approach for estimating detection probability and abundance from point counts. The Auk 117:393-408.

Oppel, S., S. Hervias, N. Oliveira, T. Pipa, C. Silva, P. Geraldes, M. Goh, E. Immler, and M. McKown (2014). Estimating population size of a nocturnal burrow-nesting seabird using acoustic monitoring and habitat mapping. Nature Conservation 7:1-13.

Oro, D. (2003). Managing seabird metapopulations in the Mediterranean: constraints and challenges. Scientia Marina 67:13-22.

Oswald, S. A., S. Bearhop, R. W. Furness, B. Huntley, and K. C. Hamer (2008). Heat stress in a high-latitude seabird: effects of temperature and food supply on bathing and nest attendance of great skuas (*Catharacta skua)*. Journal of Avian Biology 39:163-169.

Parrish, J. K., M. Marvier, and R. T. Paine (2001). Direct and indirect effects: interactions between bald eagles and common murres. Ecological Applications 11:1858-1869.

Piatt, J. F., B. D. Roberts, and S. A. Hatch (1990). Colony attendance and population monitoring of least and crested auklets on St. Lawrence Island, Alaska. Condor 92:97-106.

Piatt, J. F., A. M. Harding, M. Shultz, S. G. Speckman, T. I. Van Pelt, G. S. Drew, and A. B. Kettle (2007a). Seabirds as indicators of marine food supplies: Cairns revisited. Marine Ecology Progress Series 352:221-234.

Piatt, J. F., W. J. Sydeman, and F. Wiese (2007b). Introduction: a modern role for seabirds as indicators. Marine Ecology Progress Series 352:199-204.

Polis, G. A., and S. D. Hurd (1996). Linking marine and terrestrial food webs: allochthonous input from the ocean supports high secondary productivity on small islands and coastal land communities. The American Naturalist 147:396-423.

Ratcliffe, N., D. Guihen, J. Robst, S. Crofts, A. Stanworth, and P. Enderlein (2015). A protocol for the aerial survey of penguin colonies using UAVs. Journal of Unmanned Vehicle Systems 3:95-101.

Renner, H. M., J. H. Reynolds, M. Sims, and M. Renner (2011). Evaluating the power of surface attendance counts to detect long-term trends in populations of crevice-nesting auklets. Environmental Monitoring and Assessment 177:665-679.

Richardson, F. (1961). Breeding biology of the rhinoceros auklet on Protection Island, Washington. The Condor 63:456-473.

Robertson, G., C. A. Moreno, K. Lawton, R. Kirkwood, and J. Valencia (2008). Comparison of census methods for black-browed albatrosses breeding at the Ildefonso Archipelago, Chile. Polar Biology 31:153-162.

Rodríguez, A., A. Chiaradia, P. Wasiak, L. Renwick, and P. Dann (2016). Waddling on the dark side: ambient light affects attendance behavior of little penguins. Journal of Biological Rhythms 31:194-204.

Saenz, B. L., J. A. Thayer, W. J. Sydeman, and D. A. Hatch (2006). An urban success story: breeding seabirds on Alcatraz Island, California, 1990–2002. Marine Ornithology 34:43-49.

Sandvik, H., K. E. Erikstad, R. T. Barrett, and N. G. Yoccoz (2005). The effect of climate on adult survival in five species of North Atlantic seabirds. Journal of Animal Ecology 74:817-831.

Schreiber, E. (2001). Climate and weather effects on seabirds. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Schreiber, E. and J. Burger (2001). Seabirds in the Marine Environment. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Shonfield, J., and E. Bayne (2017). Autonomous recording units in avian ecological research: current use and future applications. Avian Conservation and Ecology 12:14.

Simeone, A., G. Luna-Jorquera, M. Bernal, S. Garthe, F. Sepúlveda, R. Villablanca, U. Ellenberg, M. Contreras, J. Muñoz, and T. Ponce (2003). Breeding distribution and abundance of seabirds on islands off north-central Chile. Revista Chilena de Historia Natural 76:323-333.

Slater, L., and G. V. Byrd (2009). Status, trends, and patterns of covariation of breeding seabirds at St Lazaria Island, Southeast Alaska, 1994–2006. Journal of Biogeography 36:465-475.

Smith, J., C. Mulder, and J. Ellis (2011). Seabirds as ecosystem engineers: nutrient inputs and physical disturbance. In Seabird islands. Ecology, invasion and restoration (C. P. H. Mulder, W. B. Anderson, D. R. Towns, and P. J. Bellingham, Editors). Oxford University Press, New York, NY, USA.

Sutherland, W. J., I. Newton, and R. Green (2004). Bird ecology and conservation: a handbook of techniques. Oxford University Press, New York, NY, USA.

Sutherland, D. R., and P. Dann (2012). Improving the accuracy of population size estimates for burrow-nesting seabirds. Ibis 154:488-498.

Tasker, M. L., P. H. Jones, T. Dixon, and B. F. Blake (1984). Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardized approach. The Auk 101:567-577.

Tasker, M. L., C. Camphuysen, J. Cooper, S. Garthe, W. A. Montevecchi, and S. J. Blaber (2000). The impacts of fishing on marine birds. ICES Journal of Marine Science 57:531-

547.

Thaxter, C. B., and N. H. Burton (2009). High definition imagery for surveying seabirds and marine mammals: a review of recent trials and development of protocols. British Trust for Ornithology Report Commissioned by Cowrie Ltd., London, UK.

Thayer, J. A., W. J. Sydeman, N. P. Fairman, and S. G. Allen (1999). Attendance and effects of disturbance on coastal common murre colonies at Point Reyes, California. Waterbirds 22: 130-139.

Thompson, S. K. (2002). Sampling, Second Edition. John Wiley & Sons, Inc., New York, NY, USA.

U. S. Fish and Wildlife Service (2005). Regional Seabird Conservation Plan, Pacific Region. U.S. Fish and Wildlife Service, Migratory Birds and Habitat Programs, Pacific Region, Portland, OR, USA.

U.S. Fish and Wildlife Service (2009). Alaska Seabird Conservation Plan. U.S. Fish and Wildlife Service, Migratory Bird Management, Anchorage, AK, USA.

Vermeer, K. (1963). The breeding ecology of the Glaucous-winged Gull (*Larus glaucescens*) on Mandarte Island, BC. Doctoral dissertation, University of British Columbia, Vancouver, Canada.

Votier, S. C., B. J. Hatchwell, A. Beckerman, R. H. McCleery, F. M. Hunter, J. Pellatt, M. Trinder, and T. R. Birkhead (2005). Oil pollution and climate have wide-scale impacts on seabird demographics. Ecology Letters 8:1157-1164.

Walsh, P., D. Halley, M. Harris, A. Del Nevo, I. Sim, and M. Tasker (1995). Seabird monitoring handbook for Britain and Ireland: a compilation of methods for survey and monitoring of breeding seabirds. JNCC/RSPB/ITE/Seabird Group. Peterborough, UK.

Wanless, S., S. Murray, and M. P. Harris (2005). The status of northern gannet in Britain and Ireland in 2003/04. British Birds 98:280-294.

Weimerskirch, H. (1998). How can a pelagic seabird provision its chick when relying on a distant food resource? Cyclic attendance at the colony, foraging decision and body condition in sooty shearwaters. Journal of Animal Ecology 67:99-109.

White, G. C., and E. G. Cooch (2017). Population abundance estimation with heterogeneous encounter probabilities using numerical integration. The Journal of Wildlife Management

2:322-336.

Williams, B. K., J. D. Nichols, and M. J. Conroy (2002). Analysis and management of animal populations. Academic Press.

Williams, K. A., P. C. Frederick, and J. D. Nichols (2011). Use of the superpopulation approach to estimate breeding population size: an example in asynchronously breeding birds. Ecology 92:821-828.

Young, R., A. Kitaysky, C. Carothers, and I. Dorresteijn (2014). Seabirds as a subsistence and cultural resource in two remote Alaskan communities. Ecology and Society 19: Art. 40.

Zador, S. G., J. F. Piatt, and A. E. Punt (2006). Balancing predation and egg harvest in a colonial seabird: a simulation model. Ecological Modelling 195:318-326.

Chapter 2. Estimating breeding population size of a cliff-nesting bird species[1]

2.1 ABSTRACT

Determining how to effectively monitor the breeding population size of a seabird species with cryptic nests presents a substantial challenge. Glaucous-winged gulls (*Larus glaucescens*) are common in and around Kenai Fjords National Park (KEFJ), Alaska, breeding in numerous colonies. We compared field counts to replicated photographic counts collected over 2-4 days at seven colonies in the KEFJ area. High variability in both count methods precluded precise abundance estimates, so we developed an intensive method of analyzing images using a modified mark-resight (MR) approach to identify all potential nest locations (PNL's, physical locations where a bird was observed in at least one image). We used a Bayesian framework to estimate the number of PNLs that were likely to be nests. We quantified the potential error rate due to misidentification of PNLs or instances when a PNL was not visible during a survey, and investigated temporal and environmental factors likely to affect each measure of abundance or attendance. Our main conclusions were 1) the modified MR approach provided a better approximation of breeding abundance than counts and addressed variability among replicate surveys; 2) PNL classification errors were few and had a negligible effect on our results; and 3) counts of all attending birds in a colony plot were influenced by different factors than counts of birds attending locations likely to be nests. We recommend an approach similar to ours – repeat photographic surveys couple with CMR/MR analytical methods (e.g. occupancy, multi-state models) – for estimating the abundance of other species with similar characteristics or in similar environments.

---

[1] Curl, J.A., Barry, R. P., and C. P. H. Mulder. 2018. Estimating breeding population size of a cliff-nesting bird species. In prep for submission to *The Condor*.

2.2 INTRODUCTION

Monitoring the abundance of wildlife species effectively is often difficult, as many species-specific characteristics (e.g. nesting strategies, life history, or behavior) can make it difficult to detect or survey individuals and populations (Ballance 2008, Renner et al. 2011, Oppel et al. 2014). Seabirds are often studied because they are relatively accessible indicators of patterns in marine environments that are otherwise difficult for researchers to observe (Cairns 1987, Piatt et al. 2007, Einoder 2009). Monitoring efforts tend to focus on either terrestrial breeding areas (Stephensen and Irons 2004, Paleczny et al. 2013) or on assemblages of seabirds at sea (Tasker et al. 1984, Maclean et al. 2012, Gall et al. 2017). Abundance is often included in many studies focused on some aspect of seabird biology, as most species nest in large colonies that are easy to find (Ainley et al. 2003, Byrd et al. 2005, Jovani et al. 2015). However, seabird nests can often be difficult to observe, especially for species that nest in burrows, crevices, or on surfaces of vertical cliff faces, making accurate estimation of breeding population size difficult.

The northern Pacific Ocean supports a diversity of seabird species (Mills et al. 2005, Springer 2005). In particular, coastal areas of Alaska provide habitat for millions of breeding seabirds of more than 35 species (U.S. Fish and Wildlife Service 2009), but much of the habitat is remote, expansive, and difficult to access. Additionally, surveys have to be timed between bouts of unfavorable weather or marine conditions. Kenai Fjords National Park (KEFJ), located in the northwestern region of the Gulf of Alaska, provides breeding habitat for numerous populations of seabirds during the spring and summer months, several of which are thought to be declining (Bailey 1977, Bailey and Rice 1989, Arimitsu et al. 2011, Phillips 2011). To address these potential declines, KEFJ designated seabird monitoring as a priority, with a focus on species that prefer to nest on open ledges of steep, vertical terrain (Phillips 2011).

Glaucous-winged gulls (*Larus glaucescens*) nest in a network of colonies in and around the Kenai Fjords region. They are among the most numerous seabirds within the park, leading to KEFJ being designated as an Important Bird Area (IBA) for this species (National Audubon Society 2015). *L. glaucescens* nests consist of low, obscure, bowl-shaped scrapes on vegetated ledges of cliff faces. Thus, nests are usually impossible to detect unless a researcher walks through a colony actively searching for them. Due to the spatial scale of the park (>700 km of coastline), the steep topography of the fjords, the lack of direct access to colonies, and the inconspicuous nature of the nests of this species, monitoring *L. glaucescens* effectively in KEFJ is a difficult undertaking.

Unfortunately, historical surveys of *L. glaucescens* and other seabirds in KEFJ have been infrequent, spatially inconsistent, and conducted using a variety of methods (Bailey 1976, Nishimoto and Rice 1987, Bailey and Rice 1989, Vequist and Nishimoto 1989, Vequist 1990, Day et al. 1997), precluding quantitative analysis of population trends. In all historic surveys, birds have been counted from boats with binoculars, though counting methods have not been consistent. Counts using high resolution digital photographs have become viable alternatives to physical counts; photographs create a permanent archive that can be analyzed by multiple observers or by multiple methods over a longer period of time and in greater detail, and counting from photographs reduces time spent at any one location in the field (Cutler and Swann 1999, Merkel et al. 2016). Capture-mark-recapture (CMR) and mark-resight (MR) approaches are two tools that are often used to estimate population parameters such as occupancy, survival, and abundance (Williams et al. 2002, Lindberg et al. 2012, Cooch and White 2017, McClintock 2016). When repeated photographs are available, they can often be analyzed in a CMR or MR framework, thereby improving estimates of breeding population abundance.

In addition to considering what survey methods to use, environmental and temporal variables such as ambient temperature, swell height, tide height, or wind speed can potentially affect if and how researchers detect individual birds and nests, either through influencing gull incubation and attendance behavior (e.g. Hamer et al. 2001), and/or by directly impacting survey methods (e.g. Certain et al. 2008). We considered the possibility that fog, rain, sun position and intensity, wind, and swell could impact how visible birds are to researchers either through binoculars or in photographs, while conditions could also impact observer comfort, focus, and effort.

The goal of this study is to determine how to estimate breeding population size for *L. glaucescens* in and around KEFJ, with specific objectives to: 1) develop sampling and analytical methods to more reliably estimate nest abundances for this species, 2) investigate how potential sources of survey error influenced our estimates, and 3) explore which temporal and environmental variables had the strongest relationships with the various measures of abundance we considered. For objectives 1 and 2, we conducted surveys at colonies and compared the performance of field counts vs. photographic counts. We also analyzed photographs using a modified mark-resight approach to estimate abundance and survey error. For objective 3, we used generalized linear models to investigate relationships between various measures of abundance and sources of environmental and temporal variability. This study made progress towards solving the problem of estimating nest abundance for a species that makes nests that are difficult to visually detect, and our general approach can be useful to managers faced with monitoring species that are similarly hard to detect or that breed on steep cliffs, in areas that are remote and infrequently visited, or in places that are impossible to directly access. Our methods can be easily adjusted based on lessons we learned during this initial attempt at estimating breeding abundance to improve inferences in future abundance estimation efforts.

2.3 METHODS

2.3.1 Study Site and Species

Our study area encompassed the coastline and associated islands of KEFJ south of Seward, Alaska (Fig. 2.1). KEFJ has a maritime climate that results in wet, temperate conditions in both summer and winter (Lindsay and Klasner 2010). The topography of KEFJ is shaped by the Harding Icefield and its associated glaciers and deep fjords. The region is characterized by steep coastal cliffs and islands comprised of granite, greywacke, and slate, and vegetated by temperate rainforest, alder patches, and coastal grasses (Giffen et al. 2014).

