Using Acoustics to Explore Fin Whale (*Balaenoptera physalus velifera*) Ecology and Habitat in British Columbia

By

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B.Sc. (Honours), University of Victoria, 2016

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Supervisory Committee

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ABSTRACT

Globally, fin whales (*Balaenoptera physalus*) were heavily targeted by commercial whaling. Despite this, some populations are recovering; their numbers are increasing in the Southern Hemisphere and North Atlantic. Fin whales are listed as vulnerable on the International Union for Conservation of Nature (IUCN), although populations worldwide show varying degrees of recovery.

Fin whales were once the most abundant large cetacean species off the coast of British Columbia (BC). They are currently listed under Canada's Species at Risk Act (SARA) as Threatened, although their status is currently in consideration for downlisting following recommendations by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2019. Although fin whales may be returning to coastal areas in BC, efforts to track their recovery in their core habitat, in deeper waters and off the shelf break, has been limited. Much of what is known about their habitat use, ecology and seasonal movements come from details from historical catch records, with recent designated studies looking to refine this knowledge.

In this thesis, I consider the potential recovery of fin whales and use acoustic recordings from two study sites in BC waters to analyze their vocalizations. If populations are recovering in BC, recording and analyzing their acoustic behaviour as they rebuild their social and physical connectivity can provide clues to how they are responding after decades of removals.

Primarily driven by the considerable number of fin whale vocalizations observed in the acoustic recordings, I create a comparative analysis of fin whale call types to provide finer resolution to the spatial and temporal distributions of vocalizations. The presence of 20 Hz and 40 Hz call types, associated with breeding and foraging behaviour, respectively, were analyzed

to determine fin whale habitat use. This comparison analysis indicated fin whales use coastal and offshore areas very differently; considerably higher call presence of both types was observed offshore, and song patterning was only present here.

The diverse range of call parameters observed within the 40 Hz call type, particularly from the offshore study location, led to further analysis for the potential for sub-division within this call type. Cluster analysis indicates the structure of 40 Hz call types is more varied than previously recognized and determines five subcategories within the 40 Hz type based on call features. I further explore the potential of subcategories within this call type by analyzing the relative presence of fin whale 40 Hz calls over daily, monthly and seasonal time periods to better understand drivers of the variability.

Fin whale song patterns in the offshore acoustic recordings at Clayoquot Slope suggest BC waters are used for courtship, breeding and calving. The difference in song structures may suggest at least two populations using these waters. Although the dominant song pattern structure matched previous findings for the west coast of North America, considerable change in pattern timing was evident. Additionally, new song patterns not previously described for this region were found.

Overall, knowledge on whale acoustic use and the value of acoustics to their ecology is still over-simplified, but our understanding increases with deeper study. Some of my observations and understanding of various fin whale acoustic signals have yet to be described in the current literature. Fin whales have a more complicated acoustic repertoire than previously thought and the variety of calls observed indicates BC is an important habitat for recovering populations.

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CHAPTER 1

Evidence of North Pacific Fin Whale (*Balaenoptera physalus velifera*) Recovery in the Canadian Pacific

Abstract

Once abundant in British Columbia (BC) waters, fin whales were heavily targeted by commercial whaling, with genetic studies suggesting population numbers in the northeast Pacific may have been reduced by up to 99% (Nigenda-Morales et al. 2023). The population is thought to be less than 50% of what it was before the large-scale removals of whaling (COSEWIC 2005). However, fin whales are slowly recovering in BC waters. Evidence collated from dedicated surveys, opportunistic sightings, and passive acoustic records are used to examine signs of recovery for the current population of fin whales in the Canadian Pacific. In considering repopulation, also evaluated are patterns of current habitat use and whether these are consistent with their pre-whaling presence, or if their distribution is reflective of recovering into a Pacific Ocean where oceanic regimes, prey availability, and anthropogenic pressures differ from pre-whaling periods. The existing literature is reviewed, as well as additions to it with more recent findings from acoustic monitoring. Understanding the drivers of these changes will help us understand the mechanisms underlying their population recovery and the potential limitations or thresholds this might have, especially as fin whales here are recovering into areas that increasingly overlap with anthropogenic disturbance.

Introduction

Large-scale industrial whaling ended in the Canadian northeast Pacific Ocean in 1967, but not before decimating cetacean populations. Once the most abundant species in this area, North Pacific fin whales (*Balaenoptera physalus velifera*) became the most heavily hunted (Pike and MacAskie 1969). Catch records show that more than 7,000 fin whales were killed in less than 60 years (1908-1967), more than any other species for the five whaling stations in British Columbia (BC) (Figure 1) for that period (Gregr 2000, Nichol et al. 2002). Over 50 years have passed since large-scale industrial whaling ended in the Canadian northeast Pacific Ocean in 1967 and fin whale recovery status in BC remains largely unknown, and our understanding of their ecology and habitat use still typically relies on the details from historical catch and commercial whaling records from the region.

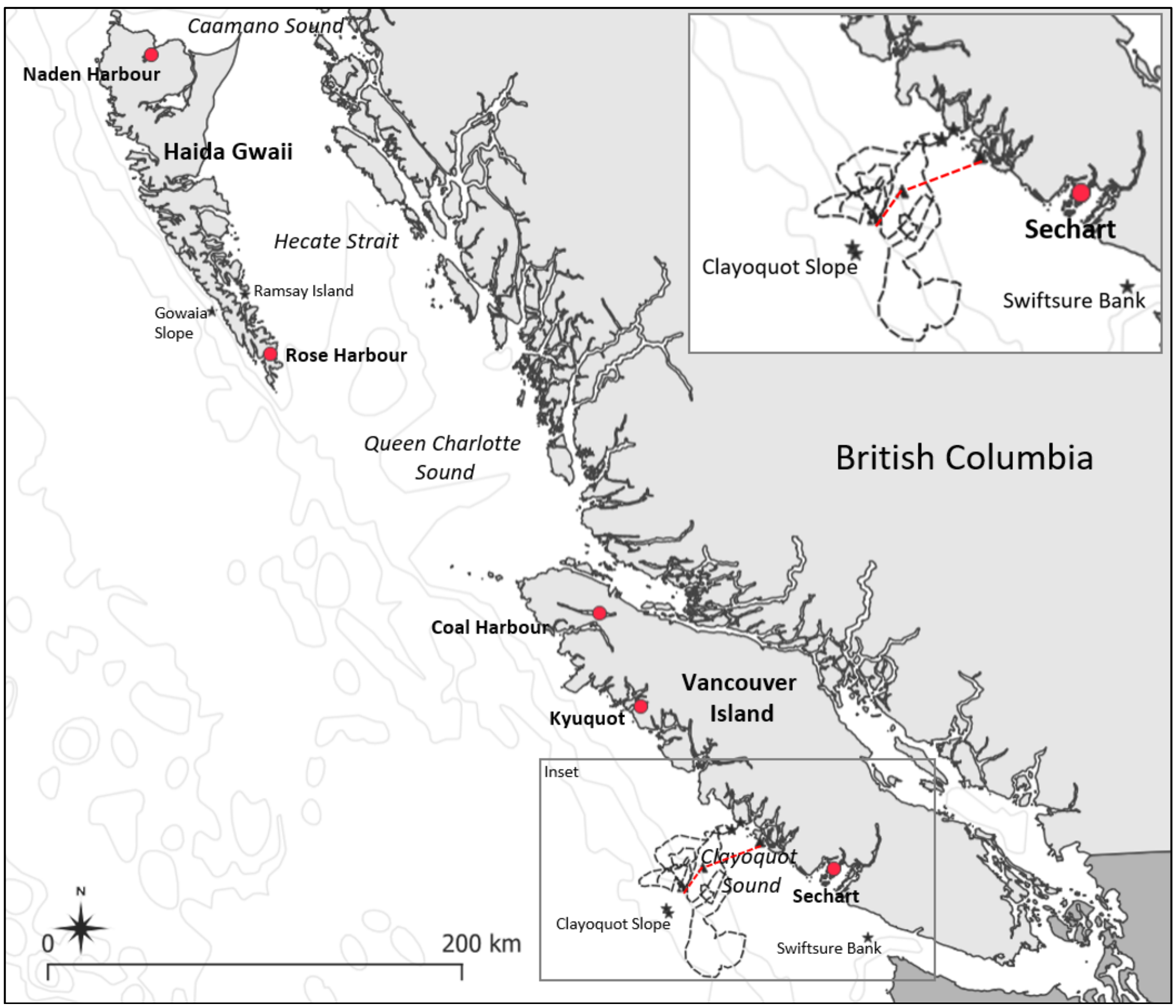

Figure 1: Map of the British Columbia coast. The five whaling stations are indicated with red circles (Naden, Rose and Coal Harbour, Kyuquot, and Sechart). The location of passive acoustic monitoring (PAM) systems discussed are shown with black stars (Gowgaia Slope and Ramsay

Island (Frouin-Mouy et al. 2022); Clayoquot Slope, Clayoquot Sound, and Swiftsure Bank (Burnham 2019, this thesis). The track of mobile PAM systems deployed in 2016, 2017 is shown with black dashed lines and bi-monthly surveys undertaken by the Strawberry Island Marine Research and Education Society (SIMRS) pelagic survey off the west coast of Vancouver Island from 1993-2007 is shown with a red dotted line, with starting, shelf crossing, and end locations marked by a black triangle (see inset).

Any new details of their ecology and habitat use must first be acknowledged in light of their response to rapid changes in population numbers due to decades of removals. Insights from previously unpublished data combined with existing literature from studies and catch records from along the BC coast can be used to consider the potential recovery of fin whales since the cessation of whaling. For context from their full geographic range, data from Alaska to California is examined here. Recent visual surveys and passive acoustic monitoring (PAM) data as new evidence of whale presence are compared to whaling records and works from that period to consider if the current patterns of presence and habitat use indicate a population recovery into areas where fin whales once prevailed, or if the extent of population growth and/or dynamic environmental variables have initiated a range expansion or shift. This will allow consideration of whether the recommendation by the Committee On the Status of Endangered Wildlife in Canada (COSEWIC) in 2019 to downlist the status of fin whales from Threatened to Special Concern that is currently being considered by the Species at Risk Act (SARA) in Canada is warranted, given the evidence. Fin whale presence along the BC coast forms the foundation of this assessment, while behavioural context will be considered where possible to ascertain spatiotemporal trends.

Whaling

Four whaling stations operated in BC between 1905-1943 during the first era of whaling. These stations were located on the west coast of Vancouver Island at Sechart and Kyuquot, and on Haida Gwaii in Rose and Naden Harbours. After World War II, during the second era of whaling, a fifth station opened in Coal Harbour on northern Vancouver Island, becoming one of the most prolific stations and one of the last operational shore-based stations in North America (Figure 1).

The industry in BC targeted five whale species: blue (*Balaenoptera musculus*), fin, humpback (*Megaptera novaeangliae*), sei (*B. borealis*) and sperm (*Physeter macrocephalus*) whales. Occasionally, north Pacific right (*Eubalaena glacialis*), Baird's beaked (*Berardius bairdii*), gray (*Eschrichtius robustus*) and minke (*Balaenoptera acutorostrata*) whales were also noted in the records (Nichol et al. 2002). A total of 24,427 whales were logged into catch records, of which 7,497 were fin whales (Gregr 2000, Ford, 2014, Nichol et al. 2002). Despite the closure of Canadian whaling stations, between 1964 and 1974, a further 201 fin whales were taken in the Pacific by Japanese whalers, with additional removals by Soviet whalers in the offshore waters, both of which are believed to have under-reported or falsified records (Ford 2014).

Despite overharvesting being evident in the early years of whaling, the BC industry increased production; limits on chaser boats per station were abandoned and whale processing became a 24-hour operation at the shore stations (Nichol et al. 2002). Initially spared from the hunt on account of their speed, strength, and use of offshore habitat, fin whales became a target species in the second era of whaling (Gregr 2000, Nichol et al. 2002). Their predictable presence in waters close enough to shore was not great enough to warrant a stronger focus until the numbers of blue and right whales had dwindled (Drucker 1951, Monks et al. 2001, Ford, 2014).

Catch numbers of fin whales steadily decreased from a peak in 1911-1912, although they still formed a substantial part of the catch. The focus on fin whales was even greater in the second era of whaling (Gregr 2000, Nichol et al. 2002). During this period fin whale catch peaked in 1958 with 573 animals, followed by another dramatic fall in catch (Gregr 2000). The overall proportion of fin whales caught from BC waters was similar to that reported for Alaskan stations (Gregr 2000), and a similar switch of target species was noted in whaling records for California (Clapham et al. 1997). Bonuses were paid based on the length of the whale, encouraging the take of more mature individuals. However, the take in this second era for fin whales was from a population that had already been exploited, which had altered the age and size structure. The minimum catch length for fin whales was set at less than the known average length at maturity and was lesser than that imposed for humpback and sei whales, typically smaller species (Flinn et al. 2002).

Recent increases in effort (e.g. Nichol et al. 2017, Nichol and Ford 2018, Nichol et al. 2018, Keen et al. 2021) have added to what is known about fin whale ecology at finer scales in BC; prior to this, knowledge of fin whale ecology and habitat use had predominantly been derived from historical catch and commercial whaling records that provide details over large spatial and temporal scales. Catch dates, location, sex, length, and a variety of measures related to diet, reproductive status, and morphology were taken (Nichol et al. 2002) and these details, along with notations of catch and whaling efforts (Pike 1968, Gregr 2000, Gregr et al. 2000) can be used to better understand the impacts of removals on fin whale populations.

Contemporary Data

Visual Data

Several dedicated, systematic surveys including vessel-based line transect surveys and mark-recapture methods have been undertaken in BC, to aid in establishing fin whale presence, habitat use, and population abundance. However, much of this work to date has been limited to the continental shelf waters (Williams and Thomas, 2007, Best et al. 2015, Harvey et al. 2017, Nichol et al. 2018), hindered by the logistics of surveying offshore areas. Exceptions include a three-month vessel-based survey in the summer of 2018 that extended to the limits of Canada's Exclusive Economic Zone (EEZ), including over 350,000 km^2 of survey area in offshore waters (Pacific region International Survey of Marine Megafauna (PRISMM), Wright et al. 2021), which started to address the lack of data on whale presence beyond the shelf break.

Smaller-scale vessel-based surveys also provide additional data on fin whale abundance in BC. An example is from bi-monthly surveys undertaken between 1993 and 2007 on the west coast of Vancouver Island by a citizen science group, the Strawberry Island Marine Research and Education Society (SIMRS, Figure 1). The results of these surveys have not been previously published and were not designed to target fin whale populations specifically. The transect began at a near-shore location north of Tofino (49.1362° N, -125.9751° W) and extended to an end point 35 nm offshore (48.8450 ° N, -126.7192° W); 24 nm of this survey were over the continental shelf, then crossed the shelf break (48.9667° N, -126.5267° W) to continue into abyssal waters, crossing several bathymetric features including submarine canyons west of Clayoquot Sound before terminating in waters exceeding 1200 meters deep (Figure 1). These surveys noted the presence of eleven cetacean species, many of which were repeatedly seen. However, fin whales were notably absent from any of the surveys conducted during this period. In contrast, humpback whales were consistently sighted on transects within and between years, with sightings sufficient to be able to distinguish seasonal movements and habitat use changes and their presence in both coastal and offshore regions (DeMeyer et al. in prep). Also, species typically affiliated with offshore habitat use and long dive times, such as sperm and beaked whales, were also sighted, which makes the paucity in fin whale presence in the sightings even more striking, especially in comparison to more recent findings from the same area. Opportunistic data collated for the BC coast by the British Columbia Cetacean Sighting Network (BCCSN) was used to look for changes in presence in time and space, and to set the SIMRS Vancouver Island surveys in a coast-wide context. For the period of the SIMRS pelagic surveys, the total reported sightings for fin whales off of southern Vancouver Island in the 1990's was five, three of which were before the surveys started in 1991-1992. No sightings were reported between 2000-2009 for southern Vancouver Island, consistent with the SIMRS survey results (Figure 2). The coast-wide sighting data suggests there may be an increasing number of fin whales in BC waters. However, there are major caveats in these survey results: these observations are opportunistic sightings that are not effort corrected. Indeed, the number of platforms observing has also increased and results may be influenced by the increasing effort in coastal areas rather than changes in whale presence. However, it does corroborate with more dedicated research that appears to be indicating an increasing use of coastal areas (Keen et al. 2021).

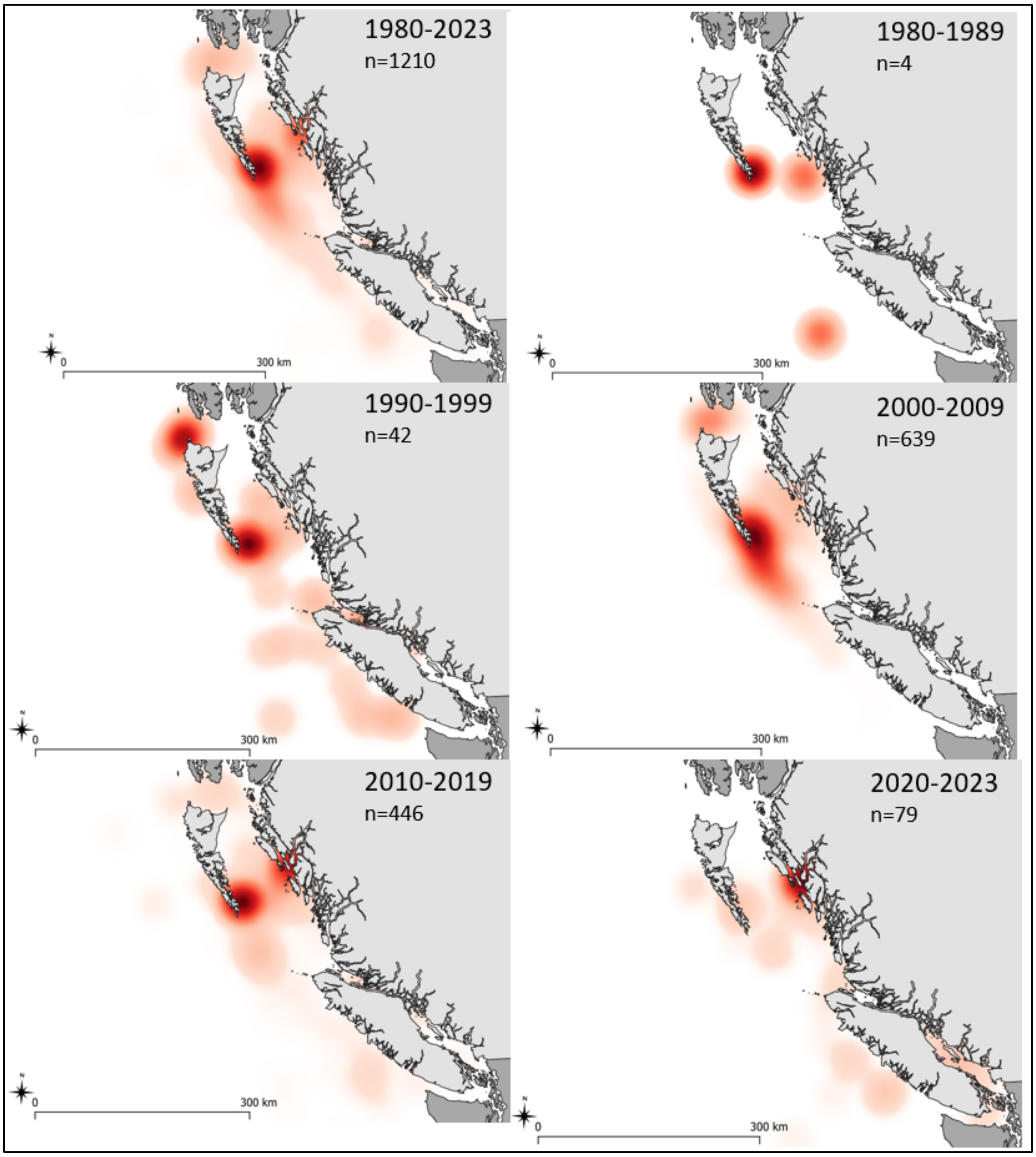

Figure 2: Sightings data of fin whales taken from the British Columbia Cetacean Sightings Network. These are opportunistic sightings, that have not been effort corrected. Kernel density maps show hot-spots of whale presence through each decade and the full length of data (1980-2023) to be visualized spatially. The number of sightings per decade is also indicated, with the shading scale not consistent between decades.

