Spatiotemporal Patterns in Acoustic Presence of Sei Whales (*Balaenoptera borealis*) in Atlantic Canada

by

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Dedication

I dedicate this thesis to all the women in science past, present and future:

To those who came before and cleared the path for me.

To those who support, encourage, and guide me, helping me up the ladder.

To those who will follow me in discovering the future we need.

"…the discoveries don't come when you're looking for them. They come when for some reason you've let go conscious control."

― Madeleine L'Engle, A Ring of Endless Light

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Abstract

As human activity in the ocean increases, so do our impacts on marine species, including whales. Whales are threatened by human activities such as shipping, fishing, and seismic surveying. While governments can take action to mitigate the threats these activities impose, they first must understand where they occur in both space and time. For species that are difficult to visually survey, like sei whales (*Balaenoptera borealis*), this creates data gaps. Passive acoustic monitoring (PAM) is a means of collecting data on the occurrence of such species. The main objective of my thesis was to ascertain the spatiotemporal presence of sei whales in Atlantic Canada (Nova Scotia, Newfoundland, and Labrador) using PAM recordings from up to 10 bottom-mounted recording stations dispersed around Atlantic Canada. This objective required that I initially characterize their vocalizations recorded off Atlantic Canada and then developing an efficient analysis approach using automated detectors.

In Chapter 2, I characterized sei whale vocalizations in Atlantic Canada. Sei whales produce downsweeps either singly or as part of multi-downsweep call types. 923 downsweeps were analyzed from six stations and on average were 1.58 s long, sweeping from 75.66 Hz to 34.22 Hz.

In Chapter 3, I examined whether downsweeps differed between two geographic regions in Atlantic Canada that had been considered different populations by whalers in the 1960's and 1970's. I found downsweeps recorded off Nova Scotia were significantly longer than those recorded off Newfoundland/ Labrador, while proportionally more doublets (two downsweep call type) were recorded off Newfoundland/ Labrador than Nova Scotia. Although sound propagation or noise could explain some differences in duration, my results suggest there may be two populations in this region.

Effective PAM studies require efficient detection and classification of a species calls from large acoustic datasets (in the case of my study, tens of thousands of hours of acoustic recordings). Current sei whale detectors tend to have high rates of error, which requires human analysts to validate the detections to increase confidence in the results, which slows down the process. In Chapter 4, I created and tested a tiered-detector approach that used multiple detectors with varying rates of error and included the validations from one detector into the analysis of the next, to reduce the overall time it takes to review sei whale detections. I found the tiered-detection approach reduced the amount of time needed for manual analysis, without losing accuracy.

Finally, in Chapter 5, I used PAM to determine the spatial and temporal occurrence of sei whales in Atlantic Canada over the two-year period. I found that sei whales were present year-round in Atlantic Canada and were heard mostly at the offshore stations, with low presence at stations less than 100 km from shore. Sei whales were absent from the northmost stations in winter. Their presence peaked in October, with a secondary peak in June.

My study provides the first description of sei whale downsweeps in Atlantic Canada. Using these characteristics, I was able to create a more efficient means of analyzing PAM data. I examined both broad-scale and long-term patterns of sei whale spatiotemporal presence in Atlantic Canada, particularly their year-round presence in the region, with peak presence in the fall. To best mitigate threats against sei whales in Atlantic Canada, all conservation and management decisions moving forward need to take this new information into consideration.

List of Abbreviations and Symbols

AMAR	Autonomous Marine Acoustic Recorder
ANOVA	Analysis of variance
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CVA	Canonical variate analysis
DB	Doublet call type
DFO	Department of Fisheries and Oceans
ESRF	Environmental Studies Research Fund
Freq.	Frequency
Hz	Hertz
IUCN	International Union for Conservation of Nature
JASCO AA	JASCO Acoustic Analysis
km	Kilometres
LDA	Linear Discriminant Analysis
LFDCS	Low Frequency Detector Classifier System
m	Metres
MANOVA	Multivariate Analysis of variance
Max.	Maximum
Min.	Minimum
MPA	Marine Protected Area
NFLD	Newfoundland/Labrador (study area)
NS	Nova Scotia (study area)
PAM	Passive Acoustic Monitoring
s	second
SARA	Species at Risk Act
SD	Standard Deviation
SL	Singlet call type
TP+	Triplet+ call type

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Absolutely no one understood how a kid from Winnipeg would want to become a whale biologist, but my family and friends seemed to take it in stride and support all my achievements, failings, and travels to achieve this singular dream. No matter when I am in the world, I know I have people who love me and are proud of what I do. All I do, I do for them.

To my parents, Mom, Dad, Roy and Deborah, and my sister Maxie, who have had to put up with this dream since I could pretty much speak, thank you for being in my corner. This was a VERY long time coming, but I could not have done it without you. I love you more than you could ever know.

Chapter 1: General Introduction and Methods

1.1 Introduction

Marine mammals are an essential part of the ocean ecosystem (Bowen 1997). They are consumers at almost every trophic level, from sirenians as primary consumers (Odell 2009) up to polar bears (*Ursus maritimus*, Stirling 2009) and killer whales (*Orcinus orca,* Ford 2009) consuming other marine mammals. Cetaceans (whales, dolphins, and porpoises) are known to fundamentally shape their local, and for migratory species, global marine ecosystems (Bowen 1997). The "Great Whales", which include all baleen species and the sperm whale (*Physeter macrocephalus*), are integral to the cycling of nutrients from ocean depths to the surface, moving nutrients from highly productive waters at high latitudes to the less productive waters close to the equator, and feeding species on the ocean floor with their carcasses after death (Roman et al. 2014). A decline in cetaceans, stemming from anthropogenic impacts, could cause massive changes in the global ocean ecosystem (Roman et al. 2014).

With increasing human presence alongside and in the oceans, there are increased threats to cetaceans (Halpern et al. 2008). Increases in marine shipping increases the threat of vessel strikes (Laist et al. 2001). Increased food demand has increased fishing pressure, sometimes directly competing with cetaceans for food (Plagányi and Butterworth 2009), while also increasing entanglements in fishing gear (Cassoff et al. 2011) and cetacean bycatch (Read et al. 2006). With more sewage, trash and runoff entering the oceans, cetaceans are now at a greater risk from contaminants negatively affecting population health (Mössner and Ballschmiter 1997). Increasing human activity has also increased noise pollution in the ocean, so much so that the ambient sound level of the Pacific Ocean has risen about 10 dB over the past 50 years (Andrew et al. 2002; McDonald et al. 2006b; Chapman and Price 2011). All this after the Great Whales faced an unprecedented decrease in numbers from global whaling between 1860 and 1986 (Rocha et al. 2014).

There has been a push globally to combat the threats facing cetaceans, to conserve and manage the remaining populations of whales, which lead to varying success. Globally, Humpback whale (*Megaptera novaeangliae*) populations have recovered relatively quickly since whaling (Stevick et al. 2003; Bejder et al. 2016), whereas the Antarctic blue whale (*Balaenoptera musculus*) has shown signs of slow recovery (Cooke 2018). To best mitigate known threats, fundamental information on species distribution, seasonality, and movement are essential. Although some populations/species, such as Pacific killer whale populations and humpback whales, have generally been well researched and their distribution and movements well documented (Prieto et al. 2012; Hill et al. 2016), many species have not received similar research attention. The International Union for Conservation of Nature (IUCN) lists 20% of whale populations as Data Deficient (IUCN 2022).

Efforts to manage and conserve cetacean populations are typically carried out at the national level. For example, in the USA, policies on whale conservation are provided through Acts such as the Endangered Species Act and Marine Mammals Protection Act, and in Canada, this is done through a series of policies including: the Species at Risk Act (SARA), the Oceans Act and the Fisheries Act. However, without baseline information of the spatiotemporal distribution and movements of a species, these policies are rendered toothless to mitigate threats.

1.1.1 Passive acoustic monitoring

Traditionally, visual sightings of cetaceans, whether collected opportunistically or through dedicated survey efforts, were the primary method used to gather information on their distribution and seasonality. Visual surveys are often limited by weather (e.g., sea state, visibility), location (e.g., if species are too far offshore and difficult to reach), and cost (e.g., expense of ships or planes used for surveying), resulting in studies that are limited in time or area covered. These limitations often lead studies that cover only a short time frame and/or a small area. The ongoing development of remote sensing technology has, however, provided a potentially less expensive means of collecting data on cetacean occurrence and distribution over longer periods of time and over larger geographic ranges.

Passive acoustic monitoring (PAM) is a non-invasive, remote sensing technique that uses a variety of acoustic recording technologies to detect and monitor animals (Zimmer 2011a). PAM uses distinct vocalizations to collect data on occurrence, distribution, behaviour, population structure and threats in the environment (Zimmer 2011b). PAM is typically not limited by weather, can be less expensive than visual surveys, and can collect data over long periods of time (months-years). It is, however, limited to monitoring species that call regularly and have well-described vocalizations that are distinguishable from those of other species, and where ambient or anthropogenic noise does not mask vocalizations or interfere with their detection. Once the data are collected, the ability to effectively analyse and summarize results can also be challenging due to the amount of intensive manual or automated data processing required to analyse up to thousands of hours of recordings (Kowarski and Moors-Murphy 2020).

Despite these limitations, PAM is becoming an increasingly common means of surveying and monitoring cetacean species (Zimmer 2011a), and can help to provide the fundamental occurrence information for data poor species facing imminent threats, such as the sei whale (*Balaenoptera borealis*).

1.1.2 Sei whale

Sei whales are the third largest species of whale, behind the closely related blue and fin (*Balaenoptera physalus*) whales. They can reach an average of 15 m in length and weigh an average of 20 tons. They are grey in colouring and similar to other rorqual baleen whales have an elongated slender body (Horwood 2009). They are similar in size and colouration to fin and Bryde's whales (*Balaenoptera brydei*), making them complicated to visually identify in the wild.

Sei whales are found in all ocean basins, mostly offshore (Horwood 2009). Similar to other baleen whale species, sei whales were targets of commercial whaling off Atlantic Canada in the late 1960s to the early 1970s (Mitchell and Chapman 1974). Over 1000 individuals were taken collectively by whaling stations off Nova Scotia and Newfoundland/Labrador from two proposed stocks, leaving an estimated 1800 individuals (based on the mark-recapture of 14 tags by whalers and visual sightings from three Fisheries Research Board of Canada census cruises) once the commercial whaling ended (Mitchell and Chapman 1974). Since the end of whaling, sei whales in Atlantic Canada have been managed as a single population, and there has been very little effort to study sei whales or determine whether they have recovered (Prieto et al. 2012).

Sei whales are listed as Endangered globally by the IUCN (IUCN 2022), and in Canada, both the Pacific and Atlantic populations are now assessed as Endangered by COSEWIC (Committee on the Status of Endangered Wildlife in Canada, COSEWIC 2019a). Currently, only the Pacific population is listed under the SARA. In Atlantic Canada, opportunistic sightings (COSEWIC 2019a), limited sightings from visual surveys (e.g., Lawson and Gosselin 2009) and acoustic detections from PAM studies (e.g., Delarue et al. 2018), confirm their presence from southern Nova Scotia to 68°N off Labrador. Most visual sightings were on-shelf where most survey effort occurred, though they have been acoustically detected at both on- and off-shelf

PAM sites (Delarue et al. 2018). There were too few sightings of sei whales during line-transect cetacean survey efforts off Atlantic Canada to provide an estimate of population size (Lawson and Gosselin 2009); however, there is likely to be fewer than 1000 individuals in the population (COSEWIC 2019a).

The objective of this thesis was to fill in data gaps on the broad-scale spatial presence and long-term temporal presence of sei whales in Atlantic Canada using PAM. To do this, I first characterized sei whale vocalizations recorded in Atlantic Canada to confirm their characteristics for use in automated detectors (Chapter 2); I then examined the vocalizations to determine whether there is evidence to support the two proposed whaling stocks (Chapter 3) and created and tested a multiple (multi-tiered) detector analysis approach using automated detector-classifiers to increase analysis efficiency (Chapter 4). All of this work was then consolidated into a broadscale study on the geographical and seasonal distribution patterns of sei whales off the coasts of Nova Scotia, Newfoundland, and Labrador (Chapter 5). My final chapter provides my overall conclusions, outlines limitations and future uses from this work (Chapter 6).

1.2 General Methods

I used recordings collected from ten recording stations off Atlantic Canada. Autonomous Multichannel Acoustic Recorders (AMARs; JASCO Applied Sciences Ltd.) were deployed between 2015-2017 by Fisheries and Oceans Canada (DFO) as part of their ongoing cetacean PAM program, and as part of an Environmental Studies Research Fund (ESRF) project conducted by JASCO Applied Sciences (Delarue et al. 2018, Figure 1-1, Table 1-1). The AMARs were bottom-moored at depths ranging between 200-2000 m and positioned 20-65 m above the ocean floor. The types of hydrophones used varied between recorders and years (Table

1-1), but generally had a sensitivity of −165 ± 3 (dB re V/μPa) from 10 Hz - kHz. All recorders were set up with a duty cycle that recorded and saved files at an 8 kHz sampling rate for 11.33 minutes every 20 minutes continuously from the start to end of deployment. The subsequent chapters describe how these recordings were used to support the different studies and analyses conducted.

1.3 Tables

*Table 1-1. Deployment details for the ten recording stations. * = stations deployed by Fisheries and Oceans Canada, ** = stations deployed by JASCO Applied Sciences*

Station	Year	Latitude (decimal degrees)	Longitude (decimal degrees)	Deployment Start – End Date	Site Depth (m)	Hydrophone Make/Model	No. of Recording Days	Chapters Used In
Emerald Basin (EMB)*	2015	43.60871	-62.86832	24 May 2015 - 19 Apr 2016	200	High Tech, Inc./ HTI-99-HF	762	2, 3 & 5
	2016	43.60949	-62.87579	16 Sep 2016 - 25 Nov 2017	205	High Tech, Inc./ HTI-99-HF		2, 3, 4& 5
Mid Gully (MGL)*	2015	43.85968	-58.91047	23 May 2015 - 23 Apr 2016	1500	GeoSpectrum/ M8Q-51	769	2, 3, 4& 5
	2016	43.86166	-58.91242	20 Sep 2016 - 1 Dec 2017	1550	GeoSpectrum/ M36-V35-100		2, 3 & 5
Stone Fence (STF)*	2015	44.4623	-57.18407	22 Sep 2015 – 1 Sep 2016	450	GeoSpectrum/ M36-V35-100	497	2, 3 & 5
	2016	44.4626	-57.18323	11 Nov 2016 - 2 Dec 2017	450	GeoSpectrum/ M8Q-51		2, 3 & 5
Station 2 (STN 2) **	2015	45.42599	−59.76398	18 Aug 2015 – 21 Jul 2016	126	High Tech, Inc./ HTI-99-HF	692	5
	2016	45.43153	-59.7725	21 Jul 2016 - 9 Jul 2017	120	GeoSpectrum/ M36-V35-100		5

Station	Year	Latitude (decimal degrees)	Longitude (decimal degrees)	Deployment Start – End Date	Site Depth (m)	Hydrophone Make/Model	No. of Recording Days	Chapters Used In
Station 6 (STN 6) **	2015	44.85309	−55.27108	22 Aug 2015 – 20 Jul 2016	1802	High Tech, Inc./ HTI-99-HF	702	5
	2016	44.8521	-55.2707	20 Jul 2016 – 23 Jul 2017	1790	GeoSpectrum/ M36-V35-100		5
Station 12 (STN 12) **	2015	57.25273	−60.00175	10 Aug 2015 – 13 Jul 2016	143	High Tech, Inc./ HTI-99-HF	705	5
	2016	57.24852	-60.0079	13 Jul 2016 – 14 Jul 2017		GeoSpectrum/ M36-V35-100		5
Station 13 (STN 13) **	2015	55.22797	−54.19047	8 Aug 2015 - 11 Jul 2016	1750	High Tech, Inc./ HTI-99-HF	703	2, 3 & 5
	2016	55.22788	−54.1901	12 Jul 2016 - 16 Jul 2017	1700	GeoSpectrum/ M36-V35-100		2, 3 & 5
Station 15 (STN 15) **	2015	50.41327	−49.19638	14 Aug 2015 - 16 Jul 2016	2000	High Tech, Inc./ HTI-99-HF	701	2, 3, 4 & 5
	2016	50.41112	−49.1959	15 Jul 2016 - 18 Jul 2017	1993	GeoSpectrum/ M36-V35-100		2, 3 & 5
Station 17 (STN 17) **	2015	44.97141	-48.73373	24 Aug 2015 – 18 Jul 2016	1282	High Tech, Inc./ HTI-99-HF	697	5
	2016	44.96777	-48.7336	19 Jul 2016 – 21 Jul 2017	1273	GeoSpectrum/ M36-V35-100		5
Station 19 (STN 19) **	2015	48.72873	−49.38087	25 Aug 2015 - 17 Jul 2016	1282	High Tech, Inc./ HTI-99-HF	691	2, 3 & 5
	2016	48.3802	−46.5254	17 Jul 2016 - 19 Jul 2017	1547	GeoSpectrum/ M36-V35-100		2, 3 & 5

1.4 Figures

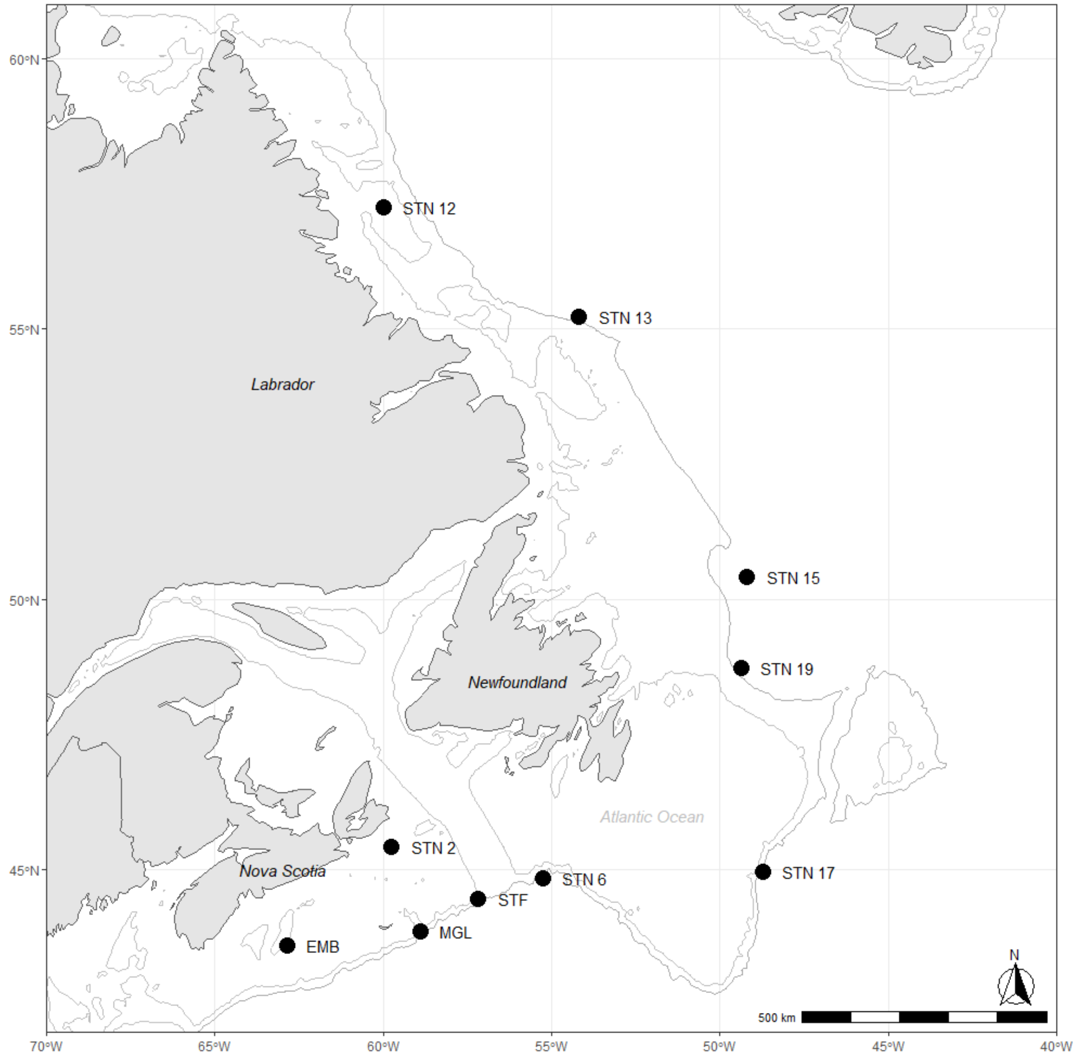


Figure 1-1. Map of selected recording stations. EMB = Emerald Basin, MGL = Mid-Gully, STF = Stone Fence, STN = Station.

Chapter 2: Call Characteristics of Sei Whales in Atlantic Canada

2.1 Introduction

Whales can be challenging to survey visually, spending most of their lives underwater. Passive acoustic monitoring (PAM), which can record underwater sounds including cetacean vocalizations, has become a common method for studying whale social structure, behaviour, occurrence, and movement (Zimmer 2011a). To use PAM effectively, however, the target species must call frequently and be distinguishable by both human analysts and automated detection algorithms (hereafter detectors) from vocalizations of co-occurring species (Zimmer 2011a) or other types of underwater sounds. Failure to adequately characterize target species' vocalizations will result in missed calls if the call characteristics are too specific, or false positives if they are too broad.

2.1.1 Sei whale vocalizations from a global perspective

Sei whales, are generally difficult to study using visually-based methods primarily because they are found in remote offshore areas, and are difficult to distinguish from closely related species in both their summer foraging grounds (fin whales, *Balaenoptera physalus*) and wintering breeding grounds (Bryde's whale, *Balaenoptera brydei*; Horwood 2009). PAM is an effective tool for studying sei whales, but only where their vocalizations have been adequately characterized.

A small number of studies have characterized sei whale vocalizations (Table 2-1). These studies found sei whales produce a variety of call types across the globe (McDonald et al. 2005; Rankin and Barlow 2007; Baumgartner et al. 2008; Calderan et al. 2014; Español-Jiménez et al. 2019; Tremblay et al. 2019). Although sei whale vocalizations have been characterized in Cape

Cod, which is in close proximity to my study area (Baumgartner et al. 2008; Tremblay et al. 2019), no studies characterizing sei whale vocalizations in Atlantic Canada have been published.

2.1.2 Sei whale vocalizations in the Northwest Atlantic

Sei whale calls have been recorded off Cape Cod, Massachusetts, in the Gulf of Maine, relatively close to my study area, concurrently with visual observations to confirm the vocalizations were recorded were produced by sei whales (Baumgartner et al. 2008; Tremblay et al. 2019). The most common vocalization recorded was a ‘low frequency downsweep’, which where characterized as starting at approximately 80 Hz, sweeping down to about 30 Hz, and lasting for an average duration of 1.5 sec (Baumgartner et al. 2008). Downsweeps occurred as singles, doublets or triplets (Baumgartner et al. 2008; Figure 2-1) or occasionally up to and including octets (pers. observation). ‘Reduced frequency downsweeps’ that sweep from approximately 50 Hz down to 30 Hz over 0.3 seconds, have also been described (Tremblay et al. 2019), but these appear to be rarer than the longer downsweeps and therefore less useful for PAM. Given the variation reported in sei whale vocalizations globally (Table 2-1), there is not known if the characteristics of sei whale vocalizations recorded in Cape Cod will be the same as those recorded in Atlantic Canada. There is also evidence that call characteristics can vary between different populations of a single whale species despite those populations living in proximity (e.g., fin whales, Delarue et al. 2009, killer whales, *Orcinus orca*, Filatova et al. 2012), so a description of sei whale vocalizations recorded in Atlantic Canada is needed if PAM is to be used to study sei whales in this region.