L. glaucescens is abundant in the northern Pacific Ocean and one of the most populous colonial marine bird species in KEFJ. Historically, *L. glaucescens* have occupied 30 to 40 colony locations within and adjacent to the park, ranging in size from 20 to >1,000 nesting pairs. Most colonies are located on vertical cliffs with a height range of 15-500m, covered with heterogeneous patches of low vegetation (see example in Figure 2.2). Existing data suggest that the average incubation period for gulls in KEFJ approximately occurs between late-May and early-June, with peak hatching in mid-July, and fledging from late July into the middle of August (Hayward and Verbeek 2008, Murphy et al. 1984).

2.3.2 Sampling Design

We surveyed seven colonies in or near KEFJ in the summer of 2013. Logistical limitations (e.g., travel time, weather, research vessel scheduling) prevented random selection of colonies; we sampled strategically to capture the range of variability between colonies and across the Kenai Fjords region. We considered colony size (small: <300 attending adults, or large: >300 attending adults), regional location (Figure 2.1), and colony attributes (e.g. island or mainland, protected or exposed) (Table 2.1).

We define breeding abundance as the number of either breeding pairs, or active nests within a region or colony of interest. To work towards finding the best method for estimating breeding gull abundance, we conducted replicate surveys at as many colonies as possible across the park. To make sampling efficient and feasible, we designated a single survey plot at each colony (hereafter ‘colony plot’). Colony plots were chosen based on natural and permanent physical features of colonies that were easy to identify, and encompassed a minimum of 10% of the estimated size of the colony (USFWS 2009). We marked colony plot boundaries on photographs immediately after they were established and before the first replicate survey at each colony plot.

2.3.3 Survey Methods

We conducted surveys from a 16’ Naiad boat in the northern region of KEFJ, and from the 53’ M/V Serac research vessel in the southern region. Colony plots were surveyed 9 or 10 times over several consecutive days. We completed all replicates at a plot within 2–4 days so that we could reasonably assume that the population was closed (i.e. no nests were added or lost during the survey period). We identified the location offering the best view and perspective of birds attending the colony plot, and recorded the latitude and longitude using a GPS. All replicate surveys were then conducted from the recorded point (or as close as was practicable). We surveyed each colony plot within each of three time periods: morning (0800–1200 hours), afternoon (1200–1600 hours), and evening (1600–2000 hours). Each replicate was conducted >2 hours apart to improve independence of counts.

For each replicate survey at a given colony plot, we completed four different procedures (UAF IACUC protocol 460969-2): 1) we completed a double observer count using binoculars (field count), 2) we took a series of photographs for counts to be completed out of the field (photo count), 3) we took a separate but similar series of photographs for modified mark-resight analyses to be completed out of the field, and 4) we measured and recorded ambient environmental conditions (tide level, swell, precipitation, cloud cover, temperature, and wind speed).

2.3.4 Field Counts

During each replicate we conducted a field count using a double observer approach. Each of the two observers simultaneously counted all individuals present in the colony plot, using Canon 10x40 imaged-stabilized binoculars. Counts were made from a distance of 50 to 300 m away from the base of cliffs, based on proximity to offshore rocks and cliff height. Counts from each observer were required to be within 5% of one another (Hutchinson 1980, AMNWR 2017), and we repeated counts within a survey as necessary until this condition was met.

2.3.5 Photo Counts

Immediately following each field count, we took photographs of the same area, making sure plot boundaries were clearly visible. Photographs were taken from 50 to 300 m away from the base of the colony cliff or island with a Canon Mark II 5D digital single lens reflex camera (dSLR) and a 24-105 mm Canon image-stabilized EF professional grade lens. We limited the range of zoom to 70-100 mm for all photos (zoom depended on the distance from the cliff and cliff height), and we used 1 to 3 photographs to encompass the colony plot area. We took standardized photographs for each replicate at each colony plot, and took additional photographs with a gradient of exposures during difficult weather conditions to ensure high image quality in photos used for analyses. Multiple images of a single colony plot were stitched together using the Microsoft Image Composite Editor (ICE). The sharpest and clearest photograph or stitched series of photographs was chosen for each replicate, and minor adjustments were made in Adobe Photoshop CS6 software to maximize the image quality and visibility of birds. Counts of birds were recorded using the Count Tool.

2.3.6 MR capture histories

Capture mark-recapture (CMR) analyses are often used in the field of wildlife ecology to estimate population parameters such as occupancy, survival, and abundance (Williams et al. 2002, Lindberg et al. 2012, Cooch and White 2017). CMR refers to the process of capturing individuals of a population, marking and releasing them to intermix back into a population, and then recapturing some proportion over a specific number of recapture periods. Mark-resight (MR) methods rely on the same overall concept as CMR analyses, but do not involve physical recapture (McClintock 2016). Both CMR and MR approaches explicitly account for imperfect detection, or how often an observer misses an organism when it is actually present.

We developed a modified MR method using data collection from photos, which relied on repeatedly finding exact physical locations in space, or potential nest locations (PNL), in every replicate photograph for a colony plot. PNLs were initially detected by the presence of an adult gull. In most MR studies, individuals are resighted, or identified by some kind of distinguishing feature, either natural (e.g. color markings) or artificial (e.g. bands, ear tags, etc.). We marked locations by labeling them on replicate photographs. In our study, we recorded whether there was a bird present or absent for every PNL in each replicate image, thus we resighted PNLs rather than marked individuals or nests. This represents a significant departure from traditional mark-resight analyses, as we do not have true MR data because we were never able to directly detect nests. Consequently, our estimates are not corrected to account for imperfect detection, and further are dependent on several assumptions about gull incubation behavior that we describe in more detail in the analytical methods below.

Immediately after taking a series of photographs for counts, an additional series of photographs were taken for MR analyses. MR photos were stitched and processed in the same way as described for photo counts. Then, for the first photograph in the replicate series for a colony plot, we "marked" all PNLs using the presence of a bird as an initial method to detect each PNL. For each subsequent replicate photograph we determined whether a previously marked location was "resighted" by detecting a bird in that PNL. New PNLs were identified and marked when a bird occurred in unmarked locations. This was repeated for each replicate (*n* = 12,008 encounters of PNL's across all colony plots and all replicates). A sighting history was created for each PNL where 1 = bird was observed and 0 = bird was not observed for each replicate. We addressed potential misidentification based on bird position (e.g. the presence of one bird spaced equidistantly between two otherwise unoccupied marked PNLs that were close together) by coding the new PNL and the adjacent sites as a 2, representing potential misidentification. We recorded a 3 when PNLs were not visible. Lack of PNL visibility occurred because of variation in boat position caused by current, wind, and swell; we adjusted *n* for a given PNL based on the number of replicates in which it was visible (Figure 2.3). We also constructed a second capture history of bird behavior to code for whether or not each observed bird was sitting (1) or standing (0). Only birds that were clearly observed to be sitting received a 1. Finally, we summed all the PNLs with a bird present for each resighting effort (replicate photograph), which gave us an estimate of plot count for MR analyses that we could compare with field and photo counts.

2.3.7 Analytical Methods

2.3.7.1 Modified MR approach

We were never able to truly detect the presence of nests. Though traditional occupancy (Mackenzie et al. 2001) or closed population CMR/MR models (Otis et al. 1978) might have provided stronger inferences, neither was feasible with the data we collected. An occupancy approach was impossible in our repeated photo approach because each PNL was defined as a location where a bird was present in ≥1 photograph, meaning that detection of PNLs was conditioned on the site being occupied (or the probability of occupancy was always 1). Additionally, we could not grid an area appropriately or consistently across repeated photographs due to variation in perspective. Therefore, our resight histories were of PNLs rather than nests, thus true nest abundance was a latent variable we could not directly estimate.

Because true nest abundance was inestimable, using attendance and sitting behavior we estimated the number of true nests under 3 sets of assumptions: 1) PNLs frequently attended by adult gulls were more likely to be nest sites than PNLs that were infrequently attended; 2) PNLs where an adult gull frequently sat (i.e. for incubation) were more likely to be nest sites than PNLs where birds infrequently sat; and 3), PNLs where gulls both attended often and sat often were the most likely PNLs to be nests. These assumptions were made because: 1) protocols for monitoring gulls suggested incubation behavior (sitting) is sometimes used to assume the relative nest abundance in locations where nests cannot be seen (AMNWR 2000), 2) *L. glaucescens* adults have been shown to incubate consistently (Vermeer 1963), and 3) we detected an underlying bimodal distribution when we initially made histograms of both attendance and sitting behavior across all resight histories, which suggested that there were two distinct underlying categories of behavior observed across PNLs. We used a Bayesian approach to classify PNLs into one of two distinct categories for each of three mixture models: 1) attendance (A, high vs. low), 2) sitting behavior (S, frequent vs. infrequent), and 3) coupled attendance and sitting behavior (A+S, high attendance/frequent sitting vs. low attendance/infrequent sitting). For each model, we estimated the probability that each PNL was in the category assumed to be more associated with nesting behavior: high attendance (Ψ), frequent sitting (Ψ'), or both high attendance and frequent sitting (Ψ''). We then assumed that the estimated number of PNLs (N) in the high category under each model might approximate nest abundance: sites with nests would have higher attendance, sites with nests would have birds sitting more frequently and consistently, and sites with both high attendance and high sitting rates would be the most likely to contain actual nests.

For the attendance model (A), we assumed that the observed state X (0, bird absent, or 1 bird present) for each PNL i had a binomial distribution, with some underlying probability π that birds would attend each PNL during each of n replicates, and can be written as:

$$X_i \sim Binomial\ (\pi_i,\ n)$$

The overall probability that a bird was present at each PNL i was the sum of two conditional probabilities: the probability a PNL is in the high attendance group (Ψ_i) multiplied by the probability a bird is observed at a PNL (s) given that the PNL exists in the high attendance category, plus the probability that PNL is in the low attendance category ($1- \Psi_i$) multiplied by the probability that a bird is observed (f) given that the PNL exists in the low attendance category.

$$\pi_i = \Psi_i * s_i + (1- \Psi_i) * f_i$$

$$\Psi_i \sim \mathit{Bernoulli}\ (t)$$

The second model (S) is similar to the first, but X is instead the state of whether a bird is sitting (1), or not sitting (0), and used only the resight history of bird behavior. The overall probability that a bird was sitting at each PNL ($\text{\o}_i$) was the sum of two conditional probabilities: the probability that the PNL existed in the frequently sitting state (Ψ'_i) multiplied by the probability a bird was observed sitting at the PNL (r), plus the probability that the PNL existed in the infrequently sitting state ($1- \Psi'_i$) and a bird was observed sitting at the PNL (g).

$$X_i \sim \mathit{Binomial}\ (\text{\o}_i,\ n)$$

$$\text{\o}_i = \Psi'_i * r_i + (1- \Psi'_i) * g_i$$

$$\Psi'_i \sim \mathit{Bernoulli}\ (t)$$

The third model (A+S) was a nested model that used both records of attendance and sitting behavior, and that incorporated both states, X for presence out of n replicates, and Y for how many sitting occasions there were out of x_i presences, that can be written as:

$$X_i \sim \mathit{Binomial}\ (\pi'_i,\ n)$$

$$Y_i \sim \mathit{Binomial}\ (\text{\o}'_i,\ x_i)$$

$$\pi'_i = \Psi''_i * s'_i + (1- \Psi''_i) * f'_i$$

$$\text{\o}'_i = \Psi''_i * r'_i + (1- \Psi''_i) * g'_i$$

In this model, the overall probability a bird is observed (π'_i) is the sum of two conditional probabilities. The first conditional probability consists of the probability that a PNL is categorized into the high attendance/frequent sitting group and a bird is observed (s') given that the PNL exists in that group (Ψ_i''), plus the probability that a PNL is in the low attendance/infrequently sitting group (f') and a bird is observed given that the PNL is in the low/infrequent group ($1-\Psi_i''$). The overall probability that a bird is observed sitting (o'_i) is also the sum of two conditional probabilities; the probability a PNL is in the high attendance/frequent sitting group (r') and a bird is observed sitting given that the PNL is in the high/frequent category (Ψ_i''), plus the probability that a PNL is in low attendance/infrequent sitting category (g') and a bird is observed sitting given that the PNL is in the low/infrequent category ($1-\Psi_i''$).

We used uninformative priors, but using a logit function we ensured s, s', f, f', r, r', g, and g' were values between 0 and 1, and we assumed that s, s', r, and r' values (the probability a bird was present or sitting respectively given they were in a category associated with nesting behaviors) were higher than f, f', g, and g' values (the probabilities a bird was present or sitting given that a PNL was in a category with lower attendance and infrequent sitting behavior) during each Markov chain Monte Carlo (MCMC) iteration.

2.3.7.2 Misidentification

We evaluated the frequency of two types of misidentification that can produce errors when generally estimating abundance from CMR/MR data (e.g. Royle and Link, 2006): false positives, or deciding a bird was present at a PNL when it was not, usually caused by a bird being present precisely in between two PNLs in close proximity; and false negatives, or when a PNL was not visible in a replicate photo because of boat location.

In order to address potential sources of false positive error, we calculated the proportion of observations that were recorded as potentially misidentified, which is a slight modification of the attendance model (model statement in appendix). We used this model because this type of error specifically affected our ability to observe birds attending the colony, and we modified the attendance model to create a related multinomial model with three possible outcomes and associated probabilities: the probability no bird was observed at a PNL, the probability a bird was observed at a PNL, and the probability that a bird was observed at or near an existing PNL but potentially associated with the wrong one (coded 0, 1, and 2 respectively), which most often occurred when a bird was equidistant from two previously marked PNLs.

We also calculated the percentage of observations where false negative errors potentially occurred, or those occasions when a bird could not be observed even if it was present, because a PNL was not visible in a photograph, most often due to boat position and the resulting perspective from which the photo was taken. For occasions when this occurred, we adjusted n to be only those replicate visits where PNL i was visible. We then compared approximate nest abundances including both sources of error to those from the attendance model.

2.3.7.3 Covariate analyses

We conducted exploratory analyses with a suite of variables to help explain variation in repeated counts and the results of our modified MR analyses. Temporal variables included Julian date and time of day (in minutes). Environmental variables included ambient temperature (^{o}C), wind speed (kph), estimated swell (m), tidal level (m), estimated cloud cover (as a factor based on %), and precipitation (ordinal categorical variable where 0 = none up to 5 = heavy rain).

We compiled count data from three different sources: field counts, photo counts, and counts from summing across the attendance of birds (sum of all 1's in a given replicate) recorded during MR photo processing. For all three, we used a GLM with an underlying Poisson distribution (Agresti 2013) to examine which variables influenced replicate counts across all colonies. Similarly, we investigated the influence of the same group of variables on bird attendance across all identified PNLs (from all colony plots), and also on bird attendance at the subset of PNLs in the high attendance/frequent sitting category from the A+S model (using an underlying logistic distribution) (Agresti, 2013).

We calculated correlations between variables and removed highly correlated variables (date, cloud cover) until we had no correlations > 0.65 (correlation matrices are in supplementary materials). Though we had multiple options for which variables to remove, we selected date due to how replicate surveys were completed (in 3-4 day chunks that were obviously correlated with weather conditions associated with those days). Cloud cover and precipitation were also highly correlated. We considered main effects models only, compiled by the glmulti package (Calcagno and Mazancourt, 2010) in R (version 3.3.2) and RStudio software, because we had a fairly small sample size ($n=77$) to estimate additional interaction parameters. To identify a set of top model(s) to consider, we used the corrected Aikake's Information Criteria, ΔAICc, and model weights (Anderson et al. 2001).

