

SOUNDSCAPES ON THE ARCTIC COASTAL PLAIN: ASSESSING SOUND  
DISTURBANCE AND THE AUDITORY SENSITIVITY OF CARIBOU (*RANGIFER  
TARANDUS*)

By

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## ABSTRACT

The Arctic Coastal Plain of Alaska is a region on traditional Inupiat land that supports millions of migratory birds and over half a million caribou (*Rangifer tarandus*) at the most critical time in their life-histories. They are an important part of seasonal subsistence activities for the surrounding rural Indigenous communities. Therefore, conservation efforts that support this ecosystem also bolster food security in the region. Monitoring this system has increasingly become a necessary and prudent task as the landscape evolves under the pressures of resource extraction and climate change. To date, limited research has been conducted on the sounds present in this environment (i.e., ‘soundscape’). Monitoring sounds may help reveal the impact of these stressors and ecosystem-wide changes. There is also a need for researchers to evaluate what portion of the soundscape wildlife can actually hear, so we can better understand how soundscape change might affect them.

I conducted two studies that apply soundscape monitoring and acoustic perception to the landscape and wildlife of the Arctic Coastal Plain. First, I evaluated the hearing thresholds of domestic *Rangifer tarandus* (reindeer) at the Large Animal Research Station at the University of Alaska Fairbanks in 2019 in order to help infer what anthropogenic sounds wild caribou may be sensitive to. Using Brainstem Auditory Evoked Response methods, I found that a caribou’s auditory system can detect all forms of anthropogenic sounds that they might encounter on the Arctic Coastal Plain, including low frequency sounds associated with oil and gas exploration. Specifically, I found they can detect sounds as low as 30 Hz with great sensitivity, expanding the known lower limit of their auditory capabilities. This means that caribou may detect sounds of seismic exploration, gravel mine blasting and other anthropogenic sounds associated with resource extraction at a great distance, and may be more affected by these sounds than previously thought.

From May through August of 2019, I used acoustic recording units stationed in a random grid across the Arctic Coastal Plain to passively monitor the soundscape study region-wide sound characteristics and their impact on vocal wildlife. Anthropogenic sound (i.e., anthrophony) is a pervasive and often overlooked consequence of land-use change, and something that has been relatively understudied in northern Alaska. For my soundscape research, I modeled the spatial and temporal distribution of anthrophony and bird vocalizations

(i.e., biophony) across developed (Oilfields surrounding Prudhoe Bay), and undeveloped (Arctic National Wildlife Refuge) areas of the Arctic Coastal Plain. Hourly detections of anthrophony were not associated strongly with infrastructure but tended to increase as the season went on. Birds were more likely to vocalize in hours when anthrophony was present, and this effect was the strongest in the early season, during migratory bird arrival and breeding. Anthrophony's effect on the soundscape may alter biological cues that vocal and non-vocal migrants use to assess habitat patches, and fitness consequences will vary by species. Further research is needed to assess how bird communities and caribou movement respond to anthrophony.

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## CHAPTER 1: General Introduction

### 1.1 SETTING THE STAGE

The Arctic Coastal Plain (ACP) of Alaska often takes center stage in conflicts over land use and management because it is a haven for wildlife and a sought-after resource for industry. Industrial sound, and its impact on wildlife, has been studied little in this system, despite increased community concerns surrounding it (Stinchcomb et al. 2020). The purpose of my work is to bridge this gap: first, by exploring how caribou (*Rangifer tarandus*)—an important subsistence species—are able to perceive sound disturbances, and second, by characterizing the qualities of the soundscape in this ecosystem throughout developed and undeveloped regions for the first time. Soundscapes are defined as all the sound present in an environment, often divided into three designations: biotic sound (biophony), human-made sounds (anthrophony) and abiotic sounds (geophony). It was legislation that opened oil and gas exploration in the Arctic National Wildlife Refuge (hereafter referred to as ‘The Refuge’) during the Trump Administration that partially prompted this research. There was a need to acquire baseline information on this system to better measure potential, environmental changes in the face of development and global climate change. Landscape changes due to climate change—while less dramatic than human developments—are more widespread, and are already actively affecting wildlife in the region (Boelman et al. 2015, Fauchald et al. 2017, Tape et al. 2010, Zhou et al. 2020).

Soundscape monitoring is a cost-effective solution for monitoring wildlife activity and industrial sound. The Refuge sits on traditional Inupiat lands and hosts the calving grounds of the Porcupine Caribou Herd (PCH) and the nesting grounds of some 180 species of migratory birds that come from nearly every continent on the globe. The diversity of bird species alone makes potential development an issue of international concern. Concerns over the PCH are also a solidly international affair since the herd is an anchor of food security and culture for Gwich’in, Inupiat and Inuvialuit communities in Alaska and the Yukon Territory (Parlee et al. 2018). The other half of my soundscape monitoring efforts took place in the oilfields surrounding Prudhoe Bay (hereafter referred to as “The Oilfields”), a region just east of The Refuge where the smaller Central Arctic Caribou Herd (CACH) calves. Caribou in that region avoid infrastructure largely during the calving period, but regularly cross roads and gravel pads in midsummer to avoid insect harassment (Prichard et al. 2020), and it’s unclear what role sound plays in this seasonal

sensitivity. The Oilfields contain four times the number of migratory aquatic birds as The Refuge (Bart et al. 2013), and is arguably a more valuable region for avian conservation based on these differences in sheer volume. While local changes in avian distributions have been documented (Amundson et al. 2019), the role that sound disturbance plays has not been investigated at this scale

Unraveling the impact that human noise (“anthrophony” hereafter) can have on wildlife and the soundscape requires both a better understanding of the wildlife themselves, and the dynamics of the soundscape around them. This thesis explores that in 2 parts: first, by testing the hearing thresholds of caribou and identifying common sounds on the ACP that fall within their hearing range, and second, by evaluating the occurrence of anthrophony and its influence on biological sounds within the soundscape. Changes in the soundscape driven by anthropogenic forces may be reflective of disturbances that directly or indirectly affect migratory birds and caribou at sensitive times in their life history, and should be taken into consideration by land managers and industry leaders. Both chapters are important points of reference for the impacts of sound at the species and ecosystem level.

## 1.2 BACKGROUND ON CARIBOU

Caribou are among one of the most important subsistence resources on the ACP and the North Slope of Alaska as a whole, and the effect that soundscape changes may have on them is not well understood. To better understand what sounds have the potential to disturb them—i.e. what sound frequencies they can even hear, I tested their hearing thresholds using domestic reindeer (also *Rangifer tarandus*). This approach comes from the field of sensory ecology, where it is important to understand how an organism perceives their environment in order to evaluate how they’re affected by a stimulus (Dominoni et al. 2020, Farina and Napoletano 2010, Winters and Higham 2015). While some studies have investigated the hearing range of a species for the purposes of understanding sound disturbance (Flydal et al. 2001, Flydal and Kilda 2003, Krausman et al. 1994), it is not always standard practice to employ the lens of sensory ecology when studying wildlife and soundscapes. My work is a case study on the importance of using hearing thresholds, and the framework I employ could be more broadly applied to other species on the ACP.

Sound disturbance may be a missing link to understanding how caribou navigate the human infrastructure and activity, and teasing out the nuances of its effect could help facilitate better

coexistence between animal and industry. Many studies have touched on the fact that the overlap between caribou and industry is not without compromise on the part of the caribou (Johnson et al. 2020, Lawhead and Prichard 2009, Prichard et al. 2020, Whitten and Cameron 1983). While calving was known to occur within The Oilfields prior to development, calving events there were rare in the 1980s, and cows appeared to avoid development and the road system more than bulls (Whitten and Cameron 1983). Cows have shown sensitivity to aircraft overflights in other systems (Maier et al. 1998), but it's unclear how much sound has contributed to range shifts or movement patterns in our area. However, the distance at which caribou avoid infrastructure during the most sensitive period in their life-history (calving) is approximately 5 km (Johnson et al. 2020), which far exceeds their ability to see any physical structures. It's possible that the caribou's avoidant behavior is mediated by sound, given that the radius of sound from industrial activity can range anywhere from 2-19km (BLM 2019). The frequency (in Hz) of these sounds, and their distribution across space and time during my study period, are important contributions that I make in both chapters.

### 1.3 BACKGROUND ON SOUNDSCAPES

Each of the broad categories defined within a soundscape (anthrophony, biophony, and geophony) provide different information about the environment (Pijanowski et al. 2011). Geophony can be used to identify certain weather events (Quinn et al. 2022) and water features, while the anthrophony can describe land-use change (Joo et al. 2011) and quantify human disturbance (Alvarez-Berrios et al. 2016, Tucker et al. 2014). Biophony can help identify the arrival and departure dates of certain migratory species (Oliver et al. 2018), and describe an area's activity patterns, biodiversity, and species richness (Goodwin et al. 2011, Tucker et al. 2014, Wimmer et al. 2013). Interactions between biophony and climatic cycles (Sueur et al. 2019), can inform us about wildlife responses to disturbance. The interactions between biophony and anthrophony can be particularly telling about broad, community level responses to human disturbance (Buxton et al. 2016, Francis et al. 2012, Vincelette et al. 2021), and this relationship is a primary focus in our soundscape work.

In other ecosystems, soundscape monitoring has shown great utility as a tool that can detect natural landscape characteristics (Fuller et al. 2015), changes in biodiversity (Bormpoudakis et al. 2013, Sethi et al. 2020), and the land-use patterns that affect them (Alvarez-Berrios et al. 2016,

Bayne et al. 2008, Duarte et al. 2015, Francis et al. 2011a, Ross et al. 2018). To date, it has not been applied to the terrestrial ecosystems of the ACP, despite an urgent need for baseline acoustic data in the face of global warming, expanding and proposed development, and increased community concern over industry sound (Stinchcomb et al. 2020). Without a record of the present soundscape, we will be unable to quantify how all these factors change it in the future. Its importance is underscored not only by what it can tell us about the environment, but also by what it can tell other organisms; some animals may use the soundscape as a cue to find resources and conspecifics (Mönkkönen and Forsman 2004), avoid predators (Fallow et al. 2010), and generally orient themselves in the environment (Slabbekoorn and Bouton 2008). Changes to this important cue can thus have potentially profound effects on community structure (Francis et al. 2012, Francis et al. 2011b) by altering the habitat use and occupancy rates of certain species (Iglesias-Merchan et al. 2018, Kleist et al. 2020, Molles et al. 2008), and the fitness of others (Halfwerk et al. 2011).

In my system, migratory birds are the main contributors to biophony, and I used birds as a proxy for biophony when evaluating the phonic interaction with anthrophony. I installed 40 acoustic recording units (ARUs) across The Refuge and The Oilfields. In these two regions, waterbirds alone have a population of 4.9 million (Bart et al. 2013), and some 180 bird species migrate to the ACP annually to breed. Of all the migratory wildlife, birds are the first to arrive, occupying snow and ice-free patches before the landscape is completely thawed (Oliver et al. 2018, Wingfield et al. 2004). Migratory birds may use the acoustic cues of other species during habitat selection (Mönkkönen et al. 1997), because it can benefit their fitness (Mönkkönen and Forsman 2001). Conspecific song in particular can encourage settlement in dispersing individuals (Molles et al. 2008), returning migrants (Hahn and Silverman 2007), and colonial species (Podolsky 1990). This mechanism could potentially aggravate the changes in community structure that anthrophony can cause within vocal species (Francis et al. 2011b), and prevent birds from occupying otherwise suitable habitat if they perceive acoustically disturbed patches as lower quality. Biophony is important not only to other birds, but to any organism that may use it to inform their habitat selection decisions (Testud et al. 2020).

It is important to monitor how land-use changes can affect biophony in order to understand if there are tangible changes in the distribution and behavior of wildlife occupying the same space. The expanding footprint of infrastructure is concurrent with climate-induced changes on the landscape, which creates more features related to thaw (thermokarsts, lakeshore erosion, small

ponds, etc.) and greater heterogeneity in the landscape overall (Raynolds et al. 2014). Habitat change and disturbance can be reflected through changes in biophony (Alvarez-Berrios et al. 2016, Bayne et al. 2008, Tucker et al. 2014), and the distribution of specific birdsongs may be the first fine-scale indicator of habitat change (Boelman et al. 2015). Monitoring biophony is therefore an important task, since wildlife movements and distributions can shift in response to such habitat change, and those shifts may make them less accessible to subsistence communities reliant on local wildlife for nutrition and cultural (Berman and Kofinas 2004, Nicholson et al. 2013). In Alaska's Arctic, an estimated 39% of one's daily caloric needs are met with subsistence foods (Northern Economics, Inc 2019), and recent surveys show that hunters have begun to avoid certain areas because of increases in developmental activity and infrastructure (SRB&A 2019). The relationship between biophony and anthrophony and the nature of anthrophony's overall presence in the landscape—both detailed in my second chapter—will provide some insight into whether decreases in wildlife subsistence resources could be related to human activity.

#### 1.4 BROADER IMPLICATIONS

Combining the principles and tools of soundscape research with sensory ecology provides us with a solid framework with which I can begin to ask our most central question: How do wildlife hear and respond to the soundscape? In my first chapter, I am able to improve our understanding of what portions of the soundscape caribou might be able to hear, and in my second chapter I expand our knowledge on the distribution of sounds that might be potentially disturbing to them. My second chapter also details the soundclass dynamics on the ACP, specifically how anthrophony and biophony interact with each other, how this interaction changes at different times during the season, and how it may be facilitated by avian behavior. Land-managers should be aware of how seasonal changes in wildlife behavior may affect their response to disturbance, and what human activities have the greatest potential for sound disturbance. The information I provide here may help them develop strategies to mitigate sound disturbance as needed, and provide a jumping off point for researchers seeking to further understand how wildlife respond to their soundscape.

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## CHAPTER 2: Exploring the Auditory Thresholds for Reindeer, *Rangifer tarandus*<sup>1</sup>

### 2.1 ABSTRACT

Current and proposed human development throughout high northern latitudes must assess and try to mitigate impacts on caribou and reindeer (*Rangifer tarandus*) herds. Sound created by development can be far-reaching, and determining the potential impacts of noise on wildlife can inform landscape use. To advance our understanding of *Rangifer*'s potential response to anthropogenic noise, we must first understand what they can hear. Using domestic reindeer from the Large Animal Research Station at the University of Alaska Fairbanks, we performed a Brainstem Auditory Evoked Response to estimate auditory thresholds of the species. We assessed the central auditory response and tested the sensitivity in six female reindeer of various ages. Prior to our work, the lowest audible frequency for the species was reported to be 63 Hz in previous studies. We identified an auditory threshold lower limit of 30 Hz in our study subjects and quantified reindeer sensitivity thresholds (dB peSPL) to frequencies ranging from 30-16,000 Hz. Our results indicate that anthropogenic sounds previously thought to be beyond the hearing range of *Rangifer*—such as seismic exploration—are likely to be audible to the species, and therefore have the potential to affect their soundscape. We compared our findings on *Rangifer* hearing with new measurements of anthropogenic sounds recorded on passive acoustic monitors distributed throughout northern Alaska, as well as biological sounds produced by the *Rangifer* themselves (e.g., vocalizations and sesamoid clicks produced by the ankles). All classes of anthropogenic sound fall within the threshold range that we identified for *Rangifer*. Our findings have important implications for the assessment of environmental impacts within *Rangifer* range and will inform future soundscape ecology research.

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<sup>1</sup> Perra, M., Brinkman, T., Scheifele, P., Barcalow, S., 2022. Exploring Auditory Thresholds for Reindeer, *Rangifer Tarandus*. *J. Vet. Behav.* 52–53, 37–44.  
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## 2.2 INTRODUCTION

The effects of human development on caribou and reindeer (*Rangifer tarandus*; hereafter *Rangifer*) populations is an unresolved concern throughout the Arctic. Several studies have investigated how *Rangifer* distribution and movement are impacted by industrial infrastructure (e.g., roads, pipeline, oil pads) or aircraft overflights (Calef et al., 1976; Smith et al., 1994; Johnson and Russell, 2014; Johnson et al., 2019). Arthur and Vecchio (2009) have described lower calf weights from calves born closer to infrastructure in the Central Arctic Herd (CACH) of Alaska, and Luick et al. (1996) noted that an increase in noise exposure could reduce the probability of pregnancy for *Rangifer* females. Wilson et al. (2016) found that the strength of a *Rangifer*'s response to roads differed between individuals and, most recently, Johnson et al. (2019) found that there is little evidence of habituation to human infrastructure in the CACH. Altogether, this supports the idea that human development has a real, albeit sometimes variable, impact on *Rangifer*.

Few studies have evaluated *Rangifer*'s auditory range, with the exception of Flydal et al. (2001) and Flydal and Kilda (2003), who presented an important advancement in understanding the auditory capabilities of the species. Inconsistencies between their work and the ethology of the species remain unexplained, specifically: the average frequency of a vocalizing bull was reported to be 55 Hz (Frey et al., 2007), but Flydal et al. (2001) reported that the lower limit of *Rangifer* hearing was 63 Hz. If the lower limit they found for *Rangifer* hearing is true, then *Rangifer* may have a limited capacity to hear their own vocalizations used during reproduction. From an evolutionary perspective, this is unlikely and warrants further evaluation (Charlton et al., 2019).

To corroborate or expand on Flydal et al.'s (2001) work, we used a Brainstem Auditory-evoked Response (BAER) threshold. The BAER test is not a true measure of hearing, like pure tone audiometry, but rather a test of hearing threshold, i.e., the lowest sound level at which the ear (specifically the auditory cortex) is still able to detect a sound. BAER threshold estimates are determined by the repeatable waves of an electroencephalogram (EEG), and give close approximation of the auditory acuity of an animal at a given time (Erwin and Husain, 2003), and don't require animal training so it is easier to test a greater number and variety of individuals (Wolski et al., 2003). However, this test can underestimate the lower frequency sensitivities when compared with behavioral studies (Gorga et al., 1988), and cross referencing behavioral and electrophysiological results, as we are doing here, may help overcome this challenge. For this

reason, the sound stimuli we used were similar to Flydal et al. (2001), with the expectation that our BAER threshold estimations would show some consistencies with the results of the behavioral experiments.

*Rangifer*'s auditory acuity is of conservation concern because anthrophony (sound made by humans) will increase with expanding infrastructure across the Arctic, and has the potential to alter movement, elevate stress, reduce reproductive rates and disrupt an organism's communication (Barber et al., 2010; Halfwerk et al., 2011; Iglesias-Merchan et al., 2018). Indigenous communities have already expressed concern about how sound disturbance is affecting their hunting practices (Stinchcomb et al., 2020). Our objective is to develop a better understanding of what sounds *Rangifer* are sensitive to by comparing the results of our BAER test to the behavioral results of Flydal et al. (2001). An updated understanding of *Rangifer*'s auditory sensitivities will help inform efforts that mitigate such disturbances, and ensure a predictable and sustainable harvest for the human communities that are nutritionally and culturally reliant on the species (Parlee et al., 2018).

## 2.3 MATERIALS AND METHODS

### 2.3.1 Audiology study space and conditions

We conducted our research during December, 2019 at the Large Animal Research Station (LARS) at the University of Alaska Fairbanks (UAF). A sound booth was constructed within a barn onsite made of 1.9cm sound board and rubber flooring to minimize the noise floor (i.e. the ambient sound level) during testing. Booth dimensions were 2.3 m wide x 5.0 m long x 2.2 m tall. Domesticated reindeer research subjects were brought into the booth where they were held into position by a halter for testing. The reindeer were habituated to the space over several weeks prior to testing; they were brought into the booth 3 times a week for 5 weeks, and were held for gradually increasing periods of time (up to 45 min). During habituation and during the experiment they were kept in pairs to minimize stress.

Six female reindeer were tested for hearing threshold estimation using a standardized BAER threshold estimation test technique (D'angelo et al., 2007). Male subjects were unavailable for testing. Animals ranged in age from yearling to 8 years. All animals were kept and cared for by UAF LARS staff. This research was conducted under Institutional Animal Care and Use (IACUC) protocol number 1508780-1 (Appendix 2A).

### 2.3.2 Audiological methods

BAER tests were run using an Intelligent Hearing Systems (IHS) hardware system and Smart EP software (Intelligent Hearing Systems, Miami Florida). Prior to testing, system output levels and frequencies were measured using a Bruel & Kjaer 2270 sound level meter (Naerum, Denmark) and by running a power spectrum analysis using Spectra Plus software (Pioneer Hill software LLC, Paulsbo, Washington). This was performed to ensure that the system was taking accurate measurements before the experiment began. No veterinary history on our subject's acoustic acuity was available, but gross ear inspection and response to stimuli were indicative of no occlusion to the ears tested, and repeatable waveform morphology was present (Figure 2.1) indicating that there was a response to stimulus.

Prior to conducting each BAER test, the ambient sound level was taken using a Bruel & Kjaer model 2270 sound level meter taking the equivalent continuous sound level (LAeq) for five (5) minutes (Table 2.1). No sedative was administered to reindeer prior to testing. A lidocaine analgesic topical cream was rubbed onto the sites of the reindeer's head where Rhythmlink™ bent-needle subdermal electrodes would be placed for the BAER test. Three electrodes were inserted to the head of the reindeer (Figure 2.2), with the test ear (negative electrode) at the dorsal border of the zygomatic arch, vertex (positive electrode) and opposite ear (ground electrode) at the dorsal border of the zygomatic arch. This corresponds to the similar electrode montage used for testing other mammals and humans as per the International 10-20 System (Homan, 1988).

Auditory stimuli were selected as gated tone bursts with 5msec rise/fall with 5msec duration for the low frequencies. The use of tone bursts allowed us to differentiate the brain's response to the signal from its response to other sounds in the environment. Stimuli were gated using a Blackman filter and were delivered at a rate of 29.1 per second to an insert that is both an ER-2 and Etymotic ear inserts. Etymotic ear inserts perform down to 20Hz (Personal communication, Intelligent Hearing Systems). A non-linear gating function like the Blackman filter provides a more precise stimulus frequency because the repetition rate prevents "spectral splatter", where the tail ends of the stimulus bleed into other frequencies (Canale et al., 2012).