2.1.3 Characterizing sei whale vocalizations

PAM requires that target calls be distinguishable not only from ambient noise, but also the vocalizations of similar species that may occur in the area. Blue (*Balaenoptera musculus)*, fin (*B. physalus*) and humpback whales (*Megaptera novaeangliae*, pers. observation) all occur in the Northwest Atlantic and are known to make downsweep vocalizations that can potentially overlap in frequency with sei whale downsweeps (Table 2-2). Discriminating between the similar vocalizations of these co-occurring species is imperative for confidently identifying sei whale calls on PAM datasets, ensuring that assessments of call occurrence are as reliable as possible.

The overall objective of this study was to characterize sei whale downsweeps recorded from 2015 to 2017 off the coasts of Nova Scotia and Newfoundland/Labrador. This information is needed to improve automated detector algorithms and develop more accurate and efficient analysis protocols for this species. Specifically, I characterized (1) the overall duration and frequency characteristics, and the variation in these characteristics, of sei whale downsweeps and (2) the duration and frequency characteristics, and associated variation, of sei whale downsweeps when analyzed by call type (e.g., singlet, doublet, etc.).

2.2 Methods

2.2.1 Data collection and preparation

I used data collected from six stations (Emerald Basin (EMB), Mid-Gilly (MGL), Stone Fence (STF) and ESRF Stations (STN) 13, 15 and 19), where relatively high numbers of sei whale vocalizations had previously been heard (Delarue et al. 2018). See Chapter 1: for recording and location details (Table 1-1, Figure 1-1).

To find downsweeps for call characterization, recording files (~11 minute recordings every 20 minutes) from all six stations were run through an automated sei whale downsweep-specific detector (Acoustic Analysis detector-classifier, JASCO Applied Sciences, Ltd., Delarue et al. 2018), which used the call characteristics from Cape Cod to identify sei whale downsweeps. This automated detector was developed to minimize missed calls, and to locate all possible sei whale downsweeps (Delarue et al. 2018). To validate detections (confirm that the detected file did contain sei whale downsweeps) files were manually viewed as spectrograms (Frequency Step 2Hz, Frame Length 0.25s, Time Step 0.05s, Hamming Window) using PAMlab (JASCO Applied Sciences, Ltd.). Two approaches were used to identify which files contained sei whale downsweeps.

For three of the six stations (EMB), MGLSTF), I organized files into 24 hours periods (00:00-23:59), then reviewed files with sei whale detections in chronological order beginning at 00:00 until I found a sei whale downsweep. I then annotated (i.e., drew a box around) the call, so I could locate each file and confirmed sei whale downsweep later for further analysis. Once a call was confirmed for a given day, I then moved on to the next day. This produced a record of the daily occurrence of sei whale downsweeps. In addition to the daily record of sei whale downsweeps based on analysis of these autodetections, I also included sei whale calls found and annotated on these same datasets during another study aimed at detecting other baleen whale species. The combined annotations resulted in an average of two files per day (n = 1,128) with sei whale downsweep annotations from all three stations.

For the remaining three stations (Station (STN) 13, 15 and 19), JASCO analysts viewed the middle five minutes of each file with a sei whale detection and annotated any sei whale downsweeps that were found in that five-minute period. In addition, the two stations with the highest number of validated sei whale detections were more intensively sampled. At STN 13 and 15, one file every hour was checked for sei whale downsweeps from mid-August to 30 Nov 2015, 1 May to 30 Nov 2016, and 1 May to mid-July 2017 (Delarue et al. 2018). Any sei whale downsweeps found were annotated. In total, sei whale downsweeps were annotated on an average of two files per day (n=1,170) from all three stations.

Once I identified files with confirmed sei whale downsweeps, I then identified and annotated every sei whale downsweep in each file, excluding echoes and modes associated with the downsweeps (Figure 2-2). I categorized each annotation by call type either as singlets (SL, a single downsweep with no downsweeps ~3 seconds before or after), doublets (DB, a pair of downsweeps within ~3 seconds of each other), or triplet+ (TP+, three or more downsweeps within ~3 seconds of each other). I also assigned individual downsweeps to one of three quality categories. High-quality downsweeps were audibly loud, had clearly visible starts and ends, no echoes or modes within the annotation and no breaks in the downsweep. Mid-quality downsweeps had clear starts and ends but were missing at least one of the other requirements. Low-quality downsweeps were relatively quiet, with unclear starts or ends, or distorted with many echoes or modes. I used high quality downsweeps with an SNR > 10 to determine call characteristics.

PAMlab automatically measures various frequency and time measurements from the annotations (see Appendix A). The start and end time measurements, and minimum, maximum, and peak frequency measurements obtained using PAMlab were used to calculate duration, bandwidth, and slope (see Appendix A). Although bandwidth and slope are not typically measured in baleen whales, they are used in detector development and so I included them here. Amplitude related characteristics were not included in this study as there is currently too much uncertainty around sei whale call source levels, and the background noise and sound propagation conditions at the recording sites (which can vary greatly over short time scales). Better understandings of both are needed to model detection range of individual downsweeps to interpret the recorded received amplitude levels of the calls. Within call types, I also measured the intra-call interval, or the time from the end of one downsweep to the beginning of the next.

2.2.2 Summary statistics

I calculated the overall mean duration, maximum and minimum frequency, bandwidth, slope, and peak frequency for all downsweeps collectively and then for the downsweeps of each call type. For call types with two or more downsweeps, I also calculated the mean intra-call interval.

2.3 Results

I found a total of 14,385 sei whale downsweeps (SL: n= 2704, DB: n = 4745, TP+ n = 214) across the six stations. Of the 14,385 downsweeps, 923 were considered high-quality with a SNR > 10 (SL: n = 240, DB n = 608, TP+ n = 75). Averaging these high quality downsweeps within each file resulted in a sample size of n = 268.

Overall, high-quality downsweeps combined (n= 268) had a mean duration of 1.58s, with a mean maximum frequency of 75.66 Hz, and a mean minimum frequency of 34.22 Hz. Summary statistics for these and the other call characteristics are presented in Table 2-3.

These characteristics did not vary greatly with call type - summary statistics for each call characteristic measured by each call type are presented in Table 2-4. The mean intra-call interval of the DB and TP+ call types combined was 2.22s (DB: 2.19 s, TP+: 2.47 s, Table 2-4). DB were the most common call type (n = 304), followed by SL (n= 240) and TP+ (n = 18). DB were the exclusive call type on 127 files (47%) and 60 days (38%), SL were the exclusive call type on 82 files (30%) and 52 days (33%), and TP+ were always found with other call types, never exclusively (Table 2-4).

2.4 Discussion

2.4.1 Downsweep characteristics

I found that the sei whale downsweeps recorded in Atlantic Canada had the same overall structure of downsweeps recorded in other locations, such as the Gulf of Maine (Baumgartner et al. 2008) and Patagonia (Español-Jiménez et al. 2019), with mean durations greater than 1 s but less than 2 s, and mean frequencies between 34 – 99 Hz (Table 2-1). This provides confidence that the downsweeps included in this study were indeed from sei whales, and not from another species. However, I found that sei whale downsweeps recorded in Atlantic Canada were, on average, longer and had a lower maximum frequency than those recorded in the Gulf of Maine, but with near equal variation (duration: 1.58 s vs. 1.38 s; max frequency 75.66 Hz vs. 82.3 Hz, respectively). This further supports that there is variability in sei whale vocalizations throughout the globe. This variability suggests using call characteristics determined from non-local populations of sei whales to identify calls on acoustic datasets could result in less accurate or less efficient PAM detections.

Once downsweeps are accurately characterized, more specific PAM detectors can be developed to better distinguish sei whale downsweeps from the ambient ocean noise or anthropogenic noise, and from downsweeps made by closely related species (Table 2-2). Sei whale downsweeps were on average 1.6 s long, while fin whale downsweeps were described as under a second in length (Delarue et al. 2009), and most blue whale downsweeps were on average 2 seconds in length (Berchok et al. 2006). This suggests that downsweep duration may be the best call characteristic to use to discriminate between sei whale vocalizations and similar vocalizations produced by fin and blue whales. The bandwidth of sei whale downsweeps overlapped with the highly variable bandwidths of fin whale downsweeps (Delarue 2004), but had shorter bandwidths (40.74 vs. 50.6 Hz) and lower peak frequencies (43.13 vs. 53.9 Hz) than blue whale downsweeps (Berchok et al. 2006), which could help to further differentiate between these two species.

2.4.2 Downsweep call types

In other studies, only DB and TP+ call types were used to identify sei whale presence, as a SL may have been misidentified as another species, and there was no evidence that the other species produced DB or TP+ (Davis et al. 2020). Although DB were the main call type in my study, almost 50% of the files and 38% of days exclusively had SL, which means that if only DBs or TP+ were required to verify presence then 50% of the files (and 38% of days) would have been excluded and the resulting sei whale call presence might only provide a partial picture of spatiotemporal patterns of occurrence. The results of my study suggest that SL can be confidently differentiated from the downsweeps of other species by duration and intra-call interval and should be included in future sei whale acoustic studies.

In the past, the intra-call interval was not a characteristic used to identify sei whales. I found that in Atlantic Canada, the intra-call interval had little variation, and was comparable to the spacing in DB off Cape Cod (Baumgartner et al. 2008) and possibly Patagonia (Español-Jiménez et al. 2019). In addition, although there is little information on the intervals between downsweeps of blue or fin whales (Delarue 2004; Berchok et al. 2006; Garcia et al. 2019), anecdotally, I observed that these other species were less consistent in the spacing between downsweeps, making DB and TP+ far more obvious (pers. obs.). This again makes the intra-call interval a potentially underutilized call characteristic for sei whale identification and could potentially be an additional characteristic used to identify sei whale calls in future studies.

2.4.3 Conclusions and future work

With the additional information on downsweep call type characteristics provided in this study, sei whale detectors can be improved to reduce false positives by excluding similar vocalizations from other species. Intra-call interval could be a useful characteristic to build into detectors, if it is distinguishable from other species and consistent with other populations of sei whales that produce downsweeps, as it is consistent within sei whale call types in Atlantic Canada. This study only used vocalizations that I was able to confidently identify and measure from recordings close to the ocean floor, and excluded other known call types (i.e., reduced downsweeps, Tremblay et al. 2019). Future research should include surface recordings concurrent with visual sei whale observations, so a more complete picture of the sei whale call repertoire can be obtained and incorporated into future detectors. Improving the performance of sei whale detectors will improve confidence in future PAM-based analyses of occurrence.

2.5 Tables

*Table 2-1. Comparison of the frequency and duration characteristics of recorded sei whale vocalizations from previous studies. Values are mean value ± standard deviation (if available). 'Likely Call Type' provides call type name given within the reference. * = similar call type as heard in Atlantic Canada. Table modified from Español-Jiménez et al. (2019)*

Source	Location	Likely call type	Year/no. vocalizations included in study	Max. frequency (Hz)	Min. frequency (Hz)	Peak frequency (Hz)	Duration (s)
Tremblay et al. 2019	New England, NW Atlantic Ocean	Reduced frequency downsweeps	2008/100	52.75	31.59	35.97	1.68
			2008/100	49.36	29.94	36.0	1.94
			2008/100	49.05	29.6	36.69	0.6
Español-Jiménez et al. 2019	Chile, SE Pacific	Low frequency downsweep*	2016/5	105.3±18.3	35.6±4.6	65.4±14.1	1.6±0.1
			2017/36	93.3±10.9	42.2±5.6	68.3±14.2	1.6±0.3
Romagosa et al. 2015	Azores, N Atlantic Ocean	Low frequency downsweep*	2012/53	99.8±13.6	37.4±8.4	52.0±11.4	1.21±0.33
Calderan et al. 2014	Auckland Islands, S Atlantic Ocean	Low frequency downsweep	2013/4	78.0±2.0	69.0±08	73.8±0.5	1.1±0.0
		Upsweep/ downsweep	2013/4	83.3±4.1	53.8±4.9	78.3±3.1	1.2±0.0
		Upsweep	2013/30	66.3±10.7	36.6±2.1	45.8±11.0	1.2±0.3

Source	Location	Likely call type	Year/no. vocalizations included in study	Max. frequency (Hz)	Min. frequency (Hz)	Peak frequency (Hz)	Duration (s)
Gedamke and Robinson 2010	E Antarctica, S Ocean	Frequency stepping	2006/ND	570	170	ND	ND
Baumgartner et al. 2008	New England, NW Atlantic Ocean	Low Frequency Downsweep*	2006–2007/108	82.3±15.2	34.0±6.2	ND	1.38±0.37
Rankin and Barlow 2007	Hawai'i, Pacific Ocean	High frequency downsweep	2002/2	100.3±11.1	44.6±2.9	ND	1.2±0.007
		Low frequency downsweep	2002/105	39.4±3.4	21±2.4		1.2±0.11
McDonald et al. 2005	W Antarctica, S Ocean	Upsweeps, tonal, downsweep, frequency stepping	2003/50	433	192	ND	0.45±0.3
Knowlton et al. 1991	Canada, N Atlantic Ocean	High frequency sweeps	1986–1989/ND	3500	1500	ND	0.5–0.8
Thompson et al. 1979	Canada, N Atlantic Ocean	High frequency sweeps	ND	3000	ND	ND	0.7

ND: no data (not included in reported results of the study)

* Call types like the downsweep call type characterized for Northwest Atlantic sei whales presented

Table 2-2. The frequency span and duration of the similar downsweep vocalizations blue, fin and sei whales recorded in Atlantic Canada.

Species	Call Type	Min. – Max. Frequency (Hz)	Duration (s)	Reference
Blue Whale	D-call	37.8±15.9 – 88.3±22.8	2.0±0.6	Berchok et al. 2006
Fin Whale	High frequency downsweep	52.6±17.6 – 80.9±17.9	0.7±0.2	Delarue 2004
Sei Whale	Full frequency downsweep	82.3±15.2 – 34.0±6.2	1.38±0.37	Baumgartner et al. 2008

Table 2-3. Summary statistics for call characteristics of sei whale downsweeps (n = 268). SD = standard deviation.

	Mean (±SD)	**Range (minimum – maximum)**	**95% Confidence Interval**
Duration (s)	1.58 (±0.31)	0.72 – 2.59	1.54 – 1.62
Min. Freq. (Hz)	34.22 (±5.63)	21.69 – 53.41	33.55 – 34.90
Max. Freq. (Hz)	75.66 (±9.29)	52.24 – 97.34	74.55 – 76.78
Bandwidth (Hz)	41.44 (±7.02)	24.77 – 59.66	40.60 – 42.28
Slope (Hz/s)	-26.91 (±5.27)	-45.04 – -14.57	-27.55 – -26.28
Peak Freq. (Hz)	43.89 (±7.47)	27.83 – 71.04	43.00 – 44.78

Table 2-4. Means (± standard deviation) of call characteristics by call type. SL = singlet (one downsweep), DB = doublet (two downsweeps within ~3 seconds of each other), TP+ = triplet+ (three or more downsweeps within ~3 seconds of each other). "Freq" = frequency.

Call Type (n)	**Duration (s)**	**Min. Freq. (Hz)**	**Max. Freq. (Hz)**	**Bandwidth (Hz)**	**Slope (Hz/s)**	**Peak Freq. (Hz)**	**Intra-call Interval**	**Total Duration**	**Number of Files**
SL (240)	1.48 (±0.31)	35.6 (±7.88)	76.93 (±12.81)	41.33 (±8.78)	-28.68 (±6.74)	45.29 (±10.01)		1.48 (±0.31)	137
DB (608)	1.64 (±0.31)	32.51 (±4.29)	73.18 (±10.3)	40.68 (±8.39)	-25.4 (±5.81)	42.27 (±7.65)	2.19 (±0.34) (n= 262)	5.46 (±0.4)	181
TP+ (75)	1.42 (±0.21)	32.93 (±4.48)	72.28 (±8.7)	39.35 (±7.15)	-27.92 (±4.76)	43.15 (±6.97)	2.47 (±0.45) (n= 31)	10.4 (±0.64)	25

2.6 Figures

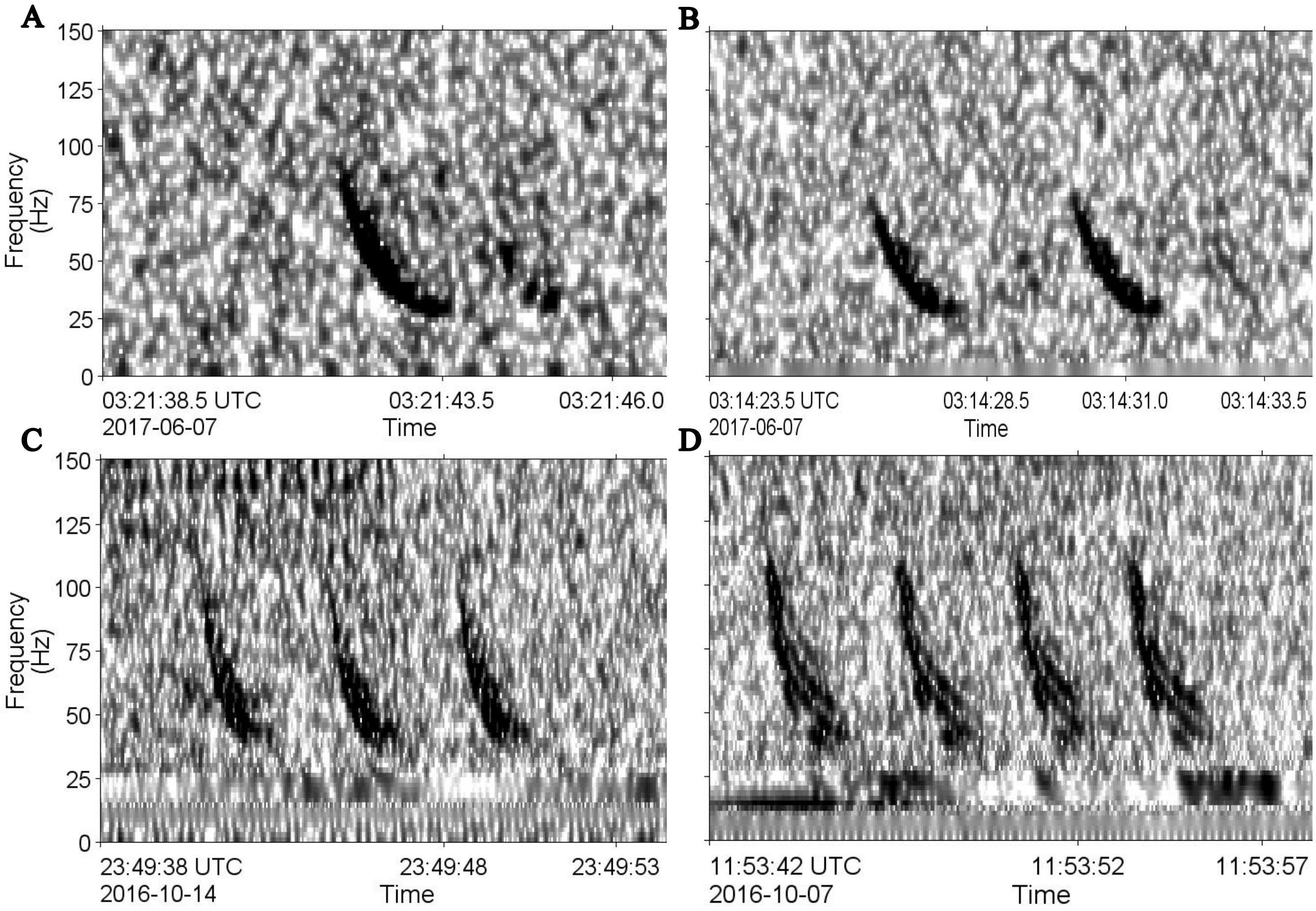


Figure 2-1. Example of sei whale full frequency downsweep vocalizations in Emerald Basin, 2015. Example of (a) singlet, (b) doublet, (c) triplet and (d) other (4+). Spectrogram settings: 30 s window, Freq. step 2 Hz, Frame length 0.25 s, Time Step 0.05s, Hamming Window.

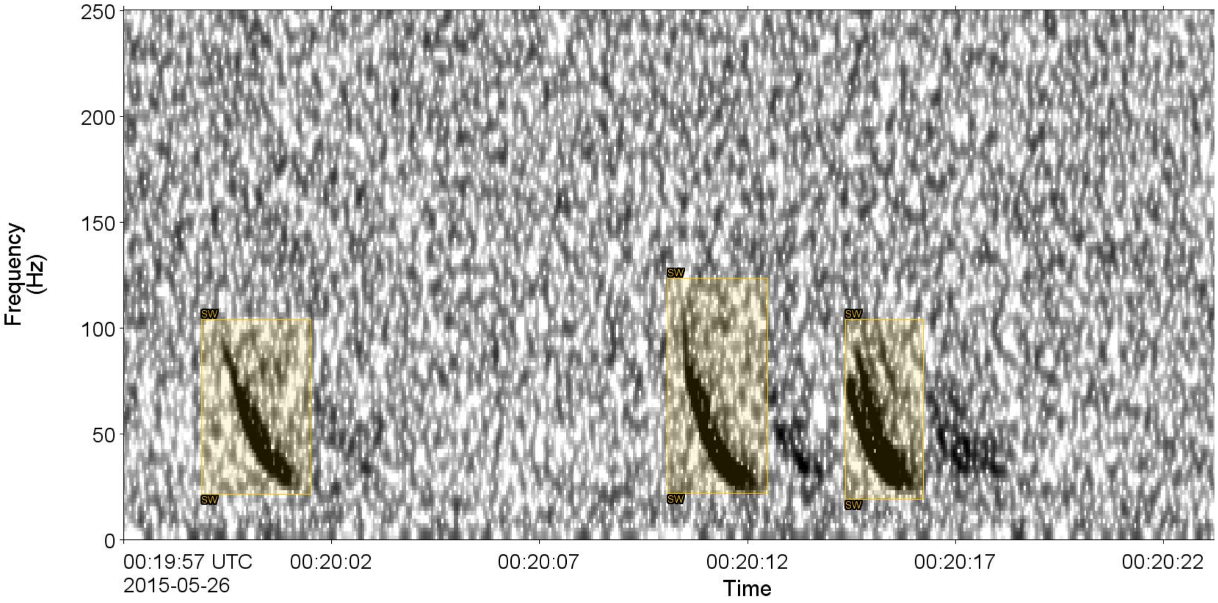


Figure 2-2. Example of annotated sei whale singlet and doublet call types. Annotation boxes were drawn to include start to end times and high to low frequencies of downsweeps and best exclude harmonics and modes/echoes (as observed around the doublet on the right). Spectrogram settings: 30 sec window, Freq step 2 Hz, Frame length 0.25 s, Time Step 0.05s, Hamming Window.