2.4 RESULTS

2.4.1 Counts

Regardless of the survey method, repeat counts showed high variability between replicates. Counts and coefficients of variation (the standard deviation divided by the sample mean) from all three methods (Field, Photo, and MR) displayed similar fluctuations (Fig. 2.4). Summing PNLs with a bird present across repeat photograph resight histories, or MR counts, often yielded the highest number of individuals observed out of the three count methods. The three methods captured similar patterns, and had comparable variability. The biggest divergences in patterns between count methods occurred at the colony plots that were most exposed and at which we experienced the worst weather (swell, wind, or rain): Steep, Surok, and Striation.

2.4.2 Modified MR approach

For the rest of this manuscript, the groups associated with nesting behavior are referred to as "high" (high rates of attending, high rates of sitting, or high rates of both), or "low" categories (low rates of attendance, low or no rates of sitting, or low rates of both). In general, the model relying only on attendance (A) estimated the largest number of PNLs in the high category in comparison to the sitting (S) model or attendance and sitting model (A+S) (Table 2.2). The S model alone was not a good approximation of nest abundance because there were many occasions where a bird was seen at a PNL only once, but was observed to be sitting, and other examples of a bird being present in every survey, but never observed to be sitting. Constructing a model that used the resight histories for both attendance and sitting shifted the distribution towards either extreme end of the bimodal distribution, 0 (low) or 1 (high) in the cumulative density distribution of posterior probabilities for each PNL (Fig. 2.5). In other words, there were fewer cases where PNLs were ambiguous to categorize in the A+S model than for the others, although the underlying bimodal distribution was apparent in all three models. PNL abundance ($\hat{N}$) in high categories was estimated for all three models, including standard deviations and 95% credibility intervals (Table 2.2).

2.4.3 Covariate analyses

The structure of the top models differed across the five different potential measures of attendance and nesting behavior we considered (Table 2.4). Colony was assumed to be an important source of variability based on differences in plot size and differences in colony characteristics, and came up as either the first or second most important variable for all methods. The only other factor found in each of the top models for most metrics was tide (Figure 2.6), though notably it was not important for the subset of PNLs in the high attendance/infrequent sitting category of our A+S model results. In general, counts of colony plots were higher during higher tides (Poisson regression models: field count, photo count, MR count). Tide was also influential for when birds were observed attending across all PNL MR resight histories (Figure 2.6). However, when looking only at the attendance of birds at PNLs in the high category (or PNLs most likely to be nests), tide was not among the most important variables (Table 2.4; Figure 2.6); instead, swell, temperature and minute of the day were more important.

2.5 DISCUSSION

Our results indicate that counting once a season, or even across replicated field or photo counts over a season, does not necessarily provide enough information to adequately estimate breeding abundance for *L. glaucescens* in KEFJ because of high variation in attendance of birds at colonies. High variability in counts occurred regardless of survey method, indicating that most of the variability was due to bird attendance and behavior, rather than counting method. Variability in counts was likely high enough to preclude simple count methods from detecting reliable trends in gull abundance over many years. This study made notable progress towards developing a good estimator for nest abundance for this species. The results of our modified mark-resight (MR) approach demonstrated that a fairly small proportion of PNLs are actually likely to be nests. We found that counting birds from photographs captured the same basic patterns as field counts and allowed us to test a more intensive method that took advantage of extra information stored in photographs that would be exceptionally challenging to collect during field surveys. We established that survey error did not notably change our nest estimates. We also identified potential sources of environmental and temporal variability influential to each attendance measure in our study. Attendance at PNLs most likely to be nests (high categories) was influenced by different environmental and temporal factors than any other measure (i.e. Field, Photo, or MR counts, or bird presence at PNLs not likely to be a nest).

Breeding seabird species have been shown to have large fluctuations in numbers at colonies on a daily, nightly, seasonal, and inter-annual basis; this variability can be driven by factors such as prey availability, predator avoidance, weather, human or other environmental disturbances, photoperiod, or other specific behavior patterns, such as immature birds that attend colonies without breeding (Hatch and Hatch 1989, Klomp and Furness 1990, Jones et al. 1990, Thayer et al. 1999, Zador and Piatt 1999, Harding et al. 2005, Gaston et al. 2006). Assessing the variation between counts for *L. glaucescens* is important because the larger the variance within replicate counts in a single year, the harder it is to detect long-term trends or changes within the population of interest (Johnson and Krohn 2001, Sims et al. 2006). Our two primary count methods – field and photo counts – both captured the same patterns of variability of attending adults at colonies. Though the main goal of the MR approach was to estimate nest abundance, it also served as a third method of counting attending adults. We expected MR counts to be similar to photo counts, but instead, MR counts were an average of 18% higher than the other count methods, likely due to intensive observation of replicate photographs for a longer period of time. Notably, MR counts were not lower in variability, which again suggests that the variability is associated with bird attendance and behavior, rather than due to survey error.

We found that there were many PNLs that were categorized as unlikely to be nests, and that it was impossible to distinguish incubating adults from birds temporarily roosting during simple counts. By tracking specific PNLs through replicate photographs, we were able to better distinguish between birds likely to be incubating versus those not likely to be sitting on nests.

The modified MR model using both attendance and sitting data (A+S) utilized the most information available in order to better distinguish between high and low categories of PNLs – basically between likely nest locations and likely non-nest locations. For the (A+S) model, the proportion of PNLs we classified in the high group ranged from 15-30% of the total number of PNLs identified overall at each colony plot, with an average of ~23% across all seven colonies.

Other studies focused on seabird colony attendance have noted that variability at colonies can sometimes be due to the attendance behaviors of the non-incubating mate or a significant number of non-breeding birds (Hatch and Hatch 1988, Klomp and Furness 1990, Gaston et al. 2006). A study by Gaston et al. (2006) found that non-breeding northern fulmars (*Fulmaris glacialis*) often picked precarious places to attend that were obviously not nests. Non-breeding and immature great skuas (*Catharacta skua*) form distinguishable "clubs" in and around colonies that can be identified by guano concentrations and trampling, and Klomp and Furness (1990) found that these individuals had notably different attendance behavior than breeding individuals, which contributed to overall variability in colony attendance. This suggests that collecting behavioral data, such as the sitting behavior in our case of *L. glaucescens* in KEFJ, or other patterns that can help distinguish between breeders and roosters, may be an important component of estimating breeding abundance, and ultimately the design of seabird colony monitoring programs.

Our modified MR approach helped us to identify which PNLs were most likely to be nests, and helped us to discern what factors may contribute to variability in repeat counts. Analyzing photographs this way allowed us both to estimate the probability that each PNL was in the high attendance category and estimate a total number of nest locations present in colony plots. These analyses are admittedly complicated and time intensive. For all replicates at one colony plot, image analysis took tens of hours and at least several work days to complete, whereas simple counts of birds in photos without marking and constructing a PNL capture history was more on the order of a few hours, and definitely <1 work day of effort. This intensive study of photographs facilitated two things: 1) it allowed an observer to be much more perceptive of minute details within photographs that were missed during photo counts, and 2) by identifying locations where birds are expected to be, an observer was better at finding birds and knowing where to look, especially when only parts (e.g. tail or head) were visible because of vegetation or a low profile due to sitting posture. Photographs can reduce the amount of time spent at each colony in the field, thereby helping to maximize survey efficiency. This is desirable anywhere remote or characterized by inclement weather or seas, or for species where minimizing disturbance is a priority.

There are a number of ways that we could improve our modified MR approach. Ground-truthing, or determining the true number of animals or nests, is often useful for calibrating the results of photographic surveys (e.g. Robertson et al. 2008). Because we were unable to ground-truth our methods, we were unable to directly estimate the true number of nests in a colony plot. At the beginning of this project, we reasoned that we could obtain a photographic ground-truth by identifying all the attended nests present within a colony plot. However, doing so proved impossible due especially to cliff topography, inconsistent vantage points because of conducting surveys from a small boat, and *L. glaucescens* nesting behavior. In addition, without true visual evidence that at least some PNLs were actual nests, we could not conclusively validate the assumptions we made in constructing models.

In the future, perhaps through a combination of climbing or walking on portions of colonies, or the use of newer technology like unmanned aerial vehicles, it may be possible to incorporate at least a partial ground-truth in KEFJ. However, there are many places where methods generating more reliable data while minimizing time in the field would be useful even without a concrete ground-truth. Our approach may be useful in some cases for the following reasons: 1) it helps account for high variability in repeated counts, especially due to attendance; 2) a primary type of data (e.g. attendance) can be improved by a secondary type (e.g. sitting behavior); and 3) there are many areas where access to colonies is in some way limited and a ground-truth is never possible.

With small adjustments in our data collection, other CMR/MR estimation methods, such as occupancy modeling or multi-event modeling could also be tested and compared to model results from this study. One reason we were unable to use occupancy approaches was that repeat photographs were taken from different vantage points, and imposing a grid without explicit spatial references would make our replicate surveys inconsistent with one another. In the future, if LIDAR (light detection and ranging) data or an accurate 3D elevational map or model were available, space in and around colonies could be divided using an appropriately sized grid, and detection/non-detection data and the spatial extent of colonies (and map their growth or shrinkage) could then be used to estimate occupancy probabilities across a sample of colonies. If occupancy was an option, and some PNLs were verified as actual nests, PNL breeding state might also be estimated using a multi-event or multistate occupancy modeling approach (Mackenzie et al. 2009, Bailey et al. 2014).

We found that the potential sources of survey error we considered had a negligible effect on the number of PNLs we categorized as nests. Other studies have suggested that failing to consider the effects of both false positive and false negative errors in MR analyses can lead to major under- or over-estimates of a population parameter (Kendall 2004, Royle and Link 2006, Miller et al. 2011). While we could not calculate true nest detection error (due to lack of a ever directly detecting nests), rates of potential misidentification were low. Birds were potentially associated with an incorrect PNL (false positive error) <2% of the time during image processing, while <1% of the time a PNL was not visible in a photo due to deviations in boat perspective (false negative error). Further, when we accounted for both potential sources of error and considered only PNLs likely to be nests, the total number of PNLs estimated to be in the "nest" category did not significantly change (see Appendix 2 for estimates). We conclude that these sources of error are not likely to impact trends for detection of trends for this species in this environment, but that these types of errors are always important to consider when designing CMR/MR studies.

Variability in attendance of seabirds at colonies is well documented in many species, including several found in KEFJ such as black-legged kittiwakes (*Rissa tridactyla*), common murres (*Uria aalge*), and horned puffins (*Fratercula corniculata*) (Harding et al. 2005, Hatch and Hatch 1988, Hatch and Hatch 1989). For these species, patterns in diurnal attendance, or specific times of day where a peak number of birds are attending colonies, have been identified in order to reduce variability between repeated counts, generally due to foraging patterns based on photoperiod, or the position of the sun. *L. glaucescens* colonies in our study had notably high variability of attendance during counts of adults.

We considered many sources of variability that could have influenced *L. glaucescens* attendance patterns. Tide was the most important factor in every measure for which we counted the total number of birds attending colony plots. In contrast, tide was among the least important for attendance of incubating birds at PNLs likely to be nests. For overall colony attendance, we found that there were more birds present at colony plots when tides were high. *L. glaucescens* forages in intertidal and nearshore areas, so a higher proportion of birds would be expected to forage at low tide (Hayward and Verbeek, 2008). In contrast, for attendance at nest locations, bird presence is likely influenced by factors other than food availability, because males and females take turns sitting on nests, resulting in fairly consistent nest attendance in this species (Vermeer 1963). We found that temperature and swell were weighted as important within models considering PNLs in the high category, suggesting that incubation behavior may be driven more by ambient weather conditions; there are temperature requirements for embryonic development in the eggs of bird species (Hamer et al. 2001).

Survey timing is also important. We conducted fieldwork during the incubation and early hatch periods (9-June – 9 July), which approximately matched the duration of incubation for this species, which is on average between 27-30 days (Vermeer 1963, Verbeek 1986). Day of the season is likely to be important to nesting behavior, as birds both move onto the nest to incubate after eggs are laid, and then incubation tapers off as chicks hatch and emerge from the nest. However, because we surveyed at individual colonies over only a couple of days and not at any colony continuously, we were unlikely to capture seasonal effects related to date within the breeding season. Instead, date was highly correlated with weather variables (precipitation, wind, swell) over the short window we surveyed. *L. glaucescens* is also somewhat asynchronous in breeding phases. In other words, birds shift through phenological breeding stages around the same time, but with some variability (Vermeer 1963). We are likely missing at least some of the overall breeding effort at colonies because our surveys were conducted over brief windows of time at each colony plot. We may have missed nests that were initiated early and then lost, or in some cases nests may have been initiated after our surveys, although the latter is less likely because we timed surveys to start well after the average start of the incubation phase (Murphy et al. 1984).

Few studies have looked at similar attendance patterns for cliff-nesting populations of *L. glaucescens* or other *Larus* gulls in general. Henson et al. (2004) found that three different detectable daily and seasonal attendance oscillation patterns in loafing, non-breeding *L. glaucescens* off the coast of the state of Washington were driven by three environmental influences: day, tidal height, and the angle of the sun above the horizon. Additionally, a study of herring gulls *(Larus argentatus)* found that differences in successful and unsuccessful breeders were related to the type of diet adults were consuming (Bukacinska et al. 1996). Our findings are on a short-term scale, and thus our results are not fully comparable to those of Henson et al. (2004), who found bi-weekly and seasonal attendance patterns at a loafing site for loafing gulls; however, our results also show a tidal effect on the attendance of non-incubating gulls. Environmental factors related to diet, as in Bukacinska et al. (1996) would be something to consider in future efforts, as this species has been shown to have similar variability to *L. argentatus* in reproductive success linked to diet quality (Murphy et al. 1984, Murphy et al. 1992), which may also be linked to variability in nest attendance (i.e. better quality parents might incubate more regularly).

The goal of project was to develop a logistically feasible, cost effective way to monitor *L. glaucescens* colonies and to provide a framework to track long-term population trends in the KEFJ region. We made progress towards these monitoring goals by using attendance and behavioral data to estimate nest abundance, evaluated the potential for error in our abundance estimation methods, and conducted an exploratory analysis identifying environmental factors important to the variability in colony attendance. Developing effective, efficient methods to monitor seabird species that make nests that are difficult to visually detect is not a simple undertaking, and there is room to improve both sampling design and analysis. However, this study can also inform some practical recommendations for monitoring efforts for this species and others in KEFJ when intensive estimation methods are not available. These recommendations include; 1) repeated counts at the study site are always better than counting once a season because variability between counts can be recorded and assessed; 2) photographs are better than field counts because photos can be archived and more intensively analyzed out of the field , 3) counts should be conducted at a consistent tidal height if overall colony attendance is the unit of interest, and 4) we found that if time and resources are limited, as many repeated surveys as possible at low tides is likely the best approximation of how many nests are present. For Kenai Fjords National Park, this initial effort to test methods can inform future decisions such as what scale and level of effort the park is willing to afford to seabird monitoring given all of the other taxa and projects competing for time and resources. We recommend an analogous general approach using repeat photography and CMR/MR abundance estimators when possible for *L. glaucescens* and other similar species in locations where visual nest detection is difficult.