Acoustic Data

Data from PAM systems have added to our knowledge base of fin whale habitat use in BC. Whale calls in the acoustic record indicate presence, but also give an idea of the whales' behavioural state. The most commonly described fin whale call is the 20 Hz downsweep, used while traveling and socializing (McDonald et al. 1995, Edds-Walton 1997, Watkins et al. 1987, Širović et al. 2013). If 20 Hz calls appear in a regular pattern in the acoustic record, with consistent inter-call intervals, it represents 'song' and forms part of the male reproductive display (Watkins et al. 2000, Croll et al. 2002, Koot 2015, Širović et al. 2013, Burnham 2019). Also noted in the literature is the 40 Hz call, principally used during foraging (Širović et al. 2013, Burnham et al. 2021, Romagosa et al. 2021).

Findings from recordings from offshore Vancouver Island by Burnham et al. (2019) were furthered here by considering an extra year of data from a 1255 m deep bottom-mounted underwater hydrophone at Clayoquot Canyon (48.6706° N, -126.8485° W; Ocean Networks Canada (ONC) node (oceannetworks.ca); Figure 1). This analysis covered a period of recordings from July 2018 to July 2019 and was considered here as they overlap spatially with the SIMRS vessel surveys. A manual aural-visual review of the offshore recordings was undertaken, systematically analyzing every fifth day. Details from similar recordings from bottom-mounted underwater hydrophones on the eastern and western coasts of Haida Gwaii (Gowgaia Slope and Ramsay Island; placed at 740 m and 150 m depth, respectively, Figure 1) were taken from analysis by Frouin-Mouy et al. (2022) to add to the coast-wide picture of whale presence using acoustic means. Using single hydrophone systems, it is not generally possible to discern the number of whales present or their location, nor is there a way to absolutely determine the absence of whales when calls were not heard. Therefore, the calls in the acoustic data represents a minimum presence. However, call number, rate, and the presence of numerous coincident calls can all indicate the relative number of whales present, and suggest migration, breeding, and foraging behaviour (Koot 2015, Burnham 2019, Burnham et al. 2019, Frouin-Mouy et al. 2022).

Population Abundance and Structure

Pre-exploitation estimates suggest that prior to the 1900's, the north Pacific fin whale population was 40,000-45,000, which was reduced to 13,620-18,680 whales by the end of commercial whaling (Ohsumi and Wada 1974). Recognition that the northeast Pacific stock was distinct in 1973 also indicated half of the existing population of fin whales were of this stock, numbering 8,520-10,970 whales after the whaling era (Ohsumi and Wada 1974).

Recent dedicated, systematic surveys on the continental shelf have estimated the population in BC to be approximately 400-500 individuals (2004-2005 survey, 496 individuals (95% CI: 202-1218) Williams and Thomas 2007; 2004-2008 survey, 446 individuals (95% CI: 263-759) Best et al. 2015). These surveys attempted to re-establish a population estimate for fin whales in the Canadian Pacific. Nichol et al. (2018) confirmed this estimate from mark-capture-recapture analysis of photo-identification data from 2009 to 2014 (405 individuals (95% CI: 363-469)). Together, the surveys and mark-capture-recapture analyses highlighted whale 'hotspots' in Hecate Strait, and Queen Charlotte and Caamano Sounds (Harvey et al. 2017; Figure 1). However, offshore surveying has been more limited and the lack of offshore population estimates was addressed by the 2018 PRISMM survey (Wright et al. 2021). Fin whale sightings numbered 213; density surface modeling interpolated these observations to suggest an estimate of 2,893 (95% CI: 2,171-3,855) fin whales for BC (Wright et al. 2021). This exceeded the earlier estimates for BC waters that were limited to evidence from the continental shelf (see COSEWIC 2019) and this study confirmed a greater prevalence of fin whales in offshore areas, addressing the known limitations of population estimates up until that point (Wright et al. 2021).

In the context of their full range along the west coast of North America, surveys conducted in northern California, Oregon, and Washington suggest a 7.5% annual increase in numbers from the mid-1990s to the mid-2000s, representing an overall five-fold increase in fin whale population size, after which abundance has been stable (Moore and Barlow 2011, Nadeem et al. 2016). Central and southern California estimates were stable in population estimates from 1991 to 2014 (Nadeem et al. 2016). In their northern range extent in Alaska, annual increases were estimated to be 4.8% between 1987 to 2003 (Nadeem et al. 2016). These kinds of population trend estimates have not been possible for fin whales in Canadian waters, especially given the lack of baseline data and challenges in surveying in offshore regions. However, analyses from 2004 – 2014 suggest stable population numbers in areas of the north coast of BC (Best et al. 2015, Nichol et al. 2018).

Habitat Use

Whaling catch records provide clues about the distribution, behaviour, and prey of fin whales. However, they have an inherent spatial bias; whaling efforts extended approximately 200 nautical miles (nm) offshore from whaling stations (Pike and MacAskie 1968), but approximately 80% of the catch was within 150 nm. Fin whales were caught in both coastal shelf and offshore waters, with the distance between the coastline and the capture site of whales increasing significantly over the course of the second whaling era (Gregr 2000). Hunting efforts on the west coast of Vancouver Island and around Haida Gwaii, in Hecate Strait and Queen Charlotte Sound (see Figure 1), were primarily in exposed waters, but occasionally in protected areas along the mainland coast and Queen Charlotte Strait (Pike and MacAskie 1969, Gregr and Trites 2001, Ford, 2014). The catch per station along the coast was similar, suggesting approximately equal availability and ease of capture of fin whales. In general, catches increased from spring to summer, and decreased from fall to winter (Gregr 2000, Nichol et al. 2002, Nichol et al. 2018). Male and female catch numbers by search distance were approximately equal, indicating little to no spatial segregation by sex. Their increased proximity to shore and presence in Hecate Strait and Queen Charlotte Sound showed a seasonal pattern, strongest in July and August, which suggests their use of more near shore waters for summer foraging (Pike and MacAskie 1968, Gregr 2000). Pregnant females were noted consistently from April until September within reach of the coastal stations (Gregr 2000). Combined, this suggests that during the whaling period BC waters were important for both reproduction and foraging.

The take of smaller bodied animals, despite the incentive toward larger whales, suggests that the fin whale population may have been segregated spatially by size, with larger or mature animals living further offshore. Analysis of body size data also suggests the existence of a local BC foraging sub-group or sub-population, of generally smaller bodied individuals (Fujino 1964, Pike and MacAskie 1968, Flinn et al. 2002). This was in addition to migrating animals, with age structuring in this population movement. Larger bodied fin whales arrived in BC ahead of smaller individuals for the northward migration, and the southward migration was led by pregnant females leaving in September to give birth (Gregr 2000).

The context of fin whale presence can be enhanced from patterns of prey abundance or oceanographic regimes. Spatial modeling of the catch data shows increased whale abundance with water depth and around bathymetric features (Gregr and Trites 2001), as well as during periods of increased chlorophyll production (Smith et al. 1986), sea surface temperature (Woodley and Gaskin 1996), and ocean circulation (Waring et al. 1993, Woodley and Gaskin 1996). All of these speak to the tie between whales and prey abundance (e.g., Woodley and

Gaskin 1996, Fiedler et al. 1998, Gregr et al. 2000, Gregr and Trites 2001). Fin whale habitat from catch data was predicted to be concentrated along the continental shelf and in a large offshore area encompassing waters up to 100 nm offshore that extended from the south end of Haida Gwaii towards Vancouver Island (Pike and MacAskie 1968, Gregr 2000, Gregr and Trites 2001).

Oceanographic variables dictate prey abundance and aggregation predicts whale presence (Gregr 2000, Gregr and Trites 2001). Convergent currents to the north of Vancouver Island, the topography, off-shelf flow, and the formation of Haida eddies, upwell nutrients in these areas and entrain zooplankton (Thomson 1981, Allen et al. 2001). The higher proportion of euphausiids in stomach contents from captured fin whales also suggests whales were concentrated on the shelf break and around other bathymetric features (Mackas and Galbraith 1992). This was distinguished from greater proportions of copepods from fin whales in sub-arctic, Alaskan, and offshore waters (Mackas 1992).

The opportunistic sighting data must be reviewed with caveats, as results may reflect increased effort, both spatially and temporally. However, similar to the whaling data, there is a spatial bias of limiting search efforts to within reach of shore stations. Consistently, most sightings per decade were reported around Rose Harbour and the southern tip of Haida Gwaii (Figure 2). The appearance of whales in near coastal or inner waterways and fjord systems has been noted by Pilkington et al. (2018) and is also reflected in the BCCSN data showing an increase from four individuals sighted on a single occasion in 1995, to a total of 163 reports from 2010 to 2023 (Figure 2). Behavioural notations starting in 2001 were paired with the sightings, showing foraging activity, although concentrated on the southern tip of Haida Gwaii, has expanded towards the mainland regions of BC (Figure 3). However, the lack of notation cannot be taken as a lack of foraging behaviours prior to this.

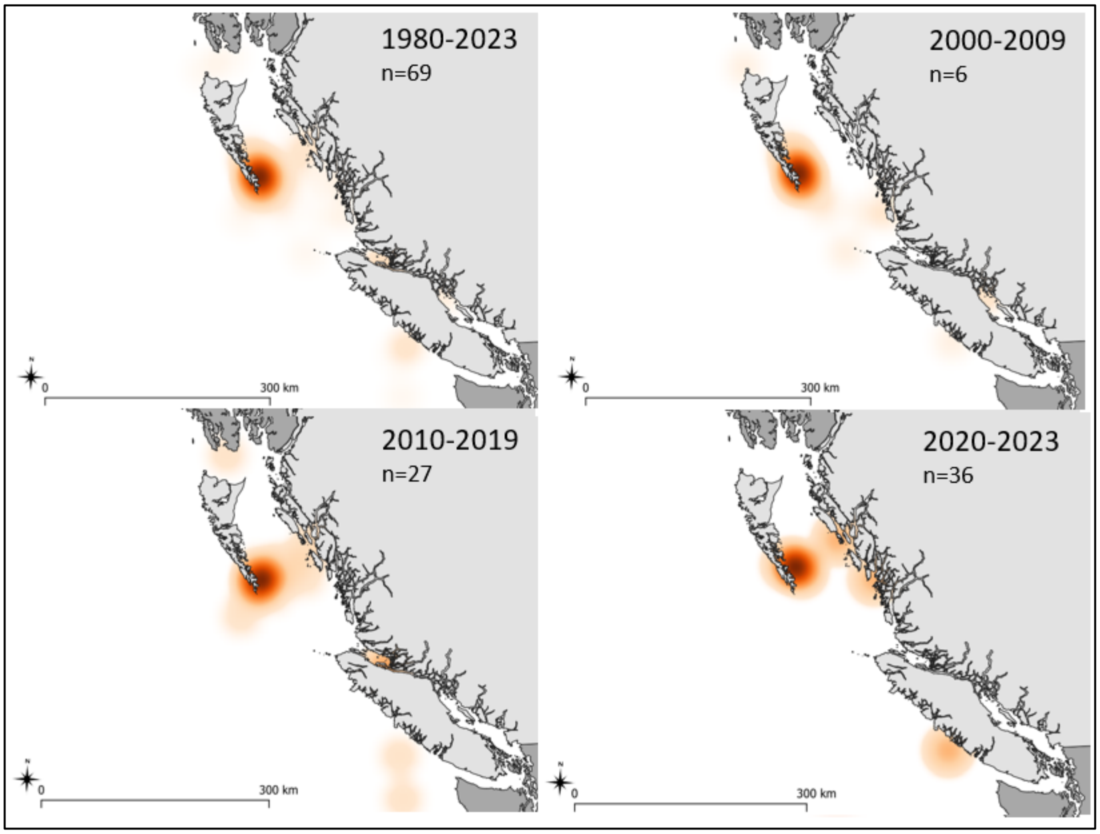

Figure 3: Sightings data taken from the British Columbia Cetacean Sightings Network, specifically noted as foraging fin whales. These are opportunistic sightings, that have not been effort corrected. Kernel density analysis shows hot-spots of whale presence through each decade and the full length of data (1980-2023) to be visualized spatially. The number of sightings per decade is also indicated, with the shading scale not consistent between decades.

Although little effort has been dedicated to these areas, the highest fin whale densities are predicted to occur in waters past the shelf break extending at least 200 nm offshore/1000 m water depth (Nichol et al. 2017, COSEWIC 2019, Wright et al. 2021). This includes the deeper waters south and east of Haida Gwaii and in some more confined waterways (Williams and Thomas 2007, Gregr and Trites 2001, Ford et al. 2010, Nichol and Ford 2018). Studies in California have also shown fin whale presence to be consistent year-round and with residency times of 30 days or more (Falcone and Schorr 2014, Scales et al. 2017), contradicting the presumed north-south migration between high-latitude feeding areas and lower latitude breeding and calving regions (Macintosh 1965, Sergeant 1997). As lesser numbers were noted in the catch records in BC over the winter, it could be that the general population migrates, while some individuals or sub-groups do not. Fin whales that forego an annual migration may represent animals of differing age, gender, reproductive status, energetic requirements/size class, predation risk, or physiological capacities from the general populus.

Review of more recent PAM data has indicated the presence of fin whales year-round in Pacific Canadian waters. However, residency of individuals is not possible to discern. The data both from Vancouver Island and Haida Gwaii indicate the presence of both the 20 Hz and 40 Hz calls, further suggesting BC is important for both feeding and breeding for fin whales (Burnham 2019, Burnham et al. 2019, Frouin-Mouy et al. 2022) throughout the year. Foraging calls were most prevalent in the spring and summer, following the spring bloom and upwelling along the shelf break (Burnham 2019, Burnham et al. 2019). The presence of 20 Hz calls in BC waters, however, substantially outnumbers the 40 Hz call type in the acoustic records. This was found in the years' worth of data analyzed from offshore Vancouver Island (Chapter 3). As per previous studies (see Burnham 2019), this additional PAM data showed the 20 Hz call was prevalent over the fall and winter period, when records from whaling and recent surveys or sightings are most scarce. Conception and calving are believed to occur in the winter (Mizroch et al. 1984, Folkens et al. 2002), which is when song was most frequent in the acoustic data off the west coast of Vancouver Island and further north (Frouin-Mouy et al. 2022, Chapters 3 and 6). Births are most common between mid-October and mid-February (Lockyer 1984, Koot 2015), with patterning in 20 Hz calls peaking towards the latter part of this period (also see Burnham 2019). Song patterning in the 20 Hz calls has been noted in recordings taken at Union Seamount, Nootka

Sound, Barkley Sound, La Perouse Bank, and Brooks Peninsula on the west coast of Vancouver Island (Ford et al. 2010, Koot 2015). Further, winter recordings in northern BC, the Bering Sea, and northern Gulf of Alaska to the Southern Californian Bight have also noted the presence of regularly patterned 20 Hz song (Moore et al. 2006, Stafford et al. 2007, Širović et al. 2013, Širović et al. 2015, Pilkington et al. 2018, Frouin-Mouy et al. 2022). Song patterning is used in courtship displays and is also thought to reflect population sub-structures. A doublet structured pattern (two tones: a backbeat and a 20 Hz note, see Burnham 2019) described by Burnham (2019) and others (Ford et al. 2010, Koot 2015) from the west coast of Vancouver Island is the most prominent pattern in the north Pacific (Širović et al. 2017) and dominated the acoustic records from the BC offshore waters from the recorder off Vancouver Island (Chapter 6). The presence of this song suggests a wide-ranging and highly connected population (Oleson et al. 2014, Širović et al. 2017). Indeed, similarity in song pattern for southern California to the southern Chukchi Sea suggests the range of this group could span the west coast of North America (Mellinger and Barlow 2003, Širović et al. 2017, Burnham 2019, Furumaki 2021). The data analyzed from July 2018 to July 2019 from offshore Vancouver Island noted nearly 110,000 fin whale calls in a subsample (roughly 10%) of a year's worth of data, with approximately 85% of the calls being 20 Hz calls and forming song patterns that peaked from October to March (Chapters 3 and 6). However, in considering the inter-call intervals, the analysis indicated an altered or modified form of the song pattern with changes in timing properties which may suggest song evolution, similar to that seen in humpback whales (see e.g. Allen et al. 2018, Chapter 6) but on longer time scales, or a progressive splintering of the population into sub-groups as their numbers recover. The whaling data already suggested a sub-group specific to foraging regions in BC (Fujino 1964, Pike and MacAskie 1968, Flinn et al. 2002); something similar might become more apparent in the data for whales undertaking courtship activities. Contrary to the catch records, which suggested whale numbers decreased from September onwards, fin whales were more acoustically present in the deep coast and offshore waters on the west coast of Vancouver Island and Haida Gwaii in the winter months, determined by both bottom-stationed and mobile PAM devices (see Ford et al. 2010, Koot 2015, Burnham 2019, Burnham et al. 2019, Frouin-Mouy et al. 2022, Figure 1). Although the number of callers is not able to be determined or distinguished from a possible increase in the rate of calling, overlapping and multiple simultaneous calls suggest multiple individuals calling for extended periods.

The collated evidence suggests fin whales are present in BC waters year-round and, while predominantly found in deeper waters past the continental shelf break, they also use areas on the shelf. Contemporary research confirms a similar habitat use pattern to pre-whaling as fin whale populations in the northeast Pacific Ocean are recovering. However, they are recovering in a marine environment that is different from what they were removed from. When a population is reduced it not only faces challenges due to small population dynamics, but the removal of individuals may, to some extent, erase knowledge of quality locations for foraging, mating, and calf rearing from the collective memory of the population (Clapham et al. 2007). This can mean the legacy of whaling persists far beyond the cessation of removal activities. Since the cessation of whaling, fin whales are starting to return to historically important habitat as the current population builds their collective memory of areas in BC waters that support their reproductive and foraging success.