Chapter 3: Geographical Variation of Sei Whale Downsweeps Recorded in Atlantic Canada

3.1 Introduction

Despite ranging widely through the world's ocean basins and having little to no geographic barriers to intermixing, there is evidence that cetaceans are often divided into separate populations (e.g., COSEWIC 2004, 2008; Aguilar and Garcia-Vernet 2009; Delarue et al. 2009; Ivkovich et al. 2010; Foote et al. 2011). Populations show differences in morphology (Mitchell and Chapman 1974; Baird et al. 2009), genetics (Hoelzel 1998; de March and Postma 2003), and/or behaviour (Matkin 2000). These differences, along with possible variation in foraging and breeding ranges, may make individual populations susceptible to different threats. For example, there are three recognized populations of killer whale (*Orcinus orca*) in the Northeastern Pacific with overlapping home ranges (Ford 2009). Although all three populations face similar threats from vessel traffic and ocean pollution (COSEWIC 2008), only the Southern Resident killer whale population is threatened by overfishing. This is because it forages exclusively on an overfished population of salmon, while unlike the other two populations, that feed on marine mammals or more abundant populations of salmon (COSEWIC 2008).

The potential for threats to differentially affect populations suggests that conservation efforts may need to occur at the population level rather than the species level. For example, in Canada, beluga whales (*Delphinapterus leucas*) are divided into seven populations that vary in risk of extinction, with status ranging from Not at Risk to Endangered (COSEWIC 2004). These differences, in turn, require population-level approaches to recovery and management (DFO 2020). Thus for many species, the first step in effective conservation is determining whether management is best achieved at the species or population level (Risch et al. 2019). This often requires determining whether there are population differences, which can be achieved by using multiple assessment tools, such as photo-identification, morphological differences, and genetic sampling (Mellinger and Barlow 2003). For highly vocal species such as cetaceans, vocalizations can be used to help determine population structure, as a first step to proper management.

PAM has been used to record the vocalizations of a variety of cetaceans, with the recordings in some cases providing evidence of population divergences based on vocal repertoire and call characteristics (Winn et al. 1981; Ford 1991; McDonald et al. 2006a; Delarue et al. 2009; Amano et al. 2014). For example, PAM recordings of blue whales (*Balaenoptera musculus*) from across their global range found that nine populations could be identified based on differences in song structure (McDonald et al. 2006a). While populations were generally separated by ocean basins and/or hemispheres, even with occasional geographic overlap, the differences in songs were maintained (McDonald et al. 2006a). The variation in songs across populations were relatively unchanged across decades of recordings, and were also associated with population differences in migration routes between feeding and breeding grounds (McDonald et al. 2006a). The results of this work suggests that song structure can be used as population identifiers, alongside, or instead of, photo-identification or genetics.

Similarly, the vocalizations of killer whales off British Columbia show differences in vocal structure between and within geographically overlapping populations (Ford 1991; Deecke et al. 2005). The population of mammal-eating killer whales have a relatively limited vocal repertoire compared to fish-eating populations (Deecke et al. 2005), which are highly vocal and have relatively large vocal repertoires (Barrett-Lennard and Ellis 2001). Fish-eating killer whales consist of two distinct populations in the northeast Pacific that can be identified by their vocal repertoire, without any need for genetic sampling or photo identification to determine to which population an individual belongs (Barrett-Lennard and Ellis 2001; Yurk et al. 2002).

Sei whales (*Balaenoptera borealis*), are currently managed as a single population (COSEWIC 2019a). Evidence collected during the whaling period (for sei whales, 1960’s to 1970’s), however, suggested that there may be two sei whale populations in Atlantic Canada (Mitchell and Chapman 1974). Sei whales off Nova Scotia coasts were treated as a separate population from the whales off Newfoundland and Labrador coasts (Mitchell and Chapman 1974). The Nova Scotia whales were believed to have originated from a population migrating north from the United States, whereas those off Newfoundland and Labrador were understood to have originated from a population migrating west from Greenland (Mitchell and Chapman 1974). The whales off Nova Scotia typically arrived in mid to late June, while those off Newfoundland and Labrador arrived in the Labrador Sea in early June (Mitchell and Chapman 1974). The Nova Scotia whales also moved in what was described as two “runs” – a northward migration up the Nova Scotian coast in June-July and a southward migration in September-November, whereas the Newfoundland and Labrador whales arrived and left the area without any defined movement (Mitchell and Chapman 1974). These observations suggest that sei whales in Atlantic Canada may not be a single population, but rather two populations using neighbouring foraging grounds (Mitchell et al. 1986).

Despite these observations, a recent genetic study on sei whales using mitochondrial control region DNA from three locations across the North Atlantic (Iceland, the Azores, and the Gulf of Maine, n= 87), showed no significant deviations from homogeneity among North Atlantic sei whales suggesting a single population. This study did not, however, include samples from Atlantic Canada, and there were high levels of uncertainty in the estimates of genetic divergence that prevented the authors from rejecting the possibility of localized populations (Huijser et al. 2018). A lack of genetic variation also does not preclude the possibility of local population differences, as seen in bottlenose dolphins (*Tursiops truncates*, Luis et al. 2021), where local populations do not differ genetically, but do show distinct differences in vocalizations.

In Atlantic Canada, threats such as seismic surveying and shipping tend to be unevenly distributed throughout the region (Simard et al. 2014; Government of Newfoundland and Labrador 2021) and could be unevenly affecting sei whales throughout the region. If these two populations are facing different threats, which vary in their short- and long-term effects mortality rates (Thomas et al. 2016), then managing them as a single population facing the same threats would be less effective. The objective of this study was thus to determine if sei whales in the North Atlantic show evidence of diverging local populations based on differences in their vocalizations. Specifically, I used PAM to determine if sei whale call characteristics differed between Nova Scotia and Newfoundland/Labrador as an indicator of two separate local populations.

Sei whales produce downsweeps, which are tonal vocalizations that start at about 80 Hz and sweep downward to about 30 Hz, (Baumgartner et al. 2008, Figure 2-1). There are three recognized call types including single downsweeps (singlets), double downsweeps (doublets), or three or more downsweeps (triplets, etc.). To determine if call characteristics differed between the two locations, I compared the duration and frequency characteristics of sei whale downsweeps and call types recorded from each location (Nova Scotia and Newfoundland/Labrador), as well as the proportion of call types recorded in each location. Call characteristics often vary with behaviour (i.e., foraging vs. mating) and behaviours often vary with season (e.g., Stafford et al. 2001; Stimpert et al. 2011; Širović et al. 2013), therefore, I also examined seasonal differences in call characteristics and proportion of call types within each location.

3.2 Methods

3.2.1 Data collection and preparation

I used recordings from the six stations described in Chapter 1: (Emerald Basin (EMB), Mid-Gully (MGL), Stone Fence (STF), Stations (STNs) 13, 15 and 19) for this study. From these recordings, I identified and validated sei whale downsweeps as described in Chapter 2:. In brief, I sampled, measured, and assigned sei whale downsweeps to specific downsweep call types (singlet (SL), doublet (DB) and triplet+ (TP+)) and quality categories (High-, Mid- and Low-quality). I categorized downsweeps by location, grouping EMB, MGL and STF as Nova Scotia (NS) stations, and STNs 13, 15 and 19 as Newfoundland/Labrador (NFLD) stations. Finally, I categorized downsweeps by season (Spring: March-May, Summer: June-August, Fall: September-November, Winter: December-February). I only used high quality downsweeps with an SNR > 10 measuring and calculating call characteristics.

3.2.2 Comparison of call characteristics between locations

I averaged call characteristics within each file, to account for the possibility that a single individual produced multiple downsweeps in a given file (see Chapter 2:). I compared the following call characteristics: duration, minimum and maximum frequency, slope, peak frequency and intra-call interval of downsweeps between the two locations, I also compared these call characteristics of downsweeps between call types and seasons within each location, and between locations (see Appendix A for definitions).

I performed a one-way multivariate analysis of variance (MANOVA), which tests for the statistically significant effect of one or more categories on multiple dependent continuous variables collectively, to determine if there were differences in call characteristics between locations. To check whether any single recording station was responsible for potential differences between locations, individual recording stations were also tested using MANOVA. I then used post-hoc canonical variate analysis (CVA, or linear discriminate analysis (LDA) in cases where there were only two factors), which maximizes the distance between the means of a linear combination of variables by category in multivariate space, to determine which of the call characteristics best explained differences between locations or stations.

I performed t-tests to determine if the intra-call interval in DB and TP+ call types differed between locations, as well as between call types within each location. Finally, I performed a two-way MANOVA and post-hoc CVA to determine if there were differences in call characteristics by call type between locations, as well as by season between locations.

3.2.3 Comparison of proportion of call types between regions

I calculated the proportion of each call type recorded at each location and in each season by location. I included all instances of call types found, regardless of the quality of the downsweeps, to calculate proportions. I visually inspected the proportions of each call type to assess differences between locations, and between seasons within each location.

3.3 Results

3.3.1 Comparison of call characteristics between locations

In total, I measured 14,385 sei whale downsweeps of varying quality and SNR across both locations. Of the 14,385 downsweeps, 923 were considered high-quality and averaging these high quality downsweeps within each file resulted in a sample size of n = 268 downsweeps (NS n = 177, NFLD n = 91). The 923 downsweeps were also averaged across call types resulting in 240 SL (NS n = 188, NFLD = 52), 608 DB (NS n = 333, NFLD = 275) and 55 TP+ (NS n = 14, NFLD n = 41).

Overall, downsweeps differed significantly between the two locations ($F_{5,266} = 6.01$, $p < 0.001$). LDA showed that while there is a lot of overlap in call characteristic variability, loadings showed that duration contributed the most to the variation between locations (Figure 3-1), with downsweeps being longer in NS than in NFLD (Table 3-1). The other call characteristics had little to or no influence on the variation in downsweeps between locations (Figure 3-1). I checked for variation between stations and found stations to be significantly different from each other ($F_{5,262} = 7.22$, $p < 0.001$). Though not presented here, visual inspection of CVA showed that all NS stations were different from NFLD stations, as expected by the differences between locations.

Irrespective of call type, downsweeps in NS were significantly longer than those in NFLD ($F_{10,1788} = 3.06$, $p = 0.001$, Table 3-2). Within each location, downsweeps varied significantly by call type (NS: $F_{10,1058} = 7.32$, $p < 0.001$; NFLD: $F_{10,724} = 5.41$, $p < 0.001$), with CVA loadings showing downsweep duration contributed the most to call type variation (Figure 3-2). Downsweeps produced as part of DB were longer than the downsweeps produced in other call types at both locations (Table 3-2).

Intra-call intervals also differed significantly between the two locations ($t_{291} = 7.30$, $p < 0.001$, Table 3-2), with intervals being shorter in NS than in NFLD. Regardless of location, intra-call interval was shorter in DB than TP+ ($t_{34} = -3.36$, $p = 0.002$).

Within location, downsweeps differed significantly between seasons (NS: $F_{15,519} = 6.10$, $P<0.001$; NFLD: $F_{15,261} = 3.56$, $p < 0.001$, Figure 3-3). CVA loadings show duration contributed the most to downsweep variation, with downsweeps being longer in Fall compared to the other seasons (Figure 3-4).

3.3.2 Comparison of proportion of call types between locations

TP+ call types constituted less than 10% of call types recorded overall; most call types were SL and DB (Figure 3-5, Figure 3-6). Visual inspection of the data showed that in NS, the proportion of SL and DB were near equal at about 50% each, while in NFLD approximately 70% of call types were DB (Figure 3-5).

TP+ call types also constituted less than 10% of call types across all seasons; (Figure 3-6). Visual inspection of the data showed that DB were the minority call type recorded in NS, except in Fall, where 70% of call types were DB (Figure 3-6). In contrast, proportionally more DB were recorded in NFLD in all seasons except in the Spring, where they constituted only about 40% of call types (Figure 3-6).

3.4 Discussion

I found that downsweeps recorded off NS had a longer duration than those off NFLD, and there were proportionally fewer DB than SL recorded off NS than NFLD. In addition, downsweeps were also longer in Fall than in other seasons, regardless of location. These differences could be indicators of two local populations of sei whales in Atlantic Canada, with the caution that background noise and sound propagation differences between regions could also contribute to the differences in calls between the two locations (see below).

3.4.1 Variation in call duration by location

I found that downsweeps recorded off NS were significantly longer than those recorded off NFLD, providing some support for the hypothesis that two local populations of sei whales exist in Atlantic Canada. Differences in call characteristics that vary geographically have been used to differentiate local populations in highly vocal species like monkeys (De La Torre and Snowdon 2009), birds (Wright 1996) and other whale species (Ford 1991). These differences, given time, can evolve into distinct repertoires that reproductively isolate one local population from another (Baker 1982; Filatova et al. 2012) and eventually lead to distinct and genetically separate populations (Baker 1982).

Identifying reproductively and genetically separate populations by differences in their acoustics is well documented in Pacific killer whales (e.g., Barrett-Lennard and Ellis 2001; Yurk et al. 2002; Filatova et al. 2012). Each population of fish-eating whales are genetically distinct and have highly specialized acoustic repertoires, despite similar behaviours, and geographic overlap (Filatova et al. 2012). Baleen whales also show differences in call characteristics across populations. For instance, fin whales in the Northwest Atlantic have inter-pulse intervals (the spacing between 20 Hz pulse calls) that differ between populations in the Gulf of St. Lawrence and the Gulf of Maine (Delarue et al. 2009). These results, combined with results from tagging studies (Mitchell 1974), photoidentification studies (Robbins et al. 2007), and contaminant load studies (Hobbs et al. 2001), suggest that what is currently considered a single population has likely diverged into at least two local populations within the Northwest Atlantic. Further, the authors suggest that the populations should be managed separately (Delarue et al. 2009). The results of my study suggest that differences in call characteristics of downsweeps recorded off NS and NFLD could be evidence of two distinct local populations of sei whales in Atlantic Canada, similar to that seen in fin whales in the region.

3.4.2 Variation in call duration by season

In both locations, downsweeps were longer in Fall than in the other seasons, as is clearly observed off Nova Scotia, where sample sizes were similar in Summer and Fall (n=76 and n=71, respectively). Changes in vocalizations with season may be related to seasonal changes in behaviour. Toothed whales, for instance, are known to change their vocalizations depending on behavioural context (Courts et al. 2020), and these changes can be as subtle as changing the duration and/or frequency, as opposed to a completely different call type (Murray et al. 1998). In baleen whales, the inter-pulse interval of fin whales has been documented to also change seasonally, with shorter intervals in the fall/winter months and longer intervals in the spring/summer (Morano et al. 2012). Sei whale downsweeps might be another example of these subtle changes of vocalizations changing with behaviour, with downsweep duration altering with seasonal behavioural shifts. However, there is not enough information on sei whale behaviour in Atlantic Canada to assess to which degree seasonal changes affect the behaviour and vocalizations of sei whales. Whether downsweeps produced in the Fall were consistently different than those produced in Spring or Winter is harder to confirm, as instances of sample sizes of one in both seasons is likely not a true example of seasonal downsweeps produced.

For variation in call characteristics between locations, there is a possibility that if the sei whale population is small (i.e., less than ~200 individuals), then given the sample size of 268 high quality downsweeps, then it is likely that at least some of the downsweeps included in the analysis (even though recorded on multiple files) are likely to be from the same individual, affecting the assumption of independence of the samples. This means that the p-values presented would increase and may not unequivocally support evidence of geographic variation. However, with no true population assessment, there is no way of knowing how many individual whales could be potentially recorded, nor can we acoustically count the number of individuals represented by these data. Results should thus be interpreted with caution. Any future population estimates would need to be considered when interpreting these results.

3.4.3 Variation in proportion of call types

Proportionally fewer DB were recorded off NS than NFLD. Other studies have found that variation in the proportion of different call types can indicate differentiated populations. For instance, two herds of harp seals (*Phoca groenlandica*), one whose breeding grounds are in the Gulf of St. Lawrence and the other in Jan Mayan. These two herds were likely to be reproductively isolated based on some evidence by tagging and morphometric studies, but still were considered a single population (Terhune 1994). Research on the call repertoires of each herd found of the 17 call types shared by the two herds, one call type was heard almost twice as often in the Gulf of St. Lawrence, and two calls types were heard two-three times as often at Jan Mayan (Terhune 1994). The authors suggested that differences in the proportion of call types were additional indicators of distinct, reproductively isolated populations. Now, these two breeding herds are considered distinct populations, with these acoustic differences being a indicator of that distinction (Lavigne 2009).

Similarly, in southern resident killer whales, closely related pods share up to 28 call types (Foote et al. 2008). However, each pod has about three call types it produces proportionally more often than the other pods (60% compared to less than 10%, Foote et al. 2008). The authors suggest that killer whales use specific call types for their pod identification, and that researchers can use the proportion of preferred call types to identify each pod. These differences in proportion were indicators of each distinction grouping, and proportion of sei whale call types produced between the different locations might also be an indicator of distinct local populations.

Differences in the number of repetitions of a given call (in this case, downsweeps) can be associated with different kinds of information (Kershenbaum et al. 2016). Variation in repetition can, for example, indicate information on predators or other environmental changes (Kershenbaum et al. 2016). Different sei whales call types may be relaying different information, and therefore the proportion of call types heard at each location could be an indicator of different sei whale needs at each location, like for foraging, threats, or mating.

It is not clear why the proportion of call types reversed in the Fall off NS with more DB than SL, or in the Summer off NFLD with more SL than DB. The difference in seasonal proportions could possibly indicate a change in behaviour, such as a transition from foraging behaviours to either migration or mating behaviours (Kowarski et al. 2019), which may be occurring at different times in each location.

3.4.4 Influence of sound propagation and noise

Differences in call duration between locations observed in this study could potentially also be explained by the differences in sound propagation between locations related to environmental factors such depth, bottom type, topography, temperature, salinity, etc., which could affect sound transmission. If that were the case, I would have expected the proportion of high-quality calls I was able to identify on the recordings to vary across recording stations, resulting in more high-quality calls at stations with better sound propagation conditions. The proportion of high-quality calls was similar (9-16%) across all stations with one exception - MGL, which was also the quietest site (Appendix B), where the proportion of high-quality calls was 28%. Although at MGL high-quality calls were still a minority, the sound propagation conditions at that station could potentially be a factor in the differences in duration seen between locations and is worth further investigating.

Differences in both sound propagation conditions and background noise (see below) would also affect the detection range of each station. Downsweeps picked up by recorders with small detection ranges would have to have been made closer to the recorder, limiting the effects of sound propagation or noise on the recorded downsweep. Downsweeps picked up by recorders with large detection ranges could be distorted or partially masked by noise before being received by the recorder. The detection ranges at all six stations were variable, showing no real consistent discernable pattern between locations (Appendix C). It is then less likely that the detection range of the recorders is a primary influence on the call characteristics of sei whales by location.

Differences in background noise levels could be another explanation for the differences in call characteristics between the two locations. which could either mask all or part of calls on the recorders, or force sei whales to alter their call characteristics to avoid masking. Noise from seismic surveys, which have increased off NFLD since the 1980's as a result of offshore oil activity (Government of Newfoundland and Labrador 2021) were recorded in my study area primarily off NFLD, but was recorded at lower received amplitude levels at NS stations from 2015-2017 as bouts of intense pulses spanning from a few weeks to five months, but with long (minimum eight months) stretches of time without surveys where the area will be much quieter (Delarue et al. 2018). Increased shipping off NS (Simard et al. 2014) generates a significant amounts of low frequency (<1000 Hz) anthropogenic noise, which in my study area during the same time was near continuous with almost no reprieve throughout the year (Delarue et al. 2018).

Downsweeps recorded off NFLD could be shorter than those off NS due to seismic noise partially masking the start or end of sei whale downsweeps on the recorders, making them appear shorter than those measured off NS. I don't believe this happening in the case of this study, as I would also have expected to see differences in the maximum and/or minimum frequencies. Since there were no differences in frequencies between locations, this suggests that the shorter downsweeps are not a result of masking.

Altering the duration of downsweeps could be a strategy used by sei whales to increase the probability that their calls will be heard amongst background noise. Whales are known to employ various strategies to overcome the masking effects caused by loud background noise (Erbe et al. 2016) and one of these strategies is to alter the characteristics of their calls in the presence of noise to be heard (Parks et al. 2007; Dahlheim and Castellote 2016) . In the presence of shipping noise off NS (Simard et al. 2014), sei whales could be extending the duration of their downsweeps so individuals can be heard through the noise. Or, given that seismic noise comes in short bursts, sei whales off NFLD may be shortening their downsweeps to call at a faster rate to be heard between the noise. Rudimentary noise profiles for my recording stations in the 30-80 Hz range show no major variations in noise between stations (Appendix B), suggesting that the presence of noise, may not be the primary factor in the different durations between locations, though the type of noise might be.

The difference observed in the proportion of singlets and doublets produced between the two locations could also be indicative of a sei whale anti-masking response to background noise by increasing the repetition rate of vocalizations to increase the chances of being heard (Erbe et al. 2016). I found a greater proportion of doublets off NFLD, which could increase the probability of a vocalization being detected by another animal in the presence of noise. If this were the case, it is surprising that triplet+ call types, which represent an even greater increase in repetition rate, were not more prominent. It is possible that production of longer call types like triplet+ call types are not as energy efficient (Holt et al. 2015) as doublets, but doublets are still effective enough to overcome masking. Even though noise levels appear to be similar over the entire timespan at both locations (Appendix B), is it possible that a more detailed investigation of noise levels in my study area could show differences that would warrant a difference in call type proportions.

Longer downsweeps and increased proportion of DB in the Fall coincided with peaks in seismic survey noise that occurred during my study time (Appendix B). Though this could potentially explain the longer downsweeps and more DB in the Fall off NFLD, it is less clear why the same pattern is seen in results off NS.

It is still not clear whether the difference in downsweep duration or call type proportions between the two locations and between seasons are exclusively the result of variation in sound propagation and/or background noise, but a thorough investigation of both these factors was outside the scope of my study. Future studies comparing downsweep durations and call type proportions before, during, and after times of seismic and shipping noise could help answer whether sei whales are deliberately altering their downsweeps or their call types in the presence of different types of noise. In addition, fine-scale temporal comparisons of changes in noise profiles to changes in sei whale vocalizing during seasonal changes (especially in and out of Fall) could help to provide a better understanding of the effects of noise on sei whale vocalizations seasonally.

3.4.5 Conclusions

Both downsweep duration and call type proportions appeared to differ between NS and NFLD, offering some support for two local populations off eastern Canada as proposed by Mitchell and Chapman (1974) and Prieto et al. (2014). Studies including quantitative noise and sound propagation profiles would aide in determining whether these variations are truly indicative of population differences or a result of other factors. If these differences are indicative of different populations, any discussions of conservation and management in the region should consider whether these possible populations should be managed separately. Future studies should expand acoustic monitoring efforts to include the Gulf of St. Lawrence, Gulf of Maine and Greenland to gauge the variation in vocalizations throughout the entire North Atlantic, as well as data from subsequent years to look at any potential inter-annual changes which could be a factor in the variation presented. Finally, ongoing acoustic research of sei whales should be conducted in tandem with photo-identification studies and genetic sampling to compare any locations identified by variation in the acoustic surveying.

3.5 Tables

Table 3-1. Summary statistics for call characteristics of sei whale downsweeps by location. NS = Nova Scotia, NFLD = Newfoundland/Labrador, SD = standard deviation, Freq. = frequency.