2.6 ACKNOWLEDGEMENTS

Funding was provided by the U.S. National Park Service (KEFJ specifically), the University of Alaska Fairbanks Center for Global Change, Alaska Climate Science Center, and the Institute for Arctic Biology at the University of Alaska Fairbanks. We thank R. Barry for statistical help, and H. Renner at the Alaska Maritime National Wildlife Refuge and L. Phillips at Denali National Park and Preserve for project oversight and input. We thank M. L. Knight, L. Phillips, E. Weiss, N. Dewberry, L. Adams, B. Robinson, S. Stark and J. Linkhart for help with fieldwork and data collection and S. Kim, M. Kansteiner, D. Kurtz, and C. Kreidman for logistical help. M. Lindberg, J. Schmidt, K. Daly, B. Meyer, S. White, M. Cameron and J. Smith provided helpful comments on previous drafts of this manuscript.

2.7 LITERATURE CITED

Agresti, A. (2013). Categorical Data Analysis, Third Ed., John Wiley & Sons, Inc., Hoboken, NJ, USA.

Ainley, D. G., R. G. Ford, E. D. Brown, R. M. Suryan, and D. B. Irons (2003). Prey resources, competition, and geographic structure of kittiwake colonies in Prince William Sound. Ecology 84:709-723.

Alaska Maritime National Wildlife Refuge (2017). Stardardized protocols for annual seabird monitoring camps at Aiktak, Buldir, Chowiet, St. George, St. Lazaria, and St. Paul islands, Cape Lisburne, and select intermittent sites in the Alaska Maritime National Wildlife Refuge in 2017. U.S. Fish and Wildlife Service Report, Homer, AK, USA. AMNWR 2017/07.

Anderson, D. R., W. A. Link, D. H. Johnson, and K. P. Burnham (2001). Suggestions for presenting the results of data analyses. The Journal of Wildlife Management 65:373-378.

Arimitsu, M., J. Piatt, M. D. Romano, and T. I. van Pelt (2011). Status and distribution of the Kittlitz's Murrelet *Brachyramphus brevirostris* in Kenai Fjords, Alaska. Marine Ornithology 39:13-22.

Bailey, E. P. (1976). Breeding seabird distribution and abundance along the south side of the Kenai Peninsula, Alaska. Unpublished report: 30 pp.

Bailey, E. P. (1977). Distribution and abundance of marine birds and mammals along the south side of the Kenai Peninsula, Alaska. The Murrelet 58:58-72.

Bailey, E. P., and B. Rice (1989). Assessment of injury to seabird and marine mammal populations along the southeast coast of the Kenai Fjords at sea: why and how. Marine Ornithology 35:127-135. Kenai Peninsula, Alaska, from the Exxon Valdez oil spill during summer of 1989. Unpublished report.

Bailey, L. L., D. I. MacKenzie, and J. D. Nichols (2014). Advances and applications of occupancy models. Methods in Ecology and Evolution 5:1269-1279.

Ballance, L. T. (2007). Understanding seabirds at sea: why and how. Marine Ornithology 35: 127-135.

Bukacińska, M., D. Bukaciński, and A. L. Spaans (1996). Attendance and diet in relation to breeding success in Herring Gulls (*Larus argentatus*). The Auk 113:300-309.

Byrd, V. G., H. M. Renner, and M. Renner (2005). Distribution patterns and population trends of breeding seabirds in the Aleutian Islands. Fisheries Oceanography 14:139-159.

Cairns, D. (1987). Seabirds as indicators of marine food supplies. Biological Oceanography, 5:261-271. Session Two: Ecology of Seabirds and Shorebirds.

Calcagno, V., and C. de Mazancourt (2010). glmulti: an R package for easy automated model selection with (generalized) linear models. Journal of Statistical Software 34:1-29.

Certain, G., and V. Bretagnolle (2008). Monitoring seabird populations in marine ecosystems: the use of strip-transect aerial surveys. Remote Sensing of Environment 112:3314-3322.

Cooch, E., and G. White (2016). Program MARK, 16th edn., a gentle introduction. Colorado State University, Fort Collins.

Cutler, T. L., and D. E. Swann (1999). Using remote photography in wildlife ecology: a review. Wildlife Society Bulletin 27:571-581.

Day, R. H., S. M. Murphy, J. A. Wiens, G. D. Hayward, E. J. Harner, and B. E. Lawhead (1997). Effects of the Exxon Valdez oil spill on habitat use by birds along the Kenai Peninsula, Alaska. Condor 99:728-742.

Einoder, L. D. (2009). A review of the use of seabirds as indicators in fisheries and ecosystem management. Fisheries Research 95:6-13.

Gall, A. E., T. C. Morgan, R. H. Day, and K. J. Kuletz (2017). Ecological shift from piscivorous to planktivorous seabirds in the Chukchi Sea, 1975–2012. Polar Biology 40:61-78.

Gaston, A. J., M. L. Mallory, H. G. Gilchrist, and K. O'Donovan (2006). Status, trends and attendance patterns of the Northern Fulmar (*Fulmarus glacialis*) in Nunavut, Canada. Arctic 59:165-178.

Giffen, B. A., D. K. Hall, and J. Y. Chien (2014). Alaska: Glaciers of Kenai Fjords National Park and Katmai National Park and Preserve. In Global Land Ice Measurements from Space (J. Kargel, G. Leonard, M. Bishop, A. Kääb, B. Raup, Editors). Springer Praxis Books, Springer, Berlin, Heidelberg.

Hamer, K. C., E. Schreiber, and J. Burger (2001). Breeding biology, life histories, and life history-environment interactions in seabirds. In Biology of Marine Birds (E.A. Schreiber and J. Burger, Editors). CRC Press, Boca Raton, FL, USA.

Harding, A., J. Piatt, G. Byrd, S. A. Hatch, N. Konyukhov, E. Golubova, and J. Williams (2005). Variability in colony attendance of crevice-nesting horned puffins: implications for population monitoring. Journal of Wildlife Management 69:1279-1296.

Hatch, S. A., and M. A. Hatch (1988). Colony attendance and population monitoring of black-legged kittiwakes on the Semidi Islands, Alaska. Condor 90:613-620.

Hatch, S. A., and M. A. Hatch (1989). Attendance patterns of murres at breeding sites: implications for monitoring. The Journal of Wildlife Management 53:483-493.

Hayward, J. L., and N. Verbeek (2008). Glaucous-winged Gull (*Larus glaucescens*), version 2.0. In The Birds of North America (P. G. Rodewald, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA. https://doi.org/10.2173/bna.59.

Henson, S. M., J. L. Hayward, C. M. Burden, C. J. Logan, and J. G. Galusha (2004). Predicting dynamics of aggregate loafing behavior in Glaucous-winged Gulls (*Larus glaucescens*) at a Washington colony. The Auk 121:380-390.

Hutchinson, A. E. (1980). Estimating numbers of colonial nesting seabirds: a comparison of techniques. Proceedings of the Colonial Waterbird Group 3:235-244.

Johnson, C. M., and W. B. Krohn (2001). The importance of survey timing in monitoring breeding seabird numbers. Waterbirds 24:22-33.

Jones, I. L., A. J. Gaston, and J. B. Falls (1990). Factors affecting colony attendance by Ancient Murrelets (*Synthliboramphus antiquus*). Canadian Journal of Zoology 68:433-441.

Jovani, R., B. Lascelles, L. Z. Garamszegi, R. Mavor, C. B. Thaxter, and D. Oro (2016). Colony size and foraging range in seabirds. Oikos 125:968-974.

Kendall, W. (2004). Coping with unobservable and mis-classified states in capture–recapture studies. Animal Biodiversity and Conservation 27:97-107.

Klomp, N., and R. Furness (1990). Variations in numbers of nonbreeding Great Skuas attending a colony. Ornis Scandinavica 21:270-276.

Lindberg, M. S. (2012). A review of designs for capture–mark–recapture studies in discrete time. Journal of Ornithology 152:355-370.

Lindsay, C., and F. Klasner (2009). Annual Climate Summary for 2007 – 2008; Kenai Fjords National Park. Natural Resource Data Series, National Park Service, Seward, AK, USA.

MacKenzie, D. I., J. D. Nichols, G. B. Lachman, S. Droege, J. Andrew Royle, and C. A. Langtimm (2002). Estimating site occupancy rates when detection probabilities are less than one. Ecology 83:2248-2255.

MacKenzie, D. I., J. D. Nichols, M. E. Seamans, and R. Gutiérrez (2009). Modeling species occurrence dynamics with multiple states and imperfect detection. Ecology 90:823-835.

Maclean, I., M. M. Rehfisch, H. Skov, and C. B. Thaxter (2013). Evaluating the statistical power of detecting changes in the abundance of seabirds at sea. Ibis 155:113-126.

McClintock, B. (2016). Mark-Resight Models. In Program MARK, 16th edn, A gentle introduction (E. Cooch and G. White, Editors). Colorado State University, Fort Collins, CO, USA.

Merkel, F. R., K. L. Johansen, and A. H. Kristensen (2016). Use of time-lapse photography and digital image analysis to estimate breeding success of a cliff-nesting seabird. Journal of Field Ornithology 87:84-95.

Miller, D. A., J. D. Nichols, B. T. McClintock, E. H. C. Grant, L. L. Bailey, and L. A. Weir (2011). Improving occupancy estimation when two types of observational error occur: non-detection and species misidentification. Ecology 92:1422-1428.

Mills, K. L., M. Naughton, and G. Elliott (2005). Seabird Conservation Planning in the Pacific Region. USDA Forest Service Gen. Tech. Rep. PSW-GTR-191.

Murphy, E. C., R. H. Day, K. L. Oakley, and A. A. Hoover (1984). Dietary changes and poor reproductive performance in Glaucous-winged Gulls. The Auk 101:532-541.

Murphy, E. C., A. A. Hoover-Miller, R. H. Day, and K. L. Oakley (1992). Intracolony variability during periods of poor reproductive performance at a glaucous-winged gull colony. Condor 94:598-607.

Nishimoto, M., and B. Rice (1987). A re-survey of seabirds and marine mammals along the south coast of the Kenai Peninsula, Alaska, during the summer of 1986. Unpublished National Park Service report.

Oppel, S., S. Hervias, N. Oliveira, T. Pipa, C. Silva, P. Geraldes, M. Goh, E. Immler, and M. McKown (2014). Estimating population size of a nocturnal burrow-nesting seabird using acoustic monitoring and habitat mapping. Nature Conservation 7:1-13.

Otis, D. L., K. P. Burnham, G. C. White, and D. R. Anderson (1978). Statistical inference from capture data on closed animal populations. Wildlife Monographs 62:3-135.

National Audubon Society. 2017. Important Bird Areas, Kenai Fjords. http://www.audubon.org/important-bird-areas/kenai-fjords.

Paleczny, M., E. Hammill, V. Karpouzi, and D. Pauly (2015). Population trend of the world's monitored seabirds, 1950-2010. PLoS ONE 10(6): e0129342. https://doi.org/10.1371/journal.pone.0129342.

Phillips, L. (2011). Monitoring for trends in the distribution and abundance of colonial nesting seabird populations on the Kenai Fjords coast. Detailed Implementation Plan, National Park Service, Seward, AK, USA.

Piatt, J. F., A. M. Harding, M. Shultz, S. G. Speckman, T. I. van Pelt, G. S. Drew, and A. B. Kettle (2007). Seabirds as indicators of marine food supplies: Cairns revisited. Marine Ecology Progress Series 352:221-234.

Renner, H. M., J. H. Reynolds, M. Sims, and M. Renner (2011). Evaluating the power of surface attendance counts to detect long-term trends in populations of crevice-nesting auklets. Environmental Monitoring and Assessment 177:665-679.

Robertson, G., C. A. Moreno, K. Lawton, R. Kirkwood, and J. Valencia (2008). Comparison of census methods for black-browed albatrosses breeding at the Ildefonso Archipelago, Chile. Polar Biology 31:153-162.

Royle, J. A., and W. A. Link (2006). Generalized site occupancy models allowing for false positive and false negative errors. Ecology 87:835-841.

Sims, M., S. Wanless, M. P. Harris, P. Mitchell, and D. A. Elston (2006). Evaluating the power of monitoring plot designs for detecting long-term trends in the numbers of common guillemots. Journal of Applied Ecology 43:537-546.

Springer, A. (2005). Seabirds in the Gulf of Alaska. In The Gulf of Alaska, Biology and Oceanography (Alaska Sea Grant College Program, Editor). Fairbanks, AK, USA.

Stephensen, S. W., and D. B. Irons (2003). Comparison of colonial breeding seabirds in the eastern Bering Sea and Gulf of Alaska. Marine Ornithology 31:167-173.

Sutherland, W. J., I. Newton and R. E. Green (2004). Bird Ecology and Conservation. Oxford University Press, New York, NY, USA.

Tasker, M. L., P. H. Jones, T. Dixon, and B. F. Blake (1984). Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardized approach. The Auk 101:567-577.

Thayer, J. A., W. J. Sydeman, N. P. Fairman, and S. G. Allen (1999). Attendance and effects of disturbance on coastal Common Murre colonies at Point Reyes, California. Waterbirds 22:130-139.

U.S. Fish and Wildlife Service (2009). Alaska Seabird Conservation Plan. U.S. Fish and Wildlife Service, Migratory Bird Management, Anchorage, AK, USA.

Vequist, G. M. (1990). Between year comparisons of seabird populations off the Kenai Fjords coast. Unpublished National Park Service report, Anchorage, AK, USA.

Vequist, G. M., and M. Nishimoto (1989). Seabird survey on the coast of Kenai Fjords during the Exxon Valdez Oil Spill, March 31 - May 3, 1989. Unpublished report.

Verbeek, N. A. (1986). Aspects of the breeding biology of an expanded population of Glaucous-winged Gulls in British Columbia. Journal of Field Ornithology 57:22-33.

Vermeer, K. (1963). The breeding ecology of the Glaucous-winged Gull (*Larus glaucescens*) on Mandarte Island, BC. Doctoral dissertation, University of British Columbia, Canada.

Williams, B. K., J. D. Nichols, and M. J. Conroy (2002). Analysis and management of animal populations. Academic Press, San Diego, CA, USA.

Williams, J. C., L. Scharf, and G. V. Byrd (2000). Ecological monitoring methods of the Aleutian Islands Unit, Alaska Maritime Wildlife Refuge. U.S. Fish and Wildlife Service Report, AMNWR 00/01.

Zador, S. G., and J. F. Piatt (1999). Time-budgets of common murres at a declining and increasing colony in Alaska. Condor 101:149-152.

Table 2.1. Colonies of *L.glaucescens* surveyed in Kenai Fjords, Alaska. Colonies chosen capture variation in size, region, and colony characteristics. The number of times each colony was surveyed (*n*), and the latitude and longitude of the survey point for each colony (in decimal degrees), and general descriptions of colony features are listed below.