Challenges for Recovery

As fin whales re-establish patterns of foraging and breeding in BC waters, they are faced with new and/or increased stressors in the marine environment. Fin whale distribution mirrors that of their prey, which whalers were aware of (Nichol et al. 2002). Fin whale sightings were most frequent along bathymetric features that aggregate prey, particularly euphausiids, which fin whales are known to target along the west coast of North America (Flinn et al. 2002). However, changing ocean regimes and anomalies of increased water temperatures in the Pacific Ocean have altered zooplankton species composition along the BC coast (Galbraith and Young 2020). With warmer ocean temperatures expected due to climate change, northward shifts in zooplankton abundance and distribution are expected (Richardson 2008). Although the response from fin whale populations is so far unknown, these changes will dictate the location, abundance, and quality of their prey, which may be reflected in future fin whale presence and habitat use. Climate change also has a role in sea level rise, ocean acidification, more intense and frequent marine heatwaves and storm events, and altered nutrient cycling and sequestration (Cao and Caldeira 2008, Hutchins and Boyd 2016, Oliver et al. 2018, Frederikse et al. 2020). The large body size, long generation time and low reproductive rates of fin whales increase their vulnerability to climate change effects, either directly or through changes in habitat suitability of prey resources. Adaptations of habitat use may become apparent as whales try to exploit localized concentrations or prey hotspots (Ramp et al. 2015, Notarbartolo di Sciara et al. 2016). More ‘opportunistic nomadism’ (Jonzen et al. 2011), contractions in range, or altered or weakened migration patterns may indicate behavioural means of adapting. Declines in reproductive success may also become apparent as a result (Kershaw et al. 2020, Notarbartolo di Sciara et al. 2016).

The consistent signs of fin whale repopulation along the BC coast (Towers et al. 2018, Keen et al. 2021) makes them increasingly vulnerable to anthropogenic threats. Propeller driven vessels have increased remarkedly both in number in operation and in vessel size in the period since whaling ceased (McDonald et al. 2006, Hildebrand 2009) and the ambient noise levels have increased, in particular in the frequencies used by fin whales (Andrew et al. 2002, McDonald et al. 2006, Hildebrand 2009, Frisk 2012, Mikis-Olds and Nichols 2016). Marine vessel traffic in BC is concentrated around Vancouver Island, especially nearest the ports of southern BC and Washington State, but international shipping routes span much of BC waters (Erbe et al. 2014). Although all large whales are susceptible to vessel strikes, fin whales are especially vulnerable (Laist et al. 2001). As the fin whale population in the Pacific Ocean increases, and vessel traffic also increases, the number of ship strikes is expected to rise. The risk of vessel strikes from increased vessel presence has been noted for fin whales in the literature (e.g., Williams and O’Hara 2010, David et al. 2011); proposed energy projects are cited as a particular risk for whales in northern BC that display site fidelity to foraging habitat (see Nichol et al. 2017, Keen et al. 2023), with similar findings reported due to the proximity of fin whale habitat to commercial shipping lanes in other regions (e.g. Castro et al. 2022). The location and population-level effects of collisions are still poorly known, but evidence from body scars and strandings are being used to try to better estimate risk. However, unreported strikes or undocumented fatalities mean that our understanding likely underestimates the level of threat this could pose for fin whales (Williams and O’Hara 2010). Vessel travel speed is likely the most important variable in estimating the risk of collision, and likelihood of lethality if it occurs (Laist et al. 2001, Vanderlaan and Taggart 2007, Keeley et al. 2021).

The effects of vessel presence extend beyond collision injury and fatalities; noise levels from propeller driven vessels have changed the marine environment of BC waters considerably. The increasing reliance on commercial ocean transport routes has been the driving force behind a global doubling in ambient sound levels every decade over the last 70 years (Hildebrand 2009, Andrew et al. 2011, Frisk 2012). Fin whales are highly acoustic animals, especially during periods of breeding and foraging. However, increasing underwater noise additions from large vessels are concentrated in the low frequencies, where fin whale calling is focused. Acoustic disturbance can induce a stress response in whales (e.g., Rolland et al. 2012), or disrupt key behaviours such as foraging, social or mating behaviours through the abandonment of these behaviours, avoidance of a key region where these areas are undertaken due to noise levels, and the reduced effectiveness of calling through acoustic masking. The full implications of the masking of fin whale communication signals are still largely undetermined, but increasing noise levels can change fin whale acoustic and behavioural patterns by modifying song characteristics and causing avoidance of areas with increased noise levels (Castellote et al. 2012, Southall et al. 2023). Passive acoustic monitoring will not only aid in tracking the assumed fin whale population recovery, but also allow an estimate of the potential level of threat of underwater acoustic disturbance. Soundscape analysis can detail the noise levels that whales are exposed to, and the level of exposure over time. Although masking and behavioural/calling modification is considered a sub-lethal effect it can increase the energetic load of a whale, while also decreasing the amount of information it is receiving about its surroundings, and so has the potential to impact their success or survival. In addition, if exposure is great enough (from noise amplitude and/or time of exposure) physiological effects such as temporary or permanent hearing impairment may result, with morphological damage also documented in cetacean species (see Erbe et al. 2019).

Other risks for fin whales include entanglement, toxicity from plastic/micro-plastic pollution from ingestion, exposure to persistent organic and heavy metal pollutants (see Fossi et al. 2012, Espada et al. 2024), harmful algal blooms, and the potential for oil spills. Risk assessments start with the consideration of the pathway of effect and risk to individuals by assessing the spatial and temporal overlap, allowing consideration of how that might escalate to risk of group or population-level consequences more broadly.

Conclusions

The collation of evidence suggests that fin whales are recovering, if not entering a period of stability in numbers of individuals. There is evidence of fin whale population increase for the Canadian Pacific, as well as repopulation of areas along the BC coast. This is further supported by the annual population growth in areas to the north in Alaska and the south in California. However, the efforts to track the recovery of the whales in their core habitat, in deeper waters and off the shelf break, is limited. This restricts our appreciation of the current population size and dynamics, with the conclusions made so far being mostly limited to on-the-shelf observations, which may represent more of a peripheral population recovery. Acoustics may be employed to fill knowledge gaps about offshore repopulation and habitat use over time and space. However, the conclusions drawn come with caveats. More field observations and genetic sampling will refine our ideas of population number, site fidelity, residency times, population dynamics and composition, including potential sub-groupings or clades (Archer et al. 2013). With their long generation and gestation times, recovery to pre-whaling numbers will be slow

(Best 1993, Zerbini et al. 2010) and the legacy of whaling removals be felt for some time to come. Worldwide, fin whale populations are experiencing varying degrees of recovery, but their numbers seem to be increasing in the Southern Hemisphere (Herr et al. 2022) and North Atlantic (Vikingsson et al. 2009). A more broad, trans-boundary appreciation of population structure may be needed, especially for mitigating threats associated with commercial shipping and climate change that are more global problems.

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CHAPTER 2

Spatial and Temporal Distribution of Whale Species From Acoustic Recordings Made on the West Coast of Vancouver Island

Abstract

Several cetacean species used habitat in BC waters before their populations were heavily reduced by commercial whaling. There is indication that some of these populations are again using historical areas in BC. Here, acoustic recordings from a coastal and an offshore site were analyzed for species vocal presence to determine their occurrence over spatial and temporal scales and to compare differences in their habitat use. The variability in species presence at the two sites indicates preferred habitat for several cetaceans, such as humpback and killer whales that favor the coastal location, compared to the offshore use by fin, blue, sei, and sperm whales. This comparative habitat study agrees with previous works on marine mammal distributions in BC and can be added to research over the coast of BC and the eastern Pacific Ocean to better understand these species' ecology and their recovery process after decades of removals.

Introduction

The productive waters off the coast of British Columbia (BC) host several cetacean species, which were heavily depleted by commercial whaling. Research on their use of habitat and range as they recover is ongoing (see Williams and Thomas 2007; Ford et al., 2010; Wright et al. 2021). As ocean regimes change (Cao and Caldeira, 2008; Hutchins and Boyd 2016; Oliver et al., 2018; Frederikse et al., 2020), the influence of different temporally and spatially dynamic biological and ecological variables could drive them into alternative areas from their historical range (Ramp et al., 2015; Record et al., 2019; Davis et al., 2020; Galbraith and Young 2020;

Peters et al., 2022). Spatial modeling and catch records of large whale species has since indicated some have an affinity for deeper offshore waters and regions of greater bathymetric complexity (Hui 1985, Gregr and Trites 2001, Clapham et al. 2004, Mizroch et al. 2009, Gregr 2011, Ivashchenko et al. 2014), with oceanographic variables influencing whale habitat use through the presence and abundance of their prey (Gregr 2000, Gregr and Trites 2001, Tynan et al. 2005). Along the west coast of Vancouver Island, data from a fixed passive acoustic monitoring (PAM) recorder indicated the use of offshore areas, with preference for the continental slope by several large whale species (Burnham et al. 2019). The research by Burnham et al. (2019) focussed on a study period during the early spring and summer; expanding the analysis to capture a year's worth of recordings will widen the temporal scope of this analysis and allow the examination of patterns of species presence in BC waters.

Whale habitat use has been associated with bathymetric complexity, used as a proxy for prey abundance (Moore et al. 2002, Calambokidis et al. 2004, Reilly and Thayer 1990, Ballance and Pitman 1998, Gregr and Trites 2001, Croll et al. 2005, Burnham et al. 2021). This has been noted particularly for those species that favour deep, offshore waters. Variables such as water depth, slope/rugosity, proximity to bathymetric features including shore or the continental shelf break correlate with whale presence, with these and dynamic oceanographic variables driving their ability to use waters off the BC coast for key behaviours such as foraging (Gregr and Trites 2001, Burtenshaw et al. 2004, Dalla Rosa et al. 2012, Burnham et al. 2021). Within BC waters, bathymetric features vary from offshore marine canyons, seamounts, and a steep continental slope, to coastal fjords and rocky coastlines, which creates increased ecosystem complexity (Ban et al. 2016). These features can also aggregate mid-trophic level species, creating some predictability as to where and/or when prey abundance may increase. Additionally, being at the confluence of several large currents results in seasonally upwelled waters in summer at the shelf break, bringing nutrient-rich water to the surface and fueling primary productivity and abundance in planktonic prey (Thomson 1981, Mackas 1992, Foreman and Merryfield 2011, Boldt et al. 2019). Due to the high biological productivity here, identification of whale habitat in BC waters is generally limited to areas of key foraging behaviour (Dalla Rosa et al. 2012, Nichol et al. 2018, Keen et al. 2018); however, habitat use extends beyond areas that provide foraging opportunities and research increasingly shows several species use BC waters in some capacity year-round (Nichol and Ford 2018, Burnham 2019, Frouin-Mouy et al. 2022).

In place of visual data, which can be logistically challenging to obtain, passive acoustic monitoring can be used to try to fill in some knowledge gaps of whale presence and habitat use. Calls in the acoustic records indicate presence of at least one individual of the identified species within the detection range and can represent the relative presence of vocalizing whale species (e.g., see Ponce et al. 2012, Burnham and Duffus 2020). Additionally, patterns in calling on multiple temporal scales and the call types used over these periods can be indicative of the social, behavioural or physiological context. Seasonally, whale calls associated with feeding, breeding, or social behaviour can be used to understand the dominant behaviour at the time and location of the recording (Stafford et al. 2001, Širović et al. 2004, Širović et al. 2013, Burnham 2019, Shabangu et al. 2019). The predominant call type, and therefore presumably behaviour, may change over time, influenced by environmental and biological factors such as prey availability (Širović et al. 2004, Oleson et al. 2007, Širović et al. 2013, Burnham 2019, Ryan et al. 2019, Wingfield et al. 2022). Additionally, diurnal patterns may indicate times where, for example, active foraging is occurring, rather than resting or social behaviours (Stafford et al. 2005, Wiggins et al. 2005, Shabangu et al. 2019).

Here, acoustic recordings from two hydrophones off Vancouver Island were analyzed to determine the occurrence of whale species in time and space, and to compare temporal and spatial patterns in their habitat use. Overlapping temporal acoustic data from a coastal and an offshore site were selected to compare species use of these two different marine environments. The spatial and temporal patterns of whale presence were used to determine residency and behavioural context of vocalizations; for each species, monthly and diurnal acoustic patterning was examined at each location. Although the focus was on calls in frequencies below 1 kHz, which excludes most odontocete species, sperm and killer whale acoustic presence was noted as their vocal range extends down into these lower frequencies.

Methods

Acoustic data collection

Acoustic data were obtained from two locations in British Columbia waters to compare a coastal to an offshore site over time. The coastal site at Swiftsure Bank was located at the mouth of the Salish Sea about 13 nautical miles west of Vancouver Island (48.515° N, -124.936° W) (Figure 1) and source recordings were obtained from the Department of Fisheries and Oceans Canada (DFO). The recordings from Swiftsure Bank were made using an Autonomous Multichannel Acoustic Recorder (AMAR G4, JASCO Applied Sciences) with an omnidirectional (GeoSpectrum M8E-132) calibrated hydrophone placed at a 74 meter depth. This hydrophone recorded continuously at a maximum sampling rate of 256 kHz with a sensitivity of -164 dB re 1 V/µPa and an effective bandwidth of 5 Hz to 128 kHz (± 6 dB bandwidth). Continuous recordings from April 15, 2018, to November 15, 2019, were examined for this study. The offshore site at Clayoquot Slope was located on the continental shelf-break about 45 nautical miles (nm) west of Vancouver Island at the base of Clayoquot Canyon (48.700° N, -126.872° W) (Figure 1) and source recordings here were obtained from the Ocean Networks Canada (ONC). Acoustic data was recorded continuously at a depth of 1255 m at a maximum sampling rate of 32 kS/sec by an Ocean Sonics icListen AF hydrophone with a sensitivity of -159 dB re 1 V/μPa and a frequency range of 1 Hz to 12 kHz (± 3 dB bandwidth). This recorder is part of the ONC Neptune Observatory cabled network and has been in place since 2009; here the focus was data between July 1, 2018, to July 1, 2019 (Ocean Network Canada Oceans 3.0 Data portal, https://data.oceannetworks.ca/home).

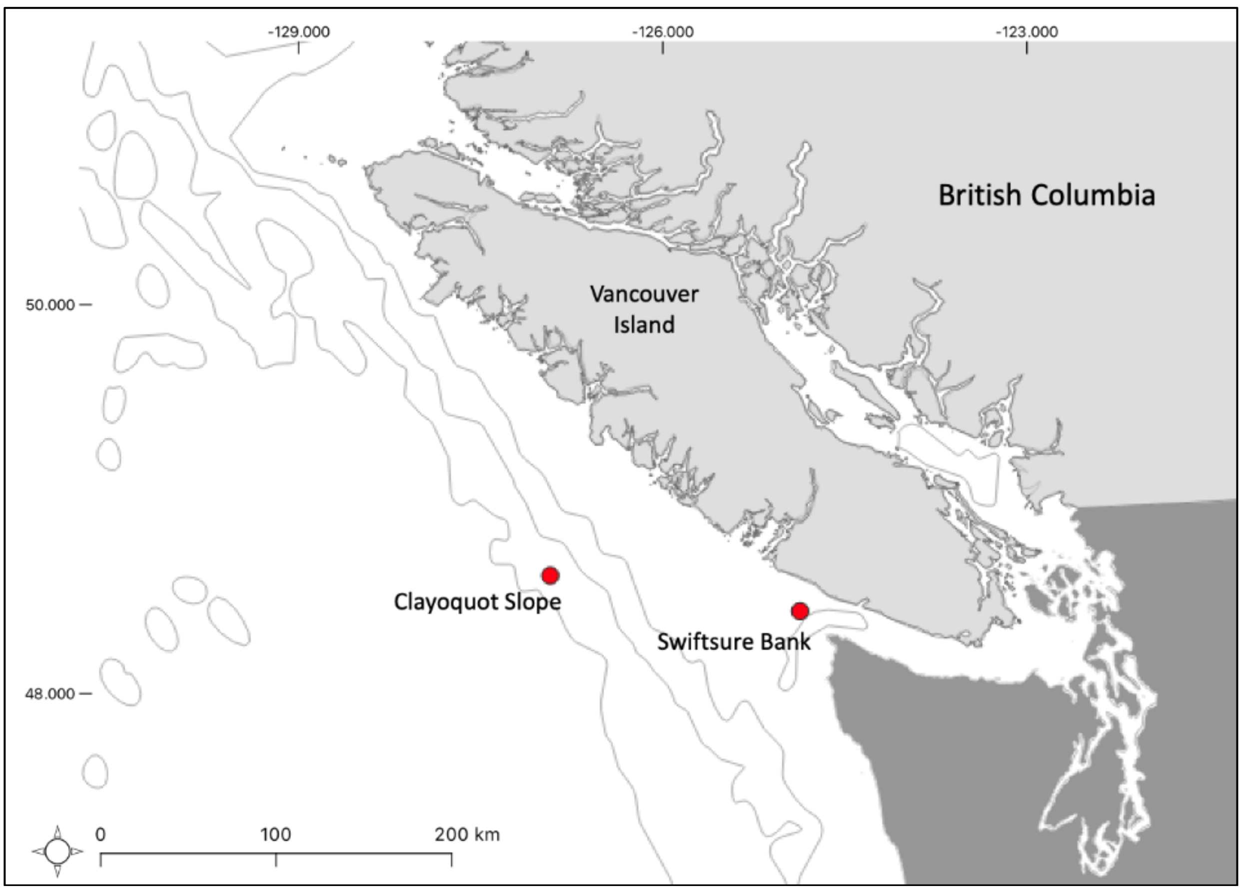

Figure 1: Map of the British Columbia coast. The two bottom mounted hydrophones providing the acoustic recordings for this study are indicated by red circles.

Data analysis

Recordings were subject to manual aural-visual verification using spectrograms generated in Raven Pro Interactive Sound Analysis Software (Version 1.6.4; Charif et al. 2010, Center for Conservation Bioacoustics 2014). A systematic sampling method was used, analyzing every other 5-minute recording in a 24-hour period of every fifth day for a 20-month period (April 15, 2018, to November 15, 2019) for Swiftsure Bank, and a full year of recordings (July 1, 2018, to June 30, 2019) for Clayoquot Slope. It is the latter recording period over which the recordings are compared. This sampling method allowed for manual analysis in excess of 10% of the total recordings at each site. Spectrograms were generated using a 256-point Hann window FFT with 50% overlap. All species present in recordings were noted. Species' vocalizations were identified in the recordings using descriptions from previous studies to confirm species identification. For each five-minute clip, species were marked as present using only a binary system and call counts were not included in this analysis. Where possible, call type or patterns known to indicate behaviour were also noted. Vessel noise in recordings was also marked as present-absent using a binary system. Vessel noise was indicated both as a direct identifiable source of noise (the presence of Lloyd's Mirror (LM) curves in the spectrogram, indicating the direct overhead passage of a vessel), and as part of the underwater ambient noise from a more remote source (the presence of vessel bands and/or noise masking natural marine sounds).