	NS (n = 177)			NFLD (n = 91)		
Characteristic	Mean ± SD	Range	95% C.I.	Mean ± SD	Range	95% C.I.
Duration (s)	1.62 ± 0.33	0.72 – 2.59	1.57 – 1.67	1.51 ± 0.24	1.02 – 2.08	1.46 – 1.56
Min. Freq. (Hz)	35.01 ± 5.83	25.63 – 53.41	34.14 – 35.87	32.70 ± 4.90	21.69 – 49.30	31.68 – 33.72
Max. Freq. (Hz)	77.06 ± 9.06	59.46 – 97.34	75.72 – 78.41	72.94 ± 9.17	52.24 – 95.96	71.03 – 74.85
Slope (Hz/s)	-26.77 ± 5.25	-45.04 – -14.57	-27.55 – -25.99	-27.20 ± 5.34	-43.04 – -15.90	-28.31 – -26.09
Peak Freq. (Hz)	44.41 ± 7.35	29.66 – 64.70	43.32 – 45.50	42.87 ± 7.64	27.83 – 71.04	41.28 – 44.46

Table 3-2. Summary statistics (mean ± standard deviation) for call characteristics of sei whale downsweeps by call type, by location. NS = Nova Scotia, NFLD = Newfoundland/Labrador, SL = singlet, DB = doublet, TP+ = triplet+, Freq. = frequency.

			NS			
Call Type	Duration (s)	Min. Freq. (Hz)	Max. Freq. (Hz)	Slope (Hz/s)	Peak Freq. (Hz)	Intra-call Interval (s)
SL (n=188)	1.49 ± 0.32	35.88 ± 8.18	76.85 ± 11.78	-28.25 ± 6.35	45.49 ± 9.79	
DB (n=333)	1.69 ± 0.34	33.06 ± 4.28	75.82 ± 10.21	-25.88 ± 5.58	42.53 ± 7.84	2.09 ± 0.35
TP+ (n=14)	1.5 ± 0.18	33.97 ± 3.65	76.44 ± 10.55	-28.24 ± 3.36	41.08 ± 6.11	2.15 ± 0.38
			NFLD			
SL (n=52)	1.43 ± 0.27	34.55 ± 6.69	77.2 ± 16.12	-30.23 ± 7.86	44.58 ± 10.85	
DB (n=275)	1.56 ± 0.26	31.85 ± 4.21	69.99 ± 9.48	-24.82 ± 6.03	41.95 ± 7.42	2.33 ± 0.27
TP+ (n=41)	1.42 ± 0.22	33.83 ± 3.79	71.17 ± 4.29	-26.78 ± 4.28	44.82 ± 6.67	2.58 ± 0.42

3.6 Figures

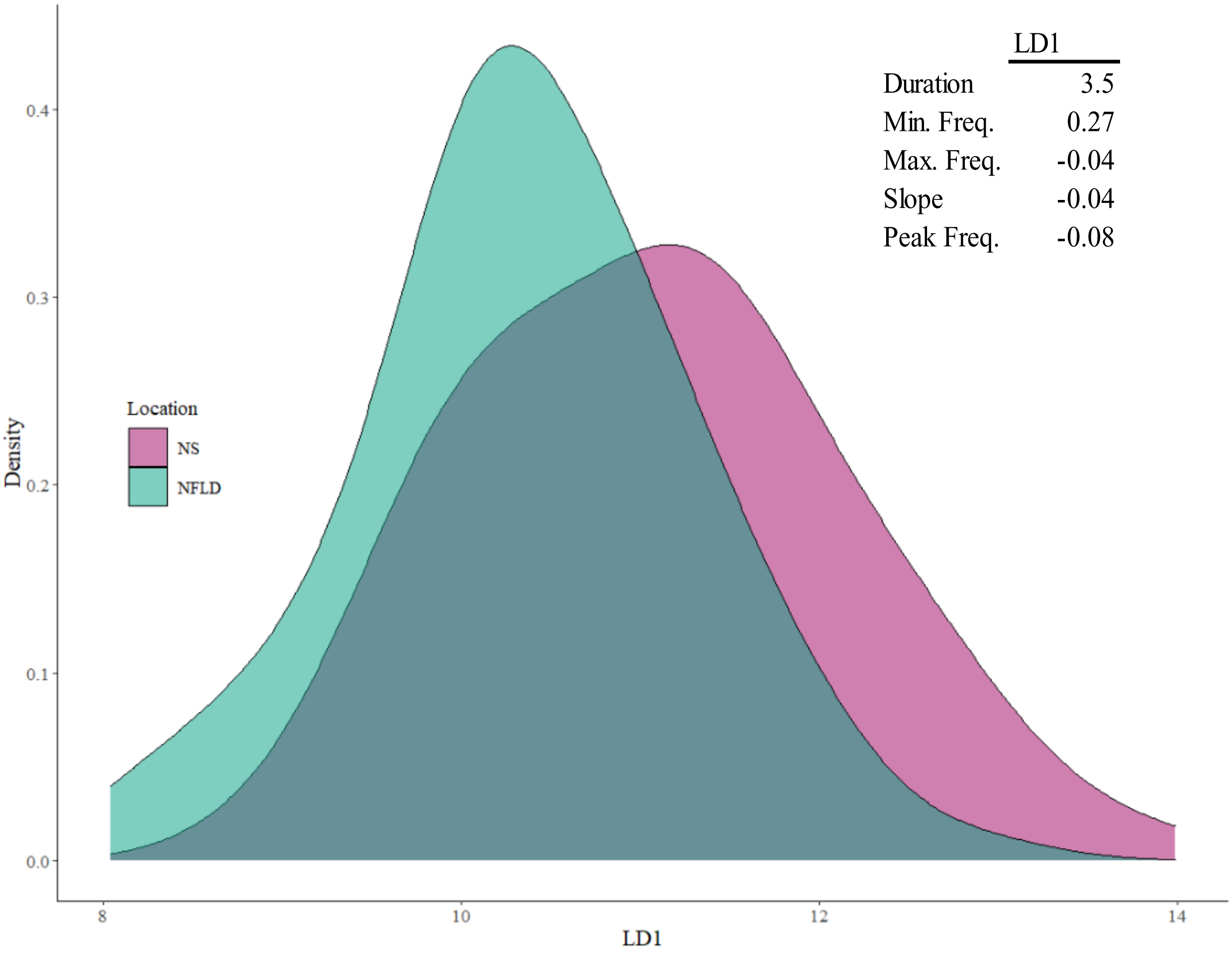
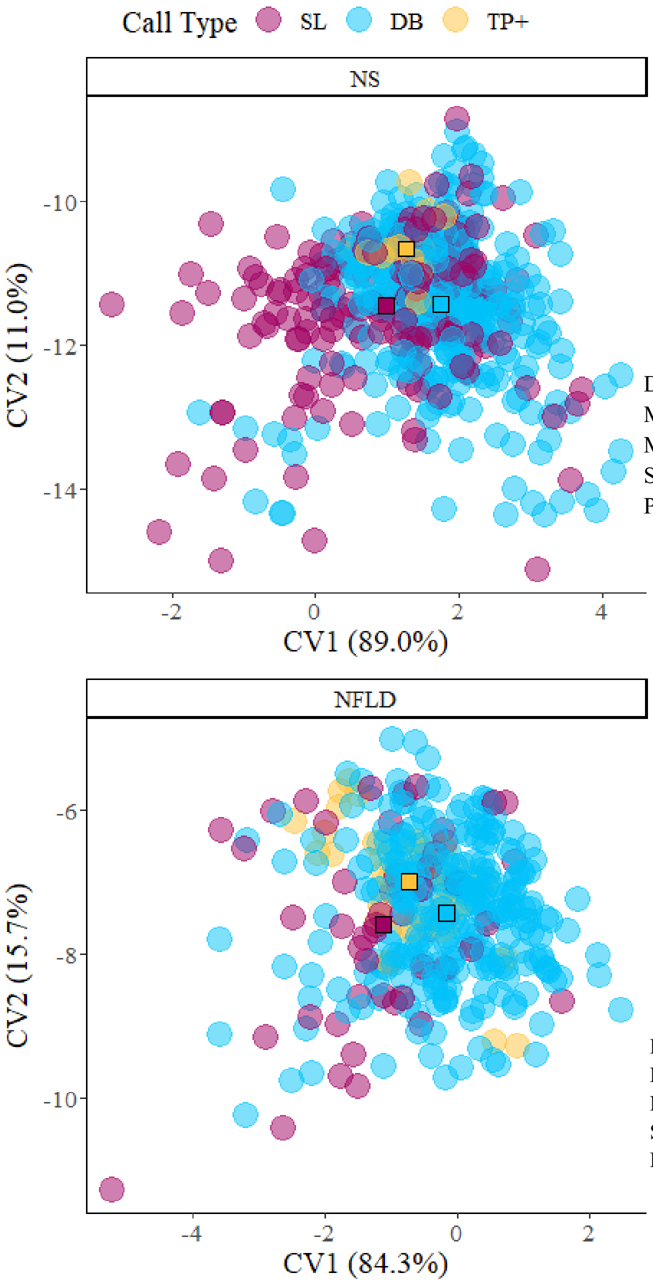


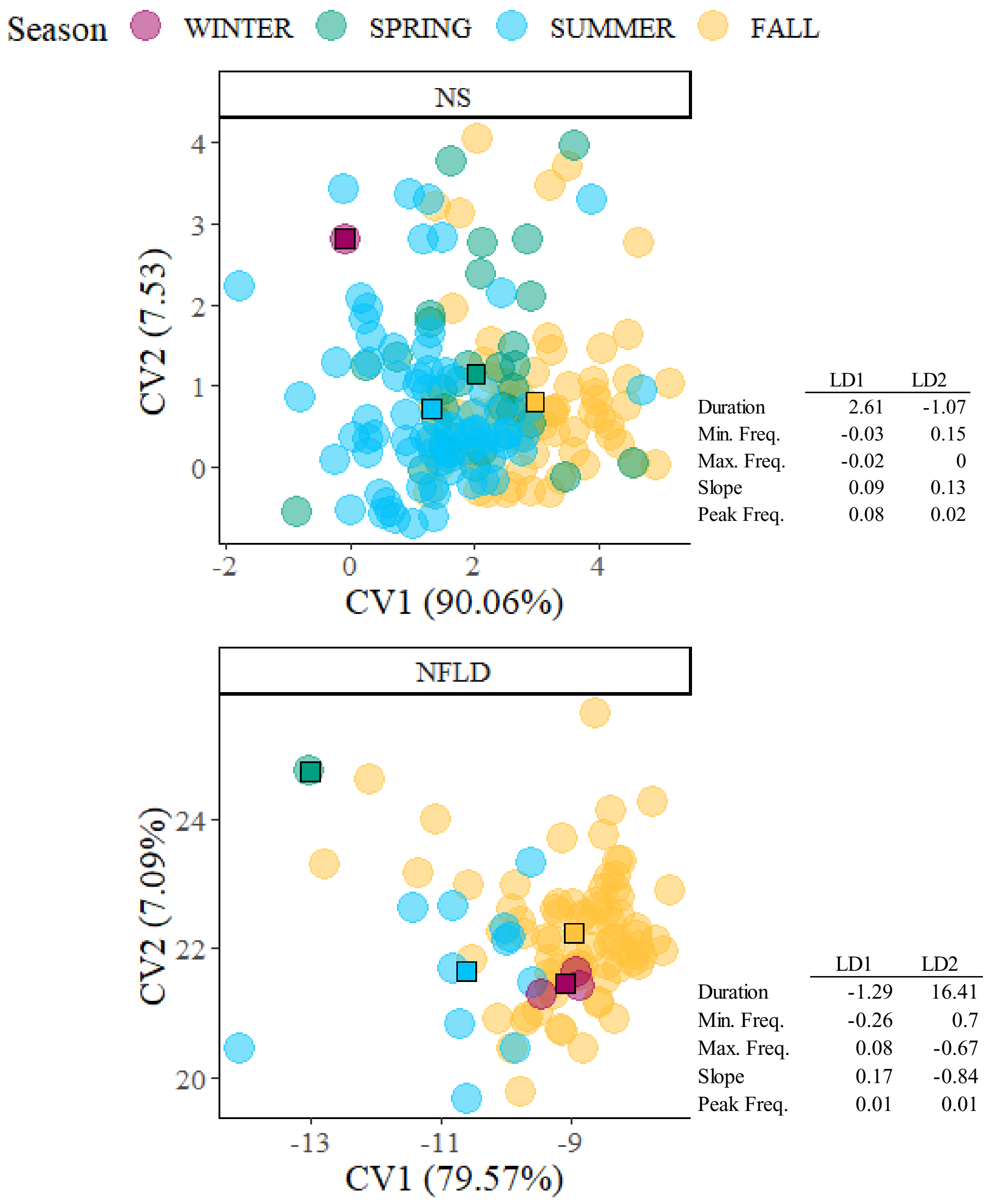
Figure 3-1. Linear discriminant analysis of downsweep characteristics by location. Box in upper-right corner provides the loadings. NS = Nova Scotia, NFLD = Newfoundland/Labrador



	LD1	LD2
Duration	2.6	-8.06
Min. Freq.	-0.08	-0.24
Max. Freq.	0	0.34
Slope	-0.03	0.4
Peak Freq.	-0.02	-0.12

	LD1	LD2
Duration	3.58	-4.06
Min. Freq.	-0.01	-0.05
Max. Freq.	-0.1	0.02
Slope	-0.04	0.17
Peak Freq.	0	0.09

Figure 3-2. Canonical variate analysis of downsweep characteristics by call type, within each location (n = 268). Boxes in lower corners provide the loadings. SL = singlet (one downsweep), DB = doublet (two downsweeps within ~3 seconds of each other), TP+ = triplet+ (three or more downsweeps within ~3 seconds of each other), NS = Nova Scotia, NFLD = Newfoundland/Labrador.



	LD1	LD2
Duration	2.61	-1.07
Min. Freq.	-0.03	0.15
Max. Freq.	-0.02	0
Slope	0.09	0.13
Peak Freq.	0.08	0.02

	LD1	LD2
Duration	-1.29	16.41
Min. Freq.	-0.26	0.7
Max. Freq.	0.08	-0.67
Slope	0.17	-0.84
Peak Freq.	0.01	0.01

Figure 3-3. Canonical variate analysis of downsweep characteristics by season, within each location (n = 268). Boxes in lower corners provide the loadings. NS= Nova Scotia, NFLD = Newfoundland/Labrador

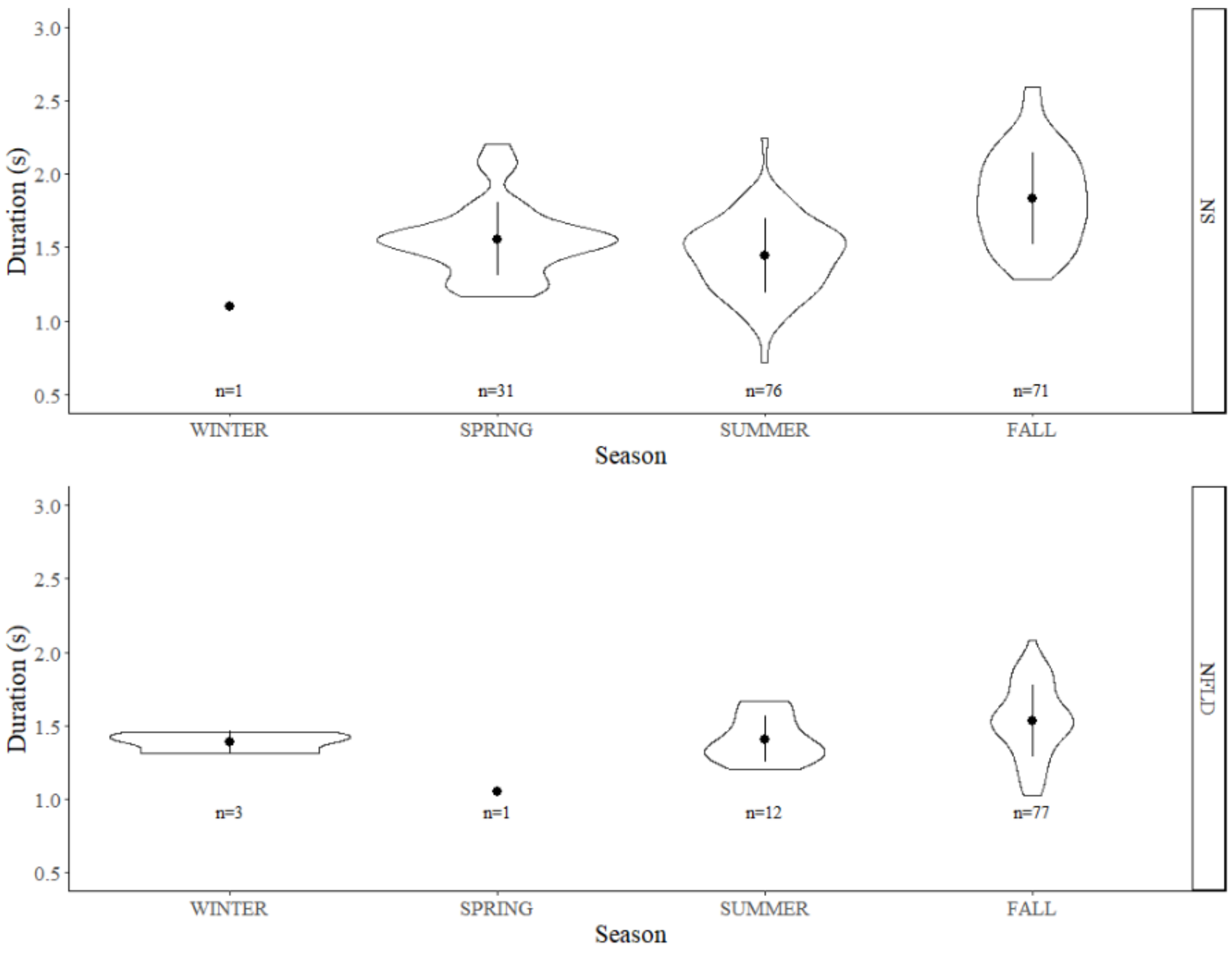


Figure 3-4. Violin plots (with mean ± standard deviation) of sei whale downsweep duration grouped by season, then by location. NS = Nova Scotia, NFLD = Newfoundland/Labrador.

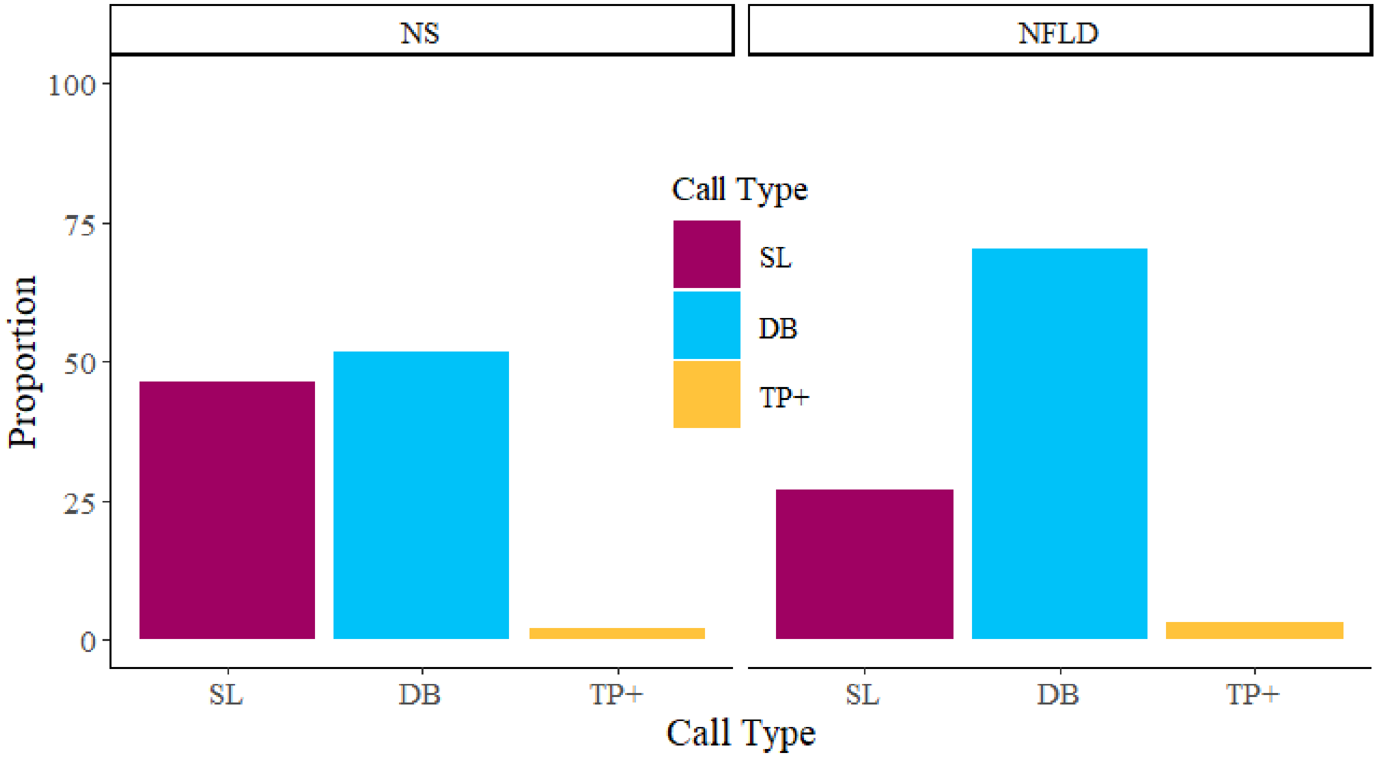


Figure 3-5. Proportion of call types heard at each location. SL = singlet (one downsweep), DB = doublet (two downsweeps within ~3 seconds of each other), TP+ = triplet+ (three or more downsweeps within ~3 seconds of each other), NS = Nova Scotia, NFLD = Newfoundland/Labrador.

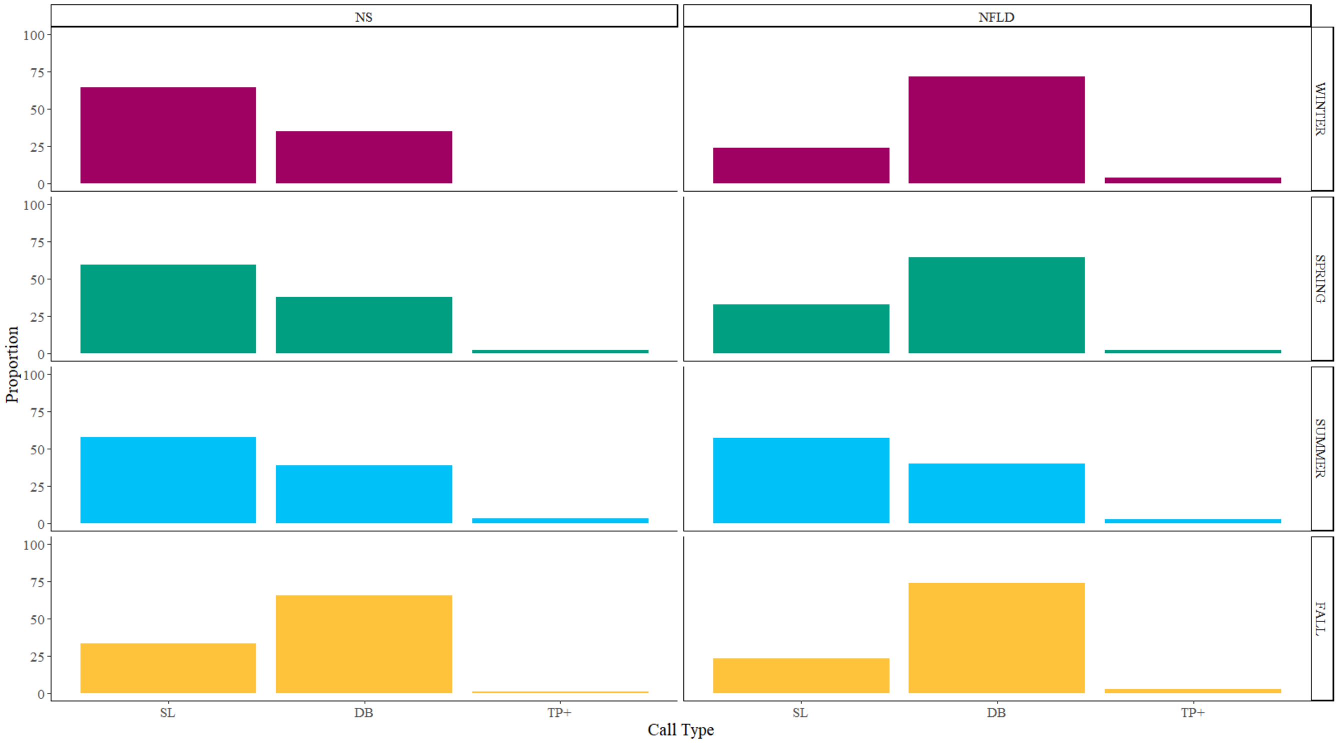


Figure 3-6. Proportion of call type heard in each season, in each location. SL = singlet (one downsweep), DB = doublet (two downsweeps within ~3 seconds of each other), TP+ = triplet+ (three or more downsweeps within ~3 seconds of each other), NS = Nova Scotia, NFLD = Newfoundland/Labrador.