Colony name	*n*	Latitude	Longitude	Size	Region	Characteristics
Chat Island	10	59.934	149.712	Small	North	Island, partially protected, cliff
Cheval Island	10	59.774	149.503	Large	North	Island, exposed, cliff
No Name Island	10	59.717	149.512	Large	North	Island, exposed, cliff
Squab Island	10	59.934	149.712	Large	North	Island, protected, hilly
Striation Island	9	59.799	150.033	Large	South	Island, protected, cliff
Surok Point	9	59.611	150.031	Large	South	Mainland, exposed, cliff
Steep Point	9	59.487	150.249	Small	South	Mainland, exposed, cliff

Table 2.2 Estimates of nest abundance and model parameters for *L. glaucescens* in Kenai Fjords National Park, Alaska estimated from each of three models for each colony. The three considered were Attendance, Sitting and Attendance + Sitting models, with upper and lower limits of 95% credibility intervals in addition to standard deviation (SD); **t** is the proportion of PNL's that were categorized as nests, **s** is the apparent detection probability for locations likely to be nests in the models with Attendance, **r** is the apparent detection probability for locations likely to be nests in the models with Sitting, **f** is the apparent detection probability of locations categorized as non-nests in models with Attendance, and **g** is the apparent detection probability of locations categorized as non-nests in models with Sitting.

Colony	Model	$\hat{N}$	SD	Lower CI	Upper CI	t	s	r	f	g
Chat	Attendance	31	6.76	22	48	0.215	0.830		0.300	
	Sitting	26	1.62	24	29	0.181		0.771		0.085
	Attendance + Sitting	25	1.69	22	28	0.172	0.830	0.950	0.330	0.260
Cheval	Attendance	42	3.34	36	49	0.315	0.862		0.316	
	Sitting	20	1.98	16	23	0.154		0.741		0.101
	Attendance + Sitting	22	3.09	17	22	0.167	0.750	0.940	0.400	0.250
No Name	Attendance	38	4.68	30	48	0.214	0.859		0.299	
	Sitting	30	1.85	27	33	0.169		0.762		0.070
	Attendance + Sitting	30	2.00	27	33	0.169	0.888	0.858	0.326	0.215
Squab	Attendance	86	4.49	78	94	0.392	0.816		0.250	
	Sitting	75	3.99	69	81	0.341		0.681		0.082
	Attendance + Sitting	77	5.07	66	84	0.349	0.812	0.825	0.292	0.272
Steep	Attendance	33	3.59	26	40	0.267	0.772		0.247	
	Sitting	20	3.96	13	28	0.166		0.541		0.088
	Attendance + Sitting	32	4.52	24	40	0.260	0.772	0.496	0.253	0.329
Striation	Attendance	41	3.90	34	48	0.188	0.875		0.279	
	Sitting	33	5.86	25	44	0.155		0.565		0.097
	Attendance + Sitting	46	5.83	35	56	0.213	0.834	0.586	0.269	0.386
Surok	Attendance	77	3.71	70	84	0.339	0.860		0.248	
	Sitting	34	4.08	28	43	0.154		0.642		0.114
	Attendance + Sitting	72	6.05	57	80	0.319	0.874	0.493	0.316	0.262

Table 2.3. The proportion of observations that represented potential false positive or false negative error in the attendance model to estimate the abundance of *L. glaucescens* nests in Kenai Fjords National Park, Alaska. Error was either from 1) *misidentification* of nest sites, which would result in a false positive detection, or 2) when sites were *not visible* because of boat perspective during surveys, which would result in a false negative detection. Number of observations (*n*) is the sum of the terms calculated by multiplying the total number of potential nest sites at each colony times the number of times the colony was surveyed. B. The estimate of PNLs in the high attendance category, with and without accounting for potential misidentification.

Colony		**Percentage of Observations**	
		Misidentification	Unavailable
	n		
Chat	1480	0.41	2.50
Cheval	1350	0.11	1.11
No Name	1820	2.03	0.82
Squab	2210	1.58	0.32
Steep	1116	0.09	0.09
Striation	1980	2.78	0.30
Surok	2052	2.49	0
Overall	**12008**	**1.67**	**0.67**

Table 2.4 Generalized linear models (GLM) that best characterized the influence of temporal and environmental covariates on bird attendance, presence, and detection across colonies of *L. glaucescens* in Kenai Fjords National Park, Alaska. Models were selected using AICc values and model weights.

Measurement Method GLM Type	**Model**	**AICc**	**ΔAIC**	**Weight**
Count	Field ~ 1 + Colony + Tide + Swell + Temp	512.04	0.00	0.252
Field count	Field ~ 1 + Colony + Tide + Swell	513.51	1.47	0.121
Poisson	Field ~ 1 + Colony + Minute + Tide + Swell + Temp	513.96	1.92	0.097
	Field ~ 1 + Colony + Tide + Swell + Temp + Wind	514.96	2.92	0.058
	Field ~ 1 + Colony + Tide + Swell + Temp + Precip	514.98	2.93	0.058
Count	Photo ~ 1 + Colony + Tide + Swell + Temp	520.74	0.00	0.176
Photographic count	Photo ~ 1 + Colony + Minute + Tide + Swell + Temp	520.76	0.02	0.174
Poisson	Photo ~ 1 + Colony + Tide + Swell + Temp + Precip	520.86	0.12	0.166
	Photo ~ 1 + Colony + Tide + Swell + Precip	522.39	1.65	0.077
	Photo ~ 1 + Colony + Tide + Swell	522.51	1.77	0.073
Count	MR ~ 1 + Colony + Tide + Swell + Wind + Precip	517.14	0.00	0.294
Mark-resight count	MR ~ 1 + Colony + Tide + Swell + Precip	518.05	0.91	0.187
Poisson	MR ~ 1 + Colony + Tide + Swell + Temp + Precip	518.63	1.49	0.139
	MR ~ 1 + Colony + Tide + Swell + Temp + Wind + Precip	518.86	1.72	0.124
	MR ~ 1 + Colony + Minute + Tide + Swell + Wind + Precip	519.78	2.64	0.079
Presence (unlikely nests)	Presence ~ 1 + Colony + Minute + Tide + Swell + Wind + Precip	12376.59	0.00	0.371
Mark-resight capture history	Presence ~ 1 + Colony + Tide + Swell + Wind + Precip	12376.75	0.16	0.342
Logistic	Presence ~ 1 + Colony + Minute + Tide + Swell + Temp + Wind + Precip	12378.59	2.00	0.137
	Presence ~ 1 + Colony + Tide + Swell + Temp + Wind + Precip	12378.72	2.13	0.128
	Presence ~ 1 + Colony + Tide + Swell + Precip	12384.10	7.51	0.009
Presence (likely nests)	Presence ~ 1 + Colony + Swell + Temp	1395.91	0.00	0.190
Mark-resight capture history	Presence ~ 1 + Colony + Minute + Swell + Temp	1397.07	1.15	0.107
Logistic	Presence ~ 1 + Colony + Swell + Temp + Wind	1397.72	1.81	0.077
	Presence ~ 1 + Colony + Tide + Swell + Temp	1397.87	1.95	0.071
	Presence ~ 1 + Colony + Swell + Temp + Precip	1397.92	2.01	0.069

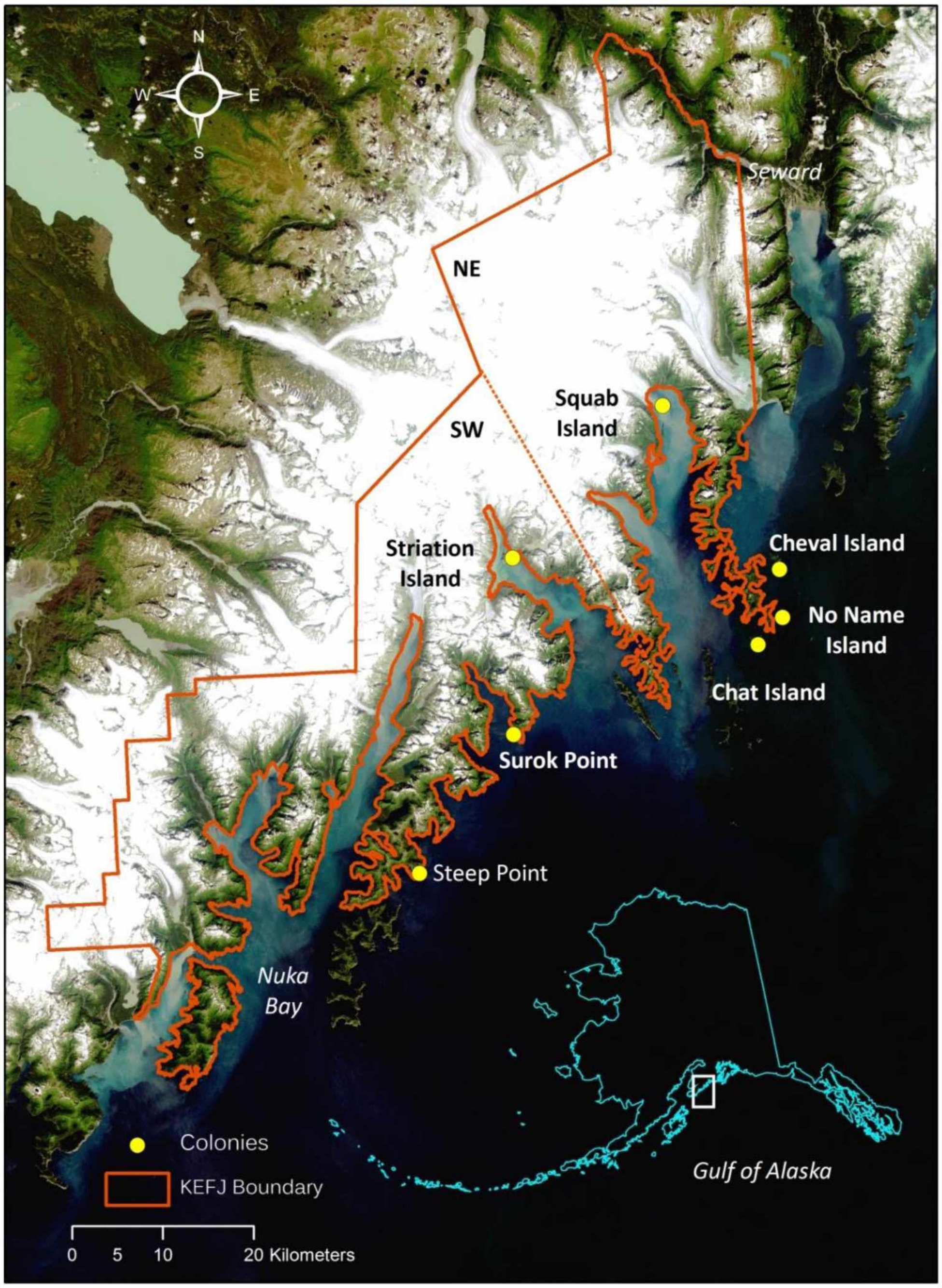


Figure 2.1 Map of Kenai Fjords National Park, Alaska (bounded area), and *L.glaucescens* colony locations surveyed during this study. Dots indicate colonies, and the dashed line approximately separates distinct regions of the park accessible by different survey vessels (NE accessible by small boat from Seward, SW accessible only by larger research vessel)

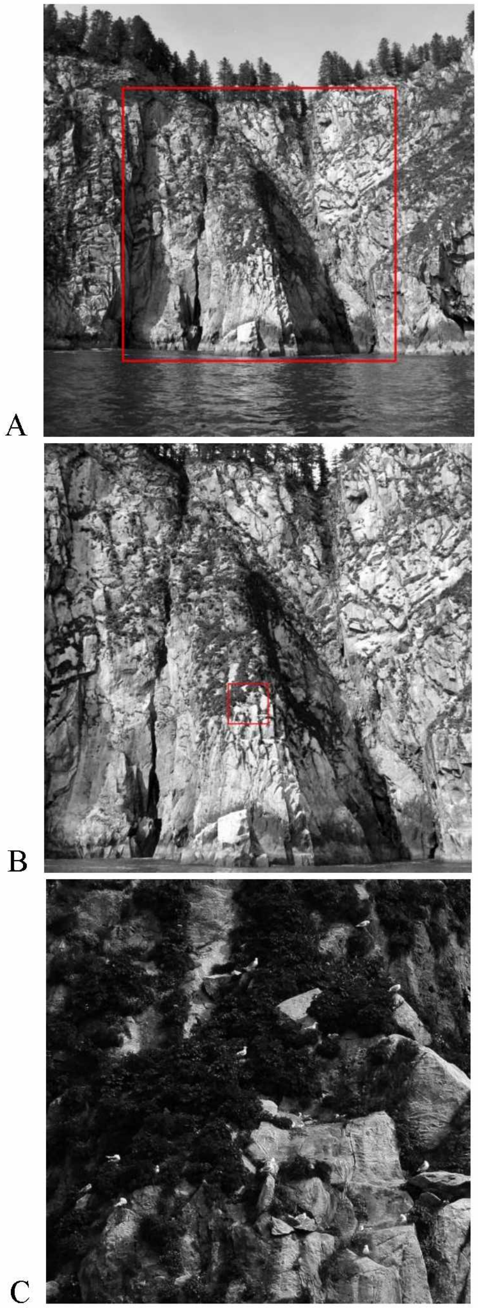


Figure 2.2 Photographs of Chat Island, an *L. glauscescens* colony in Kenai Fjords National Park, Alaska. Photos represent: (A) an overall view of the cliff containing the Chat Island colony, (B) a view that encompasses the colony plot at Chat Island, and (C) a zoomed in view of a subsection of the colony and the approximate scale of the image used to actually observe gulls.

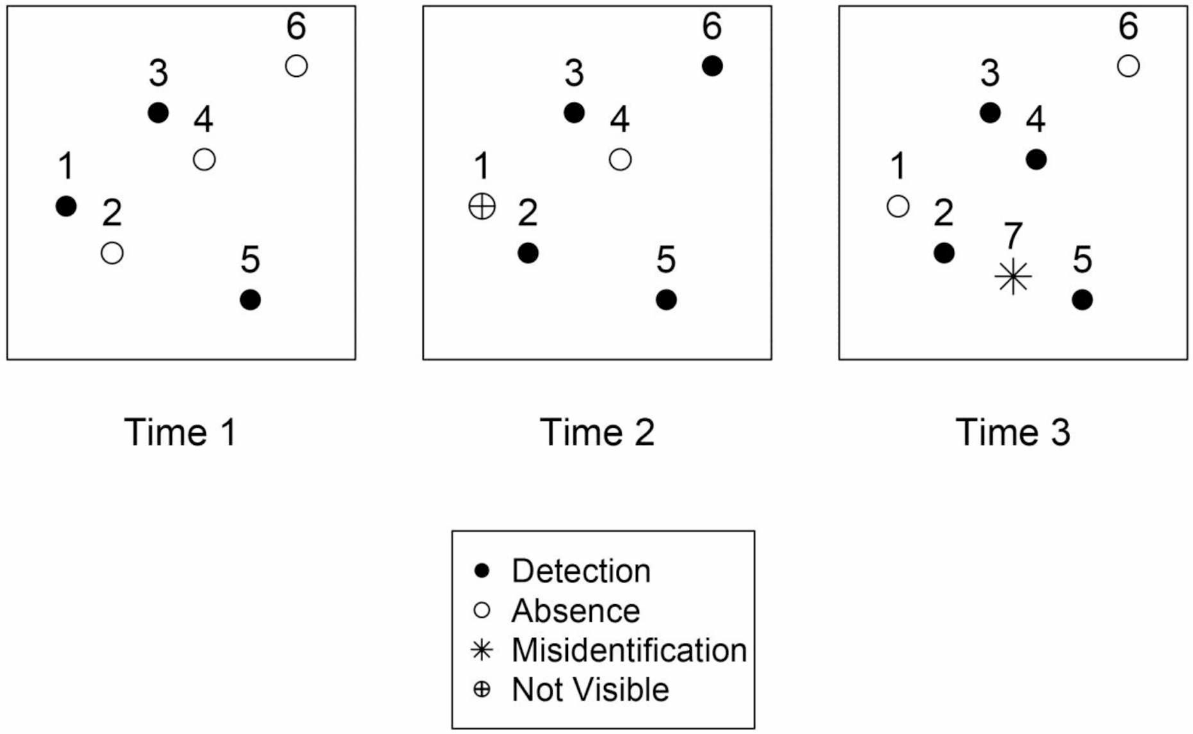


Figure 2.3 Representations of repeat photographs used to record the presence, absence, potential misidentification, and non-visibility of sites during each replicate survey at *L. glaucescens* colonies in Kenai Fjords National Park, Alaska. Scale will change for each colony and set of repeat photos, so axes are undefined. Each box represents a photo with up to 7 potential nest sites, which are indicated by the numbered points.