The prevalence of calls (i.e. number of clips with acoustic presence) for each species was compared over time between recorders. Monthly and diurnal (day, night, twilight) were examined using daylight savings dates and sunrise/sunset times, respectively, using the National Research Council of Canada's Sunrise/Sunset Calculator (http://www.nrc-cnrc.gc.ca/eng/services/sunrise/advanced.html). In analyzing the periodicity of calls, each 24-hour day was divided into two periods of time corresponding to differing light levels: day and night. A third period of time, nautical twilight (i.e. dawn and dusk), was considered for fin whale acoustic presence, as this species was the focus for this thesis. Nautical twilight was defined as two hours before and after sunrise and sunset, making up a total of eight hours of twilight conditions per day. Day and night periods varied slightly, according to the seasonal shift in daylight hours.

Chi-square goodness of fit tests were used to determine whether calls were evenly distributed among different light periods, taking into account the changing length of day and night across the year. A monthly call distribution for each species was determined, where at least one call was identified in recordings and represented as relative percentages per month. Additionally, a site comparison for species present at both locations over the study period was made to examine the potential for patterns that may indicate movement between the two sites. The analysis here combines the 20 Hz and 40 Hz fin whale call types and does not treat these independently.

Results

A total of 1,675 hours of recordings (20,095 five-minute clips) were manually analyzed from the coastal hydrophone at Swiftsure Bank and a total of 748 hours of recordings (8,971 five-minute clips) were manually analyzed from the offshore hydrophone at Clayoquot Slope. These represented samples of approximately 10 % of the recordings for the study period at each hydrophone.

Seven cetacean species were found in the recordings from the two hydrophones. However, the number of species present and their timing at the two sites differed substantially. Blue, fin, gray, humpback, killer, and sperm whales were present at both locations (see Figures 2 and 3 for example spectrograms). However, only Clayoquot Slope had sei whale calls in the recordings. Clicks and whistles attributable to delphinid species, and most likely Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) (Kanes et al. 2024), were also present only at Clayoquot Slope. The recordings from this offshore site not only had a greater species diversity, but also showed a greater proportion of recordings with whale calls (96.15%) than Swiftsure Bank (61.72%).

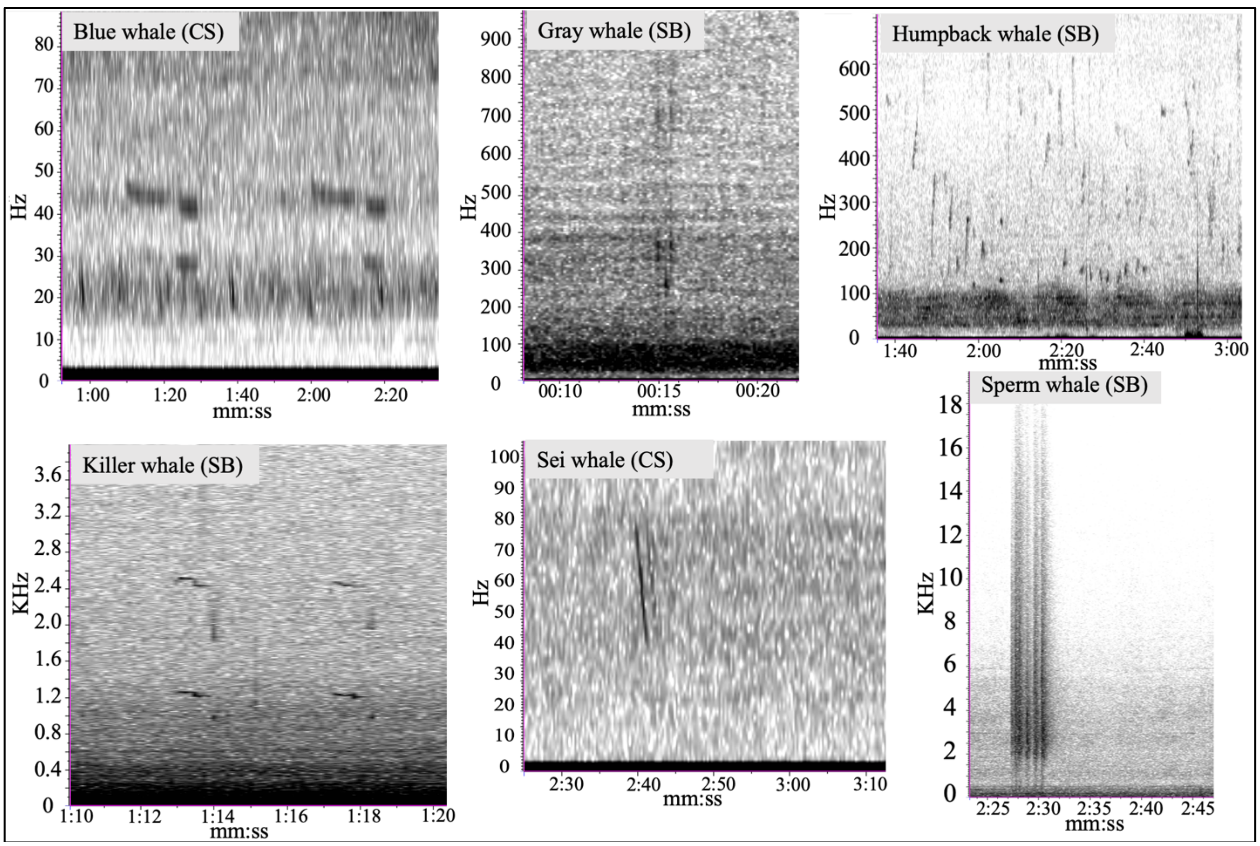

Figure 2: Examples of spectrograms of four mysticete and two odontocete vocalizations identified in the recordings (fin whale spectrograms from both sites are shown in Figure 3). For easier viewing, spectrograms are focussed on different time and frequency scales. Spectrogram was generated using a 256-point Hanning-window FFT with 50% overlap.

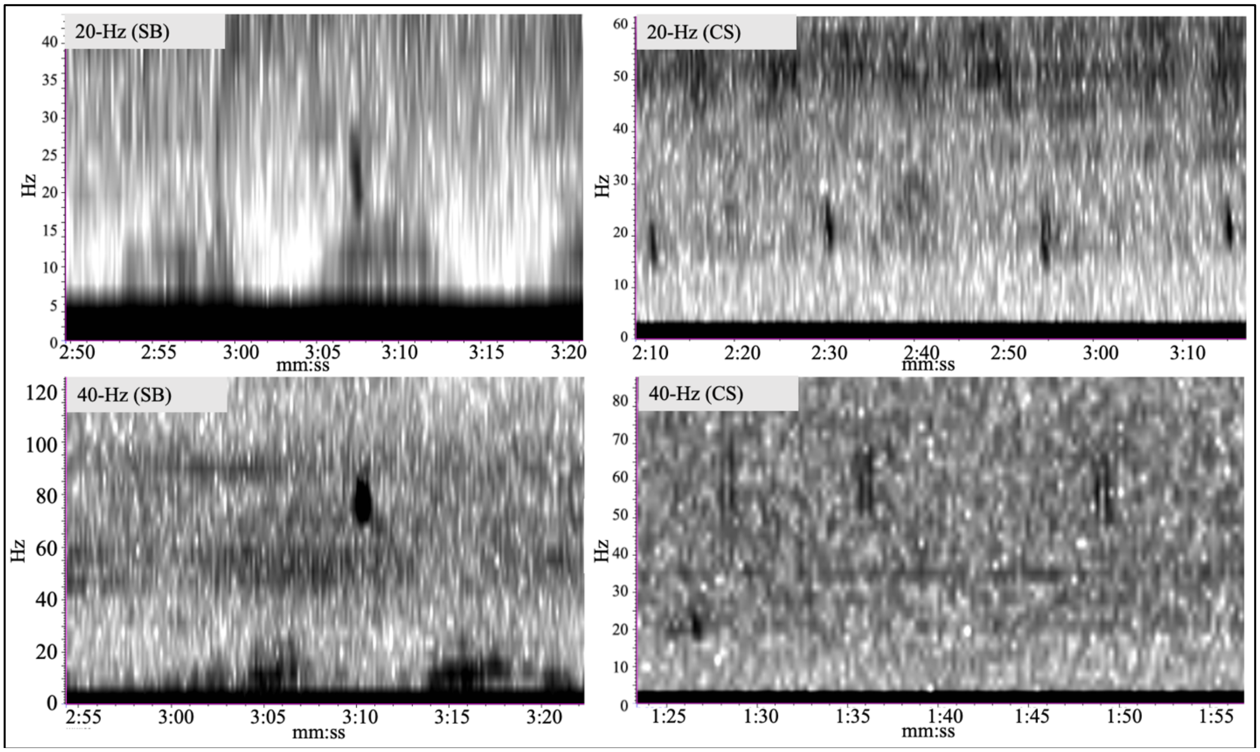

Figure 3: Examples of spectrograms of 20 Hz and 40 Hz fin whale calls identified in recordings at Swiftsure Bank (SB) and Clayoquot Slope (CS). For easier viewing, spectrograms are focussed on different time and frequency scales. Spectrogram was generated using a 256-point Hanning-window FFT with 50% overlap.

Swiftsure Bank

Humpback whale vocalizations dominated the recordings at Swiftsure Bank; they were present in all months with November marking the peak of their vocal presence (Figure 4). Humpback calls were significantly more numerous/prevalent at night than during the day (χ^2 = 79.112, df = 1, p < 0.0001). Both socializing and reproduction vocalizations were present (Fournet et al. 2015, Payne and McVay 1971). Killer whale vocalizations were also present in all months and had a peak in presence in August for both years (Figure 4). Killer whale calls were present significantly more during the day than during the night (χ^2 = 55.60, df = 1, p < 0.0001). Fin whale vocalizations were present in all but four months of recordings at Swiftsure Bank. Both the 20 Hz and 40 Hz fin whale call types were present here, in varying degrees, with a peak in acoustic presence of this species in October (Figure 4). There was no clear diel patterning in fin whale calls here (χ^2 = 0.239, df = 2, p = 0.888), although this could reflect the low statistical power of using small sample sizes that may not allow for accurate conclusions. Gray whale knock calls were present in both October and March, coinciding with their migration past Vancouver Island (Burnham and Duffus 2020), and calls were distributed evenly between day and night (χ^2 = 0.889, df = 1, p = 0.3458). Although less prominent, blue (n=3) and sperm whales (n=5) were also heard in this location. All blue whale calls were at night and sperm whale calls were evenly distributed through the diurnal cycle, although the small sample size limits a full temporal analysis.

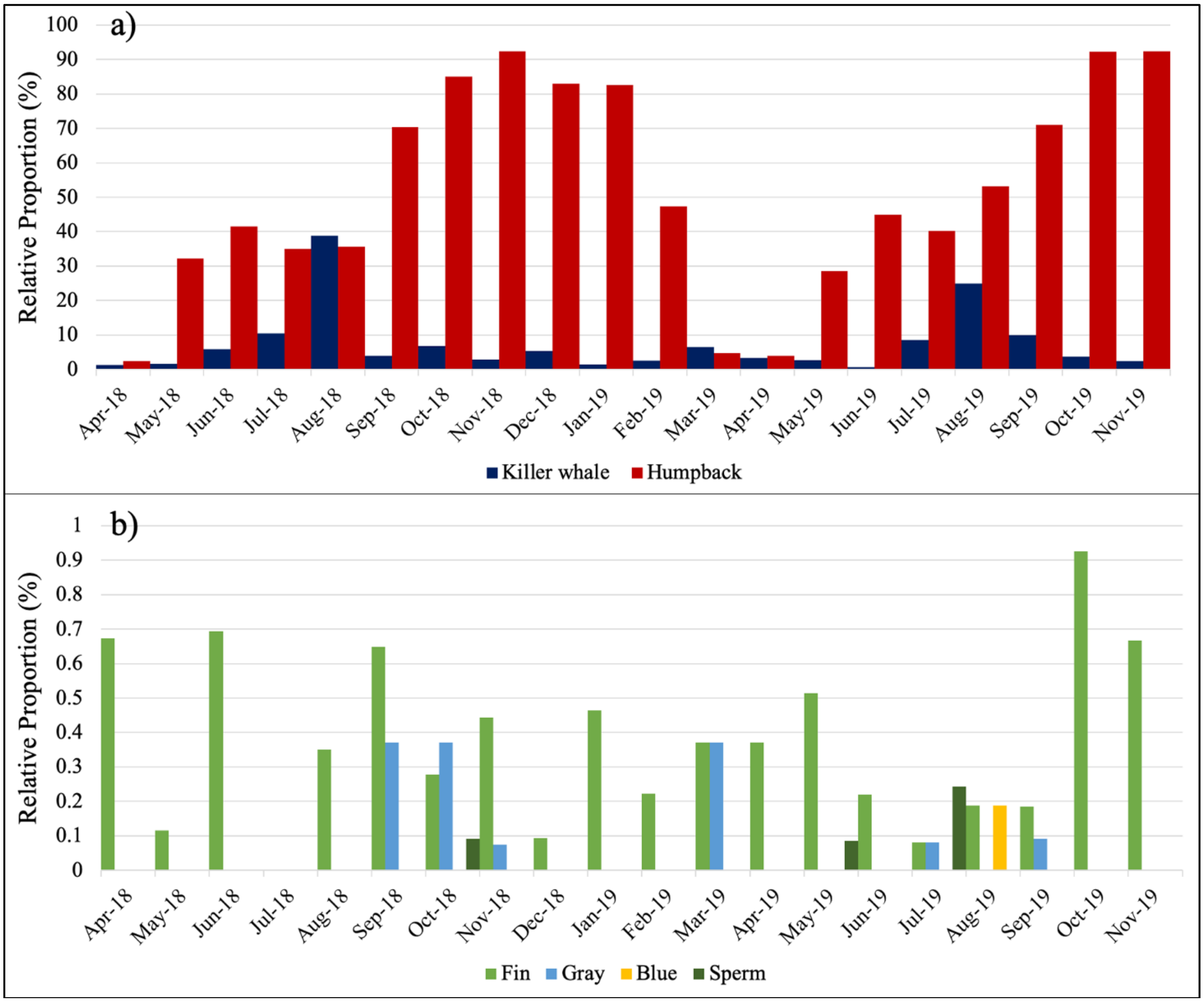

Figure 4: Monthly distribution of species present in recordings from April 2018 to November 2019 at Swiftsure Bank, where at least one call was identified in recordings and represented as relative percentages per month. Panel a) displays the monthly distribution of species with the highest acoustic presence (killer and humpback whales), while panel b) displays the monthly distribution of species with relatively lower acoustic presence (fin, gray, blue, and sperm whales). Note the use of different scales along the y-axes.

Table 1: The presence of whale calls at Swiftsure Bank by species as a proportion of the full deployment time (November 2018 to April 2019) and from the clips that have shown at least one whale call.

Species	Proportion of recordings (%)	Proportion of whale presence (%)
All whales	61.717	
Blue whale	0.001	0.020
Fin whale	0.368	0.599
Gray whale	0.075	0.122
Humpback whale	54.451	88.635
Killer whale	6.504	10.587
Sperm whale	0.025	0.041

Swiftsure Bank Vessel Presence

Vessel noise was present in 97.27% of the recordings at Swiftsure Bank and was indicated both as a direct identifiable source of noise (the presence of LM curves) and as part of the underwater ambient noise (the presence of vessel bands and/or noise masking natural marine sounds). In 2018, the highest proportion of LM curves was in July, whereas in 2019 this was in August (Figure 5). Vessel presence often visually and aurally masked whale calls, especially when LM curves were present. Over the 20-month period, there were 1,688 center LM curves present in the acoustic recordings here.

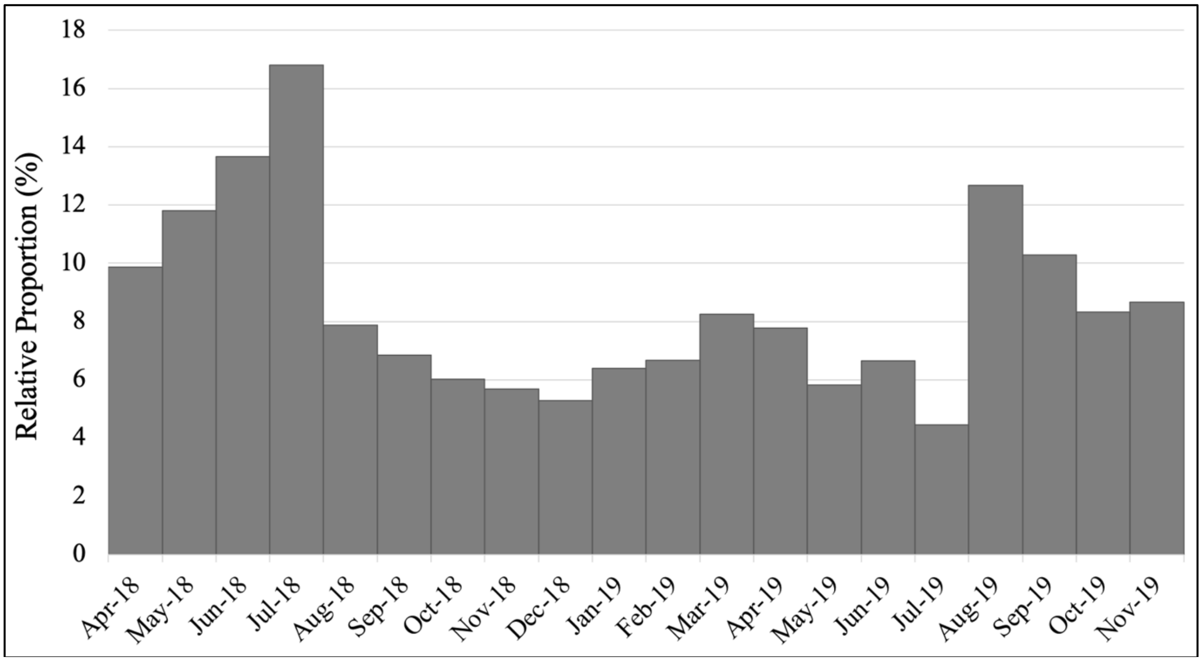

Figure 5: Monthly distribution of Loyd's Mirror (LM) curves present in recordings from April 2018 to November 2019 at Swiftsure Bank, where at least one LM curve was identified in recordings and represented as relative percentages per month.