Narrow spectrum signals tend to approximately resemble audiograms by conventional long-duration tones used in behavioral audiometry, although low frequency bursts are less likely to elicit an identifiable wave V (Goldstein and Aldrich, 1999). Even at the default sampling rate

(1/2 second long stimulus duration limit), the equipment is capable of getting a tone burst that was 10 cycles long, and provide low frequency stimuli (Appendix 2B).

The ER-2 inserts were held at the opening of the ear canal by researchers while the auditory stimuli were being delivered. The right ear of each individual was used for testing due to the orientation of the halter's anchor in relation to the equipment and the other reindeer present within the enclosure. The ground ear was tested with a click stimulus to rule out bilateral deafness. Filter settings were 10Hz for the low pass filter and 1500 Hz for the high pass filter. The EEG was amplified 100,000 times, and the BAER results were measured from 550 averaged responses (sweeps) of the rarefaction phase. The analysis time was 12 msec, and more than two BAERs were run at each frequency to ensure replication based on waveform morphology, waves I, and V latency and intensity.

BAER estimated thresholds were processed for multiple frequencies from 20 to 16000Hz, in accordance with many of the frequencies tested by Flydal et al. (2001), and we tested a minimum of three reindeer at individual frequencies. Our frequency testing range was limited by the audio equipment used to provide the stimulus, which could only provide stimuli between 20 Hz and 20000 Hz, or around the range of human hearing. While we tested at 20 Hz and saw a response, we do not consider these responses valid because our equipment does not give a flat response at that frequency (i.e. cannot determine if the animal's brain has failed to respond to the stimulus). Due to this, and the potential for acoustic artifacts at the lower limit of our equipment, responses below 30 Hz are less reliable. The engineers of our equipment do not anticipate those artifacts to be present at  $\geq 25$  Hz (personal communication, Intelligent Hearing Systems), but out of an abundance of caution we are only presenting results at 30 Hz and above. Stimulus intensities were run initially at 30 dB nHL (a decibel scale based on the limitations of human hearing) and were converted to sound pressure levels (peSPL) as per the I unit calibration/conversion table, and then verified using Spectra Plus software. The intensities were increased in 10 dB nHL steps to the point of replication, i.e. when there was a repeatable response and latency repeatability of waves I and V (Figure 2.1). Each wave is associated with a particular part of the hearing pathway, and a disruption in the pathway will result in the downstream absence of waves (Webb 2009). The presence of the first and last waves (waves I and V) demonstrate electrical activity along the full auditory pathway, and thus are good candidates to use when identifying a repeatable response. To

establish our thresholds, we used the lowest dB nHL values that an individual reindeer responded to since we were interested in identifying the best possible acuity of the species.

### *2.3.3 Estimating industrial and biological sound frequencies*

We collected anthropogenic sounds using passive acoustic monitors (Wildlife Acoustics SM4) placed at four different locations across the North Slope of Alaska, including within oilfield infrastructure. Our acoustic monitors were within the range of the CAH and collected acoustic data daily from early May to early September, 2019. Sound files were parsed using version 2.3.3 of Audacity (Audacity Team, 2020), and industrial noise signals were identified based on their sound and on their shape in the spectrogram. We identified the lowest frequency (Hz) band—or the sound’s pitch (fundamental frequency) within that signal using the frequency analysis tool. We averaged the values for several noise classes we identified in our recordings (Table 2.2). We were unable to measure the exact distance of each sound source from the recorder. Some of the sound sources were moving objects (e.g., vehicle, aircraft). However, we only used recordings where the spectrogram of the sound source was clear and all formants were easily identifiable. Our anthropony samples came predominately from three locations where the average distance from roads was 264 m, and the average distance from industrial infrastructure (e.g., drill pads, flaring pipes) was 350 m. Therefore, for all sound sources, we were well within range to measure the frequency with precision.

We used existing literature to identify the average frequency of sounds that one might encounter on the North Slope of Alaska but were not present in our acoustic recording dataset. We searched the literature using several key words and phrases: “industrial noise”, “oil and gas sound frequencies”, and “oil exploration seismic noise”. The sounds derived from this search were: “Pumps”, “diesel generator exhaust pipe”, “seismic activity”, and “flaring”. The only biological sound frequency from our recordings that we assessed was the sesamoid click produced by *Rangifer* when walking, but we were also able to obtain vocalization frequencies from a literature search (Frey et al., 2007) (key words and phrases: “rangifer tarandus” “vocalizations” “acoustic behavior), as well as unpublished data from Ericson (1972) that described the frequency range of *Rangifer* grunts as 15-1900 Hz (excluded from our results because it has not been peer reviewed). The sesamoid click is made when tendons snap over the sesamoid bones of their ankles and make a distinctive ‘click’. We used camera trap images that were collected at our acoustic

recorder sites to confirm the presence of *Rangifer* at specific times, and then found the corresponding sound recording from our recorders. Using the same method detailed above for the industrial frequencies, we identified the fundamental frequency of the click from several recordings (Table 2.2). In these cases, *Rangifer* were relatively close to the recorder (<50 m), but an exact distance could not be determined from the photos.

## 2.4 RESULTS

We determined that all (n=6) of our *Rangifer* research subjects were capable of hearing frequencies at least as low as 30 Hz (Table 2.1). The threshold at this lower limit was 30 dB peSPL, i.e. the 30 Hz sound had to be at least 30 dB peSPL to be detected by the auditory system of our study subjects. The threshold of our 30 Hz lower limit was 30 dB peSPL lower than Flydal et al.'s (2001) (30 vs 60 dB peSPL).

The frequency range of best sensitivity was broad, with sensitivity shown in the upper frequencies (3000 and 16000 Hz) and the lower (30 Hz). Hearing acuity was greatest at 3000 Hz (20 dB peSPL), and the next most sensitive frequency was 16,000 Hz (25 dB peSPL). Our subjects were least sensitive around 60-500 Hz.

Threshold ranges were variable within our cohort (Table 2.1). We used the lowest threshold values in the audiogram to demonstrate the maximum auditory acuity (Figure 2.3). The greatest range of values occurred towards the lower limit of *Rangifer* thresholds, where certain individuals demonstrated much more acuity than others (Table 2.1).

The frequencies of common anthropogenic sounds were all within *Rangifer*'s hearing range (Table 2). This includes the frequencies of seismic activity, which occur below the previously established lower limit for the species. The frequencies (i.e., 125-500 Hz) that our research subjects were less sensitive to were expressed by some classes of aircraft (jet aircrafts and propeller planes), as well as mechanical pumps, diesel generators and the human voice (Table 2.2). The frequency of the sesamoid clicks (6,378 Hz) was between the most sensitive frequencies we recorded in the upper range of their hearing (3,000 Hz and 16,000 Hz). Industrial frequencies ranged from 20-1,382 Hz (Table 2.2).

## 2.5 DISCUSSION

Our results indicated that *Rangifer* can potentially hear frequencies at least 33 Hz lower than the lower limit previously documented by Flydal et al. (2001). Specifically, they show an expansion of the lower end of the known hearing range of *Rangifer*. From this, we can now more accurately infer the potential for a response to specific sounds. This study provides an important update to the *Rangifer* Umwelt—i.e. the world that the species perceives based on the limits of their own physiology (Van Dyck, 2011). A better understanding of *Rangifer*'s auditory Umwelt will help us improve evaluations of anthropony's impact within their geographic range by identifying sounds that the species can detect.

In some regions of the North Slope of Alaska, rural residents have expressed concern over how sound disturbance affects their ability to harvest the species (Stinchcomb et al., 2020). Depending on the sound source, sounds can travel tens of kilometers from their origin (BLM, 2019). *Rangifer* are known to respond to distinctly acoustic disturbances, such as aircraft overflights (Maier et al., 1998), and more stationary acoustic disturbances created by wind turbines (Skarin et al., 2018). At their calving grounds in and around oil fields, they give infrastructure a 5 km berth (Johnson et al., 2019), an avoidance that may be in direct response to the radius of sounds caused by drill rigs (2-10 km), flares (19 km), traffic (~2 km), and aircraft overflights (17+ km), where maximum extent of the radius represents where the sound falls to ambient levels (35 dBA)(BLM, 2019). The acoustic frequencies of all these sounds are well within the hearing range of *Rangifer* (Figure 2.3). Automobiles are the only sound class that came close to our research subject's most sensitive frequency (3000 Hz), and there was no notable overlap between any industrial sound frequencies and the frequency of the sesamoid clicks. Similarly, there is no notable overlap between the industrial sounds and previously reported *Rangifer* vocalizations (Frey et al., 2007) (Figure 2.3). Future contributions should focus on what sounds—within the range we have identified here—elicit a strong behavioral response in *Rangifer*.

Although the BAER and behavioral methods are both effective means of establishing a hearing range, there are significant differences between the methods in threshold sensitivity that have been demonstrated for humans, primates, and marine mammals (Gorga et al., 1988; Szymanski et al., 1999; Ramsier and Dominy, 2010). We did not anticipate that our lower frequency estimate would be markedly lower than a behavioral test because BAER methods tend to yield less sensitive thresholds at lower frequencies than behavioral methods (Gorga et al.,

1988). However, the waveform morphology and wave I and V latencies were repeatable at our lower frequencies, indicating that those frequencies were reliably detected by our test subjects. In light of this, the low frequency difference between our results and Flydal et al.'s (2001) may actually be greater. Future research using either method with proper low frequency stimuli should be able to determine if *Rangifer* can hear sounds in the infrasonic range, i.e. below the lowest frequency humans can hear. Behavioral testing will be more accurate at determining this limit, but BAER testing allows one to test more individuals at once, and future researchers may have to consider these compromises alongside their own temporal and financial constraints.

The lower limit we established does not preclude *Rangifer*'s ability to hear their own vocalizations and suggests the species has a high acuity to those frequencies, which better aligns with evolutionary expectations (Charlton et al., 2019). The relationship between the sounds a species can make and the sounds they can hear often follow the Sensory Drive hypothesis (Endler 1992), which states that vocalizations and hearing co-evolve, and animals vocalize within the frequencies that they can best hear (Charlton et al., 2019). *Rangifer* vocalizations vary by gender and have a male and female fundamental frequency of 55 and 75 Hz, respectively (Frey et al., 2007). It is possible such results were limited by the equipment and analysis filters used by Frey et al. (2007); Frey et al.'s (2007) recorders also were not capable of registering sounds below 20 Hz, and they did not analyze acoustic information below 30 Hz when they evaluated the spectrogram of their recordings because to the bandpass filter they employed. Unpublished results from Ericson (1972) described the frequency range of *Rangifer* grunts as 15-1900 Hz.

For a wide-ranging animal like *Rangifer* with extensive migrations, the ability to hear low frequency sounds would have great utility. Low frequency sounds can be used for long distance communication (Garstang, 2004) because they attenuate less quickly than high frequency sounds (Halfwerk et al., 2011). Natural infrasound, such as that created by storm events, is generally between 1-10 Hz, and extends outside the hearing range for *Rangifer* that we have established thus far. *Rangifer* were not as sensitive to the frequencies of their vocalizations as we would expect, and were more sensitive to lower frequencies (30 Hz). This discrepancy could be due to individual variation within our cohort, or the equipment limitations described above. Individual differences in auditory response can result from age (our cohort ranged from 1-8 years-old), and future studies could increase their sample size in each age class and include male subjects to quantify meaningful differences. Further research into *Rangifer* vocalizations should also utilize equipment with low

frequency capabilities to investigate whether there is a clearer relationship between auditory sensitivity and vocal frequency.

Alternatively, it is possible that *Rangifer* are tuned in to the sounds of their walking more than their vocalizations. Their characteristic sesamoid clicks have an average frequency of 6378 Hz. Because *Rangifer*'s tendon and ankle structure may vary across different individuals based on their size, it's likely that the frequency of their clicks varies more than we have established here. However, the takeaway should not be the exact frequency value, but rather that the frequency value is high, and falls in and around the regions of best sensitivity that we and Flydal et al. (2001) have identified for *Rangifer*. Generally, clicks tend to stimulate the high frequency region of the cochlea the most (Gorga et al., 2008), and the broad range of high frequency sensitivity that both we and Flydal et al. (2001) have reported could reflect this if the purpose of such sensitivity is to locate conspecifics. Clutton-Brock (1999) has posited that these clicks are a means of keeping the herd together, but no research has been done on the topic. If such behavior helped to facilitate herd formation during migration and calving, then intense and sustained high frequency disturbance could impact their movement and distribution.

To get an idea of the kinds of sounds *Rangifer* would encounter in the wild, we present new data on the frequencies of common industrial activities in the Arctic. By comparing the two datasets, we provide new insight into what sounds *Rangifer* are likely to hear due to development and how they overlap with hearing thresholds and sensitivities (Figure 2.3). The original audiogram established for *Rangifer* (Flydal et al., 2001) reported that reindeer could only hear as low as 63 Hz, at a threshold between 61- and 79-dB SPL. This dB level indicates that for a reindeer to hear that low frequency, it would have to be as loud as a normal human conversation if someone is about a meter away. Our acuity threshold at 60 Hz was lower (40 dB peSPL), and we found that the *Rangifer* frequency threshold of hearing may be as low as 30 Hz. The hearing threshold at that frequency was 30 dB peSPL, which is quieter than someone whispering at a 1.5 m distance. It is likely that this does not represent the absolute lower limit of *Rangifer* hearing. Our research subjects were responding to the 20 Hz stimulus produced by our equipment, but we considered this unreliable due to the probable presence of sound artifacts at this low frequency. Five out of six of our research subjects exhibited clear responses below 30 Hz, but these would have to be confirmed in future studies with a more reliable stimulus from equipment with lower frequency capabilities.

However, much of the concern around anthropony-related disturbance lies with lower frequency sounds. Prior to this work, it was unclear if the *Rangifer* auditory system was capable of detecting low frequency sounds produced by seismic exploration or vocalizations of the species. Vibroseis trucks (i.e., the source of seismic sound) used in standard oil exploration methods produce much of this infrasound by using seismic waves from a vibrating plate to generate a 3D image of underground regions. Blix and Lentfer (1992) indicate the vibrating plate produces sounds around 20-30 Hz during short, 5 second bursts. Further research shows that airborne sounds generated by the trucks ranged from 17-102 Hz at a 20 m distance (Bagaini et al., 2014). Both frequency ranges overlap substantially with the lower half of our *Rangifer* audiogram (Figure 2.3). Certain individuals may be more sensitive to these low frequency disturbances than others, based on the variation we observed within our cohort. Individual differences have been previously shown in *Rangifer*'s response to roads (Wilson et al., 2016), and gender differences have been documented in tolerance of other infrastructure, with females being more sensitive than males (Helle et al., 2012). Maternal groups, in fact, demonstrate little tolerance for infrastructure around calving time (Smith et al., 1994). *Rangifer* migration models demonstrate that collective migration is often led by a small proportion of leaders (Guttal and Couzin, 2011), an idea consistent with traditional ecological knowledge, which states that herd leaders should not be hunted as it would disrupt migration (Padilla and Kofinas, 2014). Individual differences could drive population-wide shifts in movement patterns at times when aurally sensitive individuals are in leadership positions and making decisions on behalf of the herd.

The thresholds we found at certain frequencies (such as 60, 125, and 500 Hz) that were higher than Flydal et al.'s (2001) results may be due to noise exposure prior to testing. The frequencies of commonly heard industrial equipment fall within this range, but it is unclear whether this 'notch' in the curve is a true symptom of overexposure or just an artifact of the individuals tested at that frequency, since not all individuals were tested across every frequency step. Our reindeer subjects were housed near a road, and frequently exposed to the sounds of traffic and farm equipment. Temporary threshold shifts can occur due to sound exposure prior to testing (Ryan et al., 2016), which are difficult to mitigate or control for. It is possible that wild *Rangifer*—that spend a majority of their lives without industrial noise exposure—have more sensitive hearing to mechanized sounds than the thresholds presented by their captive and domestic counterparts.

It has been difficult for researchers to demonstrate that wild *Rangifer* are habituating to human disturbances, but shifts in their tolerance to human infrastructure—and the stimuli that comes with it—are evident (Johnson and Russell, 2014). Proving the presence of habituation requires that one demonstrates an individual has learned stimuli is nonthreatening, and no longer responds to it; this means repeatedly sampling the same individuals over time (Bejder et al., 2009). Individual habituation to anthrophony could be studied using an ‘acoustic collar’ (i.e., a GPS collar with an acoustic recorder attached) (similar to Lynch et al., 2013) that would be able to jointly monitor sound exposure and behavioral movement responses over time, sampling the same individual repeatedly. This tool would also allow us to identify how tolerance to anthrophony varies between individuals, and within various habitat types.

With the completion of this study, we’ve been able to answer—in large part—what sounds and sound frequencies *Rangifer* could potentially hear and be disturbed by. This is the first step in a larger effort to evaluate *Rangifer*’s behavioral response to sound. This is done not only at the recommendation of Francis and Barber (2013), but also in the spirit of the Umwelt-concept, an ethological approach which recognizes that each organism may perceive the world differently than another (Van Dyck, 2011). Researchers and decision makers are better able to predict an organism’s response to various stimuli by understanding the physiological constraints with which they perceive such stimuli. Our hope is that this knowledge will provide more opportunities to understand and manage the impacts of sound disturbance in *Rangifer*’s environment, especially as anthrophony becomes more pervasive across the Circumpolar North.

## 2.6 ACKNOWLEDGEMENTS

Authors are in order of contribution. We would like to thank L. Scheifele and all undergraduate students at the UAF Large Animal Research Station for their assistance with data collection. We would like to thank A. Prichard and D. Betchkal for constructive reviews on an earlier draft of this manuscript. Our research was funded by the National Science Foundation (award # 1839192), who had no involvement in the study design, writing or decision to submit this paper for publication.

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## 2.8 FIGURES

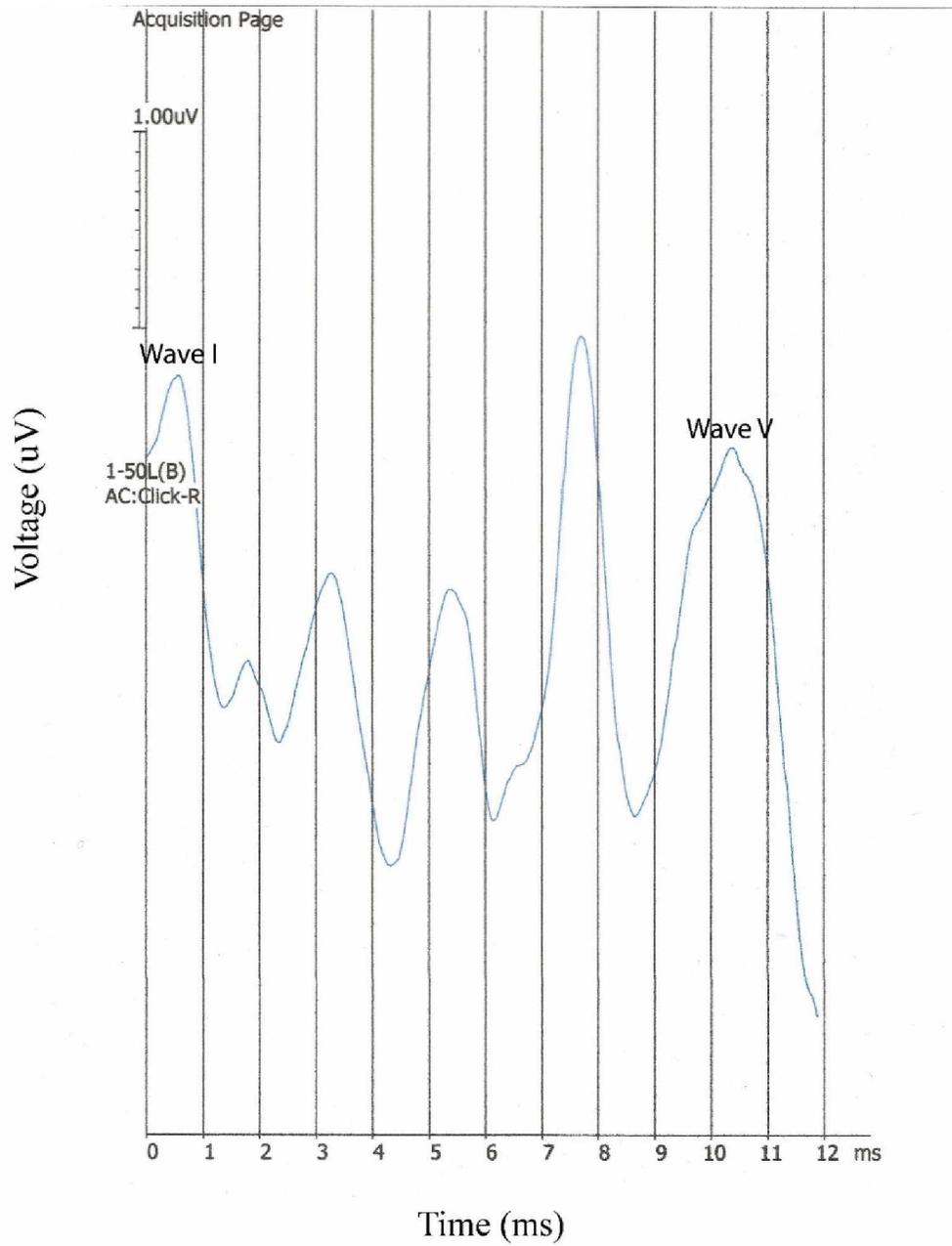


Figure 2. 1. **Example waveform.**

An example of the waveform produced during a BAER (Brainstem Auditory Evoked Response) test given to a reindeer subject; the five visible peaks in this waveform represent the reindeer auditory system's clear response to a 30 Hz stimulus