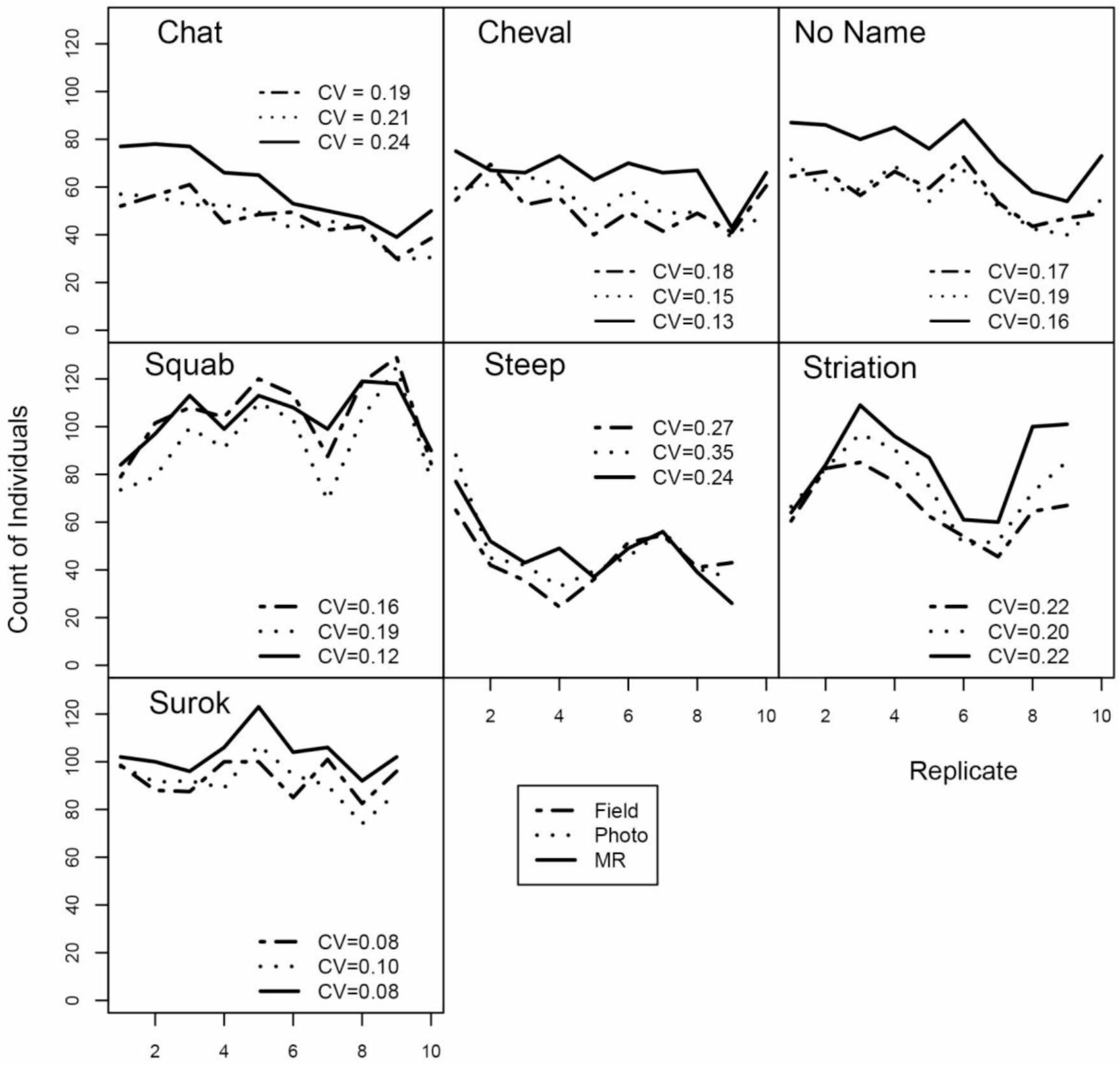


Figure 2.4 Attendance of *L. glaucescens* during replicate counts at colonies in Kenai Fjords National Park, Alaska from three different survey methods, field counts (Field), counts from photographs (Photo), and counts calculated from MR image analysis. CV is the coefficient of variation for each colony and survey method.

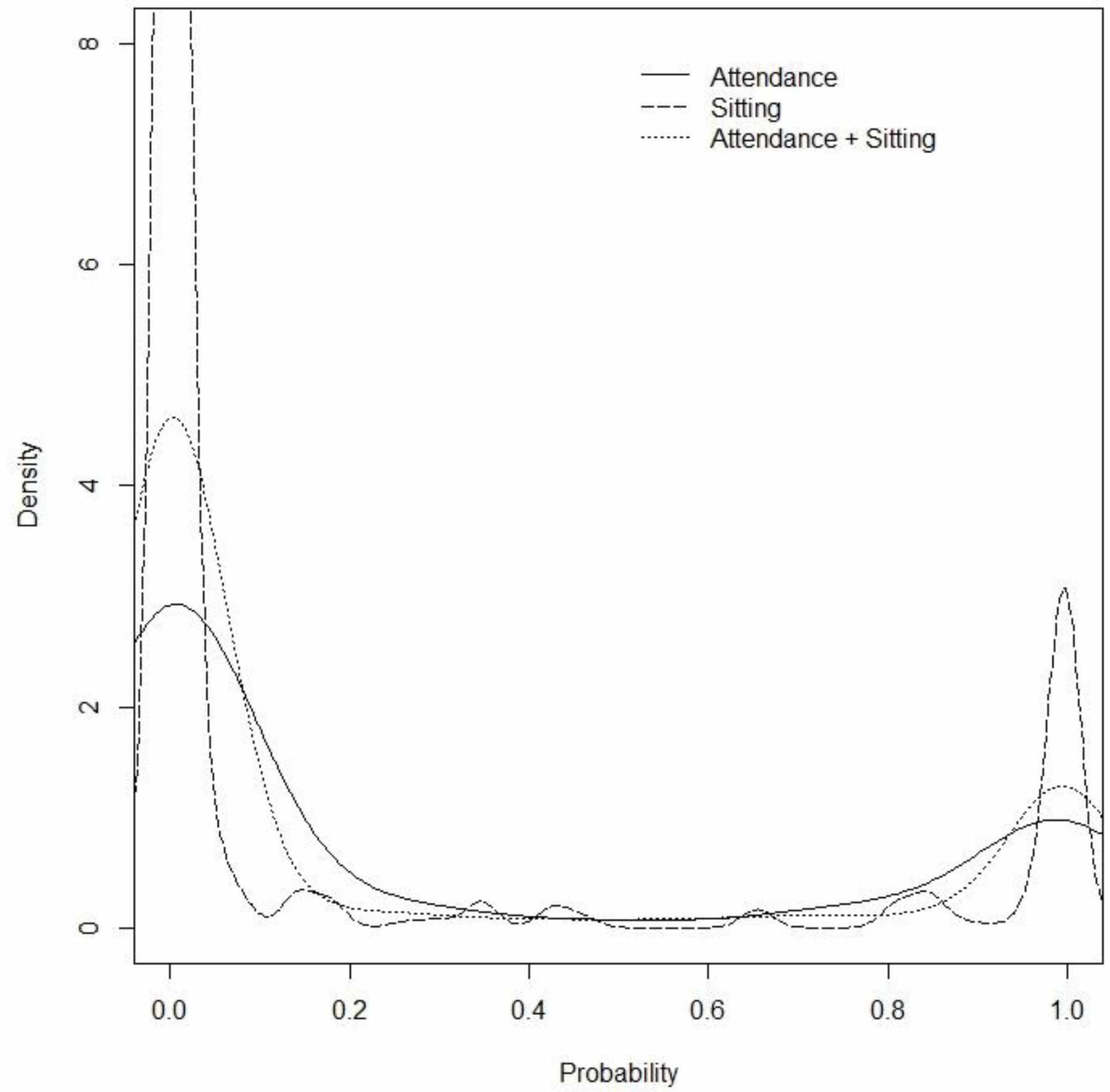
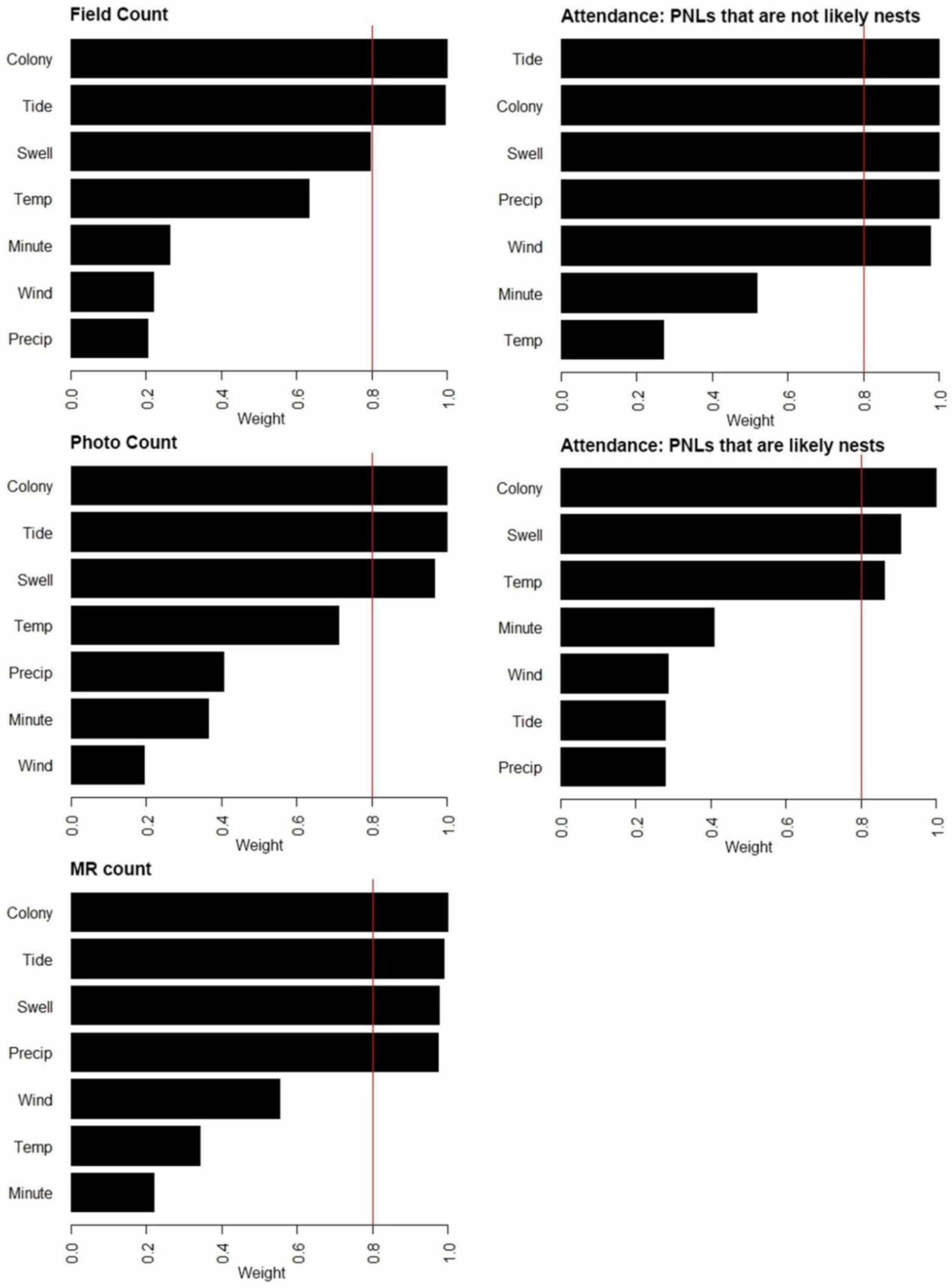


Figure 2.5 Comparison of cumulative probabilities of categories of each model (0 = low attendance and infrequent sitting, 1 = high attendance and frequent sitting) across all individual sites at all *L. glaucescens* colonies that we surveyed in Kenai Fjords National Park, Alaska. Probabilities were drawn from the results of three different mixture models: one based on just attendance, one based just on sitting behavior, and one incorporating both attendance and sitting.



Field Count

Attendance: PNLs that are not likely nests

Photo Count

Attendance: PNLs that are likely nests

MR count

Figure 2.6 Model-averaged weights of each variable included in a set of generalized linear models used to determine the influence of spatial and temporal factors on measures related to estimating the breeding abundance of *L. glaucescens* in Kenai Fjords National Park, Alaska.

Conclusion

Monitoring the abundance of species and populations is the most basic way that we gather information about communities and ecosystems. Ultimately, wildlife monitoring programs exist to inform the decisions that managers and agencies are charged to make. Robust monitoring efforts are critically important to shaping effective management outcomes. Abundance is only one component of monitoring populations, but it is the most basic way we have of measuring and communicating change in populations: how many were there in the past, how many are there now, and what the magnitude and trajectory of change might be. Thus, estimating abundance and mapping changes in population size is often a primary component of any new monitoring effort.

In Ch. 1, I describe some of the challenges in estimating seabird abundance, and tools and methods used to address them. There are many recommended methods and standard practices (Walsh et al. 1995, Bibby 2000, Sutherland et al. 2004, AMNWR 2017); however, efforts to estimate abundance vary by life history and behavior of species, regional characteristics, agency resources, modes of access, type of detections, and analytical tools. At the beginning of this project, *L. glaucescens* was identified as potentially a good initial species for developing methods because in addition to being a species important to KEFJ, it is also a large-bodied, highly visible species that could provide a good test of methods more broadly applicable to other cliff-nesting seabirds in the future. However, because *L. glaucescens* nests on vertical cliffs, makes inconspicuous nests that are difficult to see, and has variable attendance, estimating breeding abundance for this species required both the adaptation of recommended count methods for ledge-nesting species (field and photo counts) to the KEFJ environment, and the development of new methods (repeat photograph MR analyses) (Ch. 2). Moreover, though we hope these methods will prove useful for other species in KEFJ and elsewhere, each new species or location will likely require further testing and modification of existing methods.