Clayoquot Slope

Fin whale calls dominated the recordings at this site, with calls present in 70.72% of the clips examined. Fin whale vocalizations were present in all months at Clayoquot Slope and a substantially larger number of fin whale calls were heard at this site compared to Swiftsure Bank. Both the 20 Hz and 40 Hz call types were present. Fin whale acoustic presence peaked between September and January, when nearly 100% of recordings had at least one fin whale call (Table 2, Figure 6). These were not distributed evenly throughout the diel period; there were significantly more fin whale calls during the night than during day and twilight ($\chi^2 = 3421.168$, df = 2, $p < .001$). A more in-depth analysis to examine the 20 Hz and 40 Hz call types independently follows in subsequent chapters. The next most acoustically prominent species present was humpback whales, identified in 1,370 of the 8,971 clips (15.27%). Their vocal presence peaked in January, after which it declined and remained relatively low the remainder of the study period

(Figure 6). There were more humpback whale calls during the night than the day (χ^2 = 584.264, df = 1, p < 0.0001). Delphinid species were heard in 5.25% of the recordings. December marked the peak of their vocal presence, while their lowest vocal presence was in June (Figure 6). Almost all blue whale calls (n=366) were heard between October and December with a peak in December. During this period, instances of blue whale acoustic presence that spanned the entire 24-hours of the day analysed were noted, often with only short breaks (~5 -10 minutes) in calling. These calls were pulsed A and B tonal call pairs, indicative of song (Oleson et al. 2007). There were more blue whale calls during the night than the day (χ^2 = 8.053, df = 1, p = 0.0045). Other species were less prominent; sei (n=10), gray (n=4), sperm (n=52), and killer whales (n=9) were also heard here. Gray whale calls were noted at this location in July, January, and February. However, the offshore presence of these calls decreases the confidence of these findings, with the expectation that they would be foraging in July or undertaking a typically near-coast northern migration in the winter months. The acoustic presence of sperm whales was highest in May and calls were made equally between day and night (χ^2 = 0.00, df = 1, p = 1.000). Killer whale calls were also present here, with calls in June, July, February and March and a peak in vocal presence in June. Most of these calls were during daylight hours (χ^2 =5.444, df = 1, p = .0196). Due to the rarity of recorded calls of sei whales, and paucity of data generally for their presence, the call number was also noted for this species. A total of 17 sei whale calls were found in 10 5-minute clips; 12 of these calls were heard within a three-hour period from 4:10:00 PST to 7:00:00 PST on August 20, 2018, and, based on the interval between and relative strength of calls, were likely produced by a single whale.

Table 2: The presence of whale calls at Clayoquot Slope by species as a proportion of the full deployment time (July 2018 to July 2019) and from the clips that have shown at least one whale call.

Species	Proportion of recordings (%)	Proportion of Whale Presence (%)
All whales	96.154	
Blue whale	4.080	4.243
Fin whale	70.717	73.545
Gray whale	0.045	0.046
Humpback whale	15.271	15.882
Killer whale	0.100	0.104
Other odontocetes	5.250	5.460
Sei whale	0.111	0.116
Sperm whale	0.580	0.603

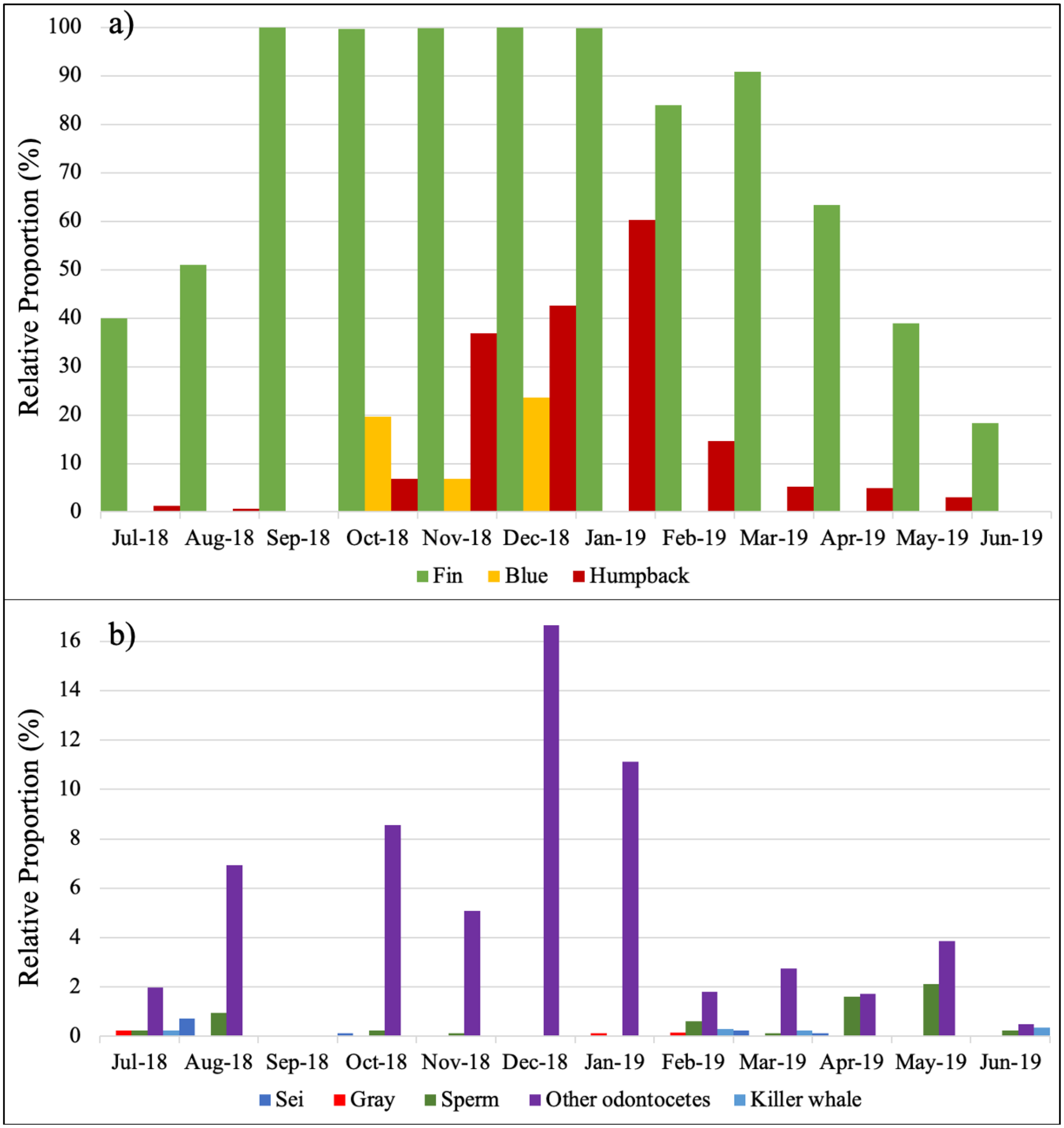

Figure 6: Monthly distribution of species present in recordings from July 2018 to June 2019 at Clayoquot Slope, where at least one call was identified in recordings and represented as relative percentages per month. Panel a) displays the monthly distribution of species with the highest acoustic presence (fin, blue, and humpback whales), while panel b) displays the monthly distribution of species with relatively lower acoustic presence (sei, gray, sperm, killer whales, and other odontocetes). Note the use of different scales along the y-axes for each panel.

Clayoquot Slope Vessel Presence

Although vessel noise was nearly continuous at Clayoquot Slope and present in 99.13% of the recordings, it was usually most often as part of the underwater ambient noise. The highest proportion of LM curves was in December 2018, although not considerably higher than other months due to the relatively low proportion of LM curve presence overall (Figure 7). A total of 244 LM curves were present in recordings over the 12-month period.

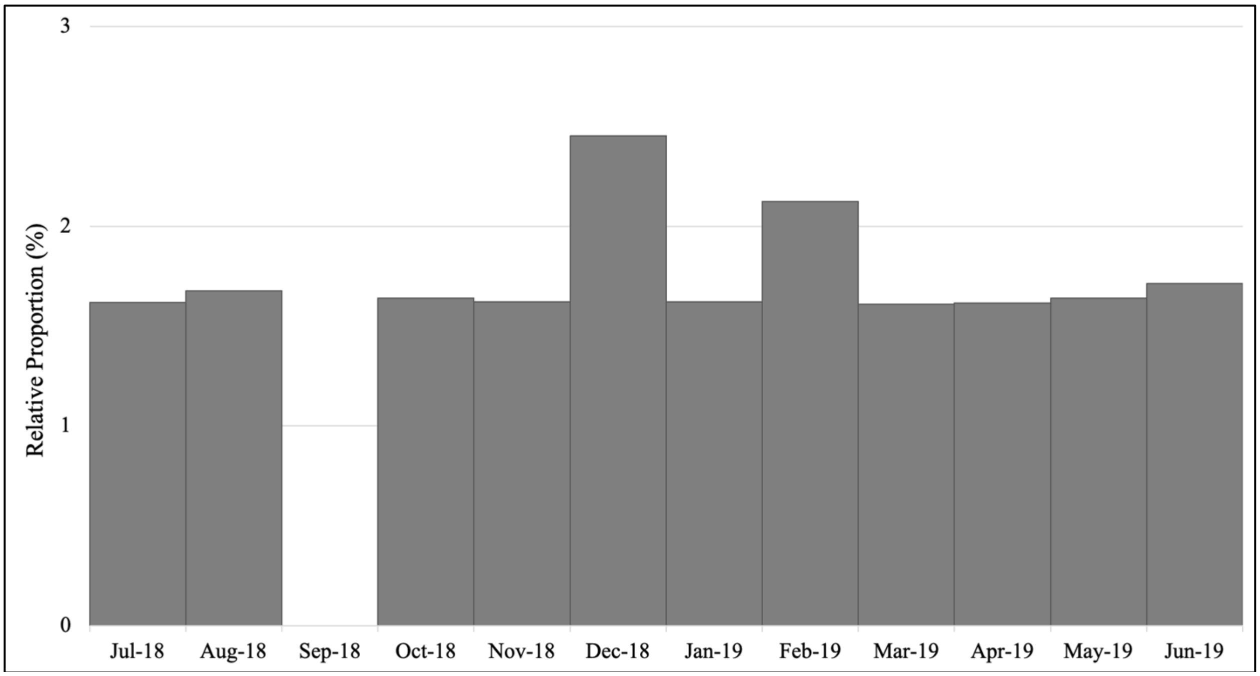

Figure 7: Monthly distribution of Loyd's Mirror (LM) curve presence in recordings from July 2018 to July 2019 at Clayoquot Slope, where at least one LM curve was identified in recordings and represented as relative percentages per month. Note the absence of LM curves in September is indicative of the decreased data availability during this month.

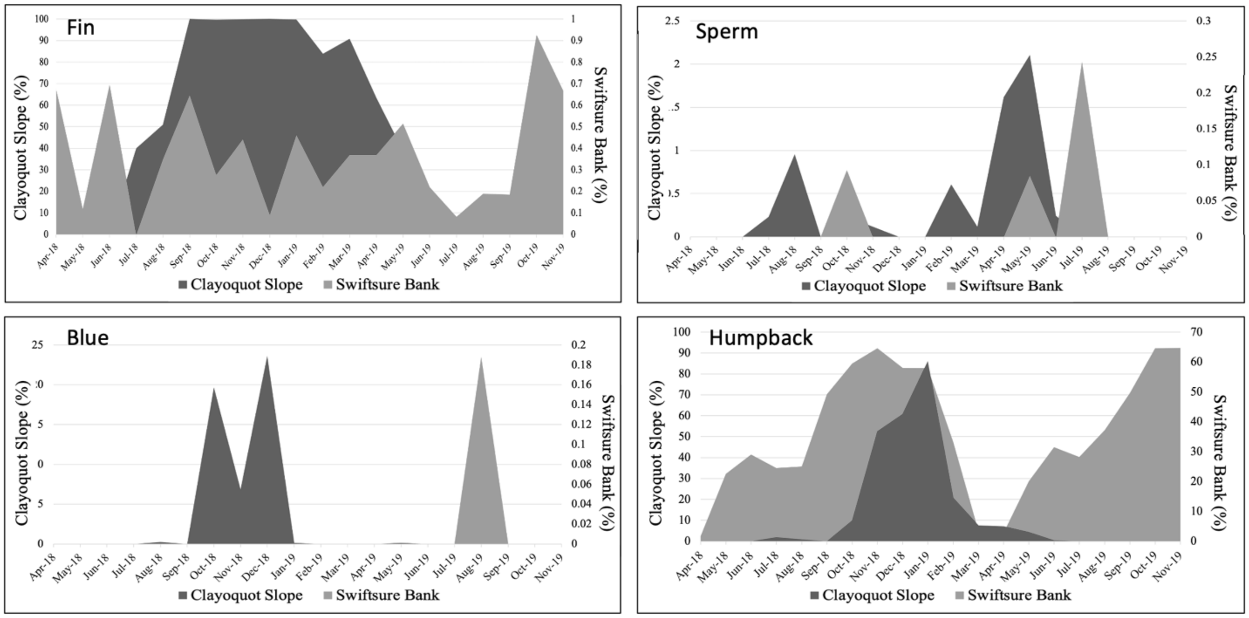

Figure 8: Site comparisons for the relative presence of species from Clayoquot Slope and Swiftsure Bank recordings to examine the potential of species movement between the two study sites, where at least one call was identified in recordings and represented as relative percentages per month. Species with significant presence at both study sites are included here, with the exception of killer whales that have presumed site-specific ecotypes. Note that for easier viewing, axes of relative proportion differ in scale.

Discussion

From recordings at the coastal site of Swiftsure Bank and the offshore site at Clayoquot Slope, eight large cetacean species were acoustically present over the study period. Both sites had blue, fin, gray, humpback, killer, and sperm whale calls present to varying degrees. However, Clayoquot Slope had the addition of sei whale calls, as well as delphinid species. Overall, Clayoquot Slope had higher whale presence (96.15% of recordings) than Swiftsure Bank (61.72% of recordings). Each site had a single whale species that made up most whale presence; Swiftsure Bank was dominated by humpback (88.64% of calls), while Clayoquot Slope had primarily fin whale calls (73.55% of calls). Together, the data provide a snapshot of relative species distributions of cetaceans in a year along the west coast of Vancouver Island that can be added to research over the coast of British Columbia and the eastern Pacific Ocean to better understand these species' ecology (Williams and Thomas, 2007; Gregr and Trites, 2001; Ford et al., 2010; Nichol et al., 2018). The variability in species presence over the two sites does indicate preferred habitat for several cetaceans, such as humpback and killer whales that favored the coastal location, compared to the offshore site use by fin, blue, sei, and sperm whales.

Overall, this study agrees with previous literature about marine mammal distributions in BC (Nichol et al. 2018, Burnham 2019, Burnham et al. 2019, Dalla Rosa et al. 2012, Wright et al. 2021, Williams and Thomas 2007, Ford et al. 2010, Gregr and Trites 2001). However, this habitat analysis further contributes to knowledge of species distributions in BC due to the constant acoustic data collection in these areas over a full annual period, which is difficult or impossible to do through visual survey methods. Considering the full annual period allowed for data collection in winter, which has been largely absent in previous visual surveys in offshore regions (Wright et al. 2021). Using acoustic methods also allowed for analyses of the distribution patterns of several cetaceans simultaneously, giving indication of how these species may interact over time and space.

It should be noted there are caveats with the use of acoustic methods. Whale acoustic presence only indicates the presence of at least one vocalizing individual, and call absence cannot be inferred to mean the absence of whales. This means that some of the patterns described here may be indicative of behaviour rather than merely intensity of habitat use. For instance, the increase in fin whale calling during the winter periods does not mean there are more fin whales during the winter period here and may simply reflect that the acoustic behaviour of individuals in winter has increased. Moreover, this research does not determine the number or relative abundance of whales from the acoustic data, as this was not possible using single hydrophones for recording at each site. Therefore, comments on whale abundance through time and space are not possible. Additionally, the behavioural context from call types was only broadly noted here and was only examined in depth for fin whale calls through subsequent chapters of this thesis. The direction of travel was also not determined as this information was unavailable using a single hydrophone set up, although calls were noted in some instances to become more and/or less prominent against background/ in magnitude over a period.

Detection ranges/ propagation distances of species' calls were not calculated for this research. However, generalizations can be made based on the likely sound transmission environment at each site and from detection range calculations previously determined for fin whale 20 Hz calls at Brooks Peninsula that used recordings from 2010 in a study area approximately 168 km north of the locations used for this research (Koot 2015). The shallow (74 m) water recordings from the coastal location at Swiftsure Bank would have a smaller detection range than the deep water (1255 m) recordings from the offshore location at Clayoquot Slope due to the increased loss of acoustic energy in shallow waters (Urick 1967). Additionally, the increased ambient noise levels from vessel noise additions at Swiftsure Bank would have affected the signal-to-noise ratio (SNR) of whale acoustic signals, likely resulting in low levels of call detection. The detection ranges calculated by Koot (2015) were 8.4 km in high ambient noise levels, 112 km in average noise levels, and 1,498 km in low ambient noise levels. Although background noise was not particularly noted for this research, based on the number of LM curves identified at each site Swiftsure Bank would likely be considered high and Clayoquot Slope considered average in ambient noise levels. The distance between the two study sites is approximately 144 km and there were no instances where the same calls were identified at both recording locations, despite the potential for large call ranges for species producing low frequency calls, such as blue and fin whales (Payne and Webb 1971, fin whale 189 dB).

At the offshore location, winter (December-January) was the annual period with the highest whale acoustic presence, whereas June and July had the overall lowest acoustic presence (Figure 6). Mostly owing to the high presence of fin whale calls, but also as contribution from humpbacks and blue whales, Clayoquot Slope had more biological noise from whales during the night in the winter season. This could be attributable to an increased detection radius during these colder periods, although this is unconfirmed as data on water properties in the offshore region is limited. Swiftsure Bank also had increased whale acoustic presence during the winter seasons (October-November) and the overall lowest acoustic presence during the spring (March-April). Swiftsure had more biological noise from whales during the night for all seasons, largely influenced by the concentration of humpback vocalizations during the night. However, the patterns of vessel presence could also be influential in the calls that are discernable in the data at a given time due to altered detection radiuses or the phenomena of acoustic masking. Detection ranges of species' calls were not considered here, but would be an extension to this work, as would considering how the acoustic landscape the whales experience might differ from the recordings received from a bottom mounted recorder (e.g., see Vagle et al. 2021).

This acoustic survey of whale presence was not focussed on a single target species, allowing for an overview of their behaviour that included some uncommon results. Sei whale sightings and acoustic detections in the eastern North Pacific are rare and, although few vocalizations attributed to sei whales were identified in the offshore recordings, their presence is notable here. These calls matched descriptions of sei whale foraging calls (Baumgartner et al. 2008, Neukirk et al. 2020) and were distinguished from blue whale D-calls in their stereotypical nature, with generally longer duration. The presence of blue whale song, as indicated by the repetition of AB calls over time, in several recordings at Clayoquot Slope during the fall suggests the west coast of North America is not only used for foraging purposes (Mate et al. 1999, Bailey et al. 2009, Szesciorka et al. 2020), but also used for breeding behaviour in some capacity for this species (Oleson et al. 2007). Sperm whale clicks used by foraging sperm whales to echolocate prey (Miller et al. 2004) were identified at both Clayoquot Slope and Swiftsure Bank. Typically, this region would be considered too high in latitude for female and immature sperm whales and is likely representative of male sperm whale foraging clicks (Rice 1989). The presence of gray whale Class 1 knock calls at Swiftsure Bank during the spring and fall seasons, both coinciding with their migration timing past Vancouver Island, is noteworthy. These calls are typically used in breeding/calving lagoons (Dalheim 1987), although have been reported during migration (Burnham et al. 2018) and in association with feeding (Burnham and Duffus 2022). Although killer whale calls were not used to determine the clan or pod level throughout the seasons, the pattern of presence over time is consistent with sightings data for southern residents but could also be representative of the increased presence of Bigg's killer whales in the area (Ford et al. 2013, Olson et al. 2018, Stewart 2023). Additionally, killer whale calls were identified in offshore recordings in the early summer and the late winter periods, which are likely indicative of offshore populations and could reflect the seasonal latitudinal shift of their distribution between California and Alaska (Ford et al. 2014).