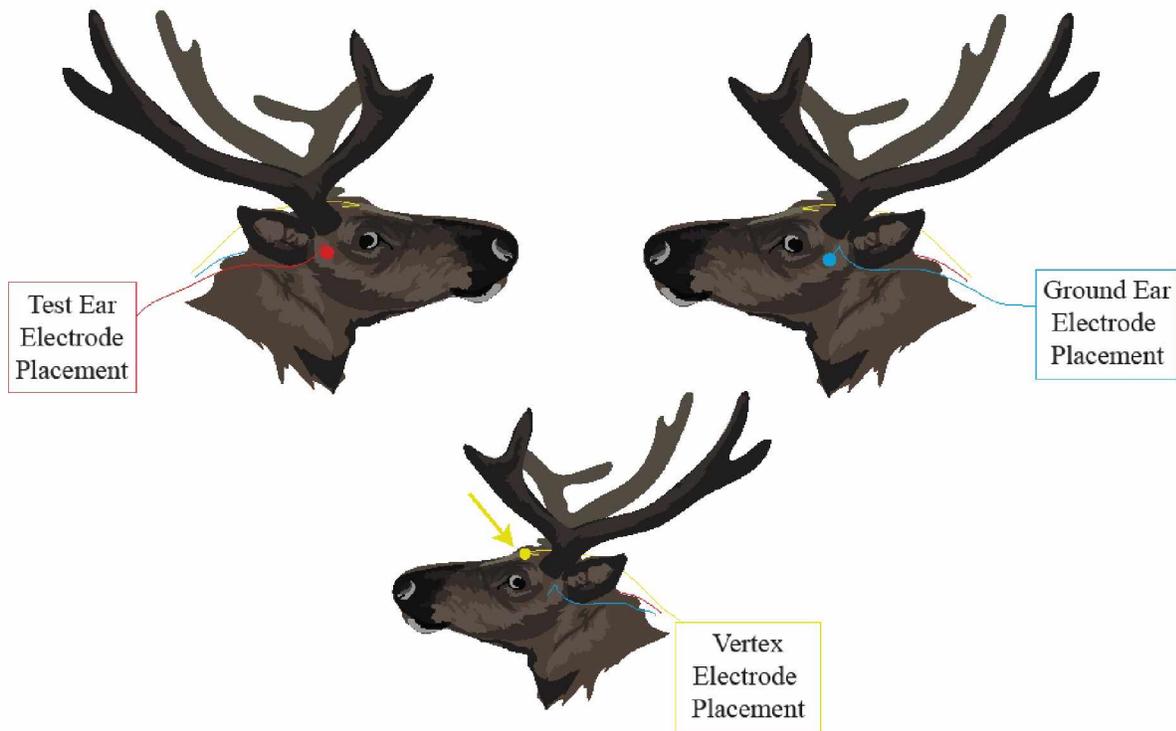


Figure 2. 2. **EEG electrodes.**

The approximate placement of the 3 bent-needles, RhythmLink™ (Columbia, SC) subdermal electrodes used to capture the EEG (electroencephalogram) for reindeer. The test ear's electrode (negative electrode) is at the dorsal border of the zygomatic arch on the right side, the ground ear's electrode is at the dorsal border of the zygomatic arch on the left side, and the vertex electrode sites in the middle of the forehead, just above the eyes. Figure 3. Rangifer audiogram established through BAER (Brainstem Auditory Evoked Response) testing, with stimulus frequency (in Hz) on the x-axis and sensitivity threshold on the Y (in dB peSPL); thresholds are the lowest level that a sound was played and still able elicit an electrophysiological response from the subject.

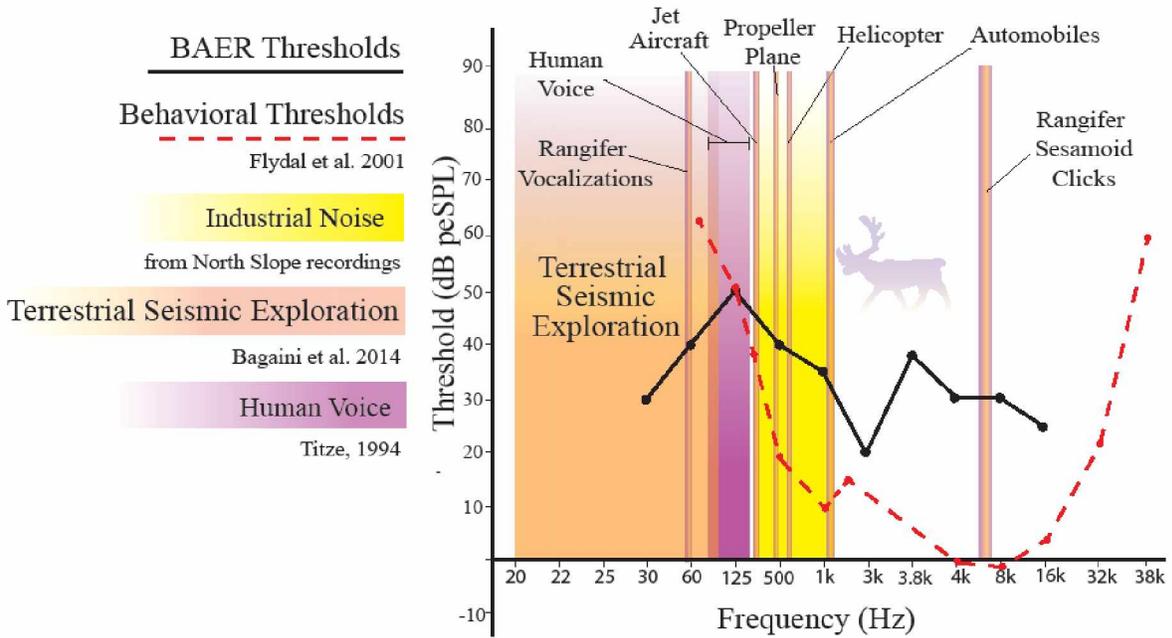


Figure 2. 3. **Audiogram.**

Rangifer audiogram established through BAER (Brainstem Auditory Evoked Response) testing, with stimulus frequency (in Hz) on the x-axis and sensitivity threshold on the Y (in dB peSPL); thresholds are the lowest level that a sound was played and still able elicit an electrophysiological response from the subject.

## 2.9 TABLES

Table 2. 1. **BAER hearing thresholds.**

The hearing thresholds determined from BAER (Brainstem Auditory Evoked Response) tests conducted on 6 female reindeer at the Large Animal Research Station at the University of Alaska Fairbanks; these thresholds are presented in dB peSPL, a decibel scale based on sound pressure levels alone, and dB NHL, a decibel scale based on the normalized hearing levels of humans. Values were originally recorded in dB NHL and then converted to dB peSPL. The reported values used to produce the audiogram are the lowest thresholds found for the individuals tested at a given frequency, in order to represent the full auditory capabilities of the species. The mean thresholds are shown in cases where  $N \geq 2$ , but generally these reflect the variation within our research subjects as opposed to the true auditory range of the species.

Frequency (Hz)	Lowest Threshold (dB peSPL)	Threshold Range (dB peSPL)	Mean (dB peSPL)	N	Lowest Threshold (dB NHL)
30	30	30-60	43.3	3	10
60	40	40-60	NA	2	30
125	50	50-60	55.0	4	30
500	40	40-70	55.0	4	20
1000	35	35-45	41.6	3	20
3000	20	20-30	25.0	3	-10
3800	38	38-78	NA	2	20
4000	30	30-60	NA	2	10
8000	30	30-50	38.3	3	10
16000	25	25-50	43.0	5	5

**Table 2. 2. Fundamental frequencies of relevant sounds.**

The mean fundamental frequency of different classes of anthropogenic noises identified from acoustic recording units placed within the North Slope of Alaska from May-September, 2019; standard deviations were not included for values cited from the literature, which sometimes stated ranges instead of means (Other values acquired from the literature include: <sup>1</sup>Values from Frey et al. (2007), <sup>2</sup>Values from Titze (1994), <sup>3</sup>Value from Marriot (2006), <sup>4</sup>Values from Bagaini et al. (2014))

Noise Class	Mean or Range Fundamental Frequency	
	(Hz)	SD
Rangifer sesamoid clicks	6378	881.1
Rangifer vocalizations	55 <sup>1</sup>	NA
Automobile	1382	124.6
Helicopter	612	33.4
Propeller plane	483	40.1
Jet aircraft	309	71.4
Human voice	85-255 <sup>2</sup>	NA
Pumps	~125-500 <sup>3</sup>	NA
Diesel generator exhaust pipe	~130 <sup>3</sup>	NA
Seismic activity	17-102.2 <sup>4</sup>	NA
Flaring	~60 <sup>1</sup>	NA

## 2.10 APPENDICES

### Appendix 2A



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#### Institutional Animal Care and Use Committee

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

April 14, 2021

To: Todd Brinkman  
Principal Investigator

From: University of Alaska Fairbanks IACUC

Re: [1695898-1] Determining the Auditory Capability of Reindeer (*Rangifer Tarandus*) Using Classical Conditioning

The IACUC reviewed and approved the New Project referenced above by Full Committee Review.

Received:	December 9, 2020
Approval Date:	December 10, 2020
Initial Approval Date:	December 10, 2020
Expiration Date:	December 10, 2021

This action is included on the December 10, 2020 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 005 "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.*

- 1 -

Generated on IRBNet

#### Figure 2A.1 IACUC Approval Letter

Evidence of IACUC approval given for our project's activities

Appendix 2B.

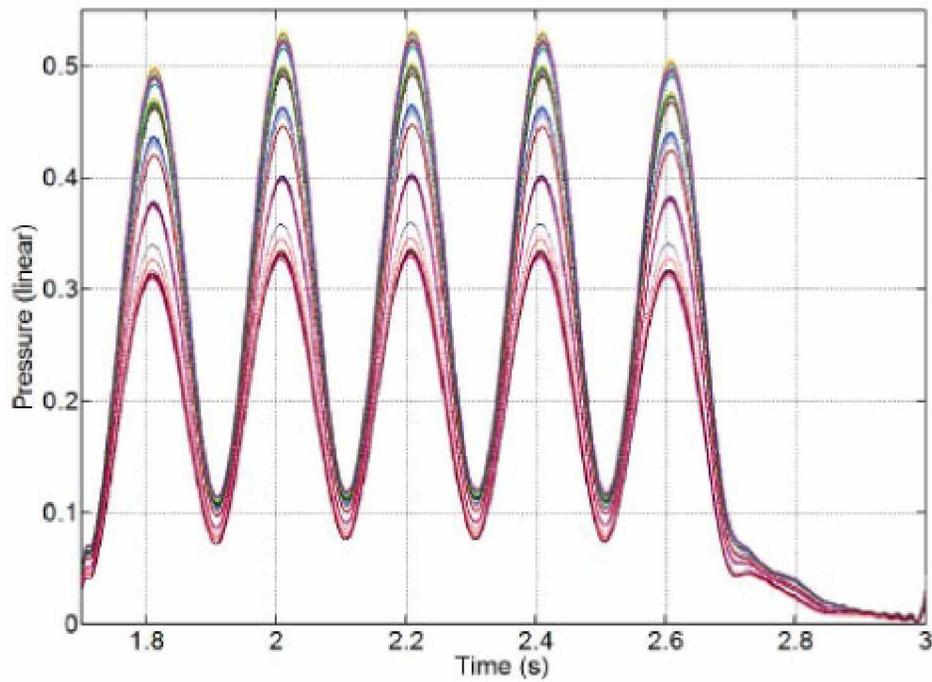


Figure 2B.1 **Tone burst example**

A spectral view of a 30 Hz pulse, showing corrected measured waveforms for 30 Hz gaited tone burst testing. (Reproduced with permission from Adam J. Hill, University of Derby, Department of Electrical and Electronic Engineering).

Appendix 2C.

Table 2C.1 **The noise floor**

Noise floor measurements taken in 5-minute LAeq (Equivalent Continuous Sound Pressure Level) in dBA for each frequency used during the BAER testing.

FREQUENCY	NOISE FLOOR
(Hz)	(dBA)
20	38
22	38
25	38
28	40
30	42
60	46
63	38
125	37
500	35
1000	35
2000	32
3000	32
4000	32
8000	32
16,000	32
20,000	32

## CHAPTER 3: Characterizing the Soundscapes of the Arctic Coastal Plain<sup>2</sup>

### 3.1 ABSTRACT

With the acceleration of rising temperatures and industrial development, the Arctic Coastal Plain of Alaska is being subject to rapid change. Over 180 species of migratory birds from every continent on the globe converge on the Coastal Plain during the spring and summer to breed. Human noise-- or ‘anthrophony’—is a consequence of development that has the potential to change the behavior, distribution and composition of avian communities there. On the Coastal Plain, anthrophony is most often industrial noise or aircraft overflights. We set out to understand how the patterns of bird vocalizations in this system respond to changes in their acoustic environment, alongside other climatic and geographic variables.

In 2019, we installed 40 acoustic recording units in a randomly assigned grid across the Prudhoe Bay oilfields and the Arctic National Wildlife Refuge, collecting sound data from May-September. We processed this data with a sound classification model that was trained and validated on a set of over 10,000 manually labeled audio clips from our study. This model labeled the presence or absence of different sound classes throughout the entire dataset. We used SnowModel to generate a timeseries of weather variables. We modeled the hourly occurrence of bird vocalizations using generalized linear mixed-effects models in 7 different, 2-week time periods across the duration of our study. The SnowModel outputs, the sound model outputs, and the distances to infrastructure and habitat features were all used as covariates during our model selection process.

Anthrophony had a strong effect on bird vocalizations in almost every time period, with birds more likely to vocalize when anthrophony was present. This effect was strongest in the early season when birds were breeding and nesting, perhaps because they are most vocal during those times. The presence of infrastructure, in contrast, had very little influence over birdsong, suggesting that sound may have a disproportionate effect on avian behavior. Bird detections also appeared sensitive to climatic variables (snow depth, air temperature, precipitation and wind speed), and birds were more likely to be detected under favorable weather conditions, or in the

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<sup>2</sup>Perra, M., Brinkman, T., Çoban, E., Mandel, M., Boelman, N., Liston, G., Reinking, A., Crimmins, S., 2022. Characterizing the soundscapes of the Arctic Coastal Plain. Manuscript in preparation for *Global Change Biology*.

presence of detectable food items, like insects. Further research is needed to determine how these relationships play out at the species level, and whether anthrophony is capable of driving shifts in avian community structure.

### 3.2 INTRODUCTION

The Arctic Coastal Plain (ACP) on the North Slope of Alaska is a unique system of intensely seasonal productivity and biodiversity, a landscape lauded for its wealth of resources by oil and gas companies, Indigenous communities, and conservationists alike. It is also a region in the throes of rapid change: since 1950, winter temperatures in Alaska have increased by approximately 4.1° C, and annual temperatures by 2.1° C; trends that are driven in large part by the direct and indirect effects of elevated greenhouse gas levels causing climate change (Walsh and Brettschneider 2019). This increase in temperature is likely to contribute to changing vegetation patterns (Fauchald et al. 2017) alongside projected advances in spring phenology, which can have ecological consequences for migratory birds (Liebezeit et al. 2014) and caribou (*Rangifer tarandus*) (Severson et al. 2021). The ACP holds the heart of energy extraction in Alaska; 95% of Alaska's 2.7-billion-barrel crude oil reserve occurs on the North Slope (US EIA, 2022), with an additional estimated 3-10.4 billion barrels of economically recoverable oil within the coastal plain of the Arctic National Wildlife Refuge (ANWR) (USGS, 2001), which was recently leased for oil exploration (BLM, 2020). With the acceleration of both climate change and industrial development, the ACP is facing an increasingly common crucible of shifting environmental norms, and may be viewed as a representative of issues faced across the circumpolar north.

Rapid warming in the Arctic is driving landscape changes that cause shifts in wildlife populations and distributions (Amundson et al. 2019, Boelman et al. 2015, Fauchald et al. 2017). Soundscape monitoring—i.e. listening to all the sounds present on the landscape—can be a useful method for measuring such change. Soundscapes can be broadly defined as an amalgamation of all the sounds in a given environment, usually broken down into three broad categories: anthrophony (human-made sound), biophony (biotic sound), and geophony (abiotic sound) (Krause 2008). Many studies have been conducted that demonstrate how soundscapes can reflect natural landscape patterns (Fuller et al. 2015), biodiversity (Bormpoudakis et al. 2013, Sethi et al. 2020) and land-use patterns that alter biological communities (Francis et al. 2011, Ross et al.

2018). Terrestrial acoustic monitoring of the soundscape in northern Alaska hasn't been widely used, despite the urgent need for baseline acoustic data and information about soundscape composition in relatively untouched environments where development is about to commence (i.e., ANWR). Soundscape monitoring may be best suited to capture changes in composition of vocal (i.e., soniferous) species on the landscape, which can allude to vegetation changes at a finer scale than existing modeling and remote sensing methods. This is important given that the heterogeneous nature of the ACP's landscape has been difficult to quantify for those using remote-sensing technologies (Myers-Smith 2020). The abundance of life on the ACP is also quite audible, hosting more than 180 species of migratory birds including millions of migratory songbirds (Pielou, 1994) and the greatest population of waterfowl in the Arctic (Bart et al. 2013). Recent advancements in the field, such as the generation of “acoustic fingerprints”, have been used successfully to distinguish between different ecosystems and predict habitat quality (Sethi et al. 2020), and the presence of certain songbirds that can be indicative of specific habitat types (Boelman et al. 2015). The challenges presented by large datasets produced by soundscape monitoring efforts are being reduced by the emergence of automated solutions (Çoban et al. 2021, Sethi et al. 2020, Towsey et al. 2018) that make soundscape monitoring an increasingly attractive—and cost-effective—tool.

The biophony produced in our study area is an important natural signal that can inform organisms about the surrounding habitat, as well as the other animals that occupy that habitat (Mullet et al. 2017). This is because soniferous animals—i.e. those that make and use sound—may be adapted to project their vocalizations across the specific physical qualities of their environment (“Acoustic Adaptation Hypothesis”: Morton 1975). Conversely, they may be equally adapted to compete effectively with the sounds of other species by vocalizing at specific times and frequencies to avoid overlap (“Acoustic Niche Hypothesis”: Krause 1993). In this way, the biophony of soundscapes is simultaneously influenced by the surrounding landscape and its occupants, and cannot help but convey information about both, which can help animals satisfy their needs (Mullet et al. 2017). The degree to which some species rely upon acoustic habitat signals is well demonstrated by acoustic enrichment studies, where animals can be attracted to disturbed or recovering habitats when recordings of a soundscape from a healthy environment are played within them (Testud et al. 2020, Gordon et al. 2019). Conspecific song can act as a cue within the acoustic habitat that many birds use to determine habitat quality, since its presence can

encourage settlement in dispersing individuals (Molles et al. 2008), returning migrants (Hahn and Silverman 2007), and colonial species (Podolsky 1990). For captive colonial birds, playback experiments can even increase their breeding behavior and reproductive success (Clark et al. 2012).

Similarly, anthrophony can tell us about the landscape because it contains the sounds of human infrastructure and land use patterns, which can in turn affect the surrounding habitat and the biophony therein (Pijanowski et al. 2011 b). The interactions between biophony and anthrophony (formally termed “phonic interactions” by Pijanowski et al. (2011 a)) may be defined by the nuances of animal behavior and sounds, as well as the spatial and temporal variation of the soundclasses themselves (Warren et al. 2006). Species whose vocalizations don’t overlap with the frequencies of anthrophony are more tolerant of human noise than those that do, and are more likely to remain in noisier areas (Rheindt 2003), in this way altering community structure (Francis et al. 2011). Such an effect can mask or disrupt acoustic cues that inform an organism about the environment—otherwise known as the “acoustic habitat” (Mullet et al. 2017)—and potentially deter them from the area. For less vocal animals, this may alter their habitat use (Drolet et al. 2016) and make them less likely to occupy areas with more anthrophony (Kleist et al. 2020).

Because organisms can use the soundscape to make decisions about their environment (Mullet et al. 2017), changing the soundscape that many animals engage with could have profound effects on their fitness (Halfwerk et al. 2011), their likelihood to settle in an area (Halfwerk et al. 2016), and the biodiversity of the animals surrounding them (Francis et al. 2011, Proppe et al. 2013). Migratory birds that use the acoustic cues of other species during habitat selection benefit more than those that don’t, because it reduces the cost of habitat assessment (Mönkkönen et al. 1999), which leads to earlier breeding and higher reproductive success (Mönkkönen and Forsman 2002). If the presence of anthrophony excludes one species from a habitat, it may indirectly exclude other birds who use the vocalizations of that species during habitat selection. When such community-wide shifts affect primary producers, even physical changes in the vegetation can manifest as a result of anthrophony exposure (Francis et al. 2012). Compromising the fitness of birds on the coastal plain has implications not just for avian demographics in Alaska, but for a suite of other ecosystems that host these migratory birds for the remainder of the year. The birds that are born and raised on the ACP are bound to winter in an assortment of inter-continental destinations, from South America and Asia, all the way to Antarctica (Brown et al. 2017,

McKnight et al. 2013, Lagassé et al. 2020). Preserving the integrity of these soundscapes is, therefore, a global issue, and one which may be of special importance for species already in decline (Brown et al. 2007).