In Ch. 2, I list our main challenges and approaches to addressing how to estimate breeding abundance for *L. glaucescens*, how we went about determining whether each potential nest location (or site with at least one detection of a bird) within a colony plot was a nest, addressing potential survey errors, and understanding what sources of variability might be impacting both surveys and bird behavior. This project was a first step in understanding how to monitor the population of *L. glaucescens* in and around KEFJ. Beyond identifying a method to estimate abundance, managers will have to decide at which scale these methods should be applied, how often monitoring should occur, and test the efficacy of these methods at detecting varying levels of population change, either through several years of repeated estimates or through a simulation study in order to inform a more permanent monitoring plan for this species.

There were many specific challenges in estimating the abundance of *L. glaucesens* in Kenai Fjords National Park: 1) KEFJ is remote and expansive; 2) colonies are numerous and spread across the park; 3) access to the coastal areas of the park is limited to air or water; 4) *L. glaucescens* nests on vertical cliff faces where nests are difficult to visually detect; 5) repeat surveys from a boat result in slightly different perspectives; 6) attendance at colonies is highly variable; 7) colonies are located in vastly different environments (e.g. the head of protected fjords vs. exposed islands and coastlines); and 8) ground-truthing abundance estimates is impractical in KEFJ. We used tools and approaches in each category I mention in Ch. 1 – access to colonies, detections of birds, and analysis of data to address each of these challenges.

Colony access in KEFJ is limiting. The closest colonies are 30 minutes apart by boat, but many are separated by up to several hours. A larger live-aboard vessel is required to get to colonies in the far part of the park (SW section, Figure 2.1), which is more expensive and limited in availability (at least if using the KEFJ research vessel, the cheapest option). Aerial surveys are expensive, limited by weather and no options exist in Seward for local charters, but surveys from the air have been shown to be an effective way to monitor seabird abundance on a large scale in the Pacific Northwest (Naughton et al. 2007). The use of unmanned aerial vehicles (UAVs) may be a cost effective and minimally invasive way to survey colonies in the future, as many can be launched from boats, are more maneuverable, and produce less noise and rotor disturbance than planes or helicopters. The modified MR approach we describe could easily be applied to repeat photographs from UAVs; UAVs and other remote sensing systems employing advanced imaging technology are becoming more common for studies looking at how to quantify seabird population size (Groom et al. 2013, Delord et al. 2015, Ratcliffe et al. 2015, McClelland et al. 2016).

We found counts of individuals (using binoculars or photographs) to be highly variable, which prompted the development of the modified mark-resight (MR) method to determine which potential nest locations (PNL) were most likely nests, vs. which locations were roosts for either mates of incubators or non-breeding individuals. Boat-based counts are difficult, both because it is challenging to keep track of physical space on a vertical cliff face and not miss or double count sections when surveying from an unstable platform, and because slight differences in perspective are difficult to detect or recognize without being able to directly compare. By analyzing high resolution photographs, we were able to both better detect birds present and estimate breeding abundance. Using repeated photographs this way also allowed us to quantify how often boat perspective caused a PNL to not be visible during a survey, and how often we potentially misidentified the state of a PNL during a survey by associating a bird with the wrong location.

We used both design and analytical approaches to address several of our challenges. We used a stratified survey design to make sure that sampled colonies represented the variation in colony size, location within the park, and type of colonies (i.e. exposed or protected, island or mainland) that exists across KEFJ. In addition, we developed a method to pair resight capture histories with a Bayesian mixing model to categorize PNLs as nests (or not). Using a Bayesian approach allowed us to incorporate a basic assumption (i.e. that birds on nests are likely present more often and sit more often), and to generate the probability that each site is the high attendance/high sitting category. This approach provided a way to approximate abundance in situations where a ground-truth is impossible or impractical, and maximized the amount of information we used as evidence for this estimate. Finally, we used both logistic and Poisson regression to examine temporal and environmental factors to consider both for surveys, and for the breeding ecology of *L. glaucesens*.

The development of new technological innovations and novel monitoring tools has given researchers more options to solve problems that may be unique to each particular challenge. This project benefited from many specific tools, such as high-resolution cameras, high powered and image-stabilized lenses, and a variety of computer software for image processing and statistical analyses (e.g. Adobe Photoshop, Microsoft Image Composite Editor, ArcGIS, R, OpenBUGS). Continued development of imaging technologies, computing capacity, and specific tools to aid in these types of analyses will make methods like ours more efficient and practical; for example, higher resolution imagery in cameras (whether handheld, on UAVs, satellites or other vehicles) (Lynch et al. 2012) or automated detection of birds or nests (Qing et al. 2011).

Abundance is only one component of population monitoring, but it is an integral part of most conservation plans and monitoring programs for seabirds (USFWS 2005, USFWS 2009, Croxall et al. 2012). Our methods could be strengthened if this approach was also used to monitor other population parameters (e.g. phenology, productivity, nest survival). Repeat photography and videography are already used to monitor some of these parameters elsewhere (Lorentzen et al. 2012, Huffeldt and Merkel 2013, Lynch et al. 2015), but our methods may be particularly useful in places where long-term, intensive monitoring is not an option, over large spatial scales, or for species or locations where ground-truth efforts are difficult or impossible. However, our methods would also benefit from being tested in locations where a robust ground-truth could be incorporated.

There are many places where a ground-truth is likely not practical or possible. We have shown that gathering behavior data is another way to improve estimates of breeding population size. If we had a robust behavior dataset on the proportion of time that birds incubate nests across our population of interest, it would help specifically define at what probability a PNL should actually be considered a nest. While we have some idea that *L. glaucescens* incubate nests consistently and mates share incubation duties from previous studies (Vermeer 1963), and also from a small set of hourly time lapse data in KEFJ (~ 15 nests across two weeks where birds were detected on known nests >95% of the time, and of those detections, were also sitting >95% of the time), we know less about other incubation behavior, like how often mates change shifts, how long incubation breaks can last, and what factors may cause birds to stand up or leave nests completely unattended.

At the outset of this project, KEFJ wanted to know how many colonies should be counted, how many times, when should surveys be timed both within seasons and also over the long term (many years), and how to translate our results into detecting significant changes in the population size of this species over time. However, we ended up taking a step back, and first spending time determining what methods we should use to estimate breeding abundance, developing new methods that might do a better job than simple counts, testing the methods we developed, and investigating what factors might affect the methods we developed. The most useful thing to come out these efforts is determining that there is additional information gained from replicate photographs as compared to counts completed in the field, and that photographs likely maximize the information gathered in the field per unit time, though it can require more time for analyses in the lab. The trade-off between information gained and the cost of field efforts in terms of staff, time, and expenses is important for KEFJ and other national parks, which are charged with protecting and conserving whole ecosystems, and often juggle with a multitude of projects simultaneously.

In the future, further delineation of specific KEFJ management goals and objectives in terms of seabirds and their place within park monitoring efforts will shape how our methods are applied, and what other types of data might best complement them. There may be more appropriate parameters to monitor than abundance that are particularly focused on understanding the drivers of environmental change and how seabird populations respond (e.g., diet and productivity, among others). Working collaboratively with the Alaska Maritime National Wildlife Refuge (AMNWR), which has a large proportion of resources dedicated to monitoring and managing seabirds across the state of Alaska, and a specific set of goals listed within the seabird conservation plan for the state of Alaska (USFWS 2009, AMNWR 2017), can assist the park in identifying future conservation priorities. Though the National Park Service and the U.S. Fish and Wildlife Service have different foci and overall missions, they have a shared interest in this particular region due to the way that land jurisdiction occurs near KEFJ – islands are part of the AMNWR, while the continental coastline is technically within park boundaries. I hope that this study has served as an important step in furthering the process of seabird research and conservation in the KEFJ region, and that the methods we developed are useful to managers interested in the abundance of colonial, cliff-nesting, and seabird species. Finally, I believe that this thesis provides a jumping off place for KEFJ to contemplate what seabirds contribute to the park, what monitoring their populations means to the mission of the park, what specific species may need attention in this and neighboring regions, what larger and complementary priorities exist among other agencies or organizations interested in seabird monitoring and management, and what the potential management options are that the park could consider.

Literature Cited

Alaska Maritime National Wildlife Refuge (2017). Standardized protocols for annual seabird monitoring camps at Aiktak, Buldir, Chowiet, St. George, St. Lazaria, and St. Paul islands, Cape Lisburne, and select intermittent sites in the Alaska Maritime National Wildlife Refuge in 2017. U.S. Fish and Wildlife Service Report, Homer, AK, USA. AMNWR 2017/07.

Bibby, C. J. (2000). Bird census techniques. Elsevier, London, UK.

Croxall, J. P., S. H. Butchart, B. Lascelles, A. J. Stattersfield, B. Sullivan, A. Symes, and P. Taylor (2012). Seabird conservation status, threats and priority actions: a global assessment. Bird Conservation International 22:1-34.

Delord, K., G. Roudaut, C. Guinet, C. Barbraud, S. Bertrand, and H. Weimerskirch (2015). Kite aerial photography: a low-cost method for monitoring seabird colonies. Journal of Field Ornithology 86:173-179.

Groom, G., M. Stjernholm, R. D. Nielsen, A. Fleetwood, and I. K. Petersen (2013). Remote sensing image data and automated analysis to describe marine bird distributions and abundances. Ecological Informatics 14:2-8.

Huffeldt, N. P., and F. R. Merkel (2013). Remote time-lapse photography as a monitoring tool for colonial breeding seabirds: a case study using thick-billed murres (*Uria lomvia*). Waterbirds 36:330-341.

Lorentzen, E., R. Choquet, and H. Steen (2012). Modelling state uncertainty with photo series data for the estimation of breeding success in a cliff-nesting seabird. Journal of Ornithology 152:477-483.

Lynch, H. J., R. White, A. D. Black, and R. Naveen (2012). Detection, differentiation, and abundance estimation of penguin species by high-resolution satellite imagery. Polar Biology 35:963-968.

Lynch, T. P., R. Alderman, and A. J. Hobday (2015). A high-resolution panorama camera system for monitoring colony-wide seabird nesting behaviour. Methods in Ecology and Evolution 6:491-499.

McClelland, G. T. W., A. L. Bond, A. Sardana, and T. Glass (2016). Rapid population estimate of a surface-nesting seabird on a remote island using a low-cost unmanned aerial vehicle. Marine Ornithology 44:215-220.

Naughton, M. B., D. S. Pitkin, R. W. Lowe, K. J. So, and C. S. Strong (2007). Catalog of Oregon Seabird Colonies. U.S. Department of the Interior, Fish and Wildlife Service, Washington D.C., USA. FWS/BTP-R1009-2007

Qing, C., P. Dickinson, S. Lawson, and R. Freeman (2011). Automatic nesting seabird detection based on boosted HOG-LBP descriptors. In Image Processing (ICIP), 2011 18th IEEE International Conference: 3577-3580.

Ratcliffe, N., D. Guihen, J. Robst, S. Crofts, A. Stanworth, and P. Enderlein (2015). A protocol for the aerial survey of penguin colonies using UAVs. Journal of Unmanned Vehicle Systems 3:95-101.

U. S. Fish and Wildlife Service (2005). Regional Seabird Conservation Plan, Pacific Region. U.S. Fish and Wildlife Service, Migratory Birds and Habitat Programs, Pacific Region, Portland, OR, USA.

U.S. Fish and Wildlife Service (2009). Alaska Seabird Conservation Plan. U.S. Fish and Wildlife Service, Migratory Bird Management, Anchorage, AK, USA.

Sutherland, W. J., I. Newton, and R. Green (2004). Bird Ecology and Conservation: a Handbook of Techniques. Oxford University Press, New York, NY, USA.

Vermeer, K (1963). The breeding ecology of the Glaucous-winged Gull (*Larus glaucescens*) on Mandarte Island, BC. Doctoral dissertation, University of British Columbia, Vancouver, Canada.

Walsh, P., D. Halley, M. Harris, A. Del Nevo, I. Sim, and M. Tasker (1995). Seabird monitoring handbook for Britain and Ireland: a compilation of methods for survey and monitoring of breeding seabirds. JNCC/RSPB/ITE/Seabird Group. Peterborough, UK.

Appendices

Appendix 1 Modified MR approach

Bayesian mixture model

Open BUGS model statements and prior

Attendance model

```
{
for(i in 1:M){
$x_i \sim \textit{Binomial}\ (\pi_i, n)$
$p_i=\Psi_i*s + (1- \Psi_i)*f$
$\Psi_i \sim$ Bernoulli (t)
}
priors:
π ~dunif(0,1)
a~dnorm(0,1)
b~dexp(0.01)
logit(f)<-a
logit(s)<-a+b
N<-sum(nest[])
}
```

Sitting Model

```
{
for(i in 1:M){
$y_i \sim \textit{Binomial}\ (ø_i, n)$
$ø_i=\Psi_i*r + (1- \Psi_i)*g$
$\Psi_i \sim$ Bernoulli (t)
}
priors:
ø ~dunif(0,1)
c~dnorm(0,1)
d~dexp(0.01)
logit(g)<-c
logit(r)<-c+d
N<-sum(nest[])
}
```

Attendance + Sitting Model

```
{
for(i in 1:M){
$x_i \sim \textit{Binomial}\ (\pi'_i, n)$
$y_i \sim \textit{Binomial}\ (ø'_i, x_i)$
$\pi'_i=\Psi''_i*s' + (1- \Psi''_i)*f'$
$ø'_i= \Psi'_i*r' + (1- \Psi''_i)*g'$
$\Psi''_i \sim \textit{Bernoulli}$ (t)
}
t ~dunif(0,1)
a~dnorm(0,0.001)
b~dexp(0.001)
c~dnorm(0,0.001)
d~dexp(0.001)
logit(f)<-a
logit(s)<-a+b
logit(g)<-c
logit(r)<-c+d
N<-sum(nest[])
}
```

Multinomial model incorporating misidentification, and PNLs not visible
(modification of Attendance model)

```
{
for(i in 1:M){
$z_{[i,1]} \sim \textit{Binomial}\ (\Theta_{[i,1]}, n_{[i,1]})$
$z_{[i,2]} \sim \textit{Binomial}\ (\Theta_{[i,2]}, n_{[i,2]})$
$\Theta_{[i,1]}= (\Psi_i*(s_1)) + ((1- \Psi_i)*f_1)$
$\Theta_{[i,2]}= (\Psi_i*(s_2)) + ((1- \Psi_i)*f_2)$
$\Psi_i \sim \textit{Bernoulli}$ (t)
}
p~dunif(0,1)
a~dnorm(0,1)
b~dexp(0.1)
c~dexp(0.01)
d~dnorm(0,1)
logit(s1)<-a
logit(f1)<-a+b
logit(s2)<-c
logit(f2)<-c+d
N<-sum(nest[])
}
```

Appendix 2 Misidentification

Estimates of the number of PNLs that were likely to be nests (in the high attendance category) using the Attendance (A) model (which does not account for potential misidentification error) and a multinomial model accounting for potential misidentification error.