Baleen whale distribution is often explained by geographical features and physical processes that create conditions of increased prey abundance (Moore et al. 2002, Calambokidis et al. 2004, Gregr and Trites 2001, Dalla Rosa et al. 2012, Moors-Murphy 2014). However, whale habitat use here may extend beyond areas of increased biological productivity to include areas favorable for breeding behaviour. Research increasingly shows several species use BC waters in some capacity year-round (Nichol and Ford 2018, Burnham 2019, Frouin-Mouy et al.

2022). Fin and humpback whales are species with similar morphological adaptations that target the same prey species in BC waters (Flinn et al 2002, Clapham et al. 1997), so resource partitioning of prey opportunities would be expected. The findings here agree with visual surveys that determined spatial portioning for fin and humpback whales during the summer period in an area further north of this study along the Vancouver Island shelf (Wright et al., 2021). However, this study also finds spatial partitioning of these species through the annual period, as indicated by the high presence of humpback whale vocalizations at Swiftsure Bank and the high presence of fin whale vocalizations at Clayoquot Slope over the study period. Winter is typically thought to be a period reserved for breeding and reproductive purposes for both humpback and fin whales (Payne and McVay 1971, Ford et al. 2010, Širović et al. 2013, Burnham 2019). The combination of humpback whale vocalizations peaking during the winter periods (Figure 4) and being produced more significantly during the night than other diel periods at Swiftsure Bank indicates this area is used for reproductive behaviour for this species that are known to produce song during the nighttime periods (Au et al. 2000, Kowarski et al. 2018). Similarly, fin whale vocalizations peaked during the winter period (Figure 6) and were produced more significantly during the night than other diel periods at Clayoquot Slope, indicating this as an area of reproductive behaviour for this species. At the offshore site a shorter window of humpback whale detections was present through this period that peaked in January 2019 (Figure 6), which may reflect humpback whales crossing over the offshore site as part of a migration pathway. Except for this short window, the general lack of spatial overlap between the two sites suggests other factors help to shape their distribution and they utilize spatial partitioning during their breeding seasons that may also be dependent on variables of depth and bathymetry (Varga et al. 2018). This may be in addition to potential prey opportunities at each site, as Swiftsure Bank and

Clayoquot Slope are both areas of increased biological productivity (McFarlane et al. 1997, Burger 2003, Johannessen et al. 2007).

Although this research does not determine the direction of travel for whales, a comparison of site use timing of species may indicate movement between offshore and coastal locations. Peaks in humpback whale call presence were in November for both 2018 and 2019 at Swiftsure Bank and in January at Clayoquot Slope (Figure 8); the lag in timing of presence may suggest humpback whales gather in coastal locations before passing through offshore waters to migratory destinations throughout the North Pacific (Calambokidis et al. 2001). Although low sample sizes did not allow for accurate conclusions, the lag in timing between the two sites also suggests sperm whales pass through offshore waters before arriving in coastal locations (Figure 8). Although the annual timing of presence was inconsistent between 2018 and 2019 at both sites, there was uniformity in the time lag between the two sites of around two months which may suggest the same sperm whales are using both sites. Again, due to a small sample size, accurate conclusions may not be possible for fin whales using Swiftsure Bank. However, the peak acoustic presence for fin whales at Swiftsure Bank was during the spring and fall periods, whereas their peak presence was in winter at Clayoquot Slope (Figure 8). This could indicate fin whales are using each site differently. Examining distributions of call types over seasonal use does confirm this and is the topic of subsequent chapters. The mixed results of diurnal pattern testing for fin whale 40 Hz calls between the offshore and coastal locations agrees with previous research north of this study area (Pilkington et al. 2018) and may also suggest differential foraging use of these locations, which will also be further examined in subsequent chapters.

Although this was not an acoustic study of vessel noise, the differences in vessel and noise presence affected the acoustic quality at each site, which may be relevant for species' habitat selection. For instance, there were seven times the number of LM curves at Swiftsure Bank than at Clayoquot Slope and vessel noise emissions often visually and aurally masked whale calls in the Swiftsure Bank recordings. This was not unsurprising; the recorder at Swiftsure Bank was positioned directly under an international shipping lane and was shallow (74 m deep), creating audio and visual conditions of acute vessel noise. This was especially the case when vessels passed directly over the hydrophone, as indicated by the presence of LM curves, upon which spectrograms were generally swamped with vessel noise interference. Whale species with relatively higher frequency repertoires (humpbacks and killer whales) were more prominent at Swiftsure Bank, while those with lower frequency repertoires (blue, fin, and sei whales) used the continental slope more. Regular and acute acoustic additions in low frequencies that are attributed to large commercial vessels (Burnham et al. 2023) at Swiftsure Bank may affect the ability of species with call repertoires in the low frequencies to send and receive acoustic signals. It is unlikely calls would have transmitted through the acute noise here or without individuals expending additional energy to circumvent the noise. Conversely, whales that call in the higher frequencies, where large vessel sound energy has less of an input, may have been better able to continue to call with less effect. The decreased direct large vessel traffic over Clayoquot Slope may allow for those species with low frequency calls to communicate to conspecifics more efficiently than in busy coastal habitats. This may indicate vessel noise that masks a species' call repertoire is also a factor that shapes their distribution.

Overall, the spatial and temporal presence of whale species in the acoustic data from the two sites agreed with previous literature about marine mammal distributions in BC; blue, fin, sperm whale populations were more common offshore, along the continental shelf edge, while humpback and killer whales were more common in the coastal location. Although Swiftsure

Bank is designated as a critical area for resident whale populations, this study shows areas along the continental slope should be further considered for protective measures for species recovering from decades of whaling. Protection measures for whale populations at Swiftsure Bank, particularly for endangered southern resident killer whales, are ongoing. There are currently no specific protection measures for whales at Clayoquot Slope, despite several at-risk whale populations utilizing this area, such as blue, fin, sei, and sperm whales, as determined in this study. Long-term monitoring would be beneficial for their management as distribution patterns may change over time and can help us better understand their flexibility and plasticity under changing ocean conditions, such as increased vessel noise, changing climates, and changing zooplankton species composition.

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CHAPTER 3

An Introduction to Using Fin Whale Acoustics to Determine Ecology and Habitat Use in BC Waters

Abstract

Fin whale populations in BC waters have experienced mass removals, but indication of their return to historical habitats implores further examination of how they are currently using this region. Here, one year of acoustic recordings were analyzed from two sites in waters off Vancouver Island for the presence of 20 Hz and 40 Hz call types, associated with breeding and foraging behaviour, respectively, to determine fin whale habitat use. The offshore location at Clayoquot Slope had considerably higher fin whale call presence of both types, each were present in all months of the study period, and song patterning was present. The coastal site at Swiftsure Bank had considerably fewer calls, most of which were the 40 Hz type, and song was absent here. This comparison analysis indicates fin whale vocalizations associated with long range communication, breeding, and foraging behaviour is concentrated along the continental slope in BC, but that some foraging occurs over a larger spatial scale that includes coastal areas.

Introduction

Fin whales (*Balaenoptera physalus velifera)* have been recovering in BC waters over the past 50 years, and with this, may have changed their feeding and breeding patterns. This change might be driven by several factors, including ocean conditions and added anthropogenic stresses (Ban and Alder 2008, Chapman and Price 2011, Ramp et al. 2015, Szesciorka et al. 2020, Holt et al. 2022, Peters et al. 2022, Heneghan et al. 2023). Their year-round presence in BC indicates at least some fin whales forego annual migration (Frouin-Mouy et al. 2022, Chapter 2), but behavioural patterns over this period here are largely unknown.

Dedicated field observations to determine current areas of critical habitat for fin whales have been limited (but see Wright et al. 2021) and mostly restricted to coastal regions (Keen et al. 2018, Nichol et al. 2018, Pilkington et al. 2018). Acoustic methods have created opportunities to survey continuously in areas more logistically challenging to cover with vessel-based work, which is especially beneficial for determining fin whale habitat that has both historically been in offshore regions (Gregr and Trites 2001, Mizroch et al. 2009) and where fin whale densities are predicted to be highest in BC waters (Wright et al. 2021). Acoustic recordings have established the presence of fin whale calls, with analysis of call types showing offshore regions of BC to represent locales for foraging and breeding or weaning activities (Burnham 2019, Burnham et al. 2019).

Fin whales produce short duration (~ 1 s), low-frequency (<100 Hz), frequency modulated calls, of which the 20 Hz and 40 Hz pulsed calls are most commonly described. The distinction between these two call types is derived from the frequency where call energy is focused (20 Hz and 40 Hz). The 20 Hz calls generally downsweep from 30 to 15 Hz (Watkins 1981, Koot 2015, Burnham 2018), and have an average sound source level of 189 dB (Širović et al. 2007, Weirathmueller et al. 2017). Fin whale 20 Hz calls are common in oceans worldwide and can either be irregular or arranged in distinct patterns (Watkins et al. 1987, Delarue et al. 2009, Morano et al. 2012, Burnham 2019). When produced irregularly, the 20 Hz calls are typically referred to as counter-calls, likely used to help to maintain herd cohesion for spatially separated whales (McDonald et al. 1995) with sound source levels that allow conspecifics to maintain contact over large distances (Payne and Webb 1971, Edds-Walton 1997). When produced in repeated regular patterns, with consistent inter-pulse intervals (IPI), the 20 Hz calls are referred to as “song” (Watkins et al. 1987). The purpose of fin whale song is still largely unknown but is considered analogous to bird song with a primary function in sexual selection (Croll et al. 2002, Oleson et al. 2014). Fin whale 20 Hz songs are regularly detected in BC, although research is only preliminary, and its patterning and extent to different geographical regions is not yet fully clear. The presence of possible mating-related and song vocalizations in the winter (Koot 2015, Pilkington et al. 2018, Burnham 2019) indicates Pacific Canada could be an important area during the winter breeding season for this major life history event.

Fin whale 40 Hz calls are even lesser known. One of the earliest descriptions of the 40 Hz call type was a 100 to 30 Hz downsweep (Watkins 1981). Although the exact function of these calls is still undetermined, calls are associated with group social calling and periods of feeding (Watkins 1981, Širović et al. 2013, Ramp et al. 2016, Wiggins and Hildebrand 2020). These calls are absent when solitary whales are foraging (Watkins 1981, Ramp et al. 2016), suggesting a communicative function while feeding in a group. Fin whale foraging call rates differ in foraging grounds (Wiggins and Hildebrand 2020), and therefore call prevalence may be dependent on prey abundance and availability (Romagosa et al. 2021, Burnham 2019). Additionally, the diel pattern typically present in fin whale 40 Hz calls varies between regions, suggesting a dietary preference between populations that take advantage of local prey behaviour (Mizroch et al. 2009, Pilkington et al. 2018, Burnham 2019).

The ability to detect fin whale calls as an indicator of presence and describe their full acoustic repertoire is a means to establish fin whale distribution patterns and ecology. Here, passive acoustic methods record fin whale vocalizations from a coastal (Swiftsure Bank) and offshore (Clayoquot Slope) location on the west coast of Vancouver Island to identify their presence and infer their use of habitat over space and time over a full year of data. Fin whale calls were identified by type and any patterning in calling was used to interpret the behavioural use of the habitat. A comparison of fin whale presence at each site was conducted, providing insight into different elements of fin whale habitat in BC waters.

Methods

Acoustic data collection

Acoustic data from two recording platforms were considered. Recordings from coastal and offshore stationary hydrophones were used off the coast of Vancouver Island (Figure 1). The coastal site at Swiftsure Bank was located at the mouth of the Salish Sea about 13 nautical miles (nm) west of Vancouver Island (48.515° N, -124.936° W) (Figure 1) and source recordings here were obtained from the Department of Fisheries and Oceans Canada (DFO). The recordings from Swiftsure Bank were made using an Autonomous Multichannel Acoustic Recorder (AMAR G4, JASCO Applied Sciences) with an omnidirectional (GeoSpectrum M8E-132) calibrated hydrophone placed at a 74 meter depth. This hydrophone recorded continuously at a maximum sampling rate of 256 kHz with a sensitivity of -164 dB re 1 V/μPa and an effective bandwidth of 5 Hz to 128 kHz (± 6 dB bandwidth). Recordings examined for this study were continuous between April, 2018, to November, 2019. The offshore site at Clayoquot Slope was located on the continental shelf-break about 45 nm west of Vancouver Island at the base of Clayoquot Canyon (48.700° N, -126.872 W) (Figure 1) and source recordings here were obtained from the Ocean Networks Canada (ONC). This hydrophone was at a depth of 1255 m and recorded acoustic data continuously at a maximum sampling rate of 32 kS/sec by an Ocean Sonics icListen AF hydrophone with a sensitivity of -159 dB re 1 V/μPa and a frequency range of 1 Hz to 12 kHz (± 3 dB bandwidth). This recorder is part of the ONC Neptune Observatory cabled network and has been in place since 2009; here the focus was data between July 1, 2018, to July 1, 2019 (Ocean Network Canada Oceans 3.0 Data portal, https://data.oceannetworks.ca/home).

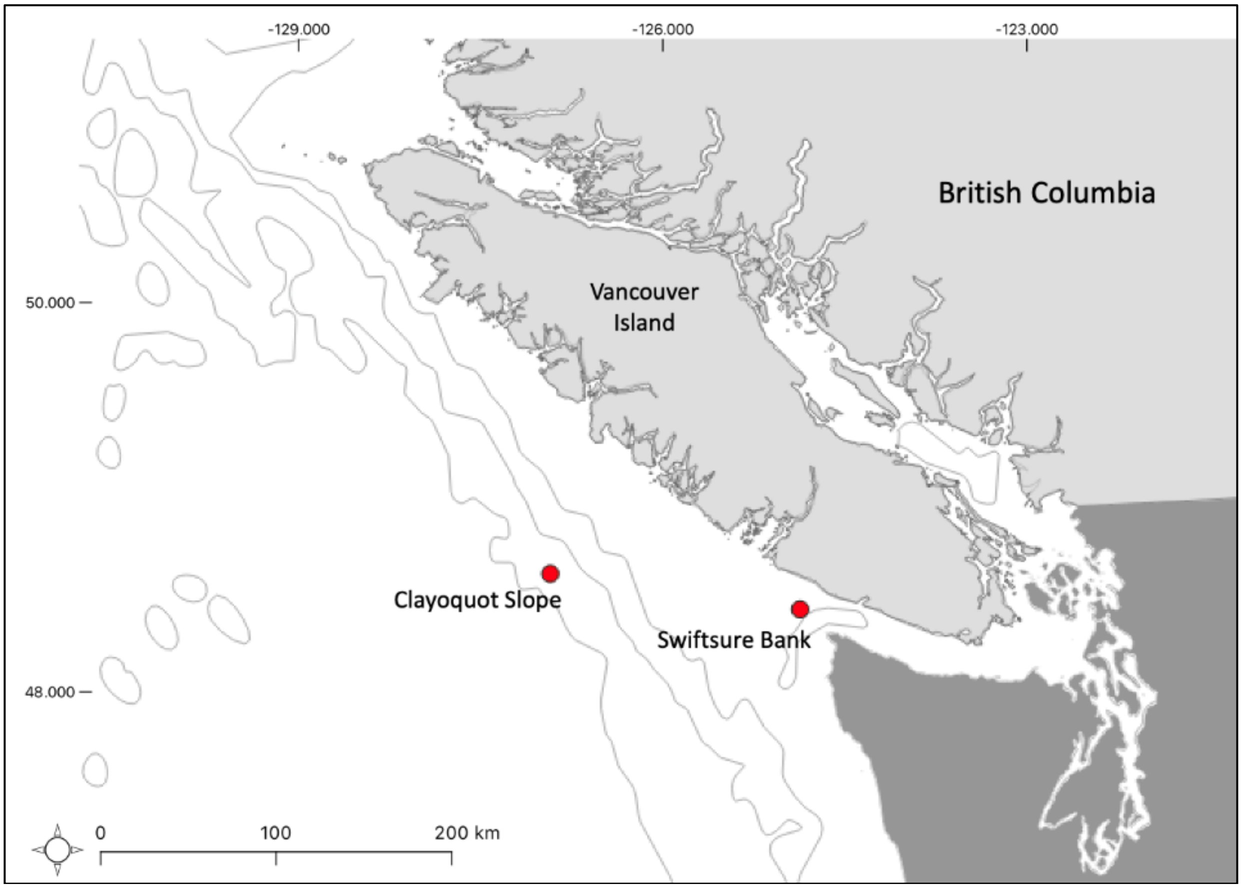

Figure 1: Map of the British Columbia coast. The two hydrophone sources providing the acoustic recordings for this study are indicated by red circles.

Data analysis

The presence of fin whale calls, as a proxy for their physical presence, was determined through manual aural-visual (AV) analysis, with comparisons to call descriptions in the literature, particularly from studies in the northeast Pacific (see Table 1). Recordings were subject to AV verification using spectrograms generated using a 256-point Hann window, 1s FFT with 50 % overlap in Raven Pro Interactive Analysis Software (Version 1.6.4; Charif et al. 2010, Center for Conservation Bioacoustics 2014). A systematic sampling method was used, analyzing every other 5-minute recording in a 24-hour period of every fifth day for a 20-month period (April 15, 2018, to November 15, 2019) for Swiftsure Bank, and a full year of recordings (July 1, 2018, to June 30, 2019) for Clayoquot Slope. This sampling method allowed for manual analysis in excess of 10% of the total recordings at each site. Annotations were made during AV analysis, including the number of calls in each data clip and IPI measurements that would indicate song patterning. For each call, frequency extents and peak frequency measurements were derived using Raven Pro Software (Charif et al. 2010, Center for Conservation Bioacoustics 2014) from manual selection of each call in the recording.

Table 1: Call parameters for 20 Hz and fin whale calls from this study and those previously reported. The number (n) of calls examined, the high-frequency to low-frequency extents (Freq. Range) and peak frequency (Peak Freq.), and call duration (Duration) are given. Calls from Swiftsure Bank and Clayoquot Slope are combined.