While the potential influence of anthrophony is strong, the scale of that impact is amplified by the effects of climate change. Temperature changes are driven not just by the increase in greenhouse gases, but also by large scale climate variables (Pacific Decadal Oscillation (PDO)) and semi-permanent low-pressure systems (i.e. the Aleutian Low) (Walsh and Brettschneider 2018), the patterns of which may be altered by climate change (Zhang and Delworth 2016, Zhang and Delworth 2007). Multiple factors work in concert to alter the composition of the habitats on the coastal plain, including but not limited to: decreasing snow cover and slope stability, increasing coastal erosion and thaw lakes, expanding wetlands, and community shifts in vegetation (Kittel et al. 2011). As mentioned, plant and animal distributions are in flux (Amundson et al. 2019, Fauchald et al. 2017, Boelman et al. 2015, Zhou et al. 2020), and the northward expansion of shrubs—and the distinct ecosystem they support—is further facilitated by human infrastructure in this system, specifically the Trans Alaska Pipeline (Dwight and Cairns 2018).

Our work provides such necessary baseline information across much of the North slope. This work is the first of this scale to generate comprehensive soundscape data, and will be a valuable reference for land managers who are evaluating the impacts of development on new and existing infrastructure. A record of such “acoustic fossils” has been lauded by many soundscape enthusiasts as a prescient and necessary practice of the field (Pijanowski et al. 2011 b).

Our objective was to use soundscape monitoring to identify and describe the composition of sound classes throughout the snow-free season so we could explore any associations between major sound classes, and the effects of different landscape variables on the extent of those sound classes. We wanted to understand where and when human made noise and birdsong occur, and the relationship that they have with each other, to gain better insight into how the impact of anthrophony can change with time and place. The circumstances under which we are less likely to hear birdsong in a soundscape could be reflective of poor habitat quality (Rossi et al. 2017), or signal that disturbances--like anthrophony--are affecting behavior and/or occupancy (Duarte et al. 2015, Duarte et al. 2011). As climate change continues in the Arctic, we hope this tool will help assist with fine scale evaluations of landscape change and the potential regime shifts in the ecosystem that may follow.

### 3.3 STUDY AREA

Our study was conducted from early May to early September, 2019, over an area that spans over 10,000 km<sup>2</sup> of the ACP (Fig. 3.1). We divided this area into two based on the degree of industrialization in each. Our developed region is heavily associated with roads and oil infrastructure and can be referred to as the “The Oilfields”. There are nearly 300 pads used for production, facilities and support (staging areas, camps, etc), over 100 exploration sites, a road network of 669 km, and a number of associated bridges (27), culverts (2037) and airstrips (13); in total, the infrastructure covers at least 7429 ha of land (Raynolds et al. 2014). Our undeveloped region is The Refuge, and it lacks a road network or any permanent infrastructure. The community of Kaktovik (Pop = 251) is located on the northwest edge of the refuge (Figure 3.1). Both areas are subject to air traffic, but sites in and around the oil fields have more scheduled commercial and small aircraft flights each day. Adjacent to the oil-field complex in our developed region, the nearby village of Nuiqsut experiences air traffic equivalent to a town 900 times its size (Stinchcomb et al. 2020), a disproportion that is due to the nearby oil activity.

Both regions overlap with caribou calving grounds; the Central Arctic Caribou Herd (CACH) calves in The Oilfields, and the Porcupine Caribou Herd (PCH) calves in The Refuge. Birds are the main contributor to our soundscape’s biophony, and their abundance appears to increase from east to west on the ACP (Bart et al. 2013). Accordingly, populations of all types of birds are several orders of magnitude higher in our developed region vs our undeveloped region, with approximately 4 million birds in our developed region compared with ~800,000 in our undeveloped region (Bart et al. 2013). The density of shorebirds, gulls, terns and jaegers is largely the same between the regions, but the distribution of waterfowl and other aquatic species in the undeveloped region is only about 60-70% as dense as it is in the developed region (Bart et al. 2013). Species richness and density of migratory bird populations tends to increase near the coast, where the wetland and riparian areas that they use are most common (Brown 2007), and general differences in the frequency of water features between the two regions may account for differences in density and abundance. The mean distance from our sites to a body of water (excluding the ocean) in our developed region is less than half that of our undeveloped region (1035 m for developed vs 2731 m for undeveloped), and sites in the developed region are generally flatter (Russell and Gunn 2019).

The coastal plains of both regions are characterized by long cold winters and short, mild summers. Average temperatures in June, can range from approximately 2-10° C in both areas (Urban and Clow 2017), with peak precipitation levels happening in August, with a monthly average of 3 cm (Weather Spark 2022). The landscape is largely snow covered at the beginning of May, and while the date at which a given site becomes free of snow may vary greatly, it can occur anywhere from mid-May to early June (Oliver et al. 2018). The distribution of vegetation types is highly heterogenous and thus difficult to quantify (Myers-Smith et al. 2020), but includes mix of tussock-sedge, tundra and dwarf shrub (Raynolds et al. 2014, Bieniek et al. 2015). During our study period, the daylength reaches 24 hours from May 15-July 27<sup>th</sup>, although the only darkness present before and after these dates is technically considered twilight, and true night does not resume until after our study concluded in the first week of September.

### 3.4 METHODS

During May 2019, 40 data-collection sites were installed at the approximate center of cells (20x20km) on a randomly assigned grid that covered the Oilfields and ANWR (Figure 3.1). Each site contained an acoustic recording unit (ARU; SM4 Wildlife Recorder, Wildlife Acoustics, Inc 2022) mounted on a metal post along with a trail camera that was used for a separate study. We chose 20km spacing between ARUs to ensure that we were not double-sampling the same sound at the same time.

The ARUs were collecting acoustic data from early May until early September of 2019. The ARUs recorded in stereo with a sample rate of 48000 Hz and gains set to 16 dB. They were visited in early July to replace batteries and SD memory cards. ARUs were programmed on a recording cycle to maximize battery life and data storage between site visits. This cycle is determined based on predictions from the SM4 configurator available through Wildlife Acoustics (Wildlife Acoustics 2022). We used a schedule that rotates between recordings of 150 minutes, with alternating breaks of 120 or 150 minutes. This variable pattern allowed us to cycle our recording periods through every hour of the day within a 4-day period. We attempted to continuously run the ARUs during the entire season but some battery depletion occurred at the end of June (before July battery replacement) and the end of August.

### *3.4.1 Acoustic data classification and processing*

We used a classification model to label our entire dataset. The model was trained using over 10,000 samples derived from our data, following procedures outlined by Çoban et al. (2021). Full details on the training process can be found in Appendix 3A.

The results generated by our model provided us with soundclass predictions that ranged from 0 to 1 for every 10 seconds of recording throughout our whole dataset. These predictions represent the model's confidence that a sound of a specific class actually occurred, with a 1 meaning that the model is 100% confident that the sound occurred, a 0.75 indicating the model was 75% confident. We used these confidence values to determine binary thresholds (0 or 1) that would specify whether or not model output for a clip qualified as an actual detection.

In order to find the most appropriate binary threshold to assign a 0 or 1 for each class, we had to test different thresholds on a validation dataset used in our model training, and a testing dataset that contained samples excluded from the training process. With the validation data, we tested all prediction values between 0-1 as potential thresholds in steps of  $1 \times 10^{-4}$ , and determined each threshold's F-score using the 'ModelMetrics' package in R (Hunt 2020) (Table 3.1). We chose F-score as our metric for defining a classification threshold because it accounts for both predictive accuracy and sensitivity (Knight et al. 2017, Powers 2011).

To convert our sound predictions to binary, we used confidence thresholds from the classification model that yielded the highest F-score in the validation data. We aggregated our binary detections to the hourly level by calculating the proportion of 10-second periods within an hour that contained detections for each soundclass, creating a value between 0 and 1, with 0 meaning that no detections occurred within an hour, 0.5 meaning that detections had occurring over 50% of the detection periods, and 1 meaning that detections occurred in all the 10-second periods within that hour.

### *3.4.2 Soundscape composition*

We explored the temporal and spatial distribution of each soundclass (bird, anthrophony, aircraft and insect) graphically using the raw, unaggregated data at the 10-second level. Bird represented the more general category of "biophony", since birds were the predominate source of biophony in our system and we wanted to model them separately from insects, given that both classes interact with each other. We plotted the temporal distribution in 2-week intervals using

ggplot2 (Wickham 2016), and the ratio of soundclass detections within those time steps. We aggregated our data to the hourly level for this plot, and calculated the ratio of detections for each soundclass per hour, where the ratio equals the number of 10-sec periods a soundclass was detected divided by all 10-sec detection periods in that hour. At this time-scale, we considered a soundclass to be present if it was detected at least once in an hour (i.e. soundclass ratio values  $>0$ ), and used that determination to evaluate the prevalence of soundclasses across time space. We produced bubble-maps with the R package “ggmap” (Kahle and Wickham 2013) to show the spatial distribution of bird and anthrophony detections, where the relative size of bubbles represented the ratio/proportion that bird or anthrophony detections occurred at each site, where ratio equals the number of soundclass detections at site  $x$  during study divided by all soundclass detections at all sites during study.

At the hourly level, we used generalized linear mixed-effects models (GLMM) to explore the relationship that the anthrophony and bird soundclasses have with each other and with weather and landscape characteristic variables. Across each of our study sites, we generated a time series of weather variables at a 250 m x 250 m spatial resolution and a 3-hourly temporal resolution using SnowModel (Liston and Elder 2006). The 3-hourly outputs were then rarefied to a 1-hour timestep to match our aggregated hourly audio data, and covariate values were extracted at the precise location of our ARUs. The SnowModel system has been utilized in a wide variety of snow-wildlife research applications (Liston et al. 2016, Reinking et al. 2018, Mahoney et al. 2018, Loe et al. 2020, Glass et al. 2021, Pedersen et al. 2021) and consists of a suite of physically-based statistical models designed to simulate the distribution and evolution of snow and other environmental variables across space and time (Liston and Elder 2006, Liston et al. 2020). Our weather covariates consisted of rain precipitation (m, total for the 3-hour time step), snow precipitation (m, total for the 3-hour time step), wind speed (m/sec, average for the 3-hour time step), air temperature (C, average for the 3-hour time step) and snow depth (m, instantaneous value at end of the 3-hour time step) for each site. Landscape characteristics were distance values that were estimated using the ‘Near’ analysis tool in ArcGIS (Esri 2020). Landscape characteristics fell into two broad categories; habitat (distance to coast, distance to waterbody, distance to river) and infrastructure (distance to road, distance to pipeline, distance to development).

We used the ‘lme4’ package in R (Bates et al. 2014) to examine the importance and effects of these variables for anthrophony and bird detections. Because we had ratio data derived from

binary results, we used a binomial distribution for the response variable in our models (Zuur et al. 2009). Because of seasonal fluctuations in the extent of bird sound, where birds are most vocal during breeding and territory establishment in the early season, we modeled the bird soundclass in 2-week intervals between May 7-August 14, 2019, resulting in 7 models. The temporal variation in anthrophony is less extreme, and so we instead included the Julian date as a variable predictor in our models as opposed to using temporal segregation. We evaluated collinearity among our predictors using variance inflation factors (Zuur et al. 2009).

We used a sequential approach to model selection. In the first step, we grouped like-variables (e.g. all weather variables), and found the best combination of variables within each group based on BIC values using an all-subsets approach. We used this ‘best version’ of each grouping in the second step, where we tested all additive combinations of these groups. The top model in each case was, therefore, the combination of these groups that had the best BIC score (Figure 3.2). For bird models’ selections the different groups included: landscape characteristics, infrastructure, weather, other soundclasses (aircraft, anthrophony), and insect. We tested the other soundclasses (anthrophony, aircraft) as separate variables in the models because they’re known to alter bird vocalizations (Vincelette et al. 2021, Warrington et al. 2017, Slabbekoorn and Peet 2003). We included Julian date as a fixed effect and both site and hour as random effects in all models. All the variables related to landscape characteristics, infrastructure and weather, along with Julian date, were scaled and centered. Although aircraft noise is a part of anthrophony, there were no issues with collinearity in any of our models, and we wanted to test if this specific type of anthrophony had a clearer effect than all of the anthrophony combined. For our anthrophony model’s selection, we included all the same groups with the exception of other soundclasses (bird and aircraft) and insect. This process resulted in 7 models of birdsong (one for each time period) and 1 model of anthrophony.

## 3.5 RESULTS

### *3.5.1 Soundscape characteristics*

In total, there were ~22 TB of audio recordings collected during our study period across 40 sites, which resulted in 13.7 million datapoints after post-processing and labelling. This equates to ~38,069 hours of audio recordings. Each datapoint in the initial dataset represented a 10-second detection period, 4% of which included anthrophony, 1.2% included aircraft, 2.5% insect, and 34%

included bird vocalizations. We used these raw values to evaluate the temporal distribution of these soundclass detections (Figure 3.3). The prevalence of the bird soundclass had clear temporal patterns throughout the season (Figure 3.3), where bird detections were most prevalent in periods 2-4 (May 21<sup>st</sup>- July 3<sup>rd</sup>) during arrival and breeding, and declined notably in periods 5-7 (July 4<sup>th</sup>- August 14<sup>th</sup>). Bird detections were least prevalent in period 7 (August 1<sup>st</sup>-14<sup>th</sup>), during departure, and we estimated a decline in the middle of the season as anthrophony and insect detections increase (period 5; July 4<sup>th</sup>-17<sup>th</sup>) (Figure 3.3). Insect detections were highest in period 5, whereas anthrophony detections were highest in period 6. Aircraft detections appeared to increase similarly to anthrophony in the later periods, but the trend was less strong.

At the hourly level, anthrophony detections occurred at least once during 20% of all hours in our study period, co-occurring with bird detections in nearly all of those instances (98%). Among our hours with an anthrophony detection, 37% were unrelated to aircraft detections, i.e. we detected anthrophony but not aircraft in a given hour. Conversely, 63% of hours with anthrophony detections were associated with aircraft detections.

The spatial distribution of bird detections did not show any clear patterns across the study as a whole (Figure 3.4). Overall, 87% of recording hours in the study had at least one bird detection. The Oilfield complex had slightly more hours with at least one bird detection than the Refuge (52% vs 48%), and each site on average contributed 1.7% (SD=0.9) of all hours with bird detections. Anthrophony, however, had a clear spatial pattern wherein a majority of the hours with anthrophony (72%) can be attributed to the Oilfields, while the remaining 28% occurred in the Refuge (Figure 3.5). Across all sites, 63% of anthrophony detections are associated with aircrafts; in the Oilfields, this is the case for 60% of anthrophony detections, while in The Refuge that was the case for 69% of them. Additionally, 6 of the most remote sites in The Refuge (mean=37km, SD=9km) had anthrophony detections in nearly a fifth of all their recording hours (mean=22%, SD=4%) (Appendix 3C).

There was no difference in the spatial distribution of bird detections between the raw data (10-sec) and the aggregated hourly data. Clearer spatial patterns arise for anthrophony detections at the 10-sec level, where 4 sites are responsible for 83% of all anthrophony detections. One site accounted for 38% of all anthrophony detections, likely because a well pad was built near the site during our study period, something we were able to confirm with that site's trail camera. These 4 sites averaged 517 m (SD =519) from the road, and 811 m (SD=734) from development and

were comparably close to infrastructure even for sites within the Oilfield Complex. At the hourly level, these 4 sites only accounted for 6% of the hours where anthrophony was detected, meaning that sound disturbance at these sites was intense (i.e. a lot of consecutive anthrophony detections in an hour) in the hours that it occurred, but it did not occur across a large number of hours compared to other sites.

### *3.5.2 Selected models*

Our best-fit model structures for bird and anthrophony soundclasses varied between time periods (Table 3.2). We provided all the models used in the selection process in Appendix 3B. The variation within anthrophony was best explained by Julian date (strongest effect), wind speed and snow precipitation. The strongest and most consistent variable that helped explain the variation in our bird models (with the exception of period 4) was anthrophony. Other variables included in the best-fit bird models varied with time period (see below).

### *3.5.3 Anthrophony*

Of the variables present in our final model, Julian date had the strongest effect and indicated that anthrophony was likely to increase toward the end of the season (Fig. 3.3). Anthrophony was more likely to be detected as snow precipitation increased and less likely to be detected as wind speed increased. The landscape and infrastructure groups of variables did not remain in the top models (Appendix 3B).

### *3.5.4 Birds*

Bird detections were modeled across 7 different time periods, with a different model structure for each period (Table 3.2). The covariates present in each top model all had a significant effect on bird detections, and the strength of these effects varied across different time periods.

Of all the covariates, anthrophony had the strongest impact on bird detections in that birds were more likely to vocalize when anthrophony was present. This effect was strongest at the beginning of the season in periods 2-3 (Figure 3.7), when birds are arriving, establishing territory and breeding. The presence of insects also had a positive effect on bird detections in later time periods, with the relationship strengthening during departure in period 7.

Weather covariates had a variable effect as the season progressed. Snow depth had the strongest positive impact on bird detections in period 2, meaning birds vocalized more at sites with deeper snow during that time (Figure 3.7). Snow depth had an otherwise negative effect on bird detections when it was included as a covariate in time periods 1 and 3. Air temperature had the strongest negative effect on bird detections, and birds were more likely to vocalize during departure as temperatures decreased in period 6 and 7. Temperature had a positive effect on bird detections during periods 1, 2 and 5. Rain precipitation had a positive effect in periods 1, 2, 4 and 5, and a negative effect in period 3. Wind speed had a negative effect in periods 1, 2, and 6, and it was the only covariate where the direction of its effect remained the same in all periods where it was present (Figure 3.7).

Covariates from the habitat and infrastructure groups (referred to as “distance” in Figure 3.7) were included less frequently, but all of them had a negative effect on bird detections and none of the covariates present occurred more than once across the 7 time periods. The effects of distance variables are counterintuitive in these models, in that a negative effect means that we are more likely to detect birds as the distance to a landscape feature gets smaller. The distance to pipeline had a negative effect in period 1, distance to coast had a negative effect in period 2, distance to river had a negative effect in period 4, and distance to road had a negative effect in period 5. Again, this means that bird detections were more likely as one got closer to these features. Distance to river was the only covariate present in the model for period 4.

### 3.6 DISCUSSION

Our study generated a large volume of novel soundscape data within the ACP of Alaska. Our advancements in the processing of ‘Big Data’ (~38,069 total hours of audio), using machine learning techniques, fostered an analysis which would have been cost prohibitive and effectively impossible had it been attempted manually. Surprisingly, a fifth of all our recording hours contained at least one anthrophony detection, while 87% of them contained at least one bird detection. 98% of these anthrophony detections occur in hours when birds are also detected, so anthrophony almost always overlaps with biophony in our system. We found that bird vocalizations (i.e. biophony) increased with anthrophony, and that this response was not spatially limited. When we combined anthrophony and biophony data with weather time-series and static landscape variables, we found a number of relationships that varied with time, suggesting seasonal

or phenological drivers. The strength of these relationships appeared to be driven by the behaviors of different life-history states—like breeding or nesting—that change throughout the season. Our study demonstrates that biophony is also sensitive to air temperature, precipitation and snow depth in the early season, and for this reason, the sounds generated by nature may be a good indicator of the environmental conditions in a given area. Biophony may act as an important cue for migrants navigating the landscape, and may have the potential to affect the spatial and temporal distribution of different species across the landscape.

### *3.6.1 Anthrophony*

Anthrophony was a prominent part of the soundscape on the ACP, and we observed that it had a positive effect on biophony detections, contrary to other studies (Joo et al. 2011, Ortega and Francis 2012, Zwart et al. 2015). It is understandable that anthrophony has been a longstanding concern of communities on the ACP (Stinchcomb et al. 2019, Stinchcomb et al. 2020), given that we found it present in a fifth of all our recorded hours. A majority of this anthrophony (63%) is associated with aircrafts, and aircraft disturbance is a common source of anthrophony to the west of our study area, where the town of Nuiqsut hosts a volume of air traffic equivalent to a city 95 times its size in the United States (Stinchcomb et al. 2020).

Anthrophony had no significant relationship to infrastructure, despite the fact that 72% of hours containing anthrophony detections occurred in the Oilfields (Figure 3.6). Sites that appeared near infrastructure, however, may be near structures that are no longer active, or are structures that have relatively quiet operations. The presence of aircraft noise may have further confounded the potential relationship between physical infrastructure and our anthrophony detections, and it's also possible that different approaches to defining infrastructure may have revealed different findings. To the best of our knowledge, only two sites were exposed to active construction (Brehmer 2019, Hilcorp Alaska, LLC 2015). These sites accounted for the most anthrophony detections at the 10-second level, but these detections were not spread over a large number of hours, and so did not have a huge influence across the entirety of the study period when we modeled our data at the hourly level.

We were more likely to detect anthrophony toward the end of the season, and Julian date had the strongest effect on anthrophony (Figure 3.7). Late-season increases in anthrophony that we observed could also be related to post-thaw gravel compaction and other activities that occur

towards the end of the summer that may involve loud equipment related to groundwork or excavation. However, given the lack of relationship with infrastructure, it might be more likely attributed to an increase in research and recreational activities in the region that are often assisted by helicopters or other aircrafts in July and August. The caribou and Dall's sheep (*Ovis dalli*) hunting seasons also begin in early August. Many hunters used small aircraft to access their hunting areas. This may explain some of the higher levels of aircraft sound in the southern sites of the Refuge as aircraft fly across the northern foothills of the Brooks Range and then turn south and fly up river drainages to access mountain terrain for Dall's sheep.

Snow precipitation had a slightly weaker, but still significant, positive effect on anthrophony detections. Anthrophony is probably detected more often in the presence of snow because of lower elevation cloud ceilings that force small aircrafts to fly closer to the ground, making their overflights easier to detect. We may not see this relationship with rain precipitation because rain is louder and more likely to interfere (i.e., mask) with a recorder's ability to hear the anthrophony. Wind can also mask sounds, which is why it has a significant, negative effect on anthrophony and bird detection in all of our models.