Chapter 4: Improved Detection and Validation of Sei Whale Downsweeps in Atlantic Canada

4.1 Introduction

Passive acoustic monitoring (PAM) is increasingly being used to determine the occurrence, distribution, and behaviour of marine mammals (Zimmer 2011b). Advances in PAM technology have resulted in audio recording datasets that have grown from megabytes to terabytes (Kowarski and Moors-Murphy 2020). It has become standard practice to use automated detector-classifier systems (DCS) to locate marine mammals on PAM recordings (Kowarski and Moors-Murphy 2020). Detector-classifier systems are automated programs (computer algorithms) designed to detect and classify target signals (e.g., whale calls) on recordings. Although DCSs speed up the process of detecting marine mammals on large PAM datasets, errors are inevitable and must be considered when creating the detectors that make up a DCS.

4.1.1 Signal detection theory and DCSs

Signal detection theory expresses the “decision-making” process of the detectors when perceiving stimuli (e.g., a call) as information rather than background noise with a calculated level of uncertainty (Wickens 2010). There are four possible outcomes when a detector perceives a stimulus: a target call can be correctly detected (“true positive”), a non-target signal can be incorrectly identified as the target call (“false positive”), a target call can be missed (“false negative”), or the detector correctly indicates that a call is not present (“true negative”). The rates and types of error are determined by detector thresholds that are pre-set by human analysts.

DCSs use a two-step process to first detect and then classify target calls. In the first step, a detector is set to a specific threshold, typically based on call amplitude, above which a call is considered to have been detected and below which it has not. In the second step, the call characteristics or parameters of detected calls are then compared to parameters based on known call characteristics of the species of interest. If they match, the calls are classified as belonging to that species. Detectors that use a high threshold and very specific call characteristics increase the probability that detected calls are target calls (i.e., fewer false positives), but also increase the probability of missing fainter target calls or target calls that don't fall within the very specific parameters (i.e., more false negatives). Detectors that use a low threshold and broad call characteristics increase the probability of detecting target calls as they are more likely to capture the full range of variability in the received calls (i.e., fewer false negatives), but also increase the probability of non-target signals being detected (i.e., more false positives). Because of these potential for errors, most detectors require human analysts to perform some level of manual validation of detections to understand how the DCS is performing, by checking for missed calls or validating classified calls by visually or aurally checking and confirming detections are correct. Despite these limitations, DCS speed up analyses of PAM data and are used regularly in baleen whale studies (Kowarski and Moors-Murphy 2020).

Various DCSs have been used to study baleen whales. Some systems use spectrogram correlation (contour-based, Au and Lammers 2016) to detect baleen whale vocalizations, while others use spectrogram pitch tracking (Baumgartner and Mussoline 2011). Both are particularly useful for detecting highly stereotypical tonal calls of baleen whales and are currently being used to detect sei whales (*Balaenoptera borealis*) in Atlantic Canada.

4.1.2 DCSs and sei whale detection in Atlantic Canada

The JASCO Acoustic Analysis (AA, Martin et al. 2014) contour-based DCS and the Low Frequency Detector and Classifier System (LFDCS, Baumgartner and Mussoline 2011) pitch-tracking detector are DCSs currently being used to detect and classify sei whale vocalizations in Atlantic Canada.

The JASCO AA detector reads recording files as spectrograms. It scans the spectrogram and creates an outline (i.e., contour) of all calls that exceeds a pre-set amplitude threshold (i.e., contour-based, Martin et al. 2014). It then measures the duration, minimum and maximum frequency, sweep rate (i.e., slope), peak frequency, and frequency span of the call (Martin et al. 2014). If the characteristics of the call match the pre-set characteristics or parameters (e.g., duration, minimum and maximum frequency) defined for sei whales, then the call is considered a match and classified as a sei whale.

The LFDCS detector scans through spectrograms of recording files and places a track along the fundamental frequency of calls that exceed a pre-set amplitude threshold, as they change over time (i.e., pitch track, Baumgartner and Mussoline 2011). Call characteristics such as mid frequency, frequency range, duration, and slope are extracted from these pitch tracks, and then compared to call characteristics in a species-specific call library, which is a collection of previously identified sei whale calls. If the call characteristics from the pitch track match the pitch tracks from the call library, then the call is classified as a sei whale (Baumgartner and Mussoline 2011).

In previous studies of sei whale vocalizations in Atlantic Canada, the JASCO AA sei whale detector was set at a low threshold, which decreased the possibility of false negatives, or sei whale calls (i.e., downsweep) being missed when present, but increased the likelihood of false positives with noise or other whale calls being misidentified as downsweeps (Delarue et al. 2018). Conversely, the LFDCS detector was set at a high threshold, which decreased the possibility of false positives, or other sounds be misidentified as a downsweep, but increased the likelihood of false negatives (Baumgartner and Mussoline 2011).

High levels of either error signifies that human analysts must validate the detections to determine if the false positives are actual target calls, or to locate missed target calls, to ensure any results accurately represent call presence on the recordings (Kowarski and Moors-Murphy 2020). Either approach, while thorough, requires a significant amount of time. This presents a challenge for researchers who want to process datasets efficiently, but accurately, to describe whale call presence.

4.1.3 Use of multiple detectors

Single detectors set with low thresholds and broad parameters result in fewer missed calls but higher rates of false positives. These detectors are often used in studies to answer questions on whale presence over space and time. For example, results from these detectors are often used in creating long-term management plans and conservation strategies that require information on the presence of a target species in a given area but require sufficient time for human analysts to sort through many false positives. However, detectors with high rates of false positives may not be suitable if confirmed presence of whales is required in near-real time (Baumgartner et al. 2013). In this case, new detectors need to be created from the original detector to confidently detect whales with minimal false positives. Having and using multiple detectors to study a single species allows researchers to get various measurements of presence at different levels of analysis.

This approach has been tested in a recent study of the endangered North Atlantic right whale (*Eubalaena glacialis*, Kowarski et al. 2020) in the Gulf of St. Lawrence. Originally, work on right whales was primarily aimed at understanding how they used waters of the Gulf of St. Lawrence and required comprehensive information on the distribution and presence of right whales in the Gulf and around Nova Scotia. For this purpose, a detector with low thresholds and broad call characteristics ensured all potential right whale calls were identified, despite the high levels of false positives and associated processing time. With increasing mortality from ship strikes and entanglement (Daoust et al. 2017), however, the need to quickly know when whales occurred in the area was required. For this purpose, a detector with a high threshold and restrictive call characteristics to increase true positives, allowed researchers to quickly identify whale calls. The high threshold and restrictive call characteristics associated with this detector, however, also meant right whale calls were likely being missed. Therefore, a second detector with a lower threshold and less restrictive parameters that could detect more right whale calls was created because fewer calls were missed with this detector. These settings also increased false positives, increasing validation time, but allowed researchers to fill in presence gaps missed by the first detector. Subsequent detectors, created with lower thresholds and less restrictive call characteristics, had more false positives and fewer missed calls, would help to fill in presence gaps as the validation times got longer.

The multiple single detectors used in this study were clearly beneficial in addressing the specific needs of the researchers. Nonetheless, each detector had associated errors, which required that analysts spend time manually validating detection and classification results. For my study, I created and tested a system of multiple detectors where validation occurred sequentially with the goal of increasing efficiency by reducing the amount of work needed for error validation.

The following example illustrates how multiple detectors in sequence could be used to increase the efficiency by which daily presence, a metric for determining whale presence, is achieved. Here, a first detector set with a high threshold and restrictive call characteristics would detect relatively few, but correct calls. Therefore, calls noted on any given day should accurately reflect the presence of the target species on that day. A second detector with a lower threshold and less restrictive call characteristics would increase the number of calls detected relative to the first detector, but also increase false positives and so more time to validate the days with detections. However, because of the accuracy of the first detector, days with confirmed calls from the first detector would not require checking thus reducing the overall processing time. This step could be repeated with additional detectors. Ultimately, the workload is reduced by including the results from the previous detector with each subsequent detector. This turns two or three individual detectors into a systematic, tiered-detector approach to the detection, classification, and validation of whale calls (Figure 4-1). I anticipated that this tiered approach would increase the efficiency of studying species whose detectors tend to be associated with high rates of error, such as those currently used for sei whale vocalizations.

The objective of this study was to create a more efficient way of validating the detections and classifications of sei whales from PAM studies for both DCSs currently used to study sei whales in Atlantic Canada. To address this goal, I first looked at the relationship between different thresholds and call parameters and their associated error rates for individual sei whale detectors to assess performance of the detectors. This step was necessary to establish the optimal settings for the detectors that would be used in the tiered approach (i.e., detectors that minimize false positives or that minimize missed calls). I then compared the efficiency of the tiered-detectors to that of a single detector, by comparing the percentage of files that needed to be validated between the tiered-detector system and a single detector to examine whether using a tiered approach analyze a smaller proportion of files to accurately assess presence.

4.2 Methods

4.2.1 Compilation of truth data

This study used datasets collected at three different stations: Emerald Basin (EMB) 2016, Mid-Gully (MGL) 2015 and Station (STN) 15 2015. The deployment details for these datasets are described in Chapter 1:. To determine the performance of individual detectors and the efficiency of the tiered-detector approach, I compared files from these recording stations with previously validated sei whale downsweeps (hereafter referred to as "truth data"; see Chapter 2:), to the detector outputs from this study. The datasets used in both chapters from each of the three stations were selected to ensure the detectors worked in the range of recording environments expected in the region, including varying levels of background noise and co-occurring species (Table 4-1). I assumed that downsweeps produced by multiple sei whales were included in the datasets because calls were often recorded on the same day at all three stations simultaneously.

4.2.2 Tiered-detector approach

Within each DCS, the tiered-detector approach used a set of detectors that varied in threshold levels and restrictiveness of parameters (Figure 4-1). Initially, I tested 5 to 6 detectors in each of the two DCSs (see below) and ultimately retained three detectors. I excluded those detectors that had too few detections to be useful, and those with so many detections that it would render the overall approach too inefficient.

4.2.3 JASCO AA DCS

The threshold for the JASCO AA DCS is based on the amplitude of the downsweep relative to the median sound level of the file (Martin et al. 2014), while the parameters used for classifying calls include duration, minimum and maximum frequencies, and peak frequency. I created and tested new detectors at various thresholds and parameter settings to potentially be included in the tiered-detector approach.

I used a subset of recordings from the three stations to initially test the new detectors, with the goal of increasing correct detections and minimizing errors. I initially set up each detector using 10 files (approximately 110 minutes of recordings in total) from each station, with sei whale calls of various quality. Once the thresholds and parameters for each detector were set, the detectors were tested 30 files from each station that were randomly selected over the year (approximately 330 minutes of recordings in total). This subset included files with different levels of background noise, other whale vocalizations, downsweeps of varying quality and, in some cases, files without calls of any type (Table 4-1). I tested some detectors designed to minimize false positive rates and others designed to minimize missed calls. Once the testing was completed, I ran all the detectors concurrently on the full year recordings from all three stations.

The three detectors that were ultimately used in the tiered system included a newly optimized high threshold sei whale detector (High), a mid threshold detector (Med) and the current, low threshold detector (Low, Table 4-2). The detections from each of the detectors was compared to the truth data to evaluate the performance of each individual detector and the efficiency of the overall approach.

4.2.4 LFDCS

The threshold for the LFDCS detector is set to detect any sound with an amplitude ≥ 10 dB above the background noise, while the classification of species is done by comparing the similarity of detected call characteristics to the call characteristics of the species-specific call libraries. The LFDCS determines similarity by measuring the mahalanobis distance (the distance between two points in multivariate space) between the pitch track of the downsweep to those in the call library. For the current sei whale detector, a downsweep with a mahalanobis distance ≤3.00 is considered correctly classified (Baumgartner and Mussoline 2011). I compared detection results at various mahalanobis distances to determine which of the similarity distances should be included in the tiered-detector approach.

The calls in the sei whale call library originally included sei whale downsweeps recorded in the Gulf of Maine, as characterized in Baumgartner et al. (2008). I added additional downsweeps from the three recording stations to the call library, to ensure that downsweeps recorded in Atlantic Canada, which potentially differ from those recorded in the Gulf of Maine (Baumgartner et al. 2008), would be correctly classified. I included all downsweeps sampled every 3rd hour (starting at 00:00) for 24 hours on the 1st, 15th and 25th day of every month for a year at each station.

Once the new samples were added to the library, I ran the LFDCS detector with the updated call library on the full year of recordings from all three stations. The first detector targeted detections with a mahalanobis distance of ≤ 2.00, which was considered a high-similarity tier, comparable to the most restrictive parameters of the AA detector. The next detector targeted detections with a mahalanobis distance from 2.00-3.00, which was considered a mid-similarity tier, one that is less restrictive than the first, but still omitting highly variable or low-quality downsweeps. The final detector targeted detections with a mahalanobis distance from 3.00-4.00, and was considered a low-similarity tier and likely to produce many false positives. The validated results from these tiers were compared to the truth data to evaluate the performance of each tier and the efficiency of the overall approach within the LFDCS.

4.2.5 Detector performance

To determine the relationship between thresholds and error rates needed to establish the various tiers for the tiered-detector approach, I evaluated the performance of each individual detector using three measures of performance: precision, recall, and an overall performance metric known as the Matthews correlation coefficient (MCC. Precision is the proportion of true positives out of all detections (true and false positives, Equation 4-1). I considered precision values over 0.80 (i.e., less than 20% of detected calls were false positives) to be high precision. Recall is the proportion of true positives out of all potential detections (true positives and false negatives, Equation 4-2). I considered recall values greater than 0.80 (i.e., missed less than 20% of the calls) to be high recall. Because of the trade-off between precision and recall, the performance of the most restrictive detector tier was considered good if it had a precision value greater than 0.8 (i.e., little to few false positives) regardless of the recall value. As well, the performance of the least restrictive detector was considered good if it had a recall value over 0.8 (i.e., little to few missed calls) regardless of the precision value.

Equation 4-1. Precision equation. Where P = precision, TP = true positive and FP = false positive

$$P = \frac{TP}{TP + FP}$$

Equation 4-2. Recall equation. Where R = recall, TP = true positive and FN = false negative

$$R = \frac{TP}{TP + FN}$$

The overall performance metric was calculated using the MCC, which is a statistical test that incorporates all four detector outcomes (true and false positives, true and false negatives) to evaluate the overall performance of a detector (Equation 4-3). The MCC score describes either a positive or negative correlation between precision and recall the further it moves away from 0.00. If both precision and recall were perfect (i.e., no false positives and no missed calls), then the MCC score is 1.00. If both the precision or recall are 0.00 (i.e., all false positives and all missed calls), then the MCC score would be -1.00.

Equation 4-3. The Matthews correlation coefficient (MCC) equation. Where TP = true positive, TN = true negative, FP = false positive and FN = false negative.

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}}$$

The precision, recall and MCC scores were calculated for each detector per file and per day. The detector output is on a per file basis. Evaluating performance at the file level allowed me to evaluate performance of the detector at a reasonable level (rather than at a per call basis). I also evaluated performance on a per day basis as well as this is a common time unit in PAM occurrence studies, and the metric I used to determine spatiotemporal presence of sei whales in Atlantic Canada (see Chapter 5:).

4.2.6 Efficiency of tiered-detector approach

To achieve my overarching goal of creating a more efficient method of analysing sei whale downsweeps from PAM studies, I needed to compare the effort required to validate the results of the tiered-detector approach to that of a single detector. In the JASCO AA DCS, the single detector used for comparison was the Low-threshold detector from the new tiered approach as it is the current single detector used for sei whale detection by JASCO (Table 4-2). In LFDCS, the single detector used for comparison was the Med-threshold detector as it is the current single detector setting used in LFDCS to detect sei whales (Baumgartner and Mussoline 2011). For me to determine the spatiotemporal presence of sei whales in Atlantic Canada, which was one of the main goals of my thesis (see Chapter 5:), it was imperative that the efficiency of detecting sei whales for presence studies be increased while still minimizing the number of calls missed by the analysis. In my study, effort was considered the number (or percentage) of files checked when validating a dataset. I considered the tiered-detector approach to be more efficient than a single detector if I needed to check fewer files in the tiered system to determine the number of files or days a sei whale was present at a recording station than with a single detector. First, I calculated the percentage of files and days from the truth data with confirmed sei whale calls (based on daily presence). I then calculated the percentage of files with sei whale detections out of the total number of files, as well as the percentage of days with sei whale detections out of the total number of days for each detector in both DCSs. I compared the percentage of files and days with detections to the percentage of files and days with confirmed sei whale calls as a measure of the effort required using the tiered-detector approach to get the same results. I then compared the total effort from the tiered-detector approach to the effort (i.e., percentage of files with detections) from a single detector in each DCS to compare the two approaches.

4.3 Results

The truth data from three stations indicated that 1,043 out of 11,579 (9%) of the files contained confirmed sei whale downsweeps (Table 4-1), and 278 out of 939 (25%) of the days had downsweeps (Table 4-1).

4.3.1 Detector performance

Per file, the High- threshold detectors in the JASCO AA DCS had the highest precision across the three stations (0.52-0.79) and the lowest recall (0.01-0.42), with this detector having the lowest false positive rates and the highest missed call rates of the three levels (Table 4-3). The Low-threshold detectors had the lowest precision (0.08-0.79) and the highest recall (0.46-0.93), with this detector having the highest rates of false positives, but the lowest rates of missed calls (Table 4-3). The precision and recall of the Med-threshold detector had similar rates of false positives and missed calls (Table 4-3). This pattern is also observed when detector performance per day is considered, where the High- threshold detector had the highest precision across the three stations (0.40-1.00) and the Low- threshold had the highest recall (0.90-1.00, Table 4-4).

Similarly, on a per file basis, the High-threshold detectors in the LFDCS had the highest precision (0.81-1.00) and the lowest recall (0.17-0.28), as well as the lowest false positive rates and the highest missed call rates of the three levels (Table 4-3). The Low-threshold detectors had the lowest precision (0.21-0.84) and the highest recall (0.47-0.72), and generally the highest rates of false positives, but the lowest rates of missed calls (Table 4-3). The precision and recall of the Med-threshold detector has similar rates of false positives and missed calls being closer to equal (Table 4-3). This pattern persists when LFDCS performance is considered per day, where the High- threshold detector had the highest precision (0.78-0.91) and the Low- threshold had the highest recall (0.90-0.98, Table 4-4).

The MCC scores for the LFDCS detectors were usually higher than those of the JASCO AA detectors both per file (LFDCS: 0.29-0.55 vs AA: 0.01-0.43,Table 4-3) and per day (LFDCS: 0.34-0.59 vs AA: 0.07-0.44, Table 4-4), but the MCC scores for all detectors were < 0.60. This is not surprising given the large contrasts between precision and recall on the High- and Low- level detectors, both on a per file (Table 4-3) and per day basis (Table 4-4).

4.3.2 Efficiency of the tiered-detector approach

The previous single JASCO AA detector (Low-threshold) had a high rate of false positives, detecting sei whales on 0.6-11x more files than files with confirmed downsweeps (Table 4-3). Similarly, sei whale detections occurred on 2-3x more days than days with confirmed downsweeps, again indicating a high level of false positives (Table 4-4). Ultimately, this means that analysts would need to check many files with false positives to find all the confirmed sei whale downsweeps. The High- and Med- threshold detectors generally detected sei whales on 0.02-.80x fewer files (Table 4-3) and 0.06-1.4x fewer days (Table 4-4) than files and days with confirmed downsweeps, indicating a higher level of missed calls. However, given their higher precision, the detections that occurred were more likely to be correct detections than false positives. This means, that after validating both the High- and Med-threshold detectors, I would have found 51-58% files with confirmed sei whales by only checking 8-57% of files with detections, before validating the Low-threshold (i.e., single) detector. After validating both the High- and Med- threshold detectors, I would have found 44-150% of days with confirmed sei whales by only checking 36-85% of days, before validating the Low-threshold detector.

The efficiency results from the LFDCS shows a similar pattern. The single detector (Med-threshold) detected sei whales in 0.40-1.11x fewer files than files with confirmed downsweeps (Table 4-3), indicating a higher level of missed calls, though interestingly detected sei whales in 1.14-1.66x more days than days with confirmed downsweeps (Table 4-4), indicating a higher level of false positives. The High-threshold detector detected sei whales 0.18-0.25x fewer files and 0.49-0.56x fewer days, but with a very high precision. The Low-threshold detector generally detected sei whales by 0.56-3.33x more files and 1.7-3.2x more days, which included more false positives. By validating the results from the High-threshold first, I would have found 30-48% of files with confirmed sei whales by checking 24-44% of files with detections and 51-64% of days with confirmed sei whales by checking 33-43% of days with detections, before validating the Low-threshold detector to ensure no sei whales are missed.

4.4 Discussion

In this study, my first goal was to determine the relationship between the pre-set thresholds and error rates of multiple detectors to assess the performance of detectors. These detectors would then be used in a tiered-detector approach to assess the presence of sei whales. My second goal was to determine whether a tiered-detector approach made the detection, classification, and validation of sei whale downsweeps more efficient than use of a single detector.

4.4.1 Performance of detectors

The performance of each detector showed the relationship between threshold and error rate. The High-threshold detector had the highest precision regardless of its recall, having the fewest false positives, while the Low-threshold detector had the highest recall overall, regardless of its precision, having the fewest missed calls. The Med-threshold detector typically showed a balance between its precision and recall. On a per file basis, however, the JASCO AA DCS High-threshold detector did not have high precision, despite it being higher than the other detectors. The Low-threshold detector, however, had high recall (> 0.80) for two of the three datasets. Per day, the JASCO AA DCS High-threshold detector only had one instance of high precision, where the Low-threshold detector always had high recall. The LFDCS High-threshold detector had high precision consistently at both the per file and per day basis, but the recall of the Low-threshold detector was only high at the per day basis. This variability in performance needs to be considered when choosing an appropriate DCS for future PAM studies.