Call Type	Author	Location	Study Period	n	Freq. Range (Hz)	Peak Freq. (Hz)	Length (s)
20-Hz	Watkins 1981	W. North Atlantic; Pacific	1958-1980		23-18		~1
	Koot 2015	Vancouver Island	2011	10,362	34.2-15.8	24.5	
	Burnham 2018	Vancouver Island	2016,2017	19,215	27.1-17.8	20.5	1.14
	This study	Vancouver Island	2018-2019	92,621	36.7-4.0	20.8	0.67
40-Hz	Watkins 1981	W. North Atlantic; Pacific	1958-1980		100-30, 'mostly 75-40'		~1
	Širović et al.2013	Bering Sea; Gulf and S. California	2005-2011	60	61.2-47.6		
	Wiggins & Hildebrand 2020	Gulf of Alaska	2015	105	60.5-33.5		
	Burnham 2019	Vancouver Island	2016, 2017	1,152	61.89-45.32	52.7	0.91
	This study	Vancouver Island	2018-2019	16,370	202.4-10.8	50.6	0.58

Histograms were produced using IBM SPSS Statistics (Version 28.0.1.1) to determine the overall distribution of peak frequencies of calls at each site and the variability in peak frequencies of calls. Calls were categorized as 20 Hz or 40 Hz types based on comparisons to frequency parameters previously reported in literature (Table 1), as well as by seasonal patterns in calling and inter-call intervals to indicate behaviour associated with call types (Širović et al.

2013). The prevalence of calls (calls/hr) was compared over time between recorders and peaks in call rates over time were determined. Seasonal (summer-winter) and monthly patterning were examined using daylight savings dates. Seasons were defined as: fall (September 23 to December 20), winter (December 21 to March 19), spring (March 20 to June 20), and summer (June 21 to September 22). Calls were examined for hourly patterns and diurnal periodicity in different light conditions by allocating each call to a period of nautical twilight, day, or night. Standard times of solar rise and set were calculated between the deployment locations using the National Research Council of Canada's Sunrise/Sunset Calculator (http://www.nrc-cnrc.gc.ca/eng/services/sunrise/advanced.html). Chi-square goodness of fit tests using a 95% confidence level were used to determine if calls were evenly distributed among different light periods.

Results

Overall, Swiftsure Bank and Clayoquot Slope both had fin whale 20 Hz and 40 Hz call types present in the recordings. There were 92,261 20 Hz calls and 16,370 40 Hz calls identified in the sample of recordings. However, the two sites differed in the number of recordings with calls, and the prevalence of each call type over different temporal scales. The distribution of peak frequency parameters of calls at both sites shows a bimodal distribution (Figure 2), highlighting the call separation into 20 Hz and 40 Hz types. It should be noted there were higher frequency calls in the latter group from both sites that did not fit typical 40 Hz call descriptions. However, for analysis purposes here, all calls higher than the 20 Hz distinction were categorized as 40 Hz calls and were more broadly considered as a single group here. Calls outside the 20 and 40 Hz distinctions are not well described in the literature, and these calls are further examined in Chapter 4 and 5.

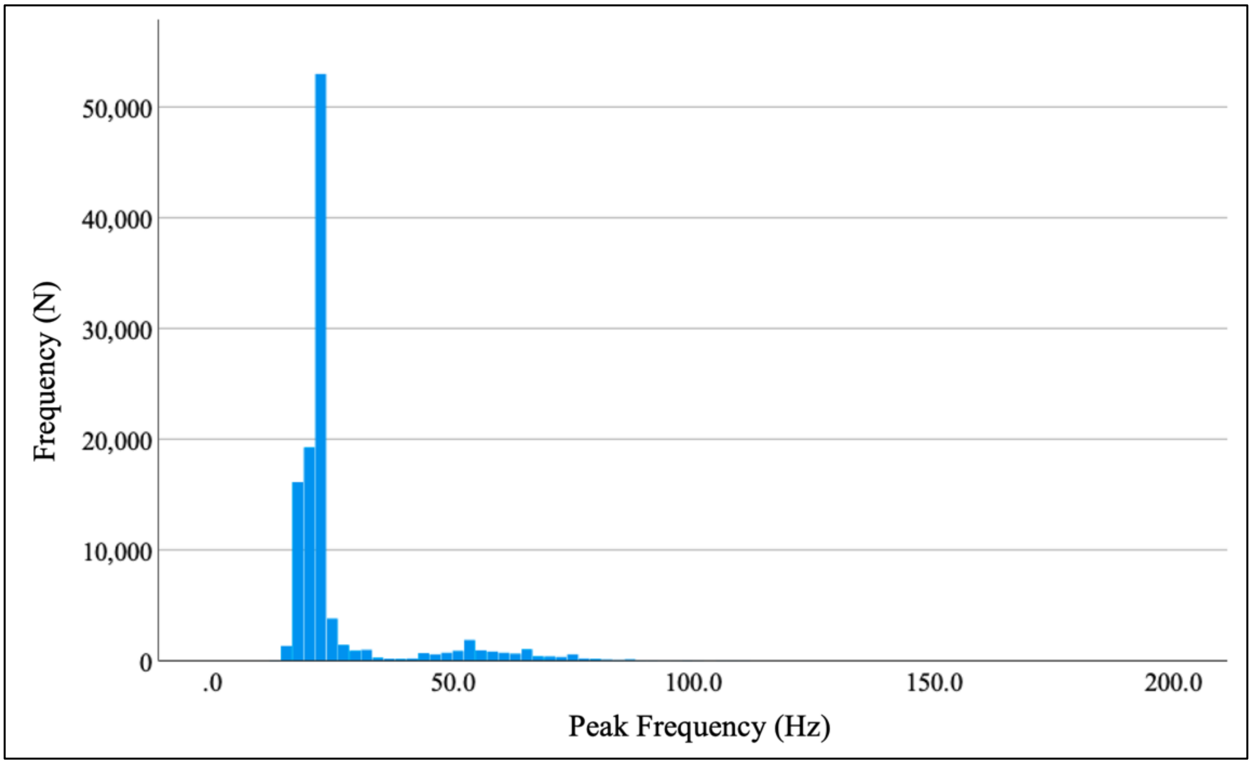

Figure 2: Histogram of peak frequencies of all calls identified at Clayoquot Slope and Swiftsure Bank (Mean=25.3 Hz, Std. Dev.=12.8 Hz, N=108,975).

Swiftsure Bank

Fin whale vocalizations were present in all but four months of the 20-month study period at Swiftsure Bank (n =112), with a peak in the number of calls in fall 2019. Calls were primarily of the 40 Hz type (n=109) and variation in the frequency extents of calls indicated a call type that centered on a higher frequency (~100 Hz). Only three 20 Hz calls were identified in the recordings here, all of which were produced as single pulses with no song patterning. The lowest frequency extent here was 13.8 Hz and the highest was 121.1 Hz. A histogram of peak frequencies of all calls here results in a unimodal distribution in peak frequencies, indicative of the presence of a single call type (Figure 3). A comparison of peak frequencies between those typically recognized as 20 Hz and 40 Hz call types showed higher variability in 40 Hz calls (56.5 ± 16.8 Hz) than in 20 Hz calls (22.1 ± 2.3 Hz). This comparison also shows 20 Hz calls here have a central peak frequency of 22.1 Hz, while 40 Hz calls have a central peak frequency of 56.5 Hz. However, statistical conclusions are not robust for the 20 Hz calls due to the particularly small sample size of the 20 Hz calls identified (n = 3).

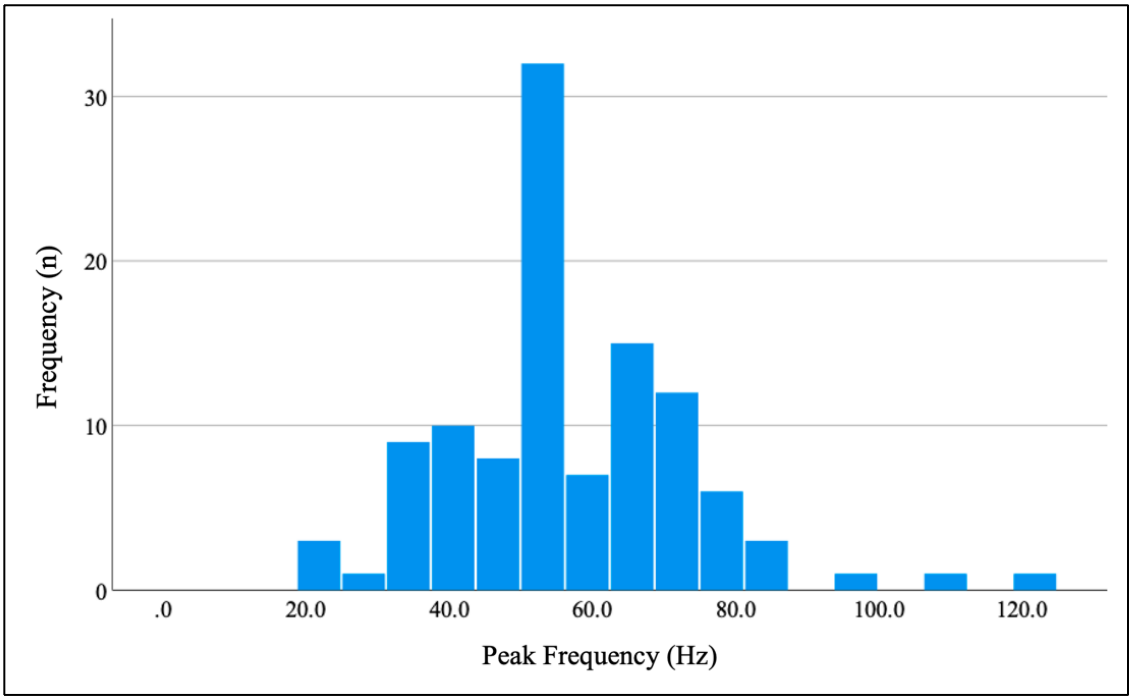

Figure 3: Histogram of peak frequencies of all calls identified at Swiftsure Bank (Mean=56.5 Hz, Std. Dev.=16.8 Hz, n=112).

Annual call presence for 40 Hz calls at Swiftsure Bank was highest in October in 2019 (0.21 calls/hr), although call rates were also high in April 2018 (0.16 calls/hr). A temporal comparison of 40 Hz call rates during spring and fall periods shows a difference in timing between 2018 and 2019 years. The peak call rate in spring 2018 was April and in 2019 this a month earlier, in March. The peak call rate in fall 2018 was September and in 2019 this was a month later, in October. There were three months without any calls present (July 2018, May and June 2019), which were during periods with an overall decrease in fin whale calls during the summer seasons (Figure 4). Months without calls here were consecutive during the early spring of 2019.

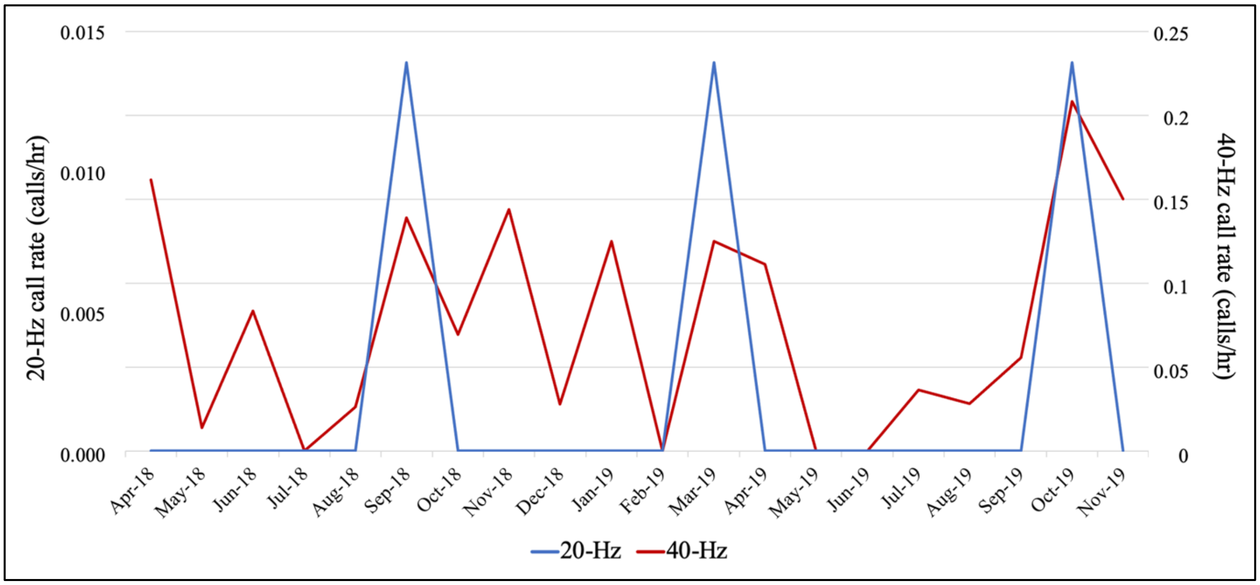

Figure 4: Monthly call rates for fin whale 20 Hz and 40 Hz calls at Swiftsure Bank, expressed as calls/hour. Note axes differ in scale for easier viewing.

All 20 Hz calls were made during the night, although low numbers (n = 3) prohibited statistical analysis. These were annually spread out, produced in September 2018, March 2019, and October 2019 (Figure 4). There was no strong diurnal pattern in the 40 Hz calls (x^2 = 0.239, df = 2, p = 0.888); calls produced in twilight, night, and day were roughly equal (n = 37, n = 35, and n=34, respectively), although, again, it is noted the statistical power of these numbers may not allow for accurate conclusions due to the small sample size.

Clayoquot Slope

Fin whale vocalizations were present in all months at Clayoquot Slope and a substantially larger number were identified here (n = 108,879) than at Swiftsure Bank. There were 92,618 of the 20 Hz and 16,261 of the 40 Hz variety here, although the dichotomous call classification was less straightforward than at Swiftsure Bank due to overlapping frequencies between 20 Hz and

40 Hz call types. A histogram of peak frequencies of all calls here does indicate a bimodal distribution in peak frequencies that agrees with separating calls into two types (Figure 5). A comparison of peak frequencies between those typically recognized as 20 Hz and 40 Hz call types showed higher variability in 40 Hz calls (50.5 ± 17.64 Hz) than in 20 Hz calls (20.8 ± 2.67 Hz). This comparison also shows 20 Hz calls have a central peak frequency of 20.8 Hz, while 40 Hz calls have a central peak frequency of 50.5 Hz. Both call types were present during all months, call type was dependent on seasonal switching, and annual, seasonal, and diurnal call patterning was evident.

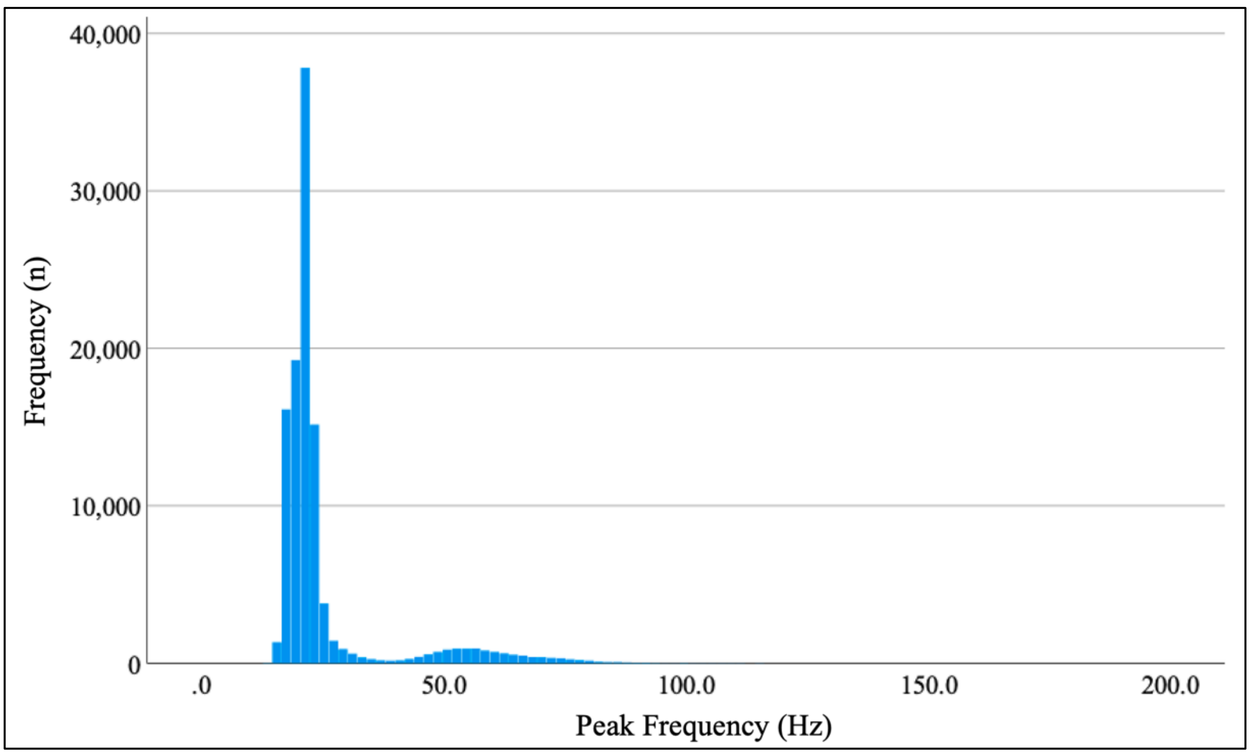

Figure 5: Histogram of peak frequencies of all calls identified at Clayoquot Slope (Mean=25.2 Hz, Std. Dev.=12.7 Hz, n=108,879).

Combining 20 Hz and 40 Hz calls indicates call rates were lowest during the summer periods, specifically July for 2018 and June for 2019, and call rates were highest during the fall between October and December (Figure 7). The 20 Hz vocalizations were present in all months but prominent during the winter, with the highest call rate in December (575.5 calls/hr) (Figure

7). The lowest 20 Hz call rates were in the late spring/early summer periods, particularly in June (0.2 calls/hr). Song patterning, indicated by regular IPIs, of the 20 Hz call was present in all months, except June, and the peak for song presence was in March (Figure 8). The 40 Hz calls were present in all months but were prominent during the late summer and spring with peaks in September (100.0 calls/hr) and April (65.8 calls/hr) (Figure 6). The two seasonal peaks in 40 Hz call rates occurred with the rise of 20 Hz calls in the late summer and the decrease in 20 Hz calls during the spring (Figure 7). The 40 Hz calls were fewest in January (3.3 calls/hr), during the winter period when 20 Hz call rates were highest (Figure 7). Seasonal proportions of each call type differed across the study region (Figure 9).