### *3.6.2 Seasonality in biophony-anthrophony relationship*

In order to capture the variable nature of biophony in our system, we chose to model bird detections in different time periods; not only does the number and composition of species on the landscape change throughout the season, the behavior of those species is also changing rapidly as they transition into several different life-history states across the season (Jacobs and Wingfield et al. 2000). Over our study period, birds go through four major life-history states: they arrive from vernal migrations, begin breeding, molt and then depart for autumnal migration. We observed the most activity in periods 2-4 (Figure 3.5), a pattern that appears to be driven by arrival and breeding, because we see the most activity when birds are arriving (Ward et al. 2016) and engaging in breeding and nesting behaviors (Brown et al. 2017, Hunt et al. 1995, Lanctot et al. 2000, Romero et al. 1998, Ruthrauff et al. 2021).

In our models, we observed that anthrophony had a strong influence on bird detections, but that its influence was clearly greatest in periods 2 and 3 (Figure 3.7). Interestingly, anthrophony occurs the least frequently in periods 1-3, and it seems likely that the fluctuating strength of this relationship is driven by the birds themselves, who can experience seasonal, physiological changes

which can affect vocal behaviors (Hunt et al. 1995, Romero et al. 1998). Anthrophony can suppress territorial behavior and vocalizations in some species (Fuller et al. 2007, Kleist et al. 2016, Warrington et al. 2017, Zwart et al. 2015), but other species, like geese, will vocalize more in the presence of perceived threats when defending their nests (Clermont et al. 2019). Acute sounds, like aircraft overflights, may be perceived as such a threat by defensive waterfowl, causing an increase in bird vocalizations following anthrophony.

Birds on the ACP may also modulate their song in order to be heard over the sound of anthrophony, as seen in other systems (Brumm 2004, Fuller et al. 2007, Slabbekoorn and Peet 2003). Our results suggest that this may happen across the spring and summer season, but that it happens most when birds are in certain life-history states in the early season (arrival and breeding). The cost of this behavior at a critical time in their life-history is unclear, although the presence of anthrophony during the breeding season has been shown to reduce avian fitness (Halfwerk et al. 2011). Louder songs do not appear to have higher metabolic costs for many birds (Zollinger et al. 2011, Zollinger and Brumm 2015), but louder or more frequent singing could have indirect costs, reducing the time available for forage (Reid 1987).

Although it seems unlikely that the prevalence of anthrophony drives this relationship in the early season, it is possible for it to alter bird responsiveness to anthrophony (Rosa and Coper, 2022). Vincelette et al. (2020) observed large differences in bird response between sites with dramatically different disturbance profiles. Bird vocal richness increased in the 10 minutes following an aircraft overflight in an area where air traffic was infrequent, but not in an area with 10 times the number of overflights. The relationship our models revealed—that birds sing more in hours when anthrophony is present—shows support for the response patterns Vincelette et al. (2020) saw at their less disturbed site. Our model structure and sampling methods support the idea that this relationship is relatively widespread, given that our models controlled for site-specific variation, and we had 40 sites across a study area that covered the full litany of habitat types across the ACP, and the variety of community structures therein. Songbird densities in similar tundra ecosystems are not notably altered by the presence of infrastructure (Smith et al. 2005), and it seems unlikely that immediate community structure changes had a large influence in bird detection patterns we observed, although follow up studies at the species level would be needed to fully evaluate community structure as a factor. It bears mentioning that the presence of oilfield infrastructure has not caused significant shifts in the densities of many avian species, specifically

waterfowl, shorebirds, loons, grebes, gulls, terns and jaegers (Bart et al. 2013), although more recent research has shown localized population shifts among many species (Amundson et al. 2019). This suggests that the drive to occupy suitable habitat may outweigh the potential effects of human activity. We should consider that many species travel through, or winter in, regions with much higher densities of people, and that human activity in the oilfields may not constitute as particularly novel or disturbing stimuli to them.

Period 4 is the only period where anthrophony is not present in the top model, where river is the only significant variable present. At that point in the season, it appears we are more likely to detect birds as we get closer to rivers. During period 4, cover likely disappeared, as snow depth was 0 cm in the following period (Appendix 3D), and the timing of insect emergence is associated with snow disappearance (Tulp and Scheckkerman 2008). Diptera—the most common order of insects in Arctic rivers and streams (Miller and Stout 1989)—are an important resource for chicks (Tulp and Scheckkerman 2008). Arctic streams and rivers are a valuable resource that support a surprising diversity of insects; beaded streams, for instance, can support arthropods that are pond specialists and stream specialists at the same time (Miller and Stout 1989). The rapid emergence of crane flies (*Tipulidae*) specifically, are important for passerines and shorebirds (Tulp and Scheckkerman 2008). It may be this seasonal event that drives the relationship we see in Period 4. However, it is important to note that we experienced significant data loss caused by programming failures in many of our ARUs in late June (period 4). Many sites recorded no data at all during this time (13 of our 40 sites), and sites with data recorded only a handful of hours. This top model is built with only ~8% of potential recording hours, using about two thirds of our sites. Other variables could have been important in this season if all data had been present, and it will be important to re-evaluate this time period in future studies.

### *3.6.3 Landscape features, weather and insects*

The influence of infrastructure and landscape features on our biophony (i.e. bird detections) appears to be more convoluted than what we observe with anthrophony, and it's complicated further by the relationships between insects and weather variables. However, the relationship between bird detections and all of these remaining variable groups appeared to be related predominately to three things: food, shelter and migration. Because the landscape is fairly open, shelter may constitute as anything from a cluster of shrubs to a snow-free patch of landscape, both

of which can offer warmer temperatures and some relief from the wind (Wingfield et al. 2004). The distance to pipeline and the distance to road were the only covariates that had a significant effect on bird detections in periods 1 and 5, respectively. The distance to coast was only relevant in period 2, and the distance to river was only relevant in period 4. Birds are detected more frequently near the coast in period 2 because species of waterfowl arrive earliest and are most associated with the coast (Ritchie et al. 1989).

Birds were more likely to vocalize near oil pipelines in the first period, perhaps because the pipeline is associated with the increased presence of shrubs (Dwight and Cairns, 2018). At this point in the life-history of some passerines, flocks of birds may roam the tundra in search of good forage (Wingfield et al. 2004). The microhabitats of shrub tops can act as important shelter and sources of forage for a variety of species (Tape et al. 2010, Wingfield et al. 2004). At the same time, dust from roads near the pipeline changes the albedo of the snowpack and may melt snow more quickly (Auerbach et al. 1997), further increasing access to shrub tops. In support of this, we also see in Figure 3.7 that birds are detected more in areas with shallower snow.

In Period 2, a strongly positive relationship with snow depth emerges—the strongest relationship observed of any non-acoustic variable. We are more likely to detect birds in areas with deeper snow at this time perhaps because the scale at which we are predicting snow depth (250 m x 250 m) is too large to capture when snow free patches are arising. The appearance of these patches initiates the arrival of migratory songbirds (Wingfield et al. 2004), and in extreme cases, birds may begin to occupy these patches on the landscape even when snow cover is still 90% (Boelman et al. 2017). The negative relationship that resumes in period 3 is likely because snow cover is less widespread, and birds are able to select snow-free areas over snowy areas at a larger scale that's captured by our data.

Wind, rain precipitation and air temperature are additional factors in the early season top models. Migratory birds in this system have demonstrated a marked ability to respond and adapt rapidly to environmental changes, in large part because their reproductive success depends upon it (Ruthrauff et al. 2021). High winds consistently reduce the likelihood of bird detections (periods 1, 3 and 6) because they can mask sounds and reduce air temperatures, and common passerines on the ACP are likely to sing less or be absent when temperatures are low (Oliver et al. 2018). Reid (1987) observed in Ipswich sparrows (*Passerculus sandwichensis princeps*) that cold temperatures induced stress and reduced song rate, and weather variables have been shown to strongly affect

song variability in other species (Schäfer et al. 2017). Higher rain precipitation is likely associated with warmer air temperatures in periods 1 and 2 that might prompt vocal behavior (because the air must be above freezing for rain to occur), and rain infiltration into the snowpack can expedite the melting of the snow (Cohen et al. 2015) and the emergence of microfeatures that flocking birds might use for shelter or forage. Both conditions—the rising of temperatures and the melting of snow—can encourage vocalizations and assist in the emergence of microfeatures that offer shelter and food. As more snow free patches emerge in season 3, the tall shrub tops that first appeared from deep snow pockets may be abandoned in favor of snow free patches where wind speeds are reduced by 75% to 90%, depending on the groundcover, and temperatures can be dramatically higher than the surrounding snow pack (Wingfield et al. 2004). By period 3 (June 3<sup>rd</sup>), rain precipitation has a negative effect on bird detections and may no longer be associated with notably warmer temperatures, and rain events in that period may have been loud enough to mask bird vocalizations.

The most distinct feature of later season periods (periods 5-7; July 4<sup>th</sup>-August 14<sup>th</sup>) is the presence of insects, many of which emerge in late June and early July, with mosquitoes generally considered “early emergers” (Laske et al. 2021). Birds are rapidly molting at the beginning of this time frame, a life-history state in which they shed and regrow their feathers, and so their ability to fly is absent or impaired. For snow buntings at least, this state coincides with when young are fledged but still dependent on parents (Green and Summers 1975), and so birds are able to leave their nest and may be doubly driven to seek resources. We were more likely to detect birds when insects were present, and molting may be a factor in this relationship, especially because half of all terrestrial birds in the Arctic are insectivores during the breeding season (Nyffeler et al. 2018). The insects detected in our model are most likely loud, aerial species—like mosquitoes, pollinators, and flies (diptera)—that can be heard by our ARUs. It’s these kinds of insects are more abundant near roads (Ste-Marie et al. 2018), and a possible explanation for the relationship in period 5, where we’re more likely to detect birds as we get closer to roads. The strength of the bird-insect relationship is strongest in period 7 (Figure 3.7) possibly because birds are foraging more aggressively to prepare for migration.

In periods 6 and 7, bird detections become more likely at colder temperatures, the opposite of what we see in periods 1, 2 and 5. At this point in this season, many species are entering a new life-history state: autumnal migration. Gambel’s White Crowned Sparrows (*Zonotrichia*

*leucophrys gambelii*)—common in our study area—depart from the breeding grounds in the fall on days when barometric pressure is high, which tends to coincide with decreasing temperatures (Chmura et al. 2020). Colder temperatures are tied to important cues for departure, and we may be more likely to detect birds at colder temperatures if cold temperatures trigger vocal flocking behaviors, like those typical of many shorebirds (O’Reilly and Wingfield, 1995).

The effect of rain precipitation in periods 5 and 6 is weak, and may be largely explained by stochasticity in acoustic masking. Birds tend to sing louder in the presence of environmental noise (Brumm 2004), and so the relationship between bird detections and rain in later periods could simply depend on the strength of rain events in a given period, and whether or not rain was consistently loud enough to mask bird vocalizations and drive a negative relationship. Wind is more consistent in its ability to mask bird vocalizations because it can cause feedback in our recorders, reducing our ability to detect birds, particularly in periods 1, 3 and 6, where we see it in the top model.

#### *3.6.4 Future directions*

This study could have been improved by modeling the data at various temporal scales to help tease out different short- or long-term effects of anthropony on the soundscape. Because our meteorological data and sound data were at vastly different scales (3-hour timesteps vs. 10-second timesteps), our hourly aggregation was a compromise to accommodate both datasets. Future research should consider scale-optimization strategies used in resource selection studies (McGarigal et al. 2016) to better understand how these relationships change at different scales. Additionally, modelling the minority of sites with high degrees of anthropony in a separate analysis would help to characterize what covariates are most important in those distinct soundscapes so we could compare them to sites where anthropony is effectively absent. Incorporating different covariates, such as vegetation class and infrastructure density, might reveal important patterns that we weren’t able to see in this analysis. Examining this dataset from new angles, and incorporating new data from the following years, will help us continue to further our understanding of the soundscape in this system, and develop ‘best practices’ for soundscape monitoring in the future.

Overall, we were able to determine that anthropony is more widespread than previously thought, due in large part to aircraft overflights. We established a positive relationship between

biophony and anthrophony that was unexpected, though it's unclear what impact this may have on wildlife. The strength of these effects depends on the time of the season, and the life-history state of the migratory birds whose vocalizations we used to approximate biophony. The bird detections that we modeled showed sensitivity to weather parameters that directly and indirectly affect the quality of different habitat patches, and birds were more likely to be detected in the presence of insects, an important food resource. Biophony (i.e. bird vocalizations) could be an important indicator of habitat quality that is used during arrival and molting, when individuals are more mobile seeking good habitat patches and/or resources. Biophony plays an active role in how some migratory species orient themselves upon arrival (Mönkkönen et al. 2002), and this behavior can be associated with greater nest success (Quinn and Ueta 2008). Changes to biophony could disrupt how species distribute themselves on the landscape, but future studies at a finer taxonomic scale would be needed to investigate this, and whether its potential effect has fitness consequences.

The baseline soundscape information we have provided should be used to inform how changes caused by human activity and global warming may affect wildlife in the future. Our training dataset is published for other research teams who wish to train their own sound labeling model to process acoustic data from this system or ones similar to it (Çoban et al. 2022), allowing for some level of continuity between our study and future efforts.

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### 3.8 FIGURES

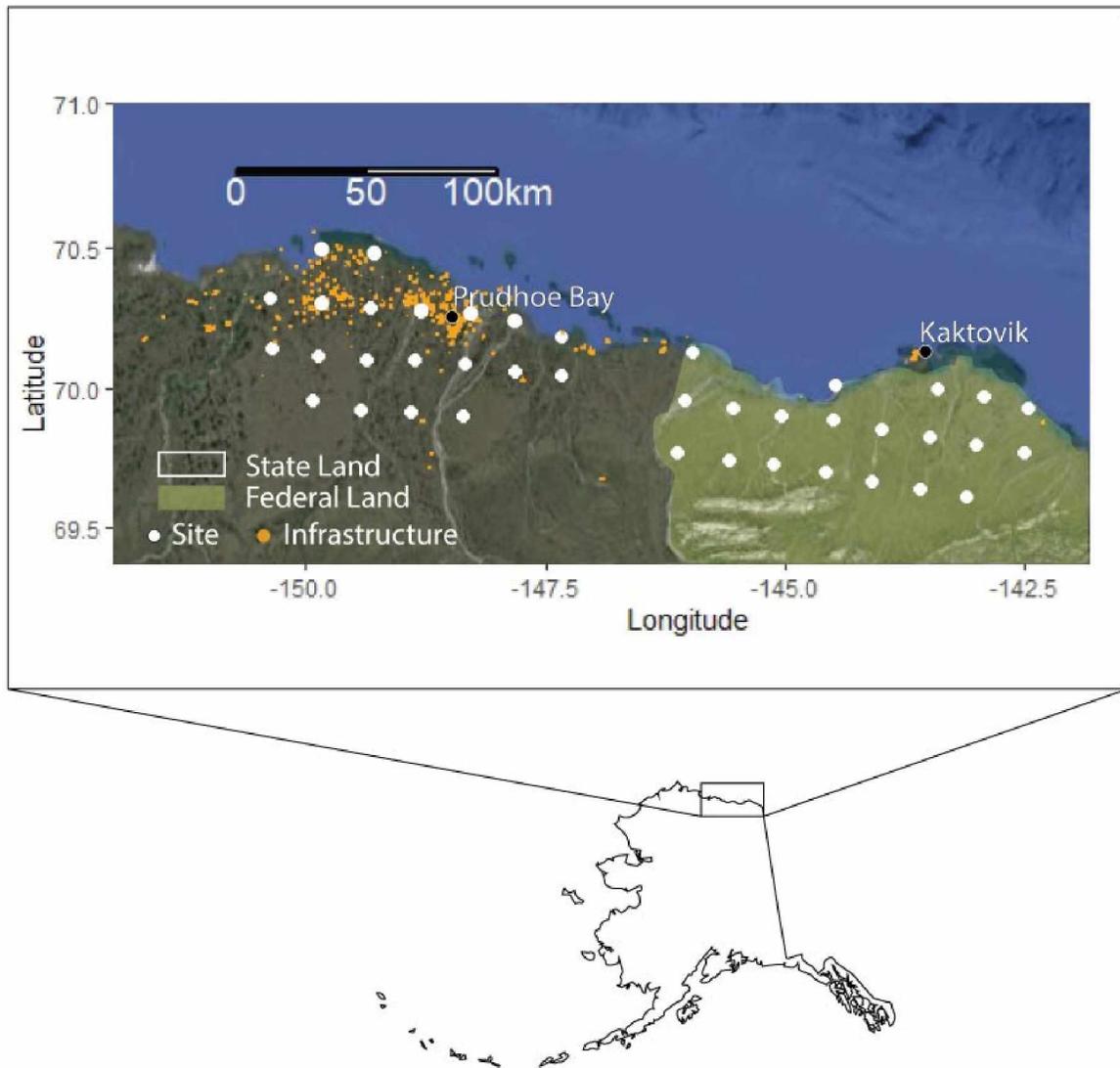


Figure 3. 1. **Study area map**

A map of our study sites with approximate locations of each site. Non-road infrastructure is indicated by orange dots, sites are presented as white dots. Federal land is highlighted, while state land is the remaining portion of the map.

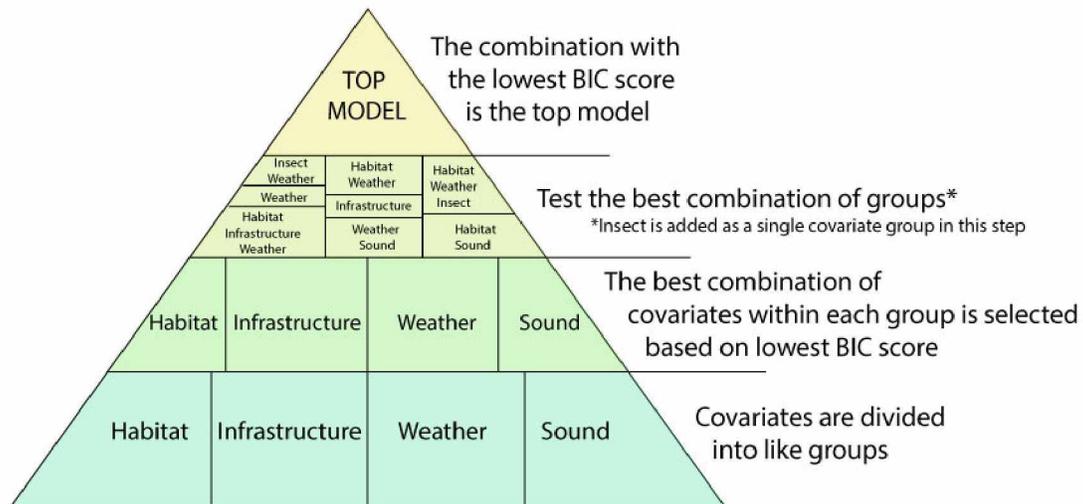


Figure 3. 2. **Model Selection Pyramid**

The model selection procedure for our models of bird. The group of weather covariates included snow depth, snow precipitation, rain precipitation, air temperature and wind speed; habitat covariates included distance to water body, distance to coast, and distance to river; infrastructure covariates included distance to development, distance to road, distance to pipeline; sound covariates included: anthrophony and aircraft; insect detections were included as a separate class. This selection process was used for each of our 7 bird models, and a similar selection process was used for our anthrophony model where only the 'weather', 'habitat' and 'infrastructure' covariate groups were used.