The LFDCS outperformed the JASCO AA DCS with consistently higher MCC scores than the AA detectors. At the per file level, LFDCS consistently had higher precision at every tier level, and half the time had higher recall. At the per day level, LFDCS again had higher precision rates with higher recall across all detector levels. This means that overall, LFDCS was able to detect sei whale downsweeps with less error (either false positives or missed calls) than the JASCO AA DCS. Although logistics prevented me from using LFDCS for my PAM study (see Chapter 5:), I recommend it as a better DCS for detecting sei whale calls in the region.

The detectors created in this study, along with those created for right whales (Kowarski et al. 2020) both illustrate how multiple detectors could be used to supply confirmed presence data with different rates of error at different speeds of analysis for a single species. Right whales are just one of three baleen whale species in Atlantic Canada currently listed under the Species at Risk Act (SARA), and sei whales are currently under consideration for listing. As monitoring and management of these species in near-real time becomes necessary, as seen with right whales (Baumgartner et al. 2013), the development of similar multiple detectors, in the same way as described in this study, will also become necessary.

Regardless of DCS and the thresholds, the precision of all detectors were repeatedly compromised by non-sei whale sounds (pers. obs.). Certain blue whale arch calls and downsweeps (see Chapter 1:, Table 2-2), and humpback whale downsweeps were detected and classified as sei whales by the high- and medium- threshold detectors and would consistently be detected and classified as sei whales by the Low-threshold detector. Seismic airgun pulses were incorrectly detected and classified at all levels of detectors almost constantly. The influence of background noise on the performance of detectors is an inherent issue with PAM studies, and thus also for the tiered approach. The issue of confounding sounds could potentially be alleviated by using detectors for other species or types of sounds (such as a seismic pulse detector) in collaboration with the sei whale detectors (see below).

In addition to using the tiered-detector approach, sei whale detectors in the future could be used in collaboration with detectors for other species to aide in the accuracy of both sei whale detections and those of other species. If a whale detector with a higher level of precision has detections on the same file as sei whales, it is more likely to be that other species. If the sei whale detector has higher precision, then it is more likely to be a sei whale. Using a compilation of detections for either species can give the opportunity to relieve analysts of validating false negatives, speeding up the validation process.

A new type of DCS, a Neural Network, using machine learning for detecting whale calls from PAM data is under development (Wang et al. 2018). This DCS uses artificial intelligence and an original sample of images of spectrograms of the target calls, to teach itself continuously to better detect target calls. The Neural Network detector is another DCS being developed for sei whale downsweep detection in the Northwest Atlantic (Thomas et al. 2019). The results from initial testing have a higher precision and recall than the AA DCS by approximately 10%. These results put the Neural Network detector approximately on par with LFDCS, but given it is still in development, it could potentially supersede the other two detectors with further advancement. (M. Thomas, pers. comm.).

4.4.2 Efficiency of tiered-detector approach

I found that the tiered-detector approach was more efficient than a single detector in both DCSs, with fewer files needing to be checked in the tiered system compared to the single detector to end up with the same results. For studies looking at detailed whale presence, using the tiered-detector approach as a replacement for single detector analysis of PAM data can therefore drastically speed up analysis time. As exampled by these datasets, exclusively using the Low-threshold detector, with its high rate of false positives, cause analysts to validate a large number of files. Instead, by first validating High-threshold detections, which is a smaller amount of files, and then the Med-threshold detector, which would incorporate some more files, the time an analyst spends on a dataset can potentially be done in half the time using half the files as with the Low-threshold detector alone.

The same performance limitations of all detectors outlined are still limitations for the tiered-detector approach. Blue whale, humpback whale and seismic airgun noise decreased the efficiency of the tiered-detector approach, though it was consistently still more efficient than a single detector. In noisy seismic areas, or during times with humpback singing, there were more false positives from all detectors than in non-noisy areas or times, increasing validation time, and likely requiring most of the Low-threshold detections to also be checked. Again, false positives caused by other species or types of sounds could be alleviated by incorporating detectors for these other species or sounds into the analysis (see above).

Many published baleen whale PAM studies analysed over 1000 hours of recordings using a combination of automated detector and manual validation (Kowarski and Moors-Murphy 2020). The manual validation of these data from a single detector could take a very long time (on the scale of months, pers. obs.); this new tiered-detector approach helps alleviate the time restriction on being able to process all this data, allowing for results to be incorporated into the conservation and management needs of a species in more quickly.

I recommend using the tiered-detector approach for other baleen whale species and their additional call types, such as blue whale arch calls or fin whale downsweeps. Not only would this be beneficial for the ongoing study of these species, but they could also work in tandem with the sei whale detectors to minimize false positives across all species.

When creating detectors for new tiered-detector approaches for other sei whale populations or other whale species, it is important to remember that while hypothetically there could be a near infinite number of detectors by constantly updating the parameters, I advise that the parameters chosen be informed by local call characteristics of the target species, rather than indiscriminately.

4.5 Tables

Table 4-1 Summary of files and days with detections checked to confirm presence of sei whale downsweeps, a general description of noise conditions of the recordings, and potential confounding calls of other marine mammals heard on each datasets.

Dataset	Files Checked (#)	Files with Downsweep (#)	Days Checked (#)	Days with Downsweeps (#)	Noise Description	Presence of Confounding Marine Mammals
EMB 2016	8638	656	436	123	Peaks of high shipping noise	Blue whale, humpback whale
MGL 2015	2475	126	336	84	Generally quiet	Occasional blue whale, humpback whale
STN 15 2015	466	261	167	71	Peaks of seismic surveying	Occasional blue whale

Table 4-2. Summary of parameters applied to the JASCO Acoustic Analysis (JASCO Applied Sciences, Ltd.) sei whale detector. High = detector with high precision, Med = detector with medium precision, Low = detector with low precision (the sei whale detector most commonly used in previous studies).

	Time-Frequency Parameters									FFT Settings			Thres-hold
Detector	**Min Freq (Hz)**	**Max Freq (Hz)**	**Min Duration (s)**	**Max Duration (s)**	**Min Bandwidth (Hz)**	**Max Bandwidth (Hz)**	**Min Sweep rate (Hz/s)**	**Max Sweep rate (Hz/s)**	**Max Peak Freq (Hz)**	**Time Resolu-tion (s)**	**Time Frame (s)**	**Freq. Resolu-tion (Hz)**	
High	20	80	1.0	1.7	30	80	-80	-12	50	0.035	0.2	3.25	5
Med	20	100	1.0	1.7	30	80	-80	-12					2.5
Low	20	150	0.5	1.7	19	120	-100	-6					3.5

Table 4-3. Summary of tiered JASCO Acoustic Analysis (JASCO Applied Science, Ltd.) and LFDCS (Baumgartner and Mussoline 2011) detector performance and efficiency on a per file basis. High = detector with high precision, Med = detector with medium precision, Low = detector with low precision (the current sei whale detector).

Per File									
JASCO									
	EMB			**MGL**			**STN 15**		
	High	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**
Precision	0.52	0.46	0.11	0.79	0.54	0.08	0.60	0.80	0.79
Recall	0.42	0.31	0.86	0.17	0.30	0.93	0.01	0.25	0.46
MCC	0.43	0.34	0.16	0.36	0.38	0.17	0.01	0.22	0.32
% Files w/ Detection	1.67	1.39	15.97	0.12	0.29	5.81	0.02	0.33	0.62
% Files w/ Detections Checked (from truth data)		27.60			10.22			1.92	
% Files w/ Confirmed Downsweeps (from truth data)		2.10			0.52			1.07	
LFDCS									
Precision	0.97	0.70	0.21	0.81	0.54	0.27	1.00	0.90	0.84
Recall	0.18	0.48	0.68	0.28	0.60	0.72	0.17	0.35	0.47
MCC	0.40	0.55	0.29	0.45	0.53	0.37	0.29	0.36	0.39
% Files w/ Detection	0.39	1.46	6.86	0.28	0.90	2.16	0.19	0.42	0.61
% Files w/ Detections Checked (from truth data)		27.60			10.31			1.92	
% Files w/ Confirmed Downsweeps (from truth data)		2.10			0.81			1.08	

Table 4-4. Summary of tiered JASCO Acoustic Analysis (JASCO Applied Science, Ltd.) and LFDCS (Baumgartner and Mussoline 2011) detector performance and efficiency on a per day basis. High = detector with high precision, Med = detector with medium precision, Low = detector with low precision (the current sei whale detector).

Per Day									
JASCO									
	EMB			**MGL**			**STN 15**		
	High	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**
Precision	0.40	0.55	0.29	1.00	0.60	0.29	0.75	0.71	0.50
Recall	0.55	0.68	0.98	0.23	0.39	1.00	0.04	0.35	0.90
MCC	0.20	0.44	0.07	0.42	0.36	0.24	0.10	0.30	0.26
% Files w/ Detection	39.45	34.86	94.95	5.65	16.37	85.12	1.18	10.29	37.94
% Files w/ Detections Checked (from truth data)		100.00			100.00			49.12	
% Files w/ Confirmed Downsweeps (from truth data)		28.21			25.00			20.88	
LFDCS									
Precision	0.91	0.47	0.30	0.78	0.58	0.35	0.91	0.64	0.53
Recall	0.50	0.77	0.98	0.44	0.85	0.97	0.45	0.73	0.90
MCC	0.59	0.38	0.15	0.49	0.57	0.32	0.51	0.43	0.34
% Files w/ Detection	15.37	46.79	90.60	14.88	38.99	72.92	10.29	23.82	35.59
% Files w/ Detections Checked (from truth data)		100.00			99.11			49.12	
% Files w/ Confirmed Downsweeps (from truth data)		28.21			26.49			20.88	

4.6 Figures

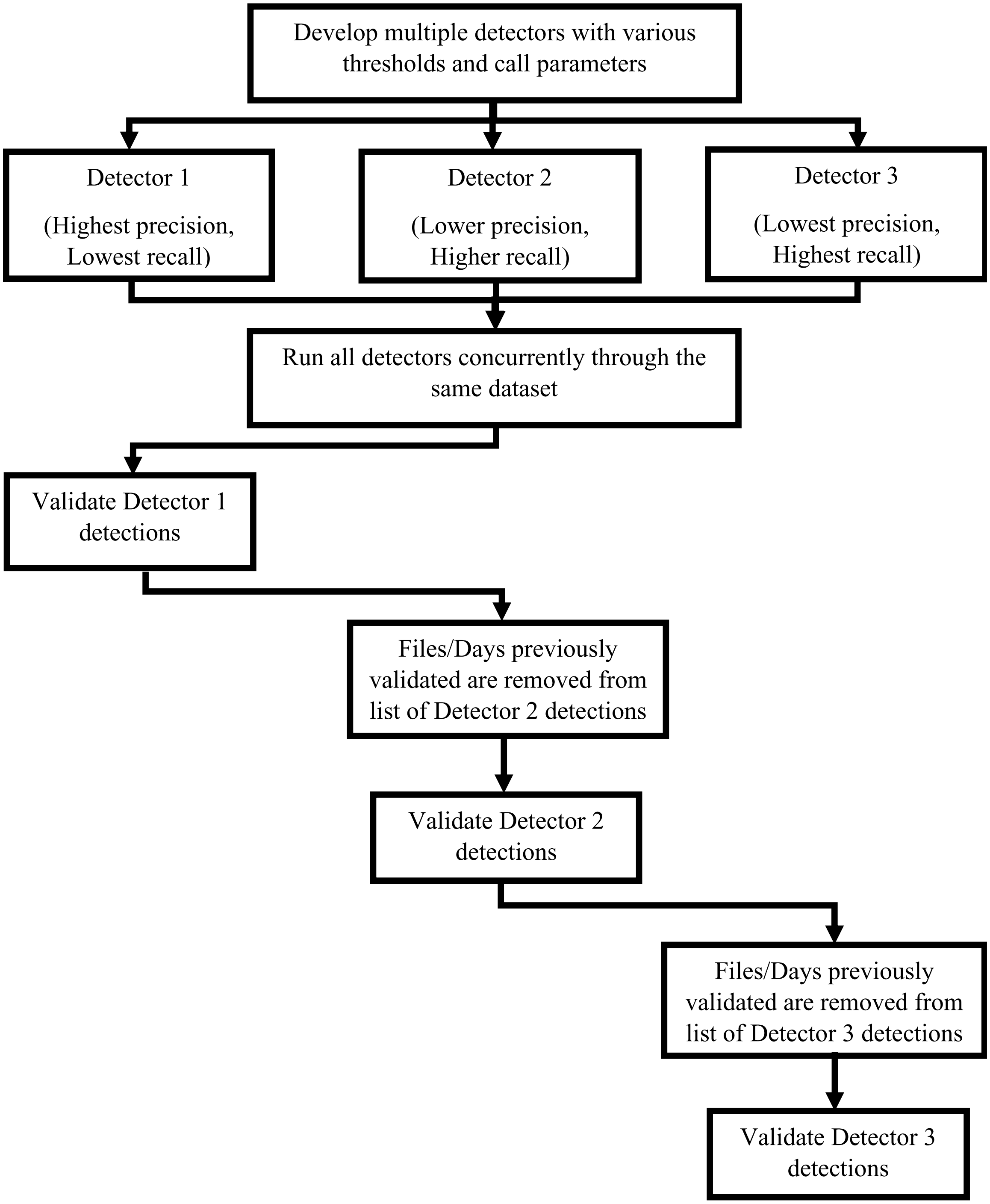


Figure 4-1. Flow chart showing the steps to validating detections, for analysis such as daily presence, from multiple detectors using the multi-detector approach

Chapter 5: Spatiotemporal Presence of Sei Whales in Atlantic Canada

5.1 Introduction

As human dependency on the ocean increases, so does our impact on whales (Halpern et al. 2008). Growth in global shipping increases the threat of ship strikes (Laist et al. 2001), while rising food demands increases fishing pressure, with fishers sometimes directly competing with whales for food (Loch et al. 2009; Plagányi and Butterworth 2009). This latter threat also increases the risk of entanglement in fishing gear (Cassoff et al. 2011) and bycatch (Read et al. 2006). Pollution, in the form of chemicals and debris, also negatively affects population health (Van Bressem et al. 2009). Underwater noise emitted by human activities is of particular concern for whales. For example, noise levels in the Pacific Ocean rose 10-12 dB between 1965 and 2004 (McDonald et al. 2006b), leading to a variety of behavioural changes in various cetacean species (Nowacek et al. 2007). These behavioural changes include the cessation of foraging or socializing, cessation or modification of vocalizing, or switching to alert and avoidance behaviour at the expense of other behaviours such as feeding or mating (Nowacek et al. 2007). Collectively, these threats are especially compounded for baleen whales, which faced an unprecedented decline due to large-scale global whaling between 1860 and 1986 (Rocha et al. 2014), and whose populations are still reduced from their pre-whaling levels (Thomas et al. 2016).

5.1.1 Threats to whales in Atlantic Canada

Many of these global threats are common causes of mortality for baleen whales in Atlantic Canada. Baleen whales are subject to lethal vessel strikes, which are a common occurrence in

Atlantic Canada (Jensen and Silber 2003) as a major shipping waterway (Forward 1982). They are often victims of entanglement due to the increased fisheries pressure (Benjamins et al. 2012; Knowlton et al. 2012), as the widespread fishing industry makes up to 30% of the Atlantic provinces GDP (Pinfold 2009). Baleen whales in the area are also affected by increases in noise pollution, from increased seismic surveying off Newfoundland/Labrador (Government of Newfoundland and Labrador 2021), and increased shipping traffic off Nova Scotia (Delarue et al. 2018).

Having an in-depth knowledge of the occurrence, movement, and distribution of whales is critical for mitigating these widespread threats. Indeed, there is evidence that this knowledge aided in the recovery of some species and/or populations, such the Australian humpback whales (*Megaptera novaeangliae*, Bejder et al. 2016) and Pacific coast grey whales (*Eschrichtius robustus*, Gavrilchuk and Doniol-valcroze 2021). In Atlantic Canada, aerial surveys identified areas and times of North Atlantic right whale (*Eubalaena glacialis*) presence, which then informed the closure of the relevant fisheries. This, in turn, reduced mortality from 12 in 2017 (Daoust et al. 2017) to zero in 2018. Given these benefits, there has been increased effort to monitor and survey baleen whales in Atlantic Canada using large aerial surveys (e.g., Lawson and Gosselin 2009) and expansive passive acoustic monitoring (PAM, e.g., Delarue et al. 2018, *In Press*). These efforts are filling data gaps in the occurrence and distribution of baleen whales, including sei whales.

5.1.2 Sei whales in Atlantic Canada

Sei whales in Atlantic Canada are likely exposed to the same threats as other baleen whale species in the area, though to what extent those threats are detrimental to their population is unknown (COSEWIC 2019a). In 2018, the Atlantic population of sei whales was assessed as Endangered (COSEWIC 2019a), and is now being considered for listing under the Species at Risk Act (SARA). Its potential listing, and any future management or conservation to follow will require broad-scale, long-term knowledge of the species' spatiotemporal presence in Atlantic Canada, which currently doesn't exist.

5.1.3 Sei whale presence via visual surveys

Sei whales have been of interest in multi-species aerial surveys in the past, however, the results of these surveys have offered limited information on their spatiotemporal presence. The 2007 Trans North Atlantic Sightings Survey (TNASS) saw one sei whale off the south coast of Newfoundland, and two sei whales between the Nova Scotia coast and the Scotian shelf (Lawson and Gosselin 2009). The 2016 North Atlantic International Sightings Survey (NAISS) documented only four sei whales, and only in the Newfoundland/Labrador strata (south coast of Newfoundland, up to the Northmost tip of Labrador; COSEWIC 2019a). Right whale focused aerial surveys of all Atlantic Canada from 2018-2021 had three sei whale sightings (one sighting of 1 individual, one sighting of 2 individuals, and one sighting of 3 individuals) exclusively in the Gulf of St. Lawrence (Johnson et al. 2021).

During these surveys, sei whales were seen on average 4.5x less often than blue whales which have a population size of < 200 mature individuals in the Northwest Atlantic and are designated as Endangered (Sears and Calambokidis 2002) by SARA, and 36.5x less than fin whales which are designated as Special Concern (COSEWIC 2019b). This suggested that though sei whales should have a similar likelihood of detection (due to their similar size) as these other species but were seen less frequently, there are likely many fewer sei whales in the region than these closely related species (COSEWIC 2019a).

5.1.4 Sei whale presence via PAM studies

PAM, with its ability to survey remotely for long periods of time over a broader range, has collected more information on sei whale presence off Atlantic Canada than the three visual surveys described above (COSEWIC 2019a). A two-year PAM study concentrated in the offshore area in and around the Gully, a Marine Protected Area east of Sable Island on the Scotian shelf, recorded sei whales throughout the summer months (~May-Aug), with a peak in July, and no sei whale presence during the winter (~November-February; Emery and Moors-Murphy 2017). Similarly, an analysis of five months of data from Emerald (east of Halifax on the continental shelf) and Roseway (off the southwest tip of Nova Scotia, on the continental shelf) Basins recorded sei whales throughout the summer, with a peak in October (Sweeney 2017). These two studies, however, were limited spatially (up to three locations, all localized to waters off Nova Scotia) and sometimes temporally (analysing only five months of recordings).

One long-term PAM study (Davis et al. 2020) using data from all three of the locations mentioned above over a span of almost 10 years found similar results, with sei whales occurring in two peaks, one in June and one in October, with almost no presence during the winter months (December-February). This study, while able to look at long-term temporal presence, was limited to only three locations off Nova Scotia, and did not include any data from the rest of Atlantic Canada. A second study (Delarue et al. 2018) conducted over two years and at over 20 locations spanning waters off both Nova Scotia and Newfoundland/Labrador found sei whales concentrated off Eastern Newfoundland and Labrador only, but present in from March to

November with a single peak in October (Delarue et al. 2018). The relatively poor performance of the detector used in this study, however, meant the estimate of sei whale presence in the region was conservative and incomplete (Delarue et al. 2018).

Although these PAM studies have offered more insight into sei whale presence than visual surveys, they were limited by time, area sampled, analysis effort, or a combination of all three, giving only a partial view of sei whale presence both spatially and temporally in Atlantic Canada. A single study, that is both broad-scale and long-term is needed to discern a better understanding of sei whale presence in order to effectively manage and conserve them in Atlantic Canada.

The goal of my study was to use PAM to fill in the data gaps of previous aerial surveys and PAM studies on the spatiotemporal presence of sei whales in Atlantic Canada. Here, I included multiple recording stations spanning most of the offshore Atlantic Canada region, with near-continuous coverage over a two-year period.

5.2 Methods

5.2.1 Data collection

I selected 10 recording stations that were monitored between 2015-2017 from those deployed by DFO and JASCO (see Chapter 1:). These stations were selected to maximize coverage from north to south and included stations both on- and off-shelf. Eight of the stations were deployed along the continental shelf, between 200-500 km off the coast, and two were inshore, less than 100 km off the coast ; deployment depths ranged from 120-2000 m deep (Figure 1-1). Chapter 1 describes the details of the deployments and the recorder set ups (see Table 1-1).

5.2.2 Sei whale detections

I used the JASCO Acoustic Analysis (AA) Detector-Classifier System (DCS), with a single sei whale downsweep detector (the Low detector, Table 4-2) to determine daily sei whale presence at three of the stations (EMB, MGL and STF, see Chapter 2:). At the remaining seven stations (STNs 2, 6, 12, 13, 15, 17, and 19), I used the tiered-detector approach to determine daily sei whale presence (see Chapter 4:, Table 4-2). The High-threshold detector with the most restricted parameters targeted high quality sei whale downsweeps, resulting in a majority of true positives but with a higher rate of missed calls. The Med-threshold detector targeted mid- and high- quality downsweeps, missing fewer downsweeps but was susceptible to more false positives. The Low-threshold detector ensured very few downsweeps were missed but at the expense of a high rate of false positives (See Chapter 4:).

5.2.3 Detection validation

To validate sei whale detections for each day, I viewed spectrograms (Frequency Step 2Hz, Frame Length 0.25s, Time Step 0.05s, Hamming Window) of each recording file that included detected downsweeps using PAMlab (JASCO Applied Sciences, Ltd.). For stations EMB, MGL and STF, I validated files with sei whale detections in each 24-hour period beginning at 0:00 and continuing through the files until a sei whale downsweep was found. Once I found a sei whale downsweep, I recorded its presence, and then moved on to the next 24-hour period with a detection (see Chapter 2:). For stations STN 2, 6, 12, 13, 15, 17 and 19, I followed the same validation process as above (see Chapter 2:), beginning first with the High-threshold detector. Days with confirmed sei whales were removed from the validation of the Med-threshold detector. I then validated the remaining days for sei whale downsweeps in the same manner.

New days with confirmed sei whales were then excluded from the validation of the Low-threshold detector and I then validated the remaining days for sei whale downsweeps. This tiered approach resulted in a record of daily presence of sei whales at each station.

Although I only statistically analysed the results of definite presence, I visually presented the results of both definite and possible presence. “Definite” presence was where I was confident the downsweeps were sei whales as they were 1.4-1.6 s long, had a frequency range of 80-30 Hz, and were part of a multi-downsweep call such as a DB or TP+ (see Chapter 2:). “Possible” presence was where downsweeps had durations between 1.0-1.2 s and therefore, possibly a fin whale downsweep (0.7±0.2 s, Table 2-2) or between 1.8-2 s, and therefore possibly a blue whale downsweep (2.0±0.6 s, Table 2-2). I included them to see if they supported or contrasted the resulting patterns of definite presence.