Colony		**Nest Category Estimates**			
		N (Attendance)	SD	N (MisID)	SD
	n				
Chat	10	31	6.76	25	3.61
Cheval	10	42	3.34	40	2.94
No Name	10	38	4.68	32	3.17
Squab	10	86	4.49	85	3.90
Steep	9	33	3.59	31	3.57
Striation	9	41	3.92	39	3.52
Surok	9	77	3.71	73	3.47
Overall	**9**	**349**	**30.49**	**325**	**24.18**

Appendix 3 Covariate analyses

General model forms

Poisson regression
for $\underline{X}$= X1,….,Xn (multiple variables)
$\log(\pi(x))=\alpha + \beta_1 X_1 + B_2 X_2 + \ldots + B_n X_n$
$\pi(x)$ = counts or rates

Logistic regression
for $\underline{X}$= X1,….,Xn (multiple variables)
$\mathrm{logit}(\pi(x))=\alpha + \beta_1 X_1 + B_2 X_2 + \ldots + B_n X_n$
$\pi(x)$ = bernoulli trials with a 0 or 1 outcome

(Agresti et al. 2013)

Correlation Matrices

All variables

	Temp	**Wind**	**Cloud**	**Precip**	**Tide**	**Swell**	**Minute**	**Day**
Temp	1	-0.03902	-0.5264	-0.62269	-0.21091	-0.23319	-0.02956	-0.79861
Wind	-0.03902	1	0.318883	0.427155	-0.12061	0.456037	0.073626	0.195927
Cloud	-0.5264	0.318883	1	0.562981	0.14442	0.350307	-0.00211	0.625093
Precip	-0.62269	0.427155	0.562981	1	0.078117	0.610771	0.226495	0.75307
Tide	-0.21091	-0.12061	0.14442	0.078117	1	0.155954	0.509489	0.065742
Swell	-0.23319	0.456037	0.350307	0.610771	0.155954	1	0.129083	0.229876
Minute	-0.02956	0.073626	-0.00211	0.226495	0.509489	0.129083	1	-0.02453
Day	-0.79861	0.195927	0.625093	0.75307	0.065742	0.229876	-0.02453	1

All variables except "Day"

	Temp	**Wind**	**Cloud**	**Precip**	**Tide**	**Swell**	**Minute**
Temp	1	-0.03902	-0.5264	-0.62269	-0.21091	-0.23319	-0.02956
Wind	-0.03902	1	0.318883	0.427155	-0.12061	0.456037	0.073626
Cloud	-0.5264	0.318883	1	0.562981	0.14442	0.350307	-0.00211
Precip	-0.62269	0.427155	0.562981	1	0.078117	0.610771	0.226495
Tide	-0.21091	-0.12061	0.14442	0.078117	1	0.155954	0.509489
Swell	-0.23319	0.456037	0.350307	0.610771	0.155954	1	0.129083
Minute	-0.02956	0.073626	-0.00211	0.226495	0.509489	0.129083	1

All variables except "Swell"

	Temp	**Wind**	**Cloud**	**Precip**	**Tide**	**Minute**	**Day**
Temp	1	-0.03902	-0.5264	-0.62269	-0.21091	-0.02956	-0.79861
Wind	-0.03902	1	0.318883	0.427155	-0.12061	0.073626	0.195927
Cloud	-0.5264	0.318883	1	0.562981	0.14442	-0.00211	0.625093
Precip	-0.62269	0.427155	0.562981	1	0.078117	0.226495	0.75307
Tide	-0.21091	-0.12061	0.14442	0.078117	1	0.509489	0.065742
Minute	-0.02956	0.073626	-0.00211	0.226495	0.509489	1	-0.02453
Day	-0.79861	0.195927	0.625093	0.75307	0.065742	-0.02453	1

All variables except "Cloud"

	Wind	Precip	Tide	Swell	Minute	Temp	Day
Wind	1	0.427155	-0.12061	0.456037	0.073626	-0.03902	0.195927
Precip	0.427155	1	0.078117	0.610771	0.226495	-0.62269	0.75307
Tide	-0.12061	0.078117	1	0.155954	0.509489	-0.21091	0.065742
Swell	0.456037	0.610771	0.155954	1	0.129083	-0.23319	0.229876
Minute	0.073626	0.226495	0.509489	0.129083	1	-0.02956	-0.02453
Temp	-0.03902	-0.62269	-0.21091	-0.23319	-0.02956	1	-0.79861
Day	0.195927	0.75307	0.065742	0.229876	-0.02453	-0.79861	1

All variables except "Day" and "Cloud"

	Wind	Precip	Tide	Swell	Minute	Temp
Wind	1	0.427155	-0.12061	0.456037	0.073626	-0.03902
Precip	0.427155	1	0.078117	0.610771	0.226495	-0.62269
Tide	-0.12061	0.078117	1	0.155954	0.509489	-0.21091
Swell	0.456037	0.610771	0.155954	1	0.129083	-0.23319
Minute	0.073626	0.226495	0.509489	0.129083	1	-0.02956
Temp	-0.03902	-0.62269	-0.21091	-0.23319	-0.02956	1

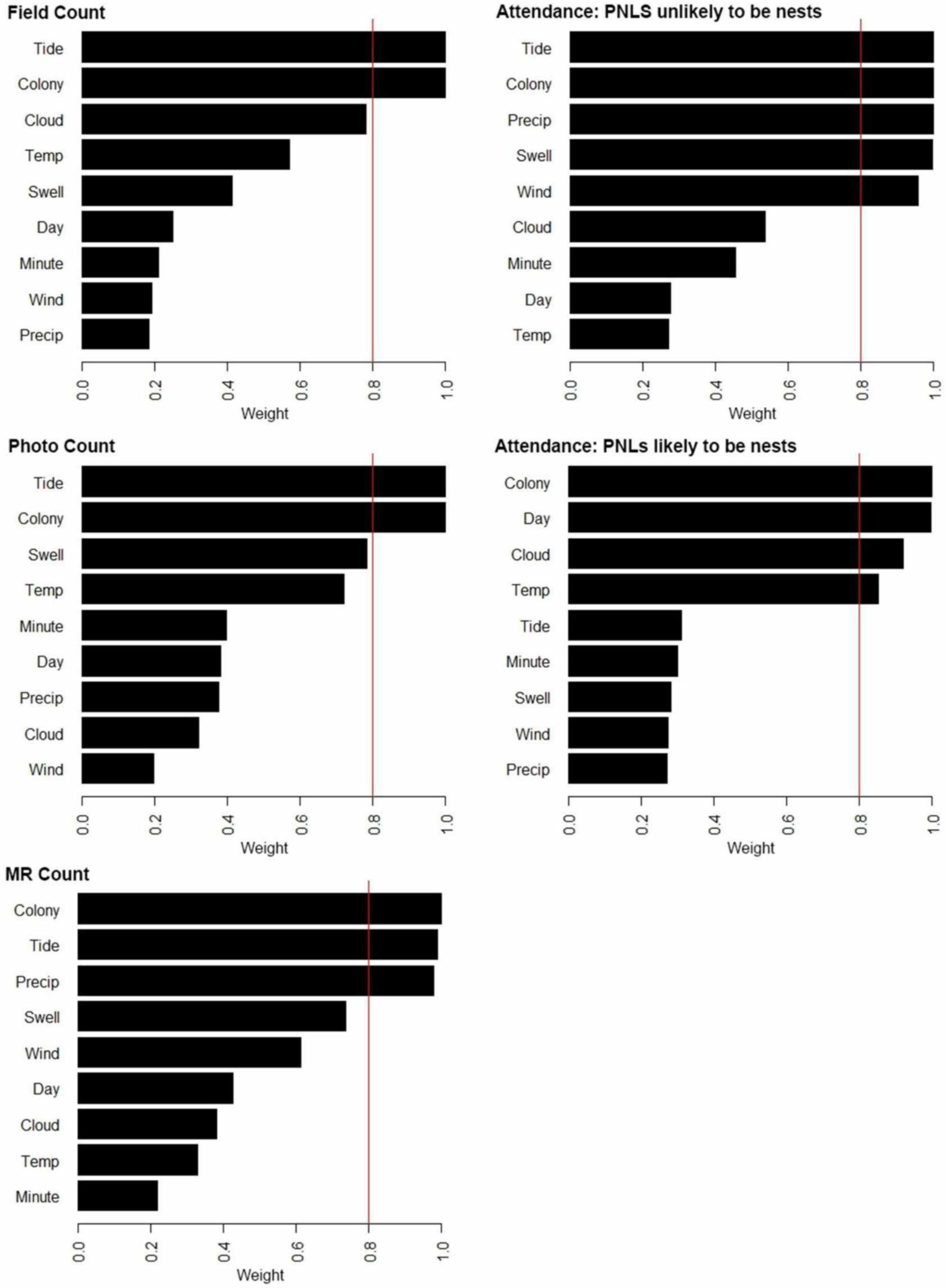
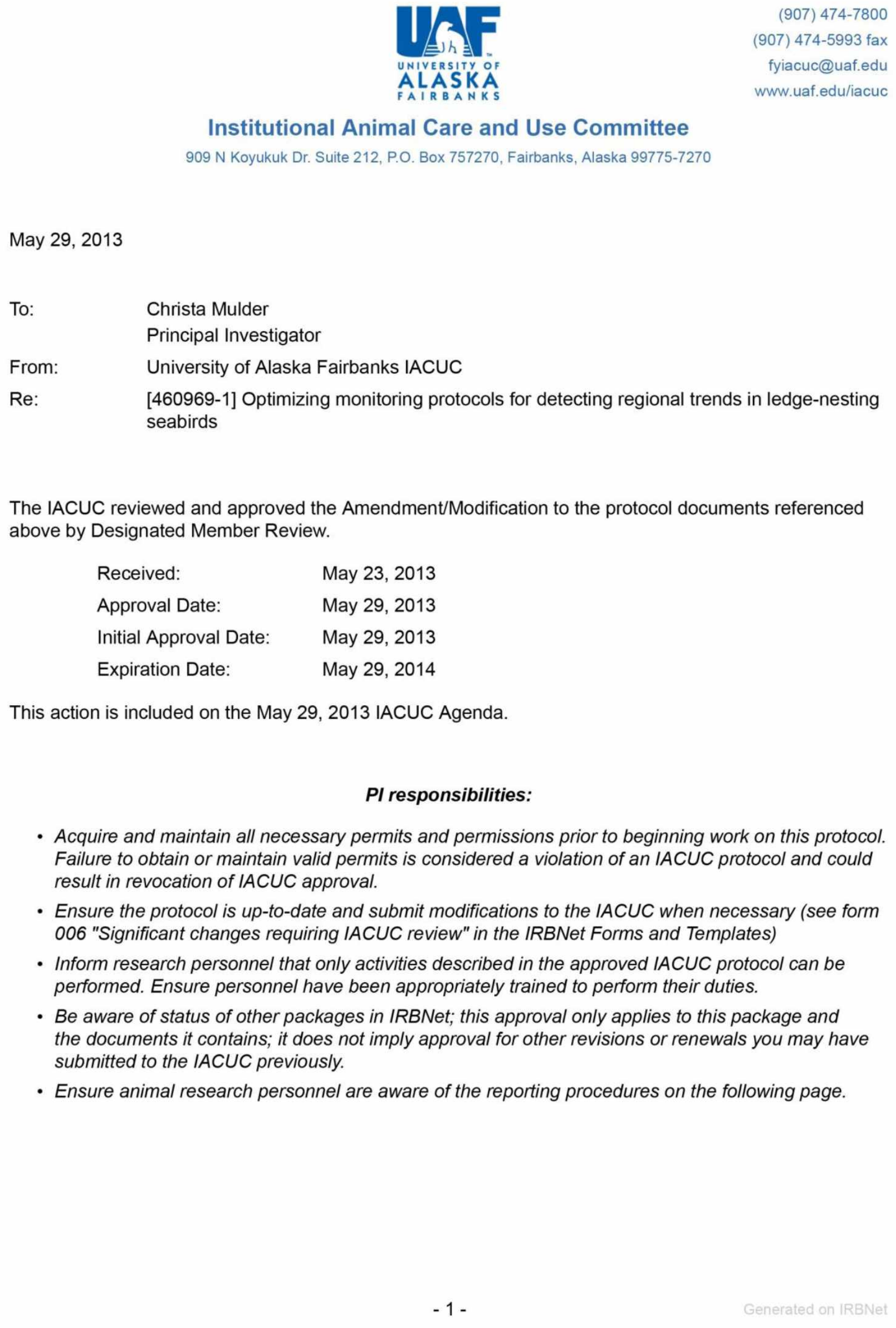


Figure A2.1 Model-averaged weights of each variable included in a set of generalized linear models used to determine the influence of spatial and temporal factors on measures related to estimating the breeding abundance of *L. glaucescens* in Kenai Fjords National Park, Alaska. This figure contains all variables, even those highly correlated, for reference.

Appendix 4 IACUC Approval Letters



UNIVERSITY OF
ALASKA
FAIRBANKS

(907) 474-7800
(907) 474-5993 fax
fyiacuc@uaf.edu
www.uaf.edu/iacuc

Institutional Animal Care and Use Committee
909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

May 29, 2013

To: Christa Mulder
Principal Investigator
From: University of Alaska Fairbanks IACUC
Re: [460969-1] Optimizing monitoring protocols for detecting regional trends in ledge-nesting seabirds

The IACUC reviewed and approved the Amendment/Modification to the protocol documents referenced above by Designated Member Review.

Received:	May 23, 2013
Approval Date:	May 29, 2013
Initial Approval Date:	May 29, 2013
Expiration Date:	May 29, 2014

This action is included on the May 29, 2013 IACUC Agenda.

PI responsibilities:

- *Acquire and maintain all necessary permits and permissions prior to beginning work on this protocol. Failure to obtain or maintain valid permits is considered a violation of an IACUC protocol and could result in revocation of IACUC approval.*
- *Ensure the protocol is up-to-date and submit modifications to the IACUC when necessary (see form 006 "Significant changes requiring IACUC review" in the IRBNet Forms and Templates)*
- *Inform research personnel that only activities described in the approved IACUC protocol can be performed. Ensure personnel have been appropriately trained to perform their duties.*
- *Be aware of status of other packages in IRBNet; this approval only applies to this package and the documents it contains; it does not imply approval for other revisions or renewals you may have submitted to the IACUC previously.*
- *Ensure animal research personnel are aware of the reporting procedures on the following page.*

UNIVERSITY OF
ALASKA
FAIRBANKS

(907) 474-7800
(907) 474-5993 fax
uaf-iacuc@alaska.edu
www.uaf.edu/iacuc

Institutional Animal Care and Use Committee

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

June 2, 2014

To:	Christa Mulder Principal Investigator
From:	University of Alaska Fairbanks IACUC
Re:	[460969-2] Optimizing monitoring protocols for detecting regional trends in ledge-nesting seabirds

The IACUC has reviewed the Progress Report by Designated Member Review and the Protocol has been approved for an additional year.

Received:	April 29, 2014
Initial Approval Date:	May 29, 2013
Effective Date:	June 2, 2014
Expiration Date:	May 29, 2015

This action is included on the June 12, 2014 IACUC Agenda.

PI responsibilities:

- *Acquire and maintain all necessary permits and permissions prior to beginning work on this protocol. Failure to obtain or maintain valid permits is considered a violation of an IACUC protocol and could result in revocation of IACUC approval.*
- *Ensure the protocol is up-to-date and submit modifications to the IACUC when necessary (see form 006 "Significant changes requiring IACUC review" in the IRBNet Forms and Templates)*
- *Inform research personnel that only activities described in the approved IACUC protocol can be performed. Ensure personnel have been appropriately trained to perform their duties.*
- *Be aware of status of other packages in IRBNet; this approval only applies to this package and the documents it contains; it does not imply approval for other revisions or renewals you may have submitted to the IACUC previously.*
- *Ensure animal research personnel are aware of the reporting procedures detailed in the form 005 "Reporting Concerns".*