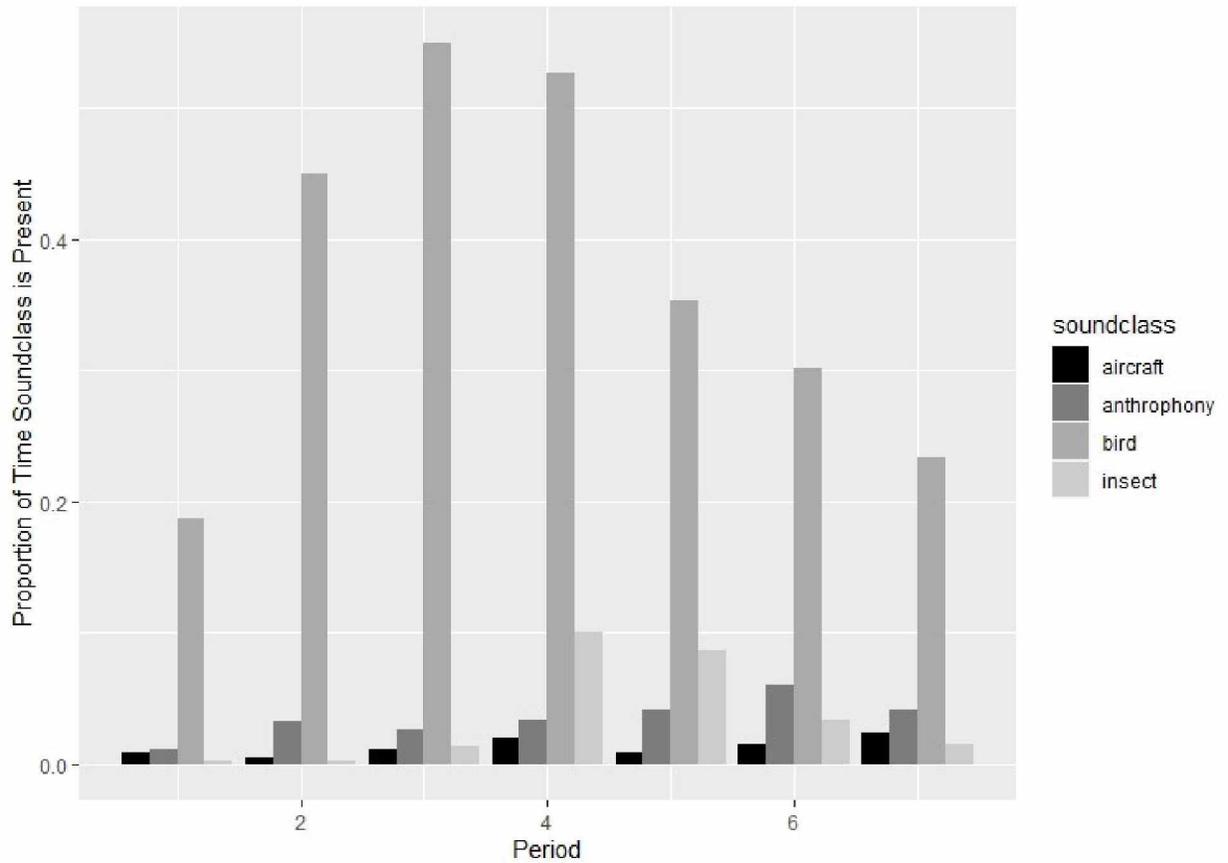


Figure 3. 3. **Barplot of seasonal soundclass prevalence**

Prevalence of different soundclasses in each time period throughout the season at the 10-second timescale, where prevalence= (number of times a soundclass is detected)/(all possible detections in a period). (Period 1: 5/7-5/20, period 2: 5/21-6/2, period 3: 6/3-6/17, period 4: 6/18-7/3, period 5: 7/4-7/17, period 6: 7/18-7/31, period 7: 8/1-8/14)

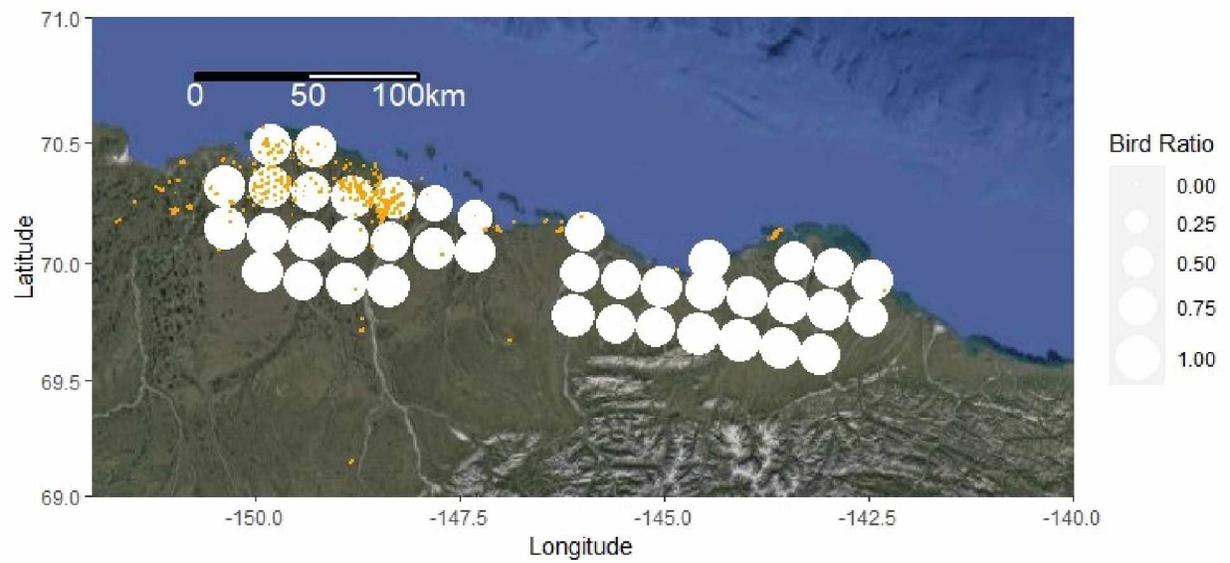
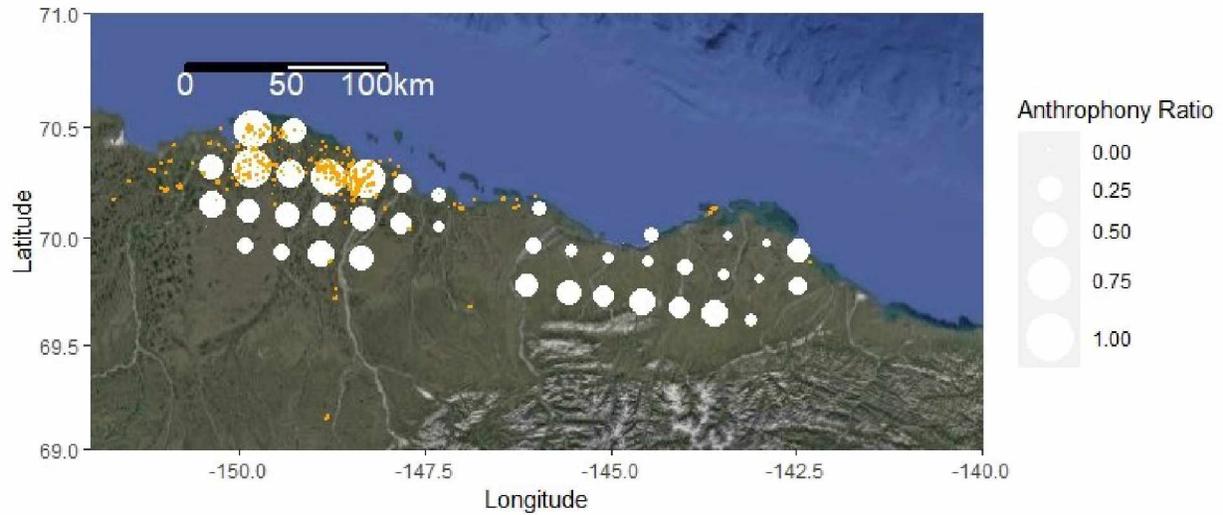


Figure 3. 4. **Bird bubblemap**

A bubblemap of all the sites in our study where the sites are represented by white dots whose size is relative to the proportion of time bird vocalizations was present at a given site across the entire season (bird ratio= (the number of hours with 1 or more bird detections at a site)/(the number of all hours recorded at a site)). The orange dots indicate the presence of infrastructure according to the North Slope Science Initiative (North Slope Science Initiative, 2021).



**Figure 3. 5. Anthrophony bubblemap**

A bubblemap of all the sites in our study, where the sites are represented by white dots whose size is relative to the proportion of hours that had 1 or more anthrophony detections at a given site across the entire season (anthrophony ratio= (the number of hours with 1 or more anthrophony detections at a site)/(the number of all hours recorded at a site)). The orange dots indicate the presence of infrastructure (excluding roads) according to the North Slope Science Initiative (North Slope Science Initiative, 2021).

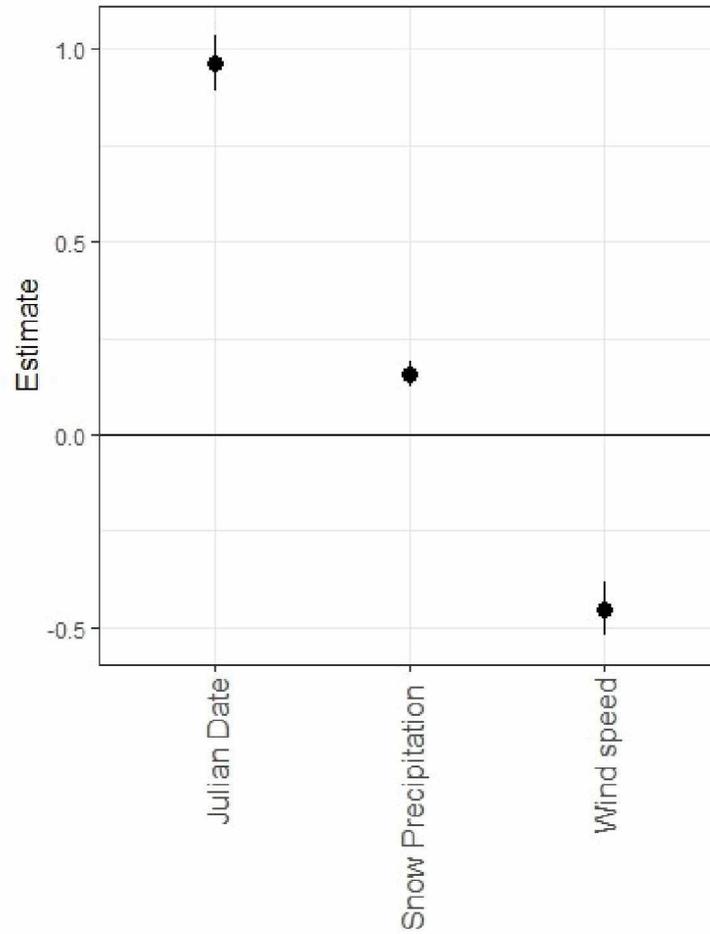


Figure 3. 6. **Graph of anthrophony model coefficient values**

Estimate values of the covariates present in our best supported GLMM of anthrophony detections represented by dots, with lines to show the confidence intervals. All covariates had a significant effect on anthrophony.

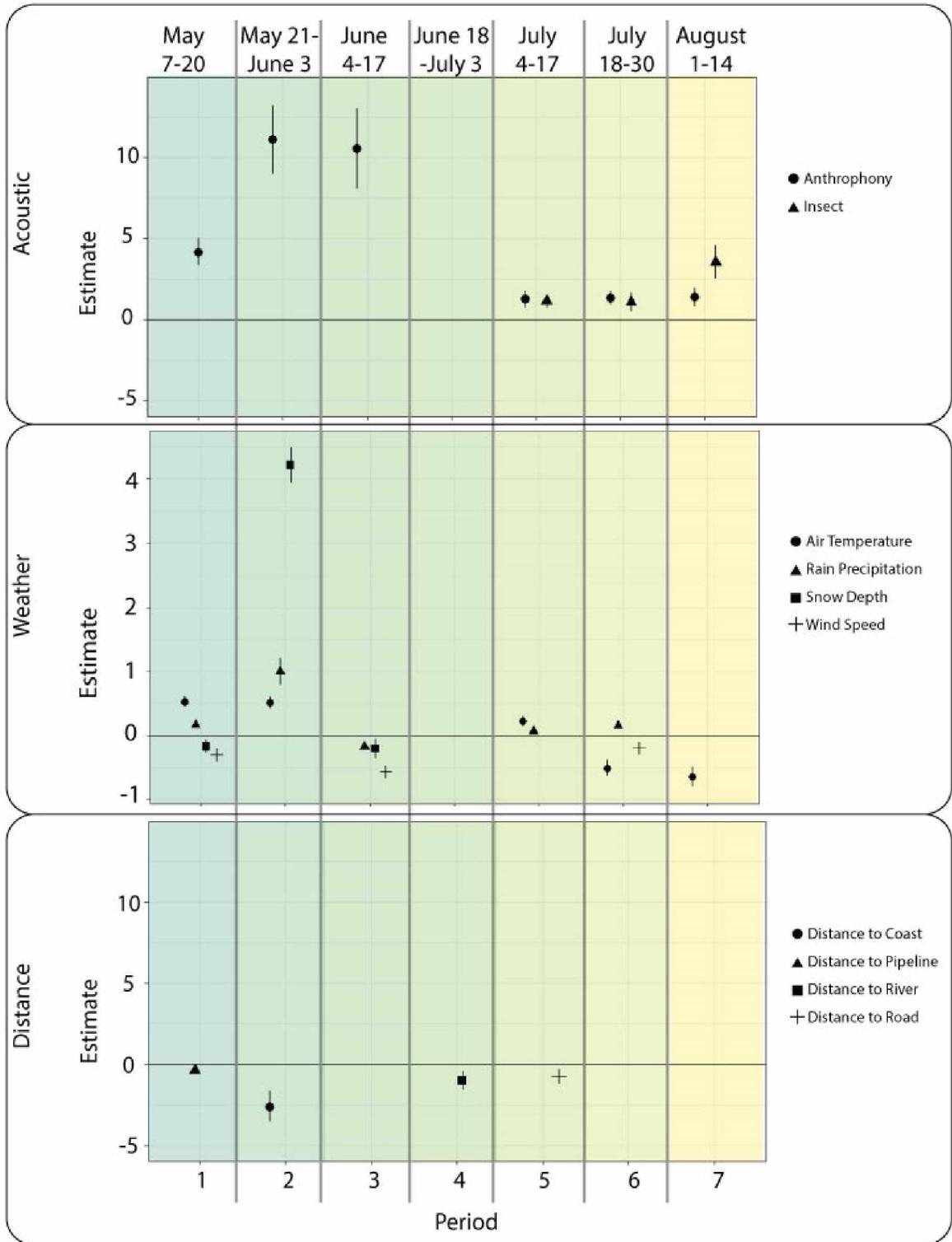


Figure 3. 7. **Graph of biophony coefficient values for all models**

Coefficient values of each covariate present in the top models across all time periods for our bird models. All covariates had a significant effect on the likelihood of bird vocalizations in a given period (Period 1: 5/7-5/20, period 2: 5/21-6/2, period 3: 6/3-6/17, period 4: 6/18-7/3, period 5: 7/4-7/17, period 6: 7/18-7/31, period 7: 8/1-8/14)

### 3.9 TABLES

Table 3. 1. **Thresholds and accuracy metrics.**

The thresholds chosen for each soundclass and their associated scores from our validation data, all of which range from 0-1. The threshold is the value of model confidence we used to trigger a binary detection at the 10-second level. The precision at that threshold measures the (number of true positives retrieved)/(the number of true positives retrieved + the number of false positives retrieved), while recall measures the (number of true positives retrieved)/(the total number of true positives present). The F-score is a balance of precision and recall.

Soundclass	Threshold	F-Score	Precision	Recall
Bird	0.720	0.932	0.939	0.924
Anthrophony	0.981	0.953	0.973	0.933
Insect	0.727	0.924	0.968	0.874
Aircraft	0.656	0.816	0.837	0.793

Table 3. 2. **Structure of Top Models.**

The best-fit model structures of the ‘anthrophony’ and ‘bird’ soundclass detection models within our study area in northern Alaska during the spring/summer of 2019. All models used ‘site’ and ‘hour’ as a random effect. We split our ‘bird’ models into 7 time periods, p.1 – p.7, of approximately 2 weeks each (Period 1: 5/7-5/20, period 2: 5/21-6/2, period 3: 6/3-6/17, period 4: 6/18-7/3, period 5: 7/4-7/17, period 6: 7/18-7/31, period 7: 8/1-8/14)

Soundclass	Model Structure
Anthrophony	~Julian Date + Wind Speed + Snow Precipitation + (1 hour) + (1 site)
Bird (p. 1)	~ Anthrophony + Distance to Pipeline + Rain Precipitation + Air Temperature + Snow Depth + Wind Speed + (1 hour) + (1 site)
Bird (p. 2)	~Distance to Coast + Anthrophony + Rain Precipitation + Air Temperature + Snow Depth + (1 hour) + (1 site)
Bird (p. 3)	~Anthrophony + Rain Precipitation + Wind Speed + Snow Depth + (1 hour) + (1 site)
Bird (p. 4)	~Distance to River + (1 hour) + (1 site)
Bird (p. 5)	~Anthrophony + Distance to Road + Insect + Rain Precipitation + Air Temperature + (1 hour) + (1 site)
Bird (p. 6)	~Anthrophony + Insect + Rain Precipitation + Air Temperature + Wind Speed + (1 hour) + (1 site)
Bird (p. 7)	Anthrophony + Insect + (1 hour) + (1 site)

### 3.10 APPENDIX

#### Appendix 3A. **Sound labeling model**

Before we began data processing, we excluded all sound files that had too much wind interference. We defined excessive wind interference as files that had an audio clipping rate of 1% or more, which indicated that the file was inaudible and other sounds could not be detected.

To generate labelled sound data, we created a subset of manually labelled audio files of variable length (3083 in total) by taking a random file from each of our 40 sites and labeling all the sounds present in that file. In this way, our subset of data represented the diversity of acoustic qualities across our study area. We used machine learning to train a sound labelling model with this subset, and the training process followed procedures outlined by Çoban et al. (2021). An expert analyst identified acoustic events (i.e. when specific sounds occurred) within 75-minute excerpts, using the file's spectrogram to identify such events from background noise. Spectrograms were visualized in Audacity 2.3.3 (Audacity 2020). Each sound event was exported as a smaller excerpt of the original file, ranging anywhere from a few seconds to a few minutes. These excerpts were cross referenced with published data from Stinchcomb et al. (2020) and Xeno Canto (xeno-canto.org); Xeno Canto is an open-source library of bird audio files and spectrograms from around the world. Each excerpt was labelled as “Anthrophony” or “Biophony”, and when the content of an excerpt was clear, anthrophony and biophony clips within each general class could be labelled with more precision (e.g., “Aircraft” or “Bird”, respectively). “Insect” was an additional soundclass labelled under biophony.

Initially, we generated a total of 3083 labeled clips. These clips could be as short as a few seconds or as long as a few minutes, and we subsequently split them into non-overlapping, 10-second clips for automatic processing. Any segments that were shorter than 10 seconds (but greater than 2 seconds) were padded with 0s so that they were the same length as the other samples. These labelled clips were divided between the training, validation and test sets so that all clips from each site were confined to just one of these sets. This allocation of sites to sets was accomplished via a multiple knapsack problem detailed in Çoban et al. (2021).

To create more training data for soundclasses that were particularly rare (anthrophony, aircraft and insect), we validated 10-second clips from the dataset that had already been labelled by a previous iteration of our classification model. We generated 1000 additional clips in search of more anthrophony samples. Half of those clips were selected from instances when the model

had high confidence ( $>0.75$ ) that anthrophony was detected, and half were randomly selected regardless of model predictions. The confidence of the model is not a prediction probability, but rather a reflection of model certainty, which is limited by the accuracy of the model itself. The threshold we chose was high enough to ensure that we would actually find clips with anthrophony. We pulled an equal number of clips from each week in the study period, only taking clips from sites that had been designated as training sites. The latter half of these clips were allocated from our training sites in proportion to the amount of anthrophony present, i.e. if 20% of all anthrophony during our study period occurred at one site, then 20% of our samples were pulled from there, and so on. These clips were labelled by trained undergraduate students independently, and their labels were reviewed by an expert labeler.

After adding our additional anthrophony samples, we had a dataset of 6616 10-second clips that were manually labeled. To ensure the accuracy of these labels, we built a user interface (UI) in Python that allowed an expert labeler to quickly access and review all of these clips. The reviewer was able to listen to each clip, view the spectrogram, and correct or validate the original labels by ticking or un-ticking boxes next to each possible soundclass. This UI was then used to label additional training samples for the ‘insect’, ‘anthrophony’, and ‘aircraft’ soundclasses. Again, we used a dataset labelled by earlier iterations of our model to pull samples from instances when the model’s confidence was high that the soundclass of interest was present. High model confidence was different for each class, and was defined as follows: 0.7 for anthrophony, 0.25 for aircraft, and 0.99 for the insect. We used multiple iterations of our model to select these clips in the hopes of providing a more diverse sample set. This process added ~4000 samples so that, ultimately, our dataset of training, validation and test data was comprised of over 10,000 clips.

The classification model itself was a four-layer deep convolutional neural network operating on 10-second clips of log mel spectrograms. In simplistic terms, these convolutional layers are a complex series of filters that process the input data. The characteristics of these filters are determined during the training process, and the layers work in concert with one another to extract the desired information from the data. In our case, this was the presence or absence of certain soundclasses which occurred alone or simultaneously. The network was trained for up to 1500 epochs; an ‘epoch’ represents each time you train a model through the dataset of training, test and validation samples, evaluating its performance and making changes. The model from the epoch with the highest minimum area under the receiver operating characteristic curve (AUC; a

common performance diagnostic in machine learning) across labels was selected for predicting over the entire dataset. The performance of the worst label was optimized to ensure a consistent level of performance across labels. This model also utilized specAugment data augmentation at training time to improve its ability to generalize to unseen data. See Çoban et al. (2021) for more details.

We determined that a soundclass was accurate enough for analysis if its AUC score was  $>0.80$ . Because birds comprise the vast majority of the biophony on the landscape, and this soundclass had relatively high accuracy compared to the minority of other biophony subclasses, we used “bird” as the class that represented all biophony. This also allowed us to investigate how insect detections—also under the umbrella of ‘biophony’—affected bird sound.