5.2.4 Spatiotemporal presence

To examine the spatiotemporal patterns of sei whale presence in Atlantic Canada, I determined the proportion of days per month with definite and possible sei whale downsweeps for each station, month, and season. Seasons were delineated by atmospheric seasons: Spring (March-May), Summer (June-August), Fall (September-November) and Winter (December-February). I performed a one-way ANOVA by station on definite presence to determine if there was variation in sei whale spatial presence across stations. If the results of this test were significant, I then conducted a post-hoc Tukey test to determine specifically where differences in presence across stations occurred. I indicated results that were both significant ($\alpha = 0.05$) and trending significant ($\alpha = 0.10$).

To determine if monthly or seasonal presence varied by station, I performed two-way ANOVAs by month and by season. If the results were significant, I then conducted a post-hoc Tukey test to determine specifically when differences in presence across months or seasons occurred and indicated significant ($\alpha = 0.05$) and trending significant ($\alpha = 0.10$) results.

5.3 Results

In total, I validated 4,639 of 6,919 recording days across the two years of data collection at the ten recording stations for the presence of sei whales (Table 5-1). Definite sei whales were recorded on a total of 1,284 recording days (27.68%), and possible sei whales were recorded on an additional 794 recording days (17.12%, Table 5-1).

5.3.1 Spatiotemporal presence

The proportion of days per month with sei whale presence (Figure 5-1) varied significantly across stations ($F_9 = 7.256$, $p < 0.001$; Figure 5-2), with sei whales present at STN 13 on over 50% of days, followed by STNs 15 and 19, with sei whales present on approximately 40% of days. In contrast, sei whales were present at STNs 12 and 2 on less than 10% of days.

Sei whale presence in Atlantic Canada varied significantly with both month (F_{11}, $p < 0.001$; Figure 5-3) and season ($F_3 < 0.001$; Figure 5-4). Sei whales were present on 50% of days in October, and on 37% of days in June (Figure 5-3). They were present on <10% of days in each month between January – April (Figure 5-3).

Sei whales were present year-round throughout Atlantic Canada, but on 10-20% more days per month in Summer and Fall on average, than in Winter and Spring. Few sei whales were generally recorded in the northern stations in the winter and early spring months (Figure 5-5). At some of these locations, there were winter and early spring months with no detections (Figure 5-5). This trend was not altered when possible presence was included (Figure 5-1).

Across stations, whale presence varied significantly with season and month (season: F_{23} = 2.043, p = 0.008; month: F_{60} = 1.568, p = 0.04). Tukey post-hoc tests showed significant (and trending significant) pairwise differences between stations (Figure 5-2), seasons (Figure 5-4) and months (Figure 5-3).

5.4 Discussion

5.4.1 Spatiotemporal presence of sei whales in Atlantic Canada

I found that sei whales were present in Atlantic Canada year-round, with peak presence in October throughout the entire region and a second peak in June off Nova Scotia (NS, see Chapter 3: for delineation of location). Sei whales were not present at the northmost stations in the winter. It is important to note that these results are conservative, as animals could be present but not calling, or present and calling but outside the detection range of the recorder. Additionally, calls could be masked by background noise or missed by the automated detectors for a variety of reasons.

I found that STN 12, the northernmost station, had the lowest presence suggesting this location might be reaching the northern limit to their range, while the next three northerly stations off Newfoundland/Labrador (NFLD, see Chapter 3: for delineation of location; STNs 13, 15, and 19) had the highest percentage of days per month with sei whale presence, with an average of 40%. This suggests that this area may be preferred over more southerly regions. There are a couple of explanations for why sei whales may prefer this area, such as a higher quantity or quality of food, at least outside the winter months (see below). Sei whales may also experience fewer threats in the northern part of the region. Whales off NS are more likely to be impacted by shipping or by the noise associated with shipping (Simard et al. 2014). The presence of ships could reduce the preference of the area for whales and/or reduce calling, and thus detection, off NS (see below). While the threat of vessel strikes might be a factor in sei whale habitat preference, noise from shipping is likely not the main deterrent, as seismic activity and the associated loud, low frequency noise are more prevalent off NFLD (Government of Newfoundland and Labrador 2021). , However, sei whale calls were heard most commonly in this area, so seismic noise generated by these activities did not appear to deter sei whales from the general area. In addition, the detection ranges of these stations weren't particularly smaller than those off NS (see below), so it appears that seismic noise did not impede my ability to detect their calls.

I found sei whale presence to be highest at stations at or off the continental shelf edge, compared to most of the on-shelf stations, especially those less than 100 km from the coast (STNs 2 and 12). This aligns with the most common understanding that sei whales, as an offshore species, are rarely seen in coastal waters (Horwood 2009). However, two recent studies in Atlantic Canada provide information that seems to contradict my findings. The first are preliminary Species Distribution Models encompassing Atlantic Canadian waters from the Bay of Fundy to northern Labrador. These models used whale sightings from multiple sources for the period of 1975-2015 and sea surface temperature, ocean depth, bathymetry and various measurements of chlorophyll concentration as proxies for prey availability to model suitable habitat for sei whales. The models indicated suitable summer habitat on the Scotian Shelf along NS, off the Flemish Cap and on-shelf off the eastern coast of Labrador (Gomez et al. 2020) based on various measures of chlorophyll levels. However, the data used in these models are biased towards on-shelf efforts and opportunistic sightings and included fewer off-shelf sightings due to less search effort in that area. Second, aerial surveys of Atlantic Canada in recent years have seen sei whales exclusively in the Gulf of St. Lawrence, where they have also been detected by PAM studies (Johnson et al. 2021), but these efforts are also heavily biased to surveying the Gulf and/or on-shelf waters. If conservation or management strategies were made based solely on these visual data, sei whales could be misconstrued as being present predominantly on-shelf, whereas my PAM results show the opposite, where they are most commonly heard off-shelf compared to on-shelf sites. These results should be factored in when considering sei whale presence and habitat preference.

Sei whales were recorded at every station in at least one month of the year and were heard year-round in Atlantic Canada. Sei whales in Atlantic Canada were expected to follow the baleen migratory pattern of feeding at high latitudes in the summer and then migrating to breeding grounds at lower latitudes in the winter (Bannister 2009). While there is evidence that sei whales do make this migration (Prieto et al. 2014), the results of this PAM study, along with other baleen whale PAM studies (Davis et al. 2020, Delarue et al. *In Press*;) suggest that at least some individuals occur in Canadian waters throughout the year. Previous studies on humpback whales suggested that individuals overwintering in northern waters were likely immature adults who choose not to expend the energy to migrate when they are not going to breed (Clapham et al. 1993), or individuals may leave and return at different times, resulting in consistent presence detected, but of different individuals throughout the year (Straley 1990). Sei whales present in Atlantic Canada over winter, similar to humpback whales, could be immature individuals, or could be staggering their departure from their foraging grounds, presenting as year-round presence.

At all stations, sei whale presence peaked in October, with a secondary peak in June/July at the southern stations. Whale presence may increase in October because prey are abundant at this time of year. If this is an indicator of more sei whales, rather than them calling more, an increase in call presence in October is likely related to increased food levels (Bannister 2009). Sei whales in Atlantic Canada eat exclusively copepods and euphausiids, based on the stomach contents from landed sei whales off the Scotian Shelf (Mitchell et al. 1986). According to long-term plankton surveys off Atlantic Canada, copepods peak around June off NS, and mostly in October off NFLD (Head and Pepin 2009). Euphausiids had less obvious trends, but generally increased throughout the summer into the fall, before declining in the winter (Head and Pepin 2009). Together this suggests that sei whale presence over the seasons may be linked, at least partially, to prey abundance.

At southern stations such as EMB and MGL, sei whales were recorded on at least one day per month throughout the year, while sei whales were absent from the northmost stations, STNs 12, 13, and 15, in the mid-winter months of January and February. This is likely due to a seasonal change in suitability of the waters off NFLD. Sea ice off the coast of NFLD starts to form late November and peaks in early February (Canadian Ice Service Archives). Sei whales, similar to other baleen whales (Delarue et al. *In Press*) are likely driven away from NFLD due to the encroaching sea ice, moving either southward to waters off NS, or starting their migration away from Atlantic Canada before individuals off NS.

5.4.2 Influence of noise

Results of this study, as with all PAM studies, are affected by the ambient noise around the recorders. Specifically, anthropogenic noise can influence the ability of the recorder and automated detectors to detect calls and can also disturb whales causing them to change their calling behaviour or stop calling, and both can affect the results of sound-based studies. In Atlantic Canada, low frequency shipping and seismic surveys are the dominant sources of anthropogenic noise in the marine environment (Delarue et al. 2018).

Increases in anthropogenic and natural noise, along with variable bathymetry can decrease the detection range of recorders for sei whale calls, resulting in some recorders having smaller detection ranges than others. This could lead to recorders missing calls in those areas (or monitoring smaller areas) and underestimating whale presence. Discrepancies in the detection ranges of different recording stations, similar to discrepancies in effort of different visual surveys, can skew acoustic data in favour of recording stations with large detection ranges. However, this appears not to be a factor in my study. There was no overlap in conservatively calculated detection ranges for each station (the range at which calls made at 50% volume will be detected 50% of the time), and though the ranges were variable at each station, there did not appear to be any consistent correlation between detection range and sei whale presence (Appendix C). Both STNs 13 and 12 had the largest detection ranges but had the highest and lowest presence, respectively. Given the variability in range size across the region, and that one of the stations with the largest detection range had some of the fewest detections (STN 12), I don’t believe that the detection range of the recording stations is a primary factor in the presence trends found.

Noise from anthropogenic and natural sources would also affect the quality of sei whale vocalizations detected by detectors. High levels of noise can lead to call masking, where noise lowers the signal-to-noise ratio of a vocalization, rendering it undetectable to conspecifics and automated detectors (Erbe et al. 2016, see Chapter 4:). If this is causing sei whales to go undetected, low presence at stations could be due to noise, rather than true absence. Some of this concern can be alleviated by using an inclusive sei whale detection that is likely to pick up very faint (or nearly masked) calls, and the most inclusive detector in my study generally had a low rate of missed calls per file (10-15%, see Chapter 4:), and therefore likely captured a majority of calls.

Finally, whales may alter their behaviour in the presence of noise in ways that could have affected my ability to determine their presence. For instance they could lessen or cease vocalizing (Fournet et al. 2018) or move away from the sound source and out of the detection area (Castellote et al. 2012). All of these responses would lead to sei whales being underrepresented in Atlantic Canada. Although there were instances where increased noise was associated with lowered sei whale presence, it was not consistent across stations or year (Appendix B).

5.4.3 Consideration of two populations

Currently sei whales in Atlantic Canada are being managed as a single population (COSEWIC 2019a). However, data from whaling (Mitchell and Chapman 1974), more recent satellite tagging (Prieto et al. 2014), and preliminary acoustic studies (see Chapter 3:) suggest the possibility that sei whales in Atlantic Canada are actually two local populations – one off NFLD and one off NS (see Chapter 3). The spatiotemporal patterns I found could also have resulted from differences in migration timing, seasonal behaviours or foraging needs of these two populations. The NFLD population could be displaying a strict migration schedule, feeding from May through November, and then migrating away from Atlantic Canadian waters for the winter and most of spring. In comparison, in the NS population could follow a more lenient migration schedule, maintaining a year-round presence while increasing in either individuals or call rates in the summer and fall.

The differences in peak presence could also be a result of two local populations. The single peak in October at NFLD stations compared to the double peak at NS stations could indicate either a difference in the foraging preferences/ needs of each individual population (if the peaks are connected to food sources, see above), or could be related to a difference in behaviours leading to peaks in call presence. Future research on whether there are two local populations, and their behaviours will give more insight into these trends in presence are connected.

5.4.4 Conclusions for surveying methods

The 2016 NIASS aerial survey took place during this PAM study (1 Aug – 26 Sept, 2016; (COSEWIC 2019a). During this timeframe, only four sei whales were sighted (COSEWIC 2019a); however, sei whales were recorded at all seven recording stations during this same timeframe. Given their distribution and seasonal presence, large-scale multispecies surveys might not be the most effective means of assessing the sei whale population in Atlantic Canada. Similar results from a line transect off the Mariana Islands for minke whales showed a minimum of 80 individuals detected via PAM, while none were sighted (Norris et al. 2017). Focusing visual surveys on localized areas or times of high sei whale presence, informed by the results of broadscale PAM efforts, could be a better allocation of resources for filling in necessary population and behaviour data, by combining results from the two (Soldevilla et al. 2014; Thompson et al. 2015).

5.4.5 Conclusions for conservation

If sei whales were listed under Schedule 1 of SARA, then a Recovery Strategy must be prepared, and would be more effective if informed by a more accurate description of species distribution and seasonality. Any decisions to mitigate threats, for example, rerouting shipping lanes or limiting the timing of seismic surveys (similar to recommendations made in Beauchamp et al. (2009)) must be made with an understanding of when and where sei whales occur.

5.5 Tables

Table 5-1. Total days validated and results of validation indicating the number of definite and possible sei whale downsweeps for each recording station, based on detections by the Acoustic Analysis (AA) detector and tiered detector system (JASCO Applied Sciences, Ltd.; Delarue et al., 2018).

	# Of Days With		
Station	**Detections**	**Definite Sei Whale Downsweeps**	**Possible Sei Whale Downsweeps**
EMB	713	271	201
MGL	635	202	119
STF	231	50	40
STN 2	631	32	135
STN 6	305	89	153
STN 12	646	5	32
STN 13	346	245	15
STN 15	402	184	20
STN 17	315	88	51
STN 19	415	118	28
TOTAL	4639	1284	794

5.6 Figures

Figure 5-1. Proportion of days per month of sei whale definite and possible presence heard at each recording station. Northmost station at the top, southmost at the bottom. See Figure 1-1 for station locations.

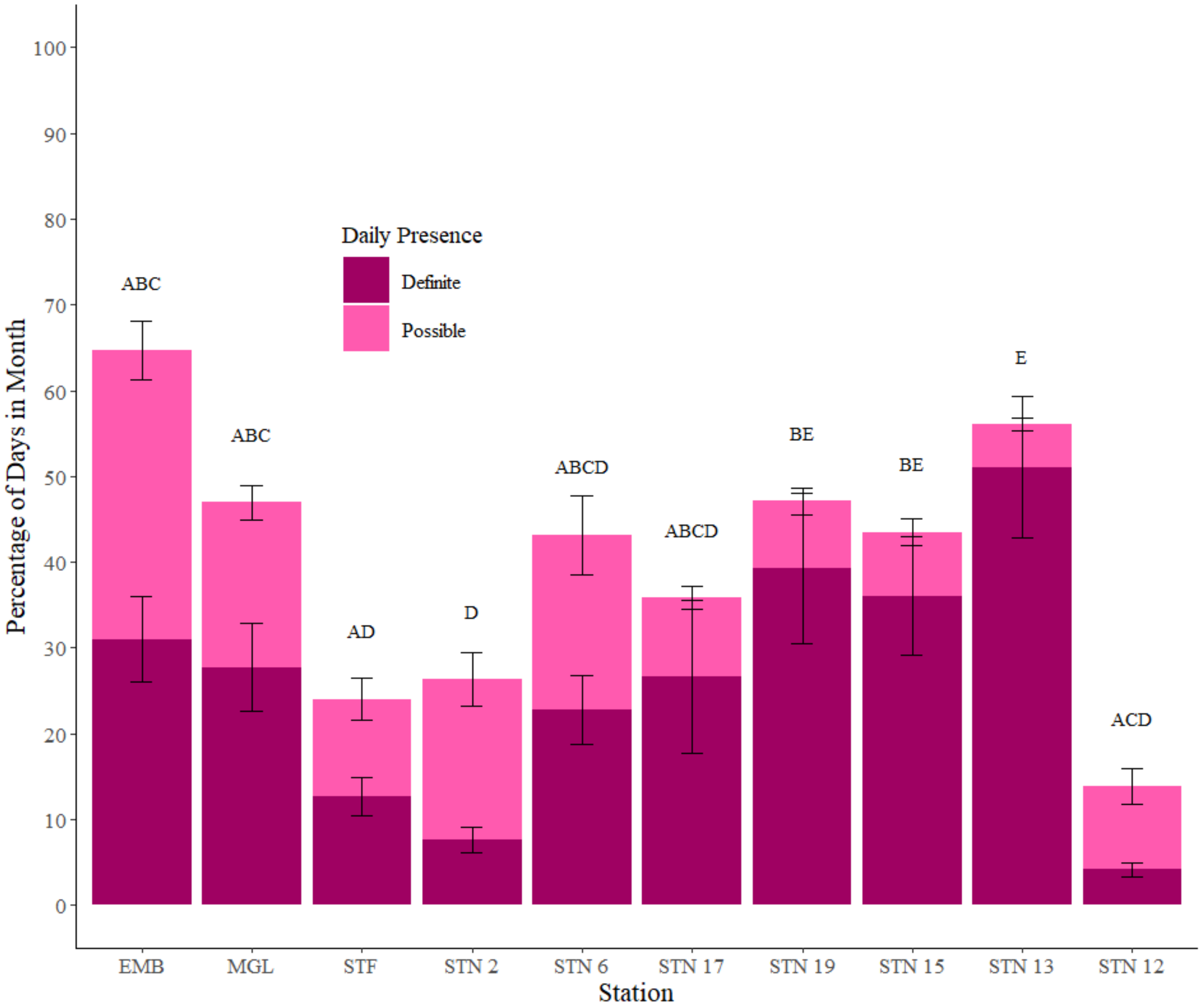


Figure 5-2. Mean (±SD) percentage of days per month with definite and possible sei whale presence by station. Letters indicate results of two-way ANOVA (Tukey-HSD test) of definite sei whale presence. Same letters indicate no difference, different letters indicate statistically significant (p< 0.05) or trending significant (p<0.10) differences. See Figure 1-1 for station locations.

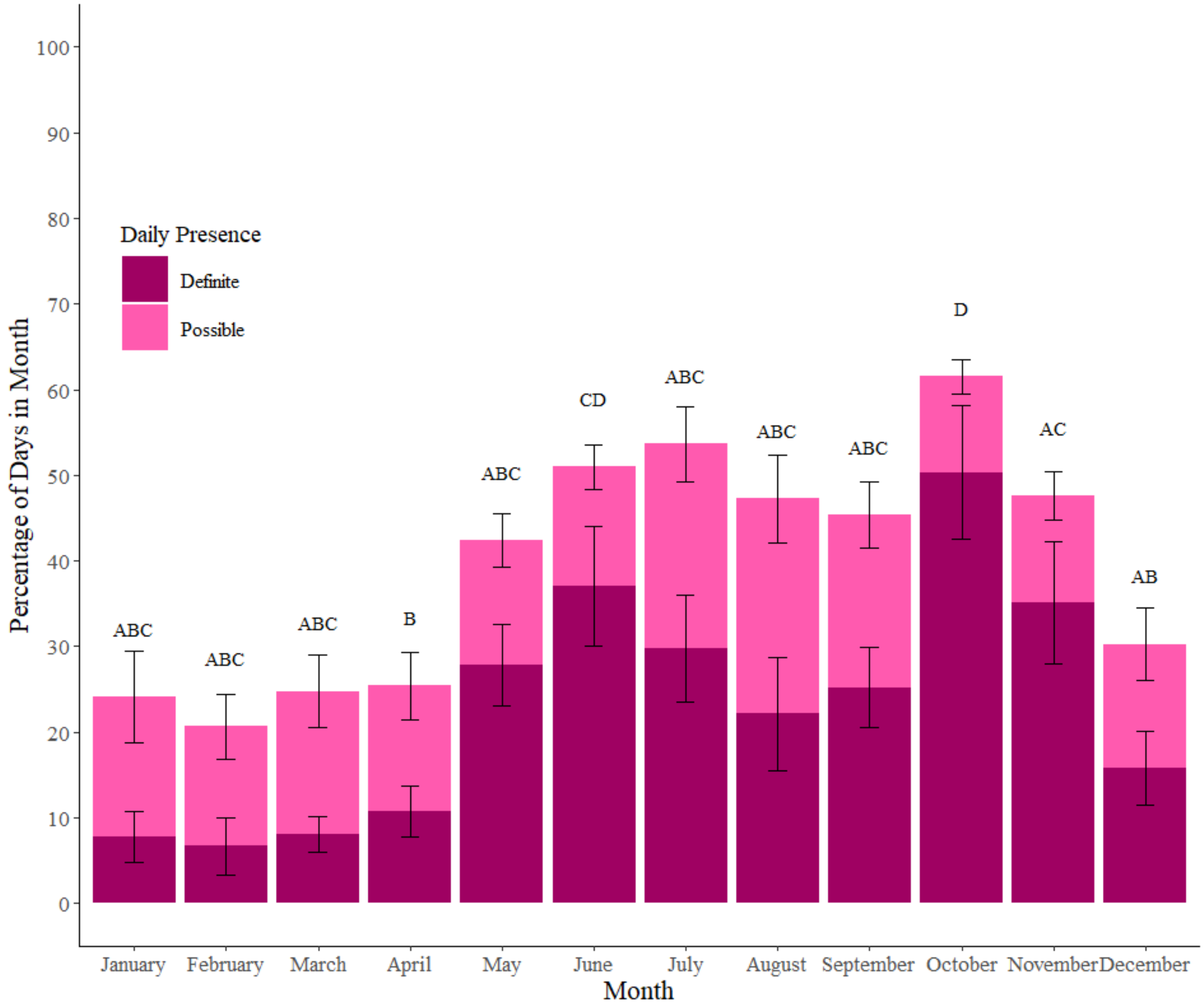


Figure 5-3. Mean (±SD) percentage of days per month with definite and possible sei whale presence by month. Letters indicate results of two-way ANOVA (Tukey-HSD test) of definite sei whale presence. Same letters indicate no difference, different letters indicate statistically significant (p< 0.05) or trending significant (p<0.10) differences.