### Appendix 3B. Model Selection Tables

Table 3B.1 Model selection table for the period 1 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	7212	1
*Habitat ALL	7102.8	1
Habitat (waterbody)	7085	1
Habitat (river)	7085.2	1
Habitat (coast)	7085	1
Habitat (waterbody + coast)	7093.8	1
Habitat (waterbody + river)	7093.9	1
Habitat (coast + river)	7093.9	1
Infrastructure ALL	7083.4	1
*Infrastructure (pipe)	7075.1	1
Infrastructure (develop)	7084.4	1
Infrastructure (road)	7220.5	1
Infrastructure (pipe + develop)	7082.4	1
Infrastructure (pipe + road)	7075.3	1
Infrastructure (develop + road)	7087.4	1
Sound ALL	6967.6	1
*Sound (anthrophony)	6965.6	1
Sound (aircraft)	7056.7	1
Weather ALL	6749.7	1
Weather (rainprecip)	6964.8	1
Weather (airtemp)	6840.5	1
Weather (snowprecip)	7077.5	1
Weather (snowdepth)	7029	1
Weather (windspeed)	7043.3	1
Weather (rainprecip + airtemp)	6798.7	1
Weather (rainprecip + snowprecip)	6969.7	1
Weather (rainprecip + snowdepth)	6951.5	1
Weather (rainprecip + windspeed)	6929.4	1
Weather (airtemp + snowprecip)	6845.5	1
Weather (airtemp + snowdepth)	6847.2	1
Weather (airtemp + windspeed)	6788.5	1
Weather (snowprecip + snowdepth)	7035.3	1
Weather (snowprecip + windspeed)	7043.5	1
Weather (snowdepth + windspeed)	6939.9	1
Weather (rainprecip + airtemp + snowprecip)	6804.1	1
Weather (rainprecip + airtemp + snowdepth)	6807.7	1
Weather (rainprecip + airtemp + windspeed)	6748.3	1
Weather (rainprecip + windspeed + snowprecip)	6933.9	1
Weather (rainprecip + windspeed + snowdepth)	6878.5	1
Weather (snowdepth + snowprecip + windspeed)	6947.1	1

*Continued from pg. 78*

Weather (snowdepth + snowprecip + airtemp)	6852	1
Weather (snowdepth + snowprecip + rainprecip)	6958.6	1
Weather (snowprecip + airtemp + windspeed)	6793.1	1
Weather (snowdepth + airtemp + windspeed)	6774.6	1
Weather (snowdepth + airtemp + windspeed+snowprecip)	6778.4	1
*Weather (snowdepth + airtemp + windspeed + rainprecip)	6745.5	1
Weather (snowprecip + airtemp + windspeed+rainprecip)	6753.2	1
Weather (snowprecip + snowdepth + windspeed+rainprecip)	6886.4	1
Weather (snowprecip + snowdepth + airtemp +rainprecip)	6813.1	1

Table 3B.2 Model selection table for the period 1 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
habitat + infrastructure	7081.6	2
sound +habitat	6973.9	2
habitat +weather	6754.5	2
infrastructure + sound	6967.4	2
infrastructure + insect	6973.6	2
infrastructure + weather	6733.3	2
sound + weather	6635.3	2
habitat + infrastructure +weather	6741.9	2
habitat + infrastructure + sound	6973.8	2
habitat + sound + weather	6644.3	2
*infrastructure + sound + weather	6626.2	2
global	6634.8	2

Table 3B.3 Model selection table for the period 2 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	10439.1	2
Habitat ALL	10451.2	2
Habitat (waterbody)	10437.3	2
Habitat (river)	10446.6	2
*Habitat (coast)	10440.4	2
Habitat (waterbody + coast)	10442.3	2
Habitat (waterbody + river)	10446.1	2
Habitat (coast + river)	10449.1	2
Infrastructure ALL	10450.5	2
Infrastructure (pipe)	10439.8	2

*Continued from pg. 79*

Infrastructure (develop)	10434.3	2
*Infrastructure (road)	10436.2	2
Infrastructure (pipe + develop)	10442.5	2
Infrastructure (pipe + road)	10442.8	2
Infrastructure (develop + road)	10442.3	2
Sound ALL	NA	2
*Sound (anthrophony)	9448.2	2
Sound (aircraft)	NA	2
Weather ALL	7572.7	2
Weather (rainprecip)	10067.6	2
Weather (airtemp)	9643.6	2
Weather (snowprecip)	10320.8	2
Weather (snowdepth)	8007.5	2
Weather (windspeed)	9648	2
Weather (rainprecip + airtemp)	9205.2	2
Weather (rainprecip + snowprecip)	10074.7	2
Weather (rainprecip + snowdepth)	7683	2
Weather (rainprecip + windspeed)	9129.9	2
Weather (airtemp + snowprecip)	9467.7	2
Weather (airtemp + snowdepth)	7906.3	2
Weather (airtemp + windspeed)	9432.3	2
Weather (snowprecip + snowdepth)	7951.1	2
Weather (snowprecip + windspeed)	9450	2
Weather (snowdepth + windspeed)	8014.2	2
Weather (rainprecip + airtemp + snowprecip)	9205.7	2
*Weather (rainprecip + airtemp + snowdepth)	7559.4	2
Weather (rainprecip + airtemp + windspeed)	8929.3	2
Weather (rainprecip + windspeed + snowprecip)	9097.6	2
Weather (rainprecip + windspeed + snowdepth)	7668	2
Weather (snowdepth + snowprecip + windspeed)	7950.7	2
Weather (snowdepth + snowprecip + airtemp)	7831.2	2
Weather (snowdepth + snowprecip + rainprecip)	7689.9	2
Weather (snowprecip + airtemp + windspeed)	9226.8	2
Weather (snowdepth + airtemp + windspeed)	7901	2
Weather (snowdepth + airtemp + windspeed+snowprecip)	7833.8	2
Weather (snowdepth + airtemp + windspeed + rainprecip)	7568	2
Weather (snowprecip + airtemp + windspeed+rainprecip)	8904.9	2
Weather (snowprecip + snowdepth + windspeed+rainprecip)	7671.1	2
Weather (snowprecip + snowdepth + airtemp +rainprecip)	7563.8	2

Table 3B.4 Model selection table for the period 2 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
habitat + infrastructure	10442.1	2
sound + habitat	9451.2	2
habitat + weather	7544	2
infrastructure + sound	9439.1	2
infrastructure + weather	7566.2	2
sound + weather	7223.2	2
habitat + infrastructure + weather	7552.8	2
habitat + infrastructure + sound	9446.8	2
*habitat + sound + weather	7209.9	2
infrastructure + sound + weather	7230.7	2
global	7218.4	2
infrastructure + sound + weather	7230.7	2

Table 3B.5 Model selection table for the period 3 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	8357.8	3
Habitat ALL	8381.8	3
Habitat (waterbody)	8366.5	3
*Habitat (river)	8365.5	3
Habitat (coast)	8366.1	3
Habitat (waterbody + coast)	8374.9	3
Habitat (waterbody + river)	8373.8	3
Habitat (coast + river)	8373.1	3
Infrastructure ALL	8378.4	3
*Infrastructure (pipe)	8363.2	3
Infrastructure (develop)	8365.4	3
Infrastructure (road)	8366.6	3
Infrastructure (pipe + develop)	8372	3
Infrastructure (pipe + road)	8370.5	3
Infrastructure (develop + road)	8372	3
Sound ALL	8069.9	3
*Sound (anthrophony)	8061.2	3
Sound (aircraft)	8348.5	3
Weather ALL	7955.1	3
Weather (rainprecip)	8358.1	3
Weather (airtemp)	8362.3	3
Weather (snowprecip)	8365.9	3
Weather (snowdepth)	8315.2	3

*Continued from pg. 81*

Weather (windspeed)	7980.4	3
Weather (rainprecip + airtemp)	8362.7	3
Weather (rainprecip + snowprecip)	8365	3
Weather (rainprecip + snowdepth)	8304.2	3
Weather (rainprecip + windspeed)	7950.7	3
Weather (airtemp + snowprecip)	8369.5	3
Weather (airtemp + snowdepth)	8322.5	3
Weather (airtemp + windspeed)	7986.1	3
Weather (snowprecip + snowdepth)	8322.7	3
Weather (snowprecip + windspeed)	7988.3	3
Weather (snowdepth + windspeed)	7981.8	3
Weather (rainprecip + airtemp + snowprecip)	8368.4	3
Weather (rainprecip + airtemp + snowdepth)	8312.2	3
Weather (rainprecip + airtemp + windspeed)	7954.9	3
Weather (rainprecip + windspeed + snowprecip)	7955.3	3
*Weather (rainprecip + windspeed + snowdepth)	7946.6	3
Weather (snowdepth + snowprecip + windspeed)	7989.5	3
Weather (snowdepth + snowprecip + airtemp)	8329.5	3
Weather (snowdepth + snowprecip + rainprecip)	8309.2	3
Weather (snowprecip + airtemp + windspeed)	7994.5	3
Weather (snowdepth + airtemp + windspeed)	7987	3
Weather (snowdepth + airtemp + windspeed+ snowprecip)	7995.3	3
Weather (snowdepth + airtemp + windspeed + rainprecip)	7949.8	3
Weather (snowprecip + airtemp + windspeed+ rainprecip)	7960.8	3
Weather (snowprecip + snowdepth + windspeed+ rainprecip)	7950.3	3
Weather (snowprecip + snowdepth + airtemp + rainprecip)	8316.4	3

Table 3B.6 Model selection table for the period 3 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
habitat + infrastructure	8371.5	3
sound + habitat	8067.8	3
habitat + weather	7954.9	3
infrastructure + sound	8062.7	3
infrastructure + weather	7953	3
*sound + weather	7727.5	3
habitat + infrastructure + weather	7961.7	3
habitat + infrastructure + sound	8070.6	3
habitat + infrastructure + insect	8353.3	3
habitat + sound + weather	7734.6	3
habitat + sound + insect	8054.5	3

*Continued from pg. 82*

infrastructure + sound + weather	7730.8	3
global	7743.1	3
Habitat + Sound + Infrastructure + Weather	7739.4	3

Table 3B.7 Model selection table for the period 4 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	711.1	4
Habitat ALL	718.2	4
Habitat (waterbody)	713.6	4
*Habitat (river)	707.1	4
Habitat (coast)	716.2	4
Habitat (waterbody + coast)	719.6	4
Habitat (waterbody + river)	711.8	4
Habitat (coast + river)	713.4	4
Infrastructure ALL	724.8	4
Infrastructure (pipe)	717.6	4
Infrastructure (develop)	717	4
*Infrastructure (road)	713.6	4
Infrastructure (pipe + develop)	723	4
Infrastructure (pipe + road)	718.4	4
Infrastructure (develop + road)	719.1	4
Sound ALL	721.6	4
Sound (anthrophony)	717.5	4
*Sound (aircraft)	715.9	4
Weather ALL	726	4
Weather (rainprecip)	712.3	4
Weather (airtemp)	717.5	4
*Weather (snowprecip)	711.3	4
Weather (snowdepth)	712.5	4
Weather (windspeed)	717.4	4
Weather (rainprecip + airtemp)	718.7	4
Weather (rainprecip + snowprecip)	711.5	4
Weather (rainprecip + snowdepth)	715.3	4
Weather (rainprecip + windspeed)	718.7	4
Weather (airtemp + snowprecip)	716.7	4
Weather (airtemp + snowdepth)	718	4
Weather (airtemp + windspeed)	723.9	4
Weather (snowprecip + snowdepth)	713.8	4
Weather (snowprecip + windspeed)	716.5	4
Weather (snowdepth + windspeed)	718.8	4
Weather (rainprecip + airtemp + snowprecip)	716.9	4

*Continued from pg. 83*

Weather (rainprecip + airtemp + snowdepth)	721.1	4
Weather (rainprecip + airtemp + windspeed)	725.1	4
Weather (rainprecip + windspeed + snowprecip)	717.8	4
Weather (rainprecip + windspeed + snowdepth)	721.8	4
Weather (snowdepth + snowprecip + windspeed)	719	4
Weather (snowdepth + snowprecip + airtemp)	717.4	4
Weather (snowdepth + snowprecip + rainprecip)	715.6	4
Weather (snowprecip + airtemp + windspeed)	722.4	4
Weather (snowdepth + airtemp + windspeed)	724.5	4
Weather (snowdepth + airtemp + windspeed+snowprecip)	723.3	4
Weather (snowdepth + airtemp + windspeed + rainprecip)	727.4	4
Weather (snowprecip + airtemp + windspeed+rainprecip)	723.4	4
Weather (snowprecip + snowdepth + windspeed+rainprecip)	721.8	4
Weather (snowprecip + snowdepth + airtemp +rainprecip)	719.5	4

Table 3B.8 Model selection table for the period 4 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
insect	732.8	4
habitat + infrastructure	707.6	4
sound +habitat	711.8	4
Habitat + insect	729	4
habitat +weather	707.6	4
infrastructure + sound	718.4	4
infrastructure + insect	719.9	4
infrastructure + weather	713.1	4
sound + insect	722.2	4
sound + weather	716.1	4
*habitat + infrastructure +weather	707.2	4
habitat + infrastructure + sound	718.8	4
habitat + infrastructure + insect	713.9	4
habitat + sound + weather	717.8	4
habitat + sound + insect	724	4
habitat + insect + weather	714	4
infrastructure + sound + insect	731.1	4
infrastructure + sound + weather	724.2	4
infrastructure + insect + weather	719.8	4
insect + weather + sound	727.9	4
insect + weather	717.7	4
global	724.8	4
Habitat + Sound + Infrastructure + Insect	730	4

*Continued from pg. 84*

Habitat + Sound + Infrastructure + Weather	723.3	4
Habitat + Sound + Insect + Weather	724.4	4
Habitat + Infrastructure + Insect + Weather	724.8	4
Sound + Infrastructure + Insect + Weather	724.3	4

Table 3B.9 Model selection table for the period 5 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	6621.2	5
Habitat ALL	6633.5	5
*Habitat (waterbody)	6617.3	5
Habitat (river)	6625.6	5
Habitat (coast)	6629.5	5
Habitat (waterbody + coast)	6625.8	5
Habitat (waterbody + river)	6625.2	5
Habitat (coast + river)	6634.3	5
Infrastructure ALL	6625.7	5
Infrastructure (pipe)	6629.4	5
Infrastructure (develop)	6621.6	5
*Infrastructure (road)	6612.2	5
Infrastructure (pipe + develop)	6627.8	5
Infrastructure (pipe + road)	6617.3	5
Infrastructure (develop + road)	6620.9	5
Sound ALL	6601.6	5
*Sound (anthrophony)	6593.3	5
Sound (aircraft)	6629.9	5
Weather ALL	6606.6	5
Weather (rainprecip)	6622.9	5
Weather (airtemp)	6587.6	5
Weather (snowprecip)	6625.3	5
Weather (snowdepth)	6623.7	5
Weather (windspeed)	6629.9	5
*Weather (rainprecip + airtemp)	6588.5	5
Weather (rainprecip + snowprecip)	6627.2	5
Weather (rainprecip + snowdepth)	6625.3	5
Weather (rainprecip + windspeed)	6631.5	5
Weather (airtemp + snowprecip)	6593.2	5
Weather (airtemp + snowdepth)	6591.5	5
Weather (airtemp + windspeed)	6596.3	5
Weather (snowprecip + snowdepth)	6627.7	5
Weather (snowprecip + windspeed)	6633.9	5
Weather (snowdepth + windspeed)	6632.2	5

*Continued from pg. 85*

Weather (rainprecip + airtemp + snowprecip)	6594.3	5
Weather (rainprecip + airtemp + snowdepth)	6592.2	5
Weather (rainprecip + airtemp + windspeed)	6597	5
Weather (rainprecip + windspeed + snowprecip)	6635.8	5
Weather (rainprecip + windspeed + snowdepth)	6634	5
Weather (snowdepth + snowprecip + windspeed)	6636.2	5
Weather (snowdepth + snowprecip + airtemp)	6597	5
Weather (snowdepth + snowprecip + rainprecip)	6629.5	5
Weather (snowprecip + airtemp + windspeed)	6601.9	5
Weather (snowdepth + airtemp + windspeed)	6600	5
Weather (snowdepth + airtemp + windspeed+snowprecip)	6605.5	5
Weather (snowdepth + airtemp + windspeed + rainprecip)	6600.8	5
Weather (snowprecip + airtemp + windspeed+rainprecip)	6602.8	5
Weather (snowprecip + snowdepth + windspeed+rainprecip)	6638.3	5
Weather (snowprecip + snowdepth + airtemp +rainprecip)	6597.9	5

Table 3B.10 Model selection table for the period 5 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
insect	6587.6	5
habitat + infrastructure	6617.7	5
sound +habitat	6626	5
Habitat + insect	6754.4	5
habitat +weather	6583.1	5
infrastructure + sound	6621	5
infrastructure + insect	6576.1	5
infrastructure + weather	6576	5
sound + insect	6596.4	5
sound + weather	6597.1	5
habitat + infrastructure +weather	6581.1	5
habitat + infrastructure + sound	6603.5	5
habitat + infrastructure + insect	6581.1	5
habitat + sound + weather	6572.8	5
habitat + sound + insect	6566.5	5
habitat + insect + weather	6566.1	5
infrastructure + sound + insect	6563.6	5
infrastructure + sound + weather	6569	5
infrastructure + insect + weather	6547	5
insect + weather + sound	6550.6	5
insect + weather	6561.5	5
global	6546.1	5

*Continued from pg. 86*

Habitat + Sound + Infrastructure + Insect	6560.1	5
Habitat + Sound + Infrastructure + Weather	6566.1	5
Habitat + Sound + Insect + Weather	6537.3	5
Habitat + Infrastructure + Insect + Weather	6551.6	5
*Sound + Infrastructure + Insect + Weather	6532.7	5

Table 3B.11 Model selection table for the period 6 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	7264.1	6
Habitat ALL	7282	6
*Habitat (waterbody)	7266.5	6
Habitat (river)	7271.3	6
Habitat (coast)	7272.8	6
Habitat (waterbody + coast)	7273.6	6
Habitat (waterbody + river)	7275.3	6
Habitat (coast + river)	7279.3	6
Infrastructure ALL	7266.9	6
Infrastructure (pipe)	7260.8	6
Infrastructure (develop)	7259.1	6
*Infrastructure (road)	7252.7	6
Infrastructure (pipe + develop)	7264.9	6
Infrastructure (pipe + road)	7258	6
Infrastructure (develop + road)	7261	6
Sound ALL	7233	6
*Sound (anthrophony)	7225.6	6
Sound (aircraft)	7272.9	6
Weather ALL	7158.7	6
Weather (rainprecip)	7231.6	6
Weather (airtemp)	7219.4	6
Weather (windspeed)	7245.9	6
Weather (rainprecip + airtemp)	7179.1	6
Weather (rainprecip + windspeed)	7216	6
Weather (airtemp + windspeed)	7196.3	6
*Weather (rainprecip + airtemp + windspeed)	7158.7	6

Table 3B.12 Model selection table for the period 6 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
insect	6587.6	6
habitat + infrastructure	6617.7	6
sound +habitat	6626	6
Habitat + insect	6754.4	6
habitat +weather	6583.1	6
infrastructure + sound	6621	6
infrastructure + insect	6576.1	6
infrastructure + weather	6576	6
sound + insect	6596.4	6
sound + weather	6597.1	6
habitat + infrastructure +weather	6581.1	6
habitat + infrastructure + sound	6603.5	6
habitat + infrastructure + insect	6581.1	6
habitat + sound + weather	6572.8	6
habitat + sound + insect	6566.5	6
habitat + insect + weather	6566.1	6
infrastructure + sound + insect	6563.6	6
infrastructure + sound + weather	6569	6
infrastructure + insect + weather	6547	6
insect + weather + sound	6550.6	6
insect + weather	6561.5	6
global	6546.1	6
Habitat + Sound + Infrastructure + Insect	6560.1	6
Habitat + Sound + Infrastructure + Weather	6566.1	6
Habitat + Sound + Insect + Weather	6537.3	6
Habitat + Infrastructure + Insect + Weather	6551.6	6
*Sound + Infrastructure + Insect + Weather	6532.7	6

Table 3B.13 Model selection table for the period 7 bird model, showing the first round of model selection within variable groups. Top models are indicated by a \*

Model Structure	BIC	Period
Null	4907.9	7
Habitat ALL	4932	7
Habitat (waterbody)	4916.3	7
*Habitat (river)	4915.2	7
Habitat (coast)	4916.4	7
Habitat (waterbody + coast)	4924.7	7
Habitat (waterbody + river)	4923.9	7
Habitat (coast + river)	4923.4	7

*Continued from pg. 88*

Infrastructure ALL	4912.6	7
Infrastructure (pipe)	4912	7
Infrastructure (develop)	4916.4	7
*Infrastructure (road)	4911.5	7
Infrastructure (pipe + develop)	4918.1	7
Infrastructure (pipe + road)	4918.9	7
Infrastructure (develop + road)	4912.9	7
Sound ALL	4893.9	7
*Sound (anthrophony)	4886.1	7
Sound (aircraft)	4916.5	7
Weather ALL	4863.1	7
Weather (rainprecip)	4910	7
*Weather (airtemp)	4841.1	7
Weather (snowprecip)	4907.7	7
Weather (snowdepth)	4911.8	7
Weather (windspeed)	4914.3	7
Weather (rainprecip + airtemp)	4845.7	7
Weather (rainprecip + snowprecip)	4910.4	7
Weather (rainprecip + snowdepth)	4917.1	7
Weather (rainprecip + windspeed)	4914.9	7
Weather (airtemp + snowprecip)	4846.4	7
Weather (airtemp + snowdepth)	4848.5	7
Weather (airtemp + windspeed)	4848.1	7
Weather (snowprecip + snowdepth)	4914.5	7
Weather (snowprecip + windspeed)	4913.6	7
Weather (snowdepth + windspeed)	4920.6	7
Weather (rainprecip + airtemp + snowprecip)	4851.2	7
Weather (rainprecip + airtemp + snowdepth)	4853.3	7
Weather (rainprecip + airtemp + windspeed)	4851.4	7
Weather (rainprecip + windspeed + snowprecip)	4914.6	7
Weather (rainprecip + windspeed + snowdepth)	4918.7	7
Weather (snowdepth + snowprecip + windspeed)	4920.5	7
Weather (snowdepth + snowprecip + airtemp)	4852.9	7
Weather (snowdepth + snowprecip + rainprecip)	4917.2	7
Weather (snowprecip + airtemp + windspeed)	4853	7
Weather (snowdepth + airtemp + windspeed)	4858.1	7
Weather (snowdepth + airtemp + windspeed+ snowprecip)	4859.6	7
Weather (snowdepth + airtemp + windspeed + rainprecip)	4861.5	7
Weather (snowprecip + airtemp + windspeed+ rainprecip)	4856.5	7
Weather (snowprecip + snowdepth + windspeed+ rainprecip)	4921.5	7
Weather (snowprecip + snowdepth + airtemp + rainprecip)	4857.7	7

Table 3B.14 Model selection table for the period 7 bird model, showing the second round of model selection between variable groups, where the variables included in each category are determined by the top models in the first round of selection. Top models are indicated by a \*

Model Structure	BIC	Period
insect	4910.1	7
habitat + infrastructure	4919.2	7
sound +habitat	4893.9	7
Habitat + insect	4916.5	7
habitat +weather	4848.2	7
infrastructure + sound	4893.1	7
infrastructure + insect	4873.9	7
infrastructure + weather	4847	7
sound + insect	4849.9	7
sound + weather	4824.5	7
habitat + infrastructure +weather	4854.4	7
habitat + infrastructure + sound	4901.1	7
habitat + infrastructure + insect	4881.5	7
habitat + sound + weather	4832	7
habitat + sound + insect	4857.6	7
habitat + insect + weather	4812.1	7
infrastructure + sound + insect	4857	7
infrastructure + sound + weather	4832.4	7
infrastructure + insect + weather	4811.2	7
*insect + weather + sound	4790.1	7
insect + weather	4805	7
global	4805.7	7
Habitat + Sound + Infrastructure + Insect	4864.9	7
Habitat + Sound + Infrastructure + Weather	4832.4	7
Habitat + Sound + Insect + Weather	4840	7
Habitat + Infrastructure + Insect + Weather	4818.6	7
Sound + Infrastructure + Insect + Weather	4798.1	7

Table 3B.15 Model selection table for anthrophony, showing all potential variable combinations. Because the null models were the top models in the 'habitat' and 'infrastructure' groups, we did not advance to a second, between-group selection process. Top model is indicated by a \*.

Model Structure	BIC
*Juliandate + snowprecip + windspeed	8218.3
Juliandate + rainprecip + snowprecip + windspeed	8220.2
Juliandate + snowprecip + windspeed + airtemp	8227
Juliandate + rainprecip + snowprecip + windspeed + airtemp	8229.6
Juliandate + windspeed	8270
Juliandate + windspeed + airtemp	8277.7
Juliandate + rainprecip + windspeed	8279.1
Juliandate + rainprecip + windspeed + airtemp	8287.3

*Continued from pg. 90*

Juliandate + snowprecip	8394.5
Juliandate + rainprecip + snowprecip	8396.2
Juliandate + snowprecip + airtemp	8404.3
Juliandate + rainprecip + snowprecip +airtemp	8405.5
Juliandate	8433.4
Juliandate + rainprecip	8441.6
Juliandate + airtemp	8443.7
Juliandate + rainprecip + airtemp	8451.8
Juliandate + coast	8442.8
Juliandate + waterbody	8443.9
Juliandate + river	8444
Juliandate + coast + river	8453.1
Juliandate + coast + waterbody	8453.6
Juliandate + river + waterbody	8454.3
Juliandate + coast + river + waterbody	8463.8
Juliandate + road	8439.3
Juliandate + develop	8442.3
Juliandate + pipe	8442.8
Juliandate + develop + road	8449.5
Juliandate + pipe + road	8450
Juliandate + develop + pipe	8452.9
Juliandate + develop + pipe + road	8460.1

Appendix 3C.

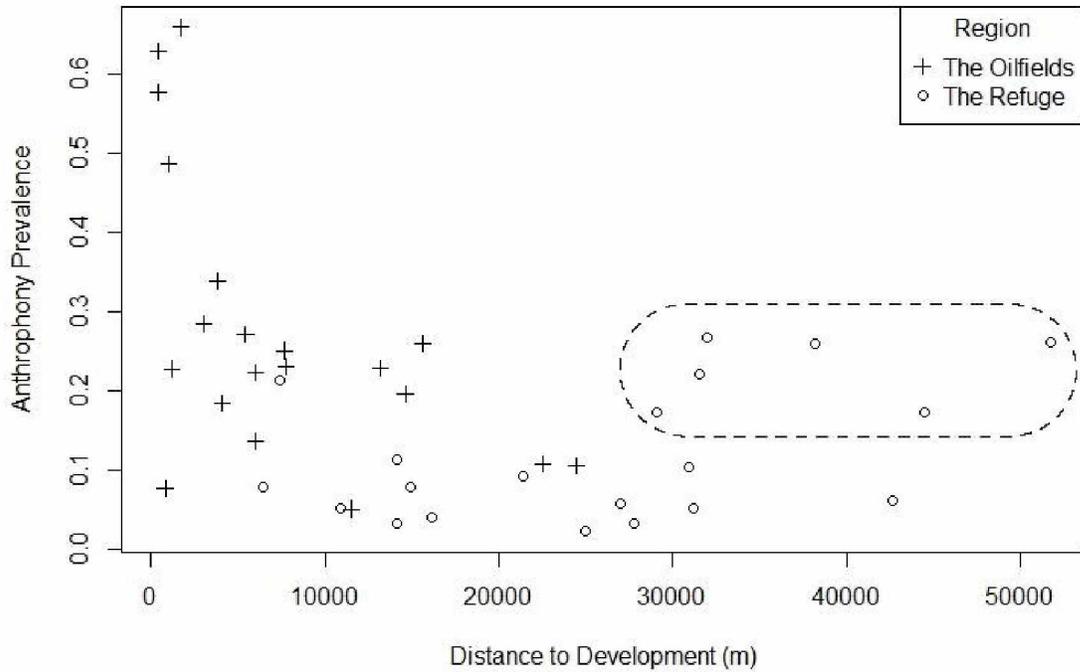
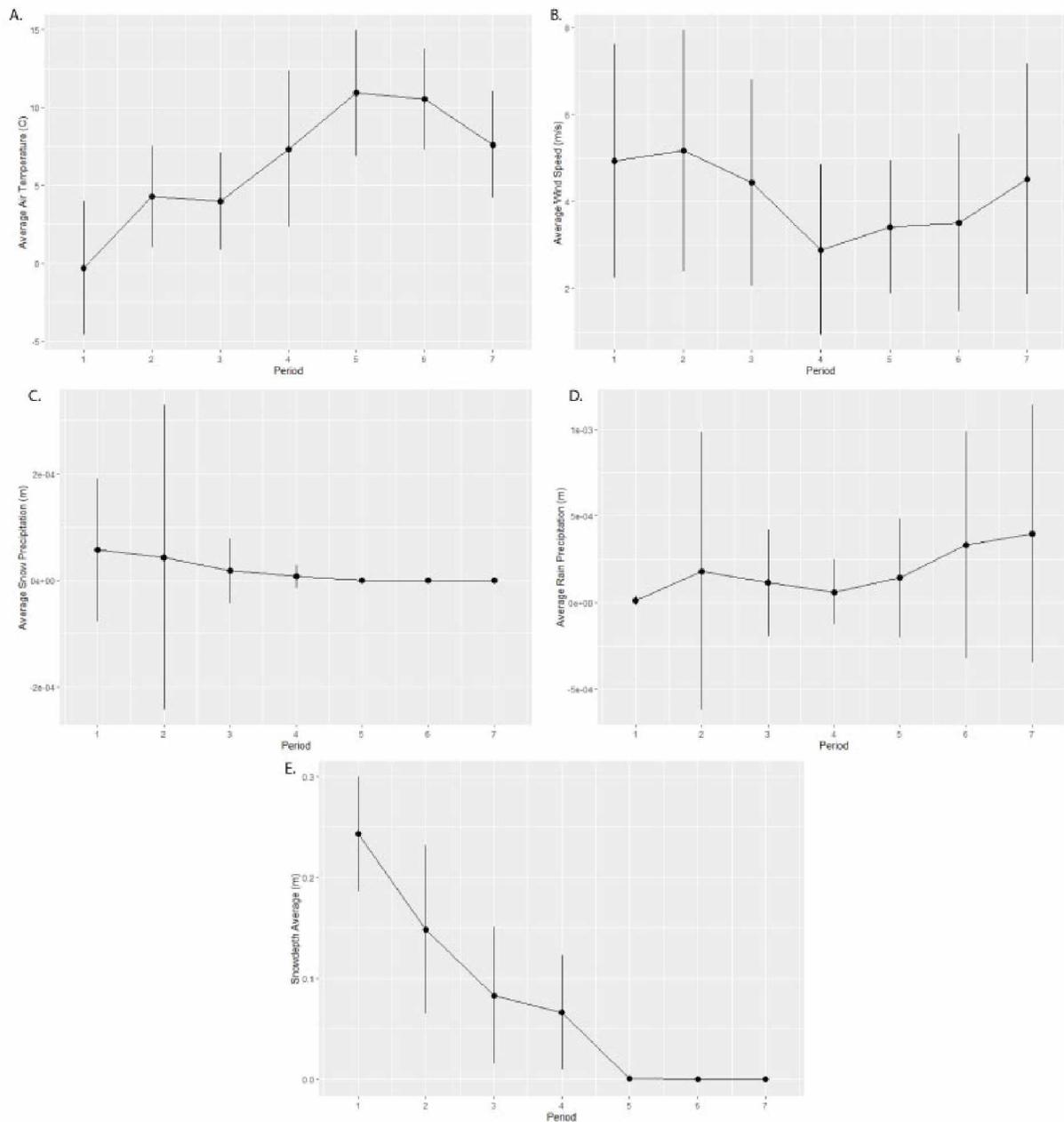


Figure 3C.1 **Anthrophony prevalence with distance to infrastructure**

The prevalence of anthrophony at each site in the two regions of our study area plotted against the distance to development (m). The dotted line identifies 6 of the southernmost sites in The Refuge where anthrophony appeared unusually high. Excluding these sites, there appears to be a trend wherein anthrophony prevalence decreases as the distance to development increases.

## Appendix 3D.



**Figure 3D.1 Weather variable averages per period.**

The per period average of weather variables tested during model selection; the average is taken from all sites, with lines that show standard deviation. Period 1: 5/7-5/20, period 2: 5/21-6/2, period 3: 6/3-6/17, period 4: 6/18-7/3, period 5: 7/4-7/17, period 6: 7/18-7/31, period 7: 8/1-8/14. A. The average air temperature (Celsius) taken from 3-hour averages; B. The average windspeed (m/s) taken from 3-hour averages; C. The average snow precipitation (m) taken from 3-hour totals; D. The average rain precipitation (m) taken from 3-hour totals; E. The average snow depth (m) taken from the instantaneous value at the end of the 3-hour time step.

## CHAPTER 4: General Discussion

My research provided novel information on caribou hearing and on the soundscapes characteristics that they encounter on the Arctic Coastal Plain (ACP) of Alaska. Anthrophony is an important soundclass to evaluate on the ACP not only because it can exceed the footprint of the infrastructure creating it, but also because sounds generated from human activity, like air traffic, can bring disproportionate levels of disturbance to otherwise remote areas (Stinchcomb et al. 2020). I have taken the first step to a broader understanding of sound disturbance in caribou by 1) testing their ability to perceive it using Brainstem Auditory Evoked Response (BAER) methods (Chapter 2), and 2) documenting the soundscape characteristics of their environment and that of bird communities (Chapter 3). I was also able to identify a new lower limit of the caribou's hearing threshold (Perra et al. 2022), and determined that they are able to hear any anthrophony that they might encounter in the Oilfields. I outlined the prevalence of anthrophony on the ACP using a randomized grid of acoustic recording units and a sound-labelling model that automatically processed over 45,000 hours of audio recordings. From this, I modeled bird vocalizations (biophony), and showed that birds are more likely to vocalize when anthrophony is present. This work is the first to document the soundscape characteristics of this system and demonstrate a clear relationship between biophony and anthrophony on the ACP. As caribou and migratory birds are vital subsistence species in Alaska (Bacon et al. 2011, Parlee et al. 2018), identifying their ability to respond to and perceive potentially disturbing stimuli goes hand-in-hand with measuring the extent of that stimuli so we can have a holistic understanding of how these species are affected by current and future land-use practices in the region.

In chapter 2, I used captive reindeer as my research subjects because they are the same species as wild caribou. I found that they were more aurally sensitive at the lower frequency ranges than we expected, based on previous research by Flydal et al. (2001), who used behavioral studies to determine the hearing range and sensitivity of reindeer. I used the BAER method in my study, employing an electroencephalogram (EEG) to measure the auditory system's response directly when we played a sound stimulus, rather than relying on trained individuals to perform a task to indicate that they'd perceived the sound. Generally, behavioral methods are considered more sensitive than BAER methods at the lower end of a species' hearing range (Gorga et al. 1988). Surprisingly, I recorded a clear, repeatable response from the reindeers' auditory system

at 30 Hz, while Flydal et al. (2001) recorded a response to sounds no lower than 61 Hz. However, we were limited by our equipment to measure frequencies below 30 Hz, and it's possible that caribou can hear lower than this given reports that caribou can vocalize as low as 15 Hz (Ericson 1972), near infrasonic frequencies. Regardless, they are capable of hearing the sound of seismic exploration, which is used in the winter during oil and gas exploration. A subset of caribou from the Central Arctic and Teshekpuk herds overwinter near the village of Nuiqsut, west of the Oilfields studied in my second chapter. These caribou would be vulnerable to exploration activities, and are an important resource for subsistence hunters who mainly access them in the winter months (Native Village of Nuiqsut et al. vs BLM et al. 2019).

Future impact statements for industrial activity should more thoroughly consider the potential for anthrophony to displace pockets of caribou away from Native communities that rely on them for food security and cultural traditions. Chapter 2 has provided an updated audiogram that—used in conjunction with the upper hearing range established by Flydal et al. (2001)—provides information on what frequencies and dB levels might be perceived by caribou. Land managers should be able to combine this information with estimates of sound propagation from various sources to evaluate how aurally sensitive caribou may be to certain activities on the ACP.

In Chapter 3, I evaluated the soundscape on the ACP during the spring and summer seasons of 2019 using sites across the oilfields surrounding Prudhoe Bay (hereafter, the Oilfields), and the Arctic National Wildlife Refuge (The Refuge). I defined the acoustic environment that the caribou regularly encountered by using generalized linear mixed-effects models (GLMMs) of bird vocalizations in 7, 2-week periods. I found a clear relationship between bird vocalizations and anthrophony, where birds are more likely to vocalize when anthrophony was present across nearly all periods. This relationship was strongest in the early season, when migratory birds were arriving and breeding. The effect of this relationship may propagate through the ecosystem in a variety of ways, for species that use bird vocalizations as an indicator of habitat quality. Some migratory birds, for example, are exceptionally sensitive to meteorological changes in the early season, with a series of hormonal feedbacks that respond to environmental stressors and regulate behaviors like breeding and singing (Wingfield et al. 2004, Ramenofsky and Wingfield 2017). Not only do they occupy snow free patches first, but they also sing from them (Oliver et al. 2018), and the vocalizations of some species—like Lapland longspurs (*Calcarius lapponicus*)—can be heard by humans up to 1km away on calm days (Hussell and Montgomerie 2020). Birds may advertise

snow free patches in the early season, and in that way provide important biological cues that other avian migrants and incoming caribou can use to navigate the ACP during the nesting and calving season, respectively.

The response that birds have to anthropony could affect the perceived quality of their habitat, thus affecting the distribution patterns of incoming migrants, since conspecific and heterospecific presence is an important cue for many birds (Mönkkönen and Forsman 2002, Cunningham et al. 2016, Swift et al. 2017), and birds may seek heterospecifics by song (Mönkkönen et al. 1996). In other systems, migratory birds that use heterospecific cues, like song, in their settlement decisions had greater reproductive success (Mönkkönen and Forsman 2002). Another study has found that a variety of passerines are attracted to the sound of traffic (Hennigar et al. 2019), and we could see similar responses in our system if increased birdsong in sound-disturbed areas acts as an attractant. More studies are needed to evaluate how this dynamic is affecting community structure, and if certain species are suffering or benefiting disproportionately to soundscape change. Additionally, evaluating this same dataset at a finer timescale would help determine whether or not birds are changing the timing of their song in response to anthropony, as Vincelette et al. (2021) have observed in Denali National Park, Alaska, USA.

Static landscape features—such as the distance to infrastructure or water features—had individual significance in certain periods, but not others, and were not the strongest or most consistent driver of bird vocalizations. Birds vocalized more near pipelines in period 1, closer to the coast in period 2, closer to the river in period 4, and closer to the road in period 5. With the exception of period 2—which is likely the result of a pulse of arriving migrants—these relationships are all potential responses to seasonal variations in forage availability. The attraction to rivers in period 4, for instance, is likely related to the emergence of aquatic insects, and in the periods following, we were more likely to detect birds in the presence of more audible, aerial insects. Studies at a finer scale that incorporate vegetation characteristics would likely reveal more detailed habitat-driven geographic patterns than I have shown Chapter 3.

The extent of sound disturbance on the ACP was also detailed in my second chapter, and it was clear that a majority of sound disturbance (83%) occurred at my sites in the Oilfields. However, it's important to note that a majority of the hours (63%) where anthropony was detected included aircraft detections, and there were no significant relationships between

anthrophony detections and infrastructure when I modelled anthrophony detections with a GLMM. Likely, this is due to sites at the southern extent of The Refuge, where there was more anthrophony than expected due to aircraft activity. Because those sites are some of the most remote—i.e. furthest from infrastructure—they may have confounded the relationship with anthrophony and infrastructure that seems to be present in the Oilfields. In evaluating anthrophony prevalence in the raw, ten-second data, I was able to see that the most intense hours of anthrophony disturbance occurred at only 4 sites in the Oilfields. Chronic disturbance may therefore be easy for most bird species to avoid because many habitat types are widespread, especially riparian areas and wetlands vital for many shorebirds. In The Refuge, riparian and wetland habitats are more limited, and disturbances in them would be more consequential. Caribou may also be flexible in their ability to avoid chronic sound disturbance for most of the season, but in midsummer be forced to cross these high disturbance areas in The Oilfields to access insect relief along the coasts (Prichard et al. 2020).

How caribou respond to anthrophony, and to the soundscape in general, should be the focus of future research. Biophony is a possible indicator of habitat quality, as mentioned above. Conveniently, caribou are well suited to detect birdsong—their hearing is incredibly sensitive between 3-16 kHz (Flydal et al. 2001). At these frequencies, caribou can hear sound levels below human hearing thresholds (i.e., 0 dBnHL). This sensitivity overlaps with the vocalizations of the two most common birds on the ACP: Lapland longspurs and semipalmated sandpipers (*Calidris pusilla*) (Troy 1996). Lapland longspurs vocalize between 2-6 kHz (Male and Nol 2005), and semipalmated sandpipers vocalize around 3.5 kHz (Miller 1983). Both of these species are early arrivers that nest in habitat types relevant to caribou. Lapland longspurs nest in sedge-dominated tussock tundra (Boelman et al. 2015) that contain *Eriophorum vaginatum* (cottongrass), and semipalmated sandpipers nest in graminoid tundra or near riparian habitats (Brown et al. 2007) that are historically important for caribou (Miller et al. 2013). Caribou may be adapted to hear heterospecific vocalizations if it helps them navigate the environment and find areas with good forage, especially during calving. More research is warranted to explore how caribou navigate their acoustic environment.

Caribou appear most sensitive to infrastructure during calving, when they avoid it at a distance that exceeds their ability to see it on the landscape (Johnson et al. 2020), and it is possible that their perception of anthrophony may play a role in this behavior. The idea that the physical

presence of seldom-used infrastructure has little impact on how caribou behave in the Oilfields is further emphasized by important work from Prichard et al. (2022). They found that calving caribou took no issue with inactive drilling pads that were elevated above the surrounding environment, but that they avoided roads with constant traffic, keeping a distance of 5km. Human activity appears to play a large role in how caribou respond to potential disturbances, in that they are most responsive when there is more activity present (Haskell et al. 2008, Eftestøl et al. 2019). In the Oilfields specifically, calving is the most sensitive period of time for caribou avoidance, i.e., the time when they are displaced from infrastructure at the greatest distances (Johnson et al. 2020, Prichard et al. 2020). To evaluate the degree to which anthropony is responsible for caribou displacement during this period in the season, researchers should use caribou equipped with audio-recording collars (or ‘audio collars’) to collect real time movement-response data.

GPS collars that have an audio recorder attached, sometimes called ‘audio collars’, could provide real-time information about how caribou move when they’re exposed to different sounds or soundscapes. Acoustic collars have been used to successfully monitor behavior (Lynch et al. 2013, Yan et al. 2019), but have yet to be used as a way to monitor a species-specific response to the soundscape. This method would allow researchers to evaluate how caribou move when anthropony of varying intensities is present, or if they exhibit any preferences for birdsong or other biophony. Overall soundscape preferences could be determined by comparing the soundscapes most commonly encountered by caribou to the soundscapes recorded by a stationary grid of audio recorders. Additionally, acoustic collars could provide firsthand data of insect harassment; most research approximates of insect harassment are based on weather variables (Witter et al. 2012), and using audio data could help clarify our current assumptions about when harassment actually happens, and what the behavior consequences are of harassment.

Both of my chapters have provided novel information and important points of reference that can be used as jumping off points for future research. It’s important for researchers to consider the auditory perspective when assessing disturbance of a species or landscape, and soundscapes can capture a variety of geographic, climatic and biological change. The landscape on the ACP is facing dramatic shifts as global climate change alters the permafrost, vegetation, and weather patterns (Bieniek et al. 2015, Fauchald et al. 2017, Zhang and Delworth 2016). While industry expansion will no doubt force soundscape change in its own way, extreme stochastic events related

to climate change may be an even greater force as researchers continue to monitor the ACP's soundscape. Migratory species of birds overwinter continents apart from one other, and challenging conditions on the wintering grounds, during migration, or both may have undue effects on avian populations. Changing land use practices and rising temperatures within and outside of our system may also facilitate outbreaks of highly pathogenic avian influenza virus (HPAIV) (Morin et al. 2018), which can have devastating effects when entering species of waterfowl and shorebirds that often congregate in interspecies flocks. Currently, HPAIV is circulating in Alaskan populations of migratory birds with outcomes unknown (ADFG 2022). We should continue to monitor how the acoustic environment evolves under these stressors, and develop a better understanding of how it may affect vocal and non-vocal species interactions with each other and the landscape around them.

The tools I have helped develop for processing big data may be widely applied to other acoustic datasets, and incorporated into larger efforts to generalize sound labeling tools to all systems (similar to Sethi et al. 2020). The dataset of sounds I labeled manually will also be available to the public (Çoban et al. 2022) so that others can use them to train and improve their own sound labeling models to process acoustic data from our system, or similar environments. Researchers in bioacoustics should consider employing a similar strategy that I've used here, evaluating species auditory sensitivity and their soundscape in tandem. Doing so will get us closer to determining what constitutes as an actual acoustic disturbance for species of interest.

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