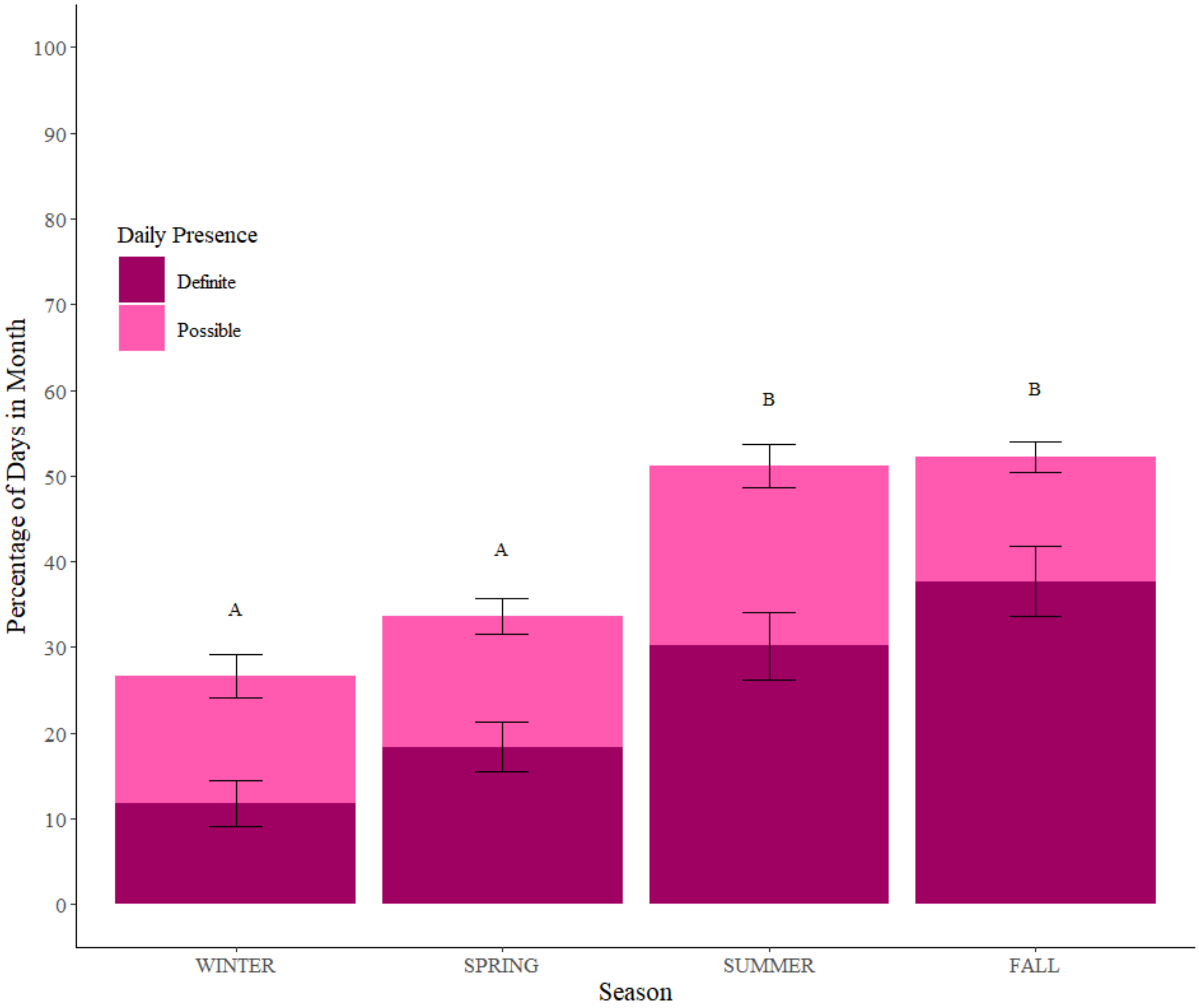


Figure 5-4. Mean (±SD) percentage of days per month with definite and possible sei whale presence by season. Letters indicate results of two-way ANOVA (Tukey-HSD test) of definite sei whale presence. Same letters indicate no difference, different letters indicate statistically significant ($p< 0.05$) or trending significant ($p<0.10$) differences.

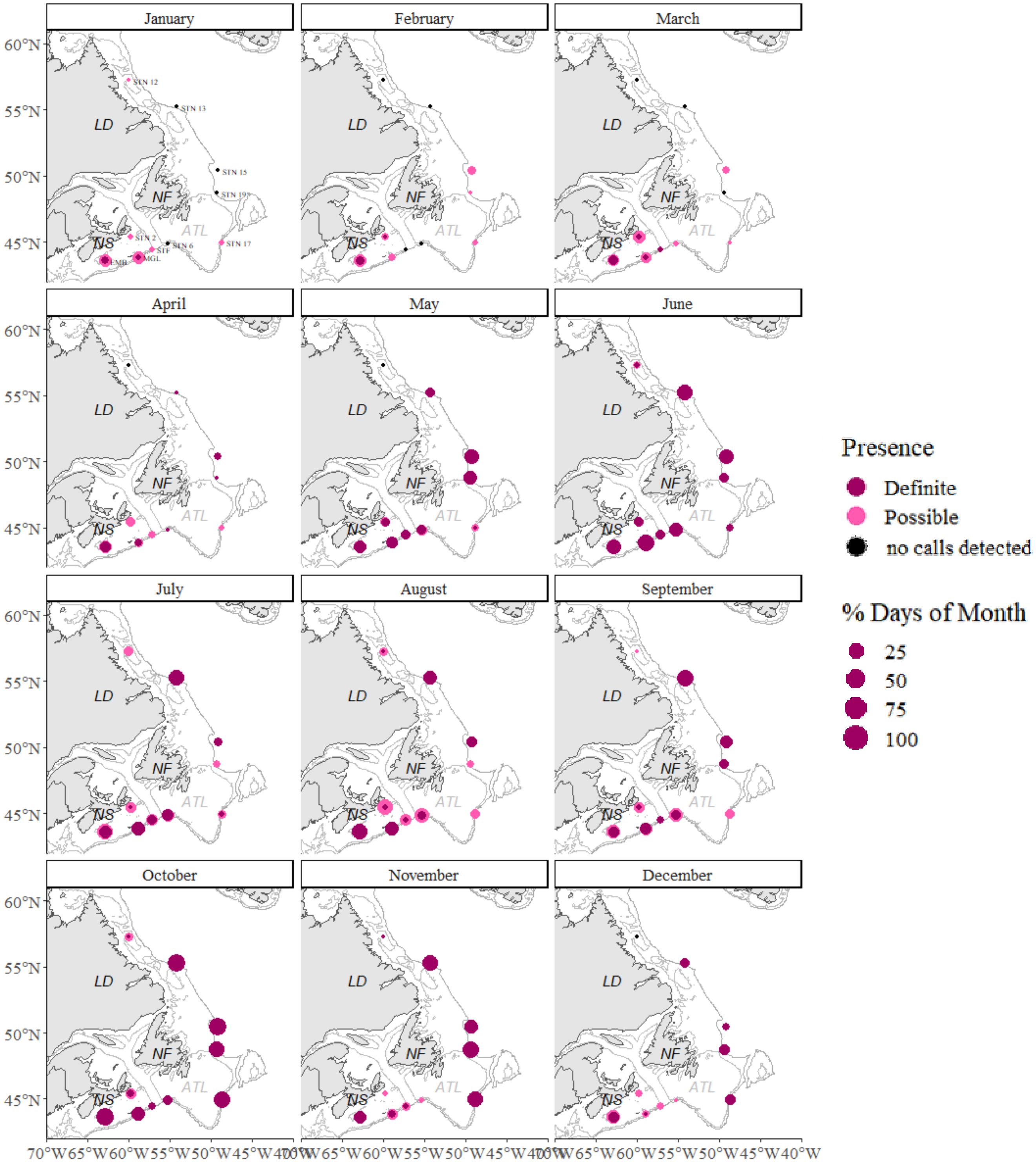


Figure 5-5. Percentage of days per month with definite and possible sei whale presence at each station.

Chapter 6: General Conclusions

Sei whales have been historically difficult to identify visually, but acoustically they make distinct vocalizations that when properly characterized make them prime candidates for PAM studies. PAM is an effective means of remotely observing patterns of occurrence, distribution, movement, and potentially behaviour for this data poor species. The results of my study highlight the effectiveness of PAM as a means of studying whale occurrence, but only when the calls are properly characterized and used to make automated detection more efficient and specific to the region.

As PAM becomes more common, it is necessary to find ways of making the analysis accurate and efficient, including using a combination of automated detection and human manual validation. Before this tool can be used effectively, however, targeted calls must be characterized, so they are easily and properly identified by both automated detectors and human analysists. My study was made more accurate using call characteristics of locally recorded individuals, and any PAM studies of sei whales or other whale species in other regions should use their own local call characteristics for best identification practices. My tiered-detector approach aimed to make the analysis of the tens of thousands of hours of audio recordings regularly recorded by PAM more efficient. The approach can be used to aid in researching the occurrence and distribution patterns of other sei whales, and other whale species, globally. Once the preliminary and necessary data preparation is done, then researchers can begin to answer the important biological questions necessary for species management.

I found some evidence that sei whale downsweep characteristics and calling patterns differed between whales recorded off Nova Scotia compared to those recorded off Newfoundland/Labrador. In addition to some differences in their spatiotemporal presence, this suggests that what is currently considered a single population of sei whales might actually be two separate local populations. Additional research on sei whales, including photo identification and genetic surveys, may contribute to our understanding of population structure. In the meantime, though, managers may need to consider sei whales a single population in this region. However, future evidence suggesting two populations would need to be incorporated into management decisions.

Finally, I found that sei whales are present year-round in Atlantic Canada, with an increased presence through the summer and peaking in October. I also found that off-shelf stations off Newfoundland/ Labrador had the highest overall presence, consistent with the current description of sei whales as an offshore species. Information on the seasonal distribution of this species can be incorporated into the decision-making process related to shipping routes, seismic surveying, and fisheries management with the aim of limiting their negative impacts on sei whales.

Like all PAM studies, the results of my work were limited by noise affecting the production, recording, and detection of sei whale vocalizations. The spatiotemporal results are indicative of minimum presence but cannot specify numbers of individuals or guarantee a lack of presence when they were not recorded. Future work can use the information of their spatiotemporal presence to indicate "hotspots" for targeted visual surveys for photoidentification or behavioural studies, and targeted acoustic studies to better understand the effects of noise on calling rates or behaviour.

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Appendix A: Definitions relating to sei whale downsweeps

Table A-1. Description of extraction and calculation of call features by JASCO's Acoustic Analysis software PAMlab based on the annotation boxes drawn. Descriptions provided by JASCO Applied Sciences, Ltd.

Call Feature	Description
Start Time	time offset (ToffStart) relative to annotation box absolute start time (T0) such that the time window starting at T0 and ending at T0+ToffStart contains 2.5 % of the annotation box energy
Stop Time	time offset (ToffEnd) relative to annotation box absolute start time (T0) such that the time window starting at T0+ToffEnd and ending at the annotation box absolute end time contains 2.5% of the annotation box energy
Signal to Noise (SNR) Ratio	$SNR = 20 \times \log_{10} \frac{\sqrt{\frac{1}{T}\int_{T2}^{T3} s(t)^2\, dt}}{\sqrt{\frac{1}{T}\int_{T0}^{T1} n(t)^2\, dt}}$ where s(t) is the pressure time-series of the annotated call, n(t) is the pressure time series at the preceding window, signal to noise ratio; T2 and T3 are the start and ending point of the annotated calls defined by startdur_90 and enddur_90; T0 and T1 are the start and ending point of the noise window. The noise window has the same duration and bandwidth as the 90% energy click window and is separated by 2 ms from the annotation window

*Table 0-2. Description of extraction and calculation of call characteristics by JASCO's Acoustic Analysis software PAMlab based on the annotation boxes drawn (noted by *), and call characteristics calculated from extracted call features (noted by **). Descriptions of extracted call characteristics provided by JASCO Applied Sciences, Ltd.*

Call Characteristic	Description
Duration**	Stop Time – Start Time
Min. Frequency*	Frequency value such that the band between Fmin and FminX contains 2.5% of the annotation box energy
Max. Frequency*	Frequency value such that the band between FmaxX and Fmax contains 2.5% of the annotation box energy
Bandwidth**	Max. Frequency – Min. Frequency
Slope**	(Min Frequency – Max Frequency)/(Stop Time – Start Time)
Intra-call spacing**	End time of first downsweep within a call type to start time of next downsweep
Peak Frequency*	frequency at peak SPL

Table 0-3. Descriptions of categorical variables associated with sei whale (Balaenoptera borealis) downsweeps.

Call Category	Description
Location	Based on the two stock division suggested in Mitchell and Chapman (1974). Nova Scotia (NS; along the Nova Scotia coast, up to the Southern coast of Newfoundland) and Newfoundland/Labrador (NFLD; North coast of Newfoundland up into the Labrador Sea)
Season	Months of the year grouped into atmospheric season. SPRING (March, April May), SUMMER (June, July, August), FALL (September, October, November) and WINTER (December, January, February)
Call Type	Presence of similar downsweep within ~3 seconds of one another: Singlet (SL, one downsweep), Doublet (DB, 2 downsweeps), Triplet + (TP+, three or more downsweeps)

Appendix B: Noise Profiles of Recording Stations

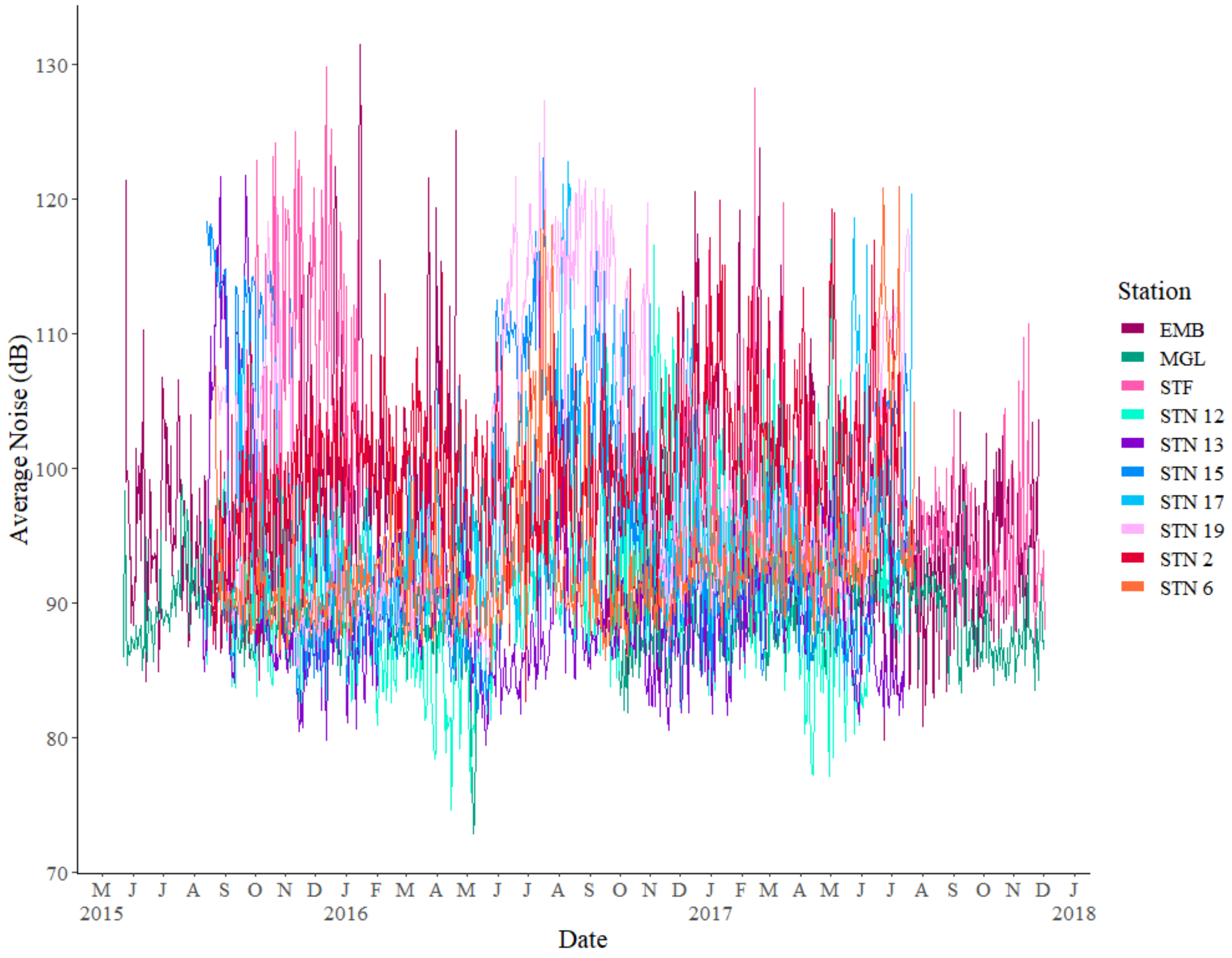

Figure 0-1. Average noise level (dB) between 31 - 80 Hz recorded at all ten stations from 2015-2017.

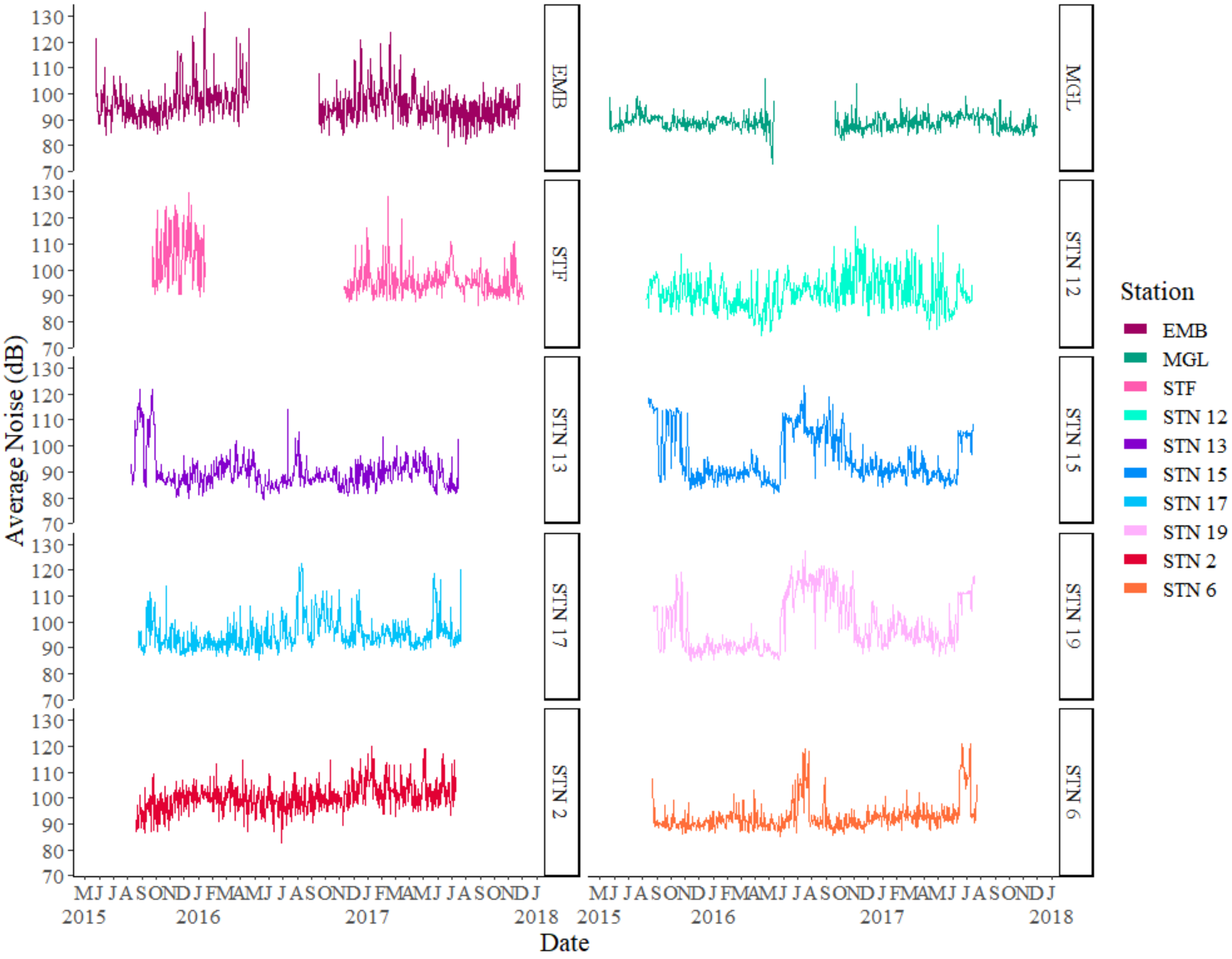

Figure B-2. Average noise level (dB) between 31 - 80 Hz recorded at each station from 2015-2017.

Appendix C: Detection Range Modelling

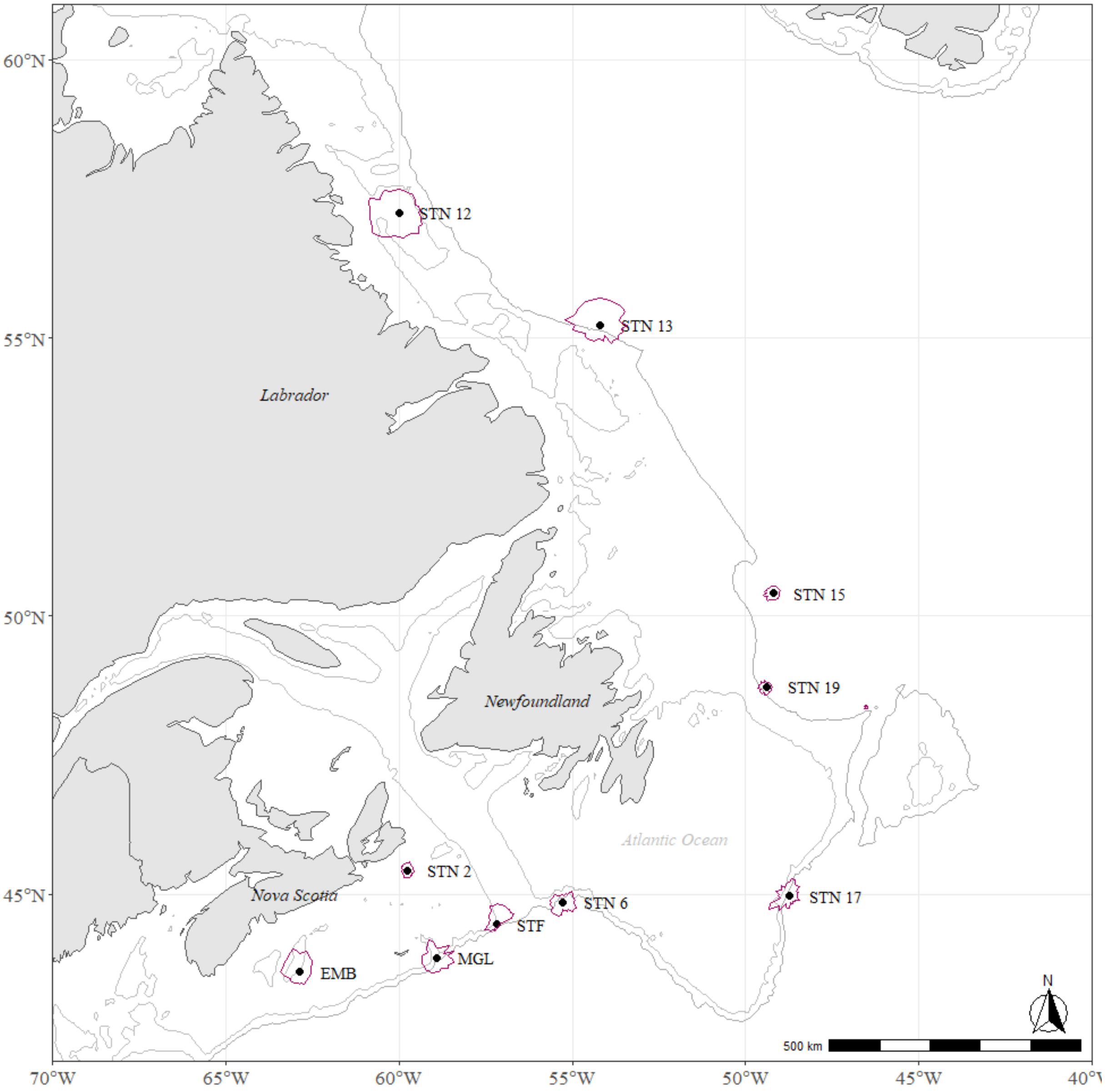

Figure 0-1. Detection range modelling for sei whale downsweeps with a source level of (mean ±SD) 177± 5 dB (Romagosa et al. 2015) assuming calls made at 50% volume will be detected 50% of the time.