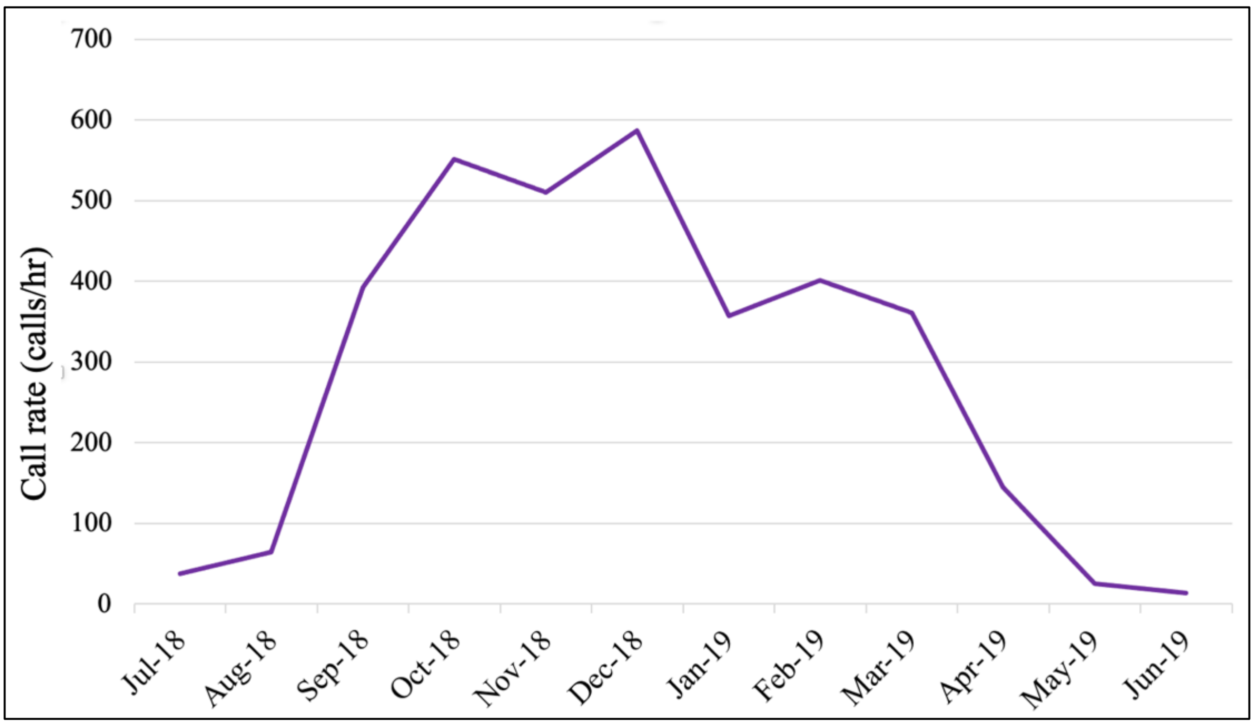

Figure 6: Monthly call rates for all fin whale calls at Clayoquot Slope (combined 20 Hz and 40 Hz), expressed as the number of calls per hour.

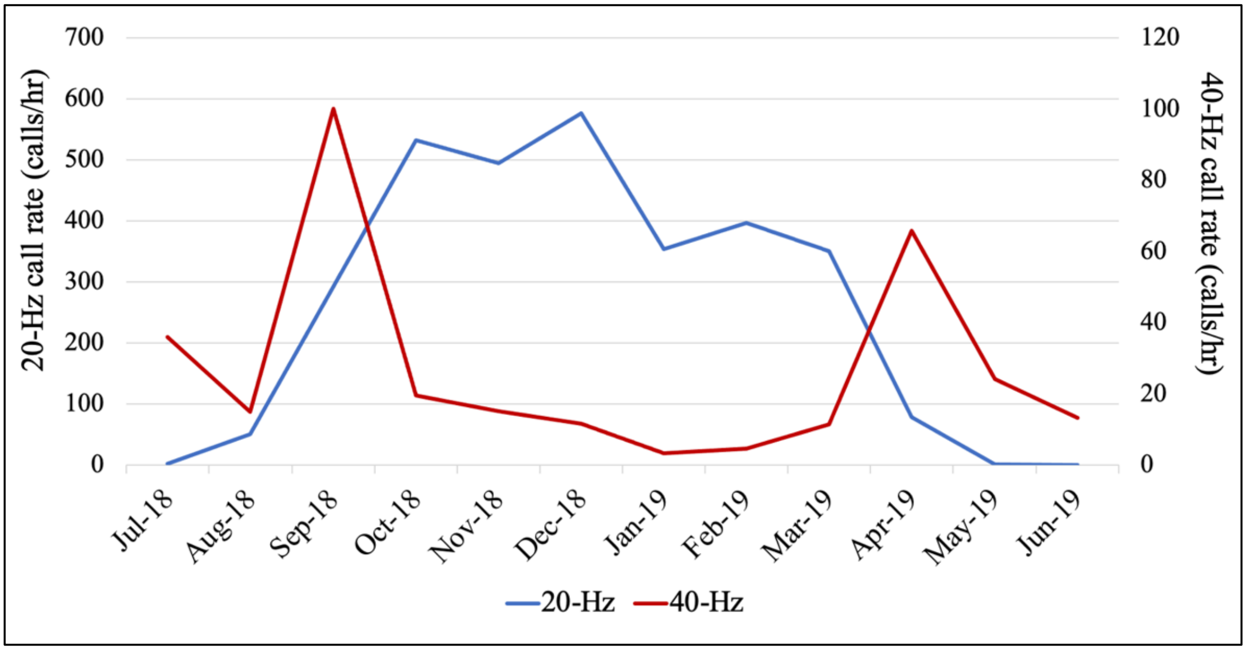

Figure 7: Monthly call rates for fin whale 20 Hz and 40 Hz calls at Clayoquot Slope. Call rates are subject to the amount of data analyzed per month and expressed as number of calls per hour. Note that for easier viewing, axes differ in scale.

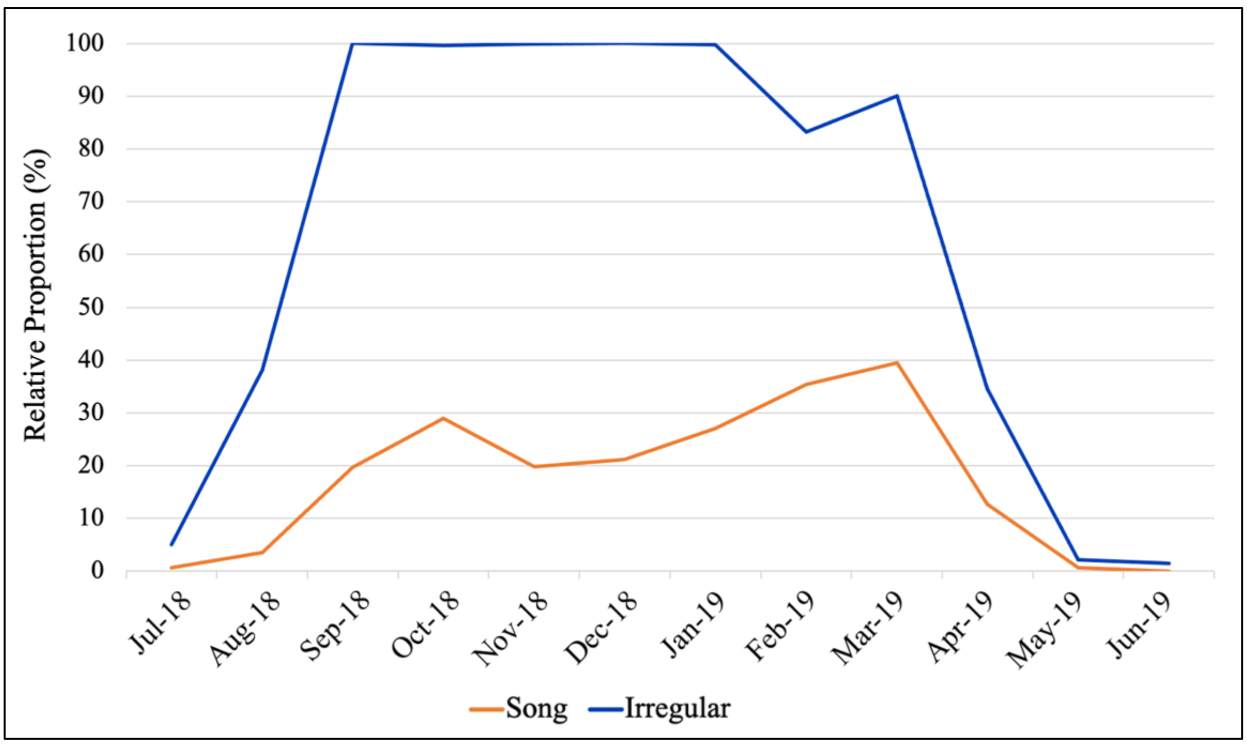

Figure 8: Monthly distribution of song and irregular 20 Hz call presence from July 2018 to June 2019 at Clayoquot Slope, represented as the percentage of recordings with call presence.

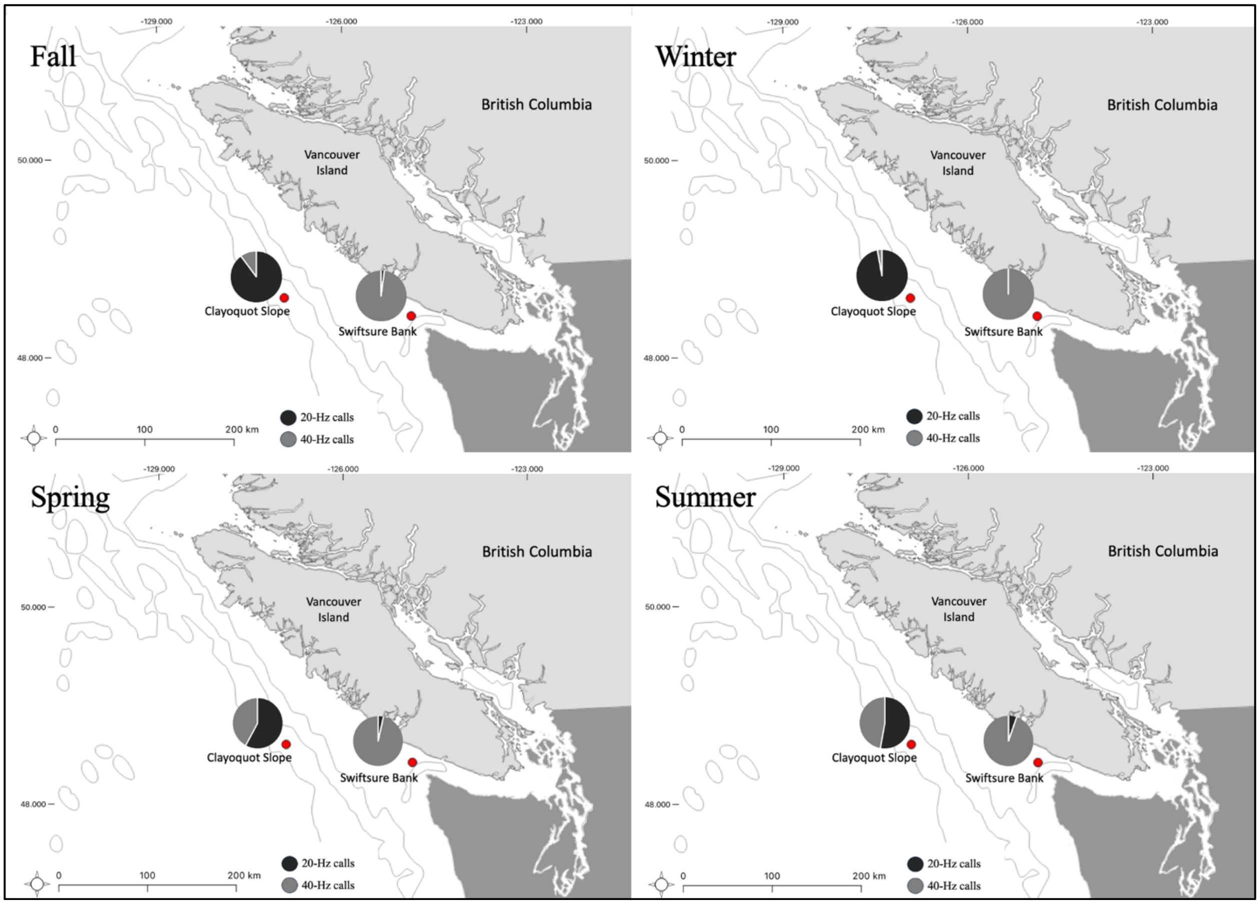

Figure 9: Seasonal proportions of fin whale 20 Hz and 40 Hz calls at each study location. Red dots are the hydrophone locations. Fall = September 23 to December 20; winter = December 21 to March 19; spring = March 20 to June 20; summer = June 21 to September 22.

A diurnal pattern was evident for both call types here. The 20 Hz calls were produced significantly more at night than during day and twilight ($\chi2 = 4626.128$, df = 2, $p < 0.001$) and, separating twilight into dawn and dusk periods showed more 20 Hz calls were made during dawn than dusk ($\chi2 = 995.572$, df = 1, $p < 0.0001$). The 40 Hz calls were produced more frequently during the day than during night and twilight ($\chi2 = 494.233$, df = 2, $p < 0.001$) and more 40 Hz calls were made during dusk than during dawn ($\chi2 = 393.405$, df = 1, $p < 0.0001$).

Discussion

Fin whales were acoustically present throughout the annual period in recordings from two locations in BC waters and both 20 Hz and 40 Hz call types were identified. The two study sites differed in the number of recordings with calls and the prevalence of each call type over different temporal scales. The coastal site at Swiftsure Bank had considerably fewer calls, most which were the 40 Hz type, and song was absent here. The offshore location at Clayoquot Slope had higher call rates of both call types, each were present in all months of the study period, and song patterning was present. The timing of call type presence supports their separation in call function, indicating a difference in dominant behaviour states over the annual period. Average frequencies for the 40 Hz call type at both locations were higher than expected and the considerable variation in peak frequencies of the 40 Hz call identified here has stimulated a more in-depth analysis of this call type (Chapters 4 and 5).

The acoustic presence of fin whales in the recordings was the foundational stage of this habitat assessment. However, this should be considered a minimum, as the absence of calls does not indicate the absence of whales. The patterns described here may then be indicative of behavioural states in which calls are produced disproportionally rather than merely intensity of habitat use. This research does not determine the number or relative abundance of whales from the acoustic data, thus relative call rates are used instead here. Detection ranges/ propagation distances of species' calls were not calculated for this research. However, based on calculations previously determined at Brooks Peninsula (Koot 2015), the detection radius for fin whale calls at Swiftsure Bank is likely much smaller (8.4 km) than at Clayoquot Slope (112 km). The distance between the two study sites is approximately 144 km and there were no instances where the same calls were identified at both recording locations, despite the potential for large call ranges for species producing low frequency calls, such as blue and fin whales (Payne and Webb 1971, fin whale 189 dB).

The broad classification used here to distinguish the 20 Hz and 40 Hz calls was based on previous descriptions of these call types. However, calls classified as the 40 Hz type had central frequencies of 56.5 Hz and 50.5 Hz at Swiftsure Bank and Clayoquot Slope, respectively. This agrees with recently reported frequency parameters of 40 Hz calls from BC that had an average frequency of 52.7 Hz (Burnham 2019). Combined, these are all higher than the 40 Hz call name would suggest. Additionally, there was high variability in peak frequency parameters for this call type at both sites, with frequency extents outside of previous descriptions in the literature. Research on this call type has been limited overall and findings here highlight the oversimplification of the fin whale's call repertoire so far. The high variability and further research into this call type follows in Chapters 4 and 5.

Considerably higher call rates offshore than at the coastal location indicate Clayoquot Slope and Swiftsure Bank may represent a core and peripheral habitat function. A comparison of call rates between the two sites, and the lack of 20 Hz calls and song at the coastal location, indicates behaviour associated with 20 Hz and 40 Hz calls is concentrated along the continental slope in BC. The findings here agree with previous research on fin whale presence and descriptions of habitat use, which indicate their distribution is dependent on latitude, bathymetry, and depth (Gregr 2000, Nichol et al. 2018, Burnham 2019, Burnham et al. 2019, 2021, Wright et al. 2021), all which are proxies for prey abundance and availability (Mackas et al. 1980, Dalla Rosa et al. 2012, Burnham 2019). Even at their lowest, 40 Hz call rates offshore (3.3 calls/hr in January) were greater than when call rates were highest at the coastal location (0.2 calls/hr in October). The preference of fin whales in BC for offshore waters may be influenced by several factors, including access to abundant prey resources that support their year-round presence. The offshore recorder is proximal to Clayoquot Canyon and other submarine canyons here that entrain localized prey aggregations in areas of bathymetrical relief (Mackas et al. 1980, Burnham et al. 2019) that likely provide predictable prey availability persisting outside of seasonal upwelling. Their use of calls associated with foraging behaviour throughout the annual period here, even during breeding and calving seasons, further highlights the significance of the continental shelf break in supporting individuals using this region year-round instead of undergoing a north-south migratory pattern. Combined, this suggests the calls heard were not purely those of whales transiting the offshore waters of Vancouver Island, but that this area supports key life history stages of fin whales.

Seasonal call type switching was evident at the offshore location. The winter was a period of increased 20 Hz vocalizations here, both irregular 20 Hz calls and those with song patterning. This was during a period that is typically thought to be reserved for breeding and reproductive function for this region (Mizroch et al. 2009). However, the annual pattern for 40 Hz call timing was not as straightforward as previous studies have reported (Širović et al. 2013). Instead, two annual peaks in 40 Hz call rates were evident; one was in the fall and the other in the spring. The lowest of these peaks was during the spring upwelling season here (Chandler et al. 2018) that suggests an overall shift to foraging behaviour to exploit more abundant prey resources during this period of high biological production. However, 40 Hz call rates were highest in September during a period when 20 Hz call rates were beginning to increase going into the winter breeding season, suggesting the use of 40 Hz calls intensifies as mating season approaches (Figure 7). Likewise, almost half of the 40 Hz calls at Swiftsure Bank were during the fall (44.95%). The reasoning behind the increase in 40 Hz calls during this period is unclear. It may indicate this call type serves different roles throughout the annual period or feeding during seasonal movements. Further analysis of this call type may distinguish 40 Hz calls made between the spring and fall periods here and is the subject of Chapters 4 and 5.

Months with the fewest fin whale calls for the offshore location corresponded with those for the coastal location for both years analyzed (July 2018 and June 2019). Although the absence of calls does not necessarily mean the absence of whales, this could indicate fin whales are either not using this this area or not vocalizing during this period. Fin whale movement patterns here are relatively unknown. Further research like this, comparing recordings from several sites over the same time period, may help us refine our understanding of fin whale movement patterns, as well as the presence and timing of migration, and home ranges.

A comparison of diurnal 40 Hz call timing at each site may indicate different foraging patterns for whales using each habitat. The use of 40 Hz calls during the day offshore may be reflective of foraging activity concentrated to capitalize on prey swarms that aggregate during the day at depth (Flinn et al. 2002, Wiggins et al. 2005). Although no strong diurnal patterning of 40 Hz calls was evident at Swiftsure Bank, this could reflect the low statistical power of using small sample sizes here that may not allow for accurate conclusions. Site specific diurnal patterns are consistent with research on fin whale acoustic behaviour in BC waters north of this study area, where diurnal periodicity was present at the offshore location and in an area west of Vancouver Island but absent in Hecate Strait (Pilkington et al. 2018). The reason for this configuration remains unclear, but it may indicate that the fin whales foraging offshore are more influenced by the daily movements of prey or are targeting different prey species. Further analysis of 40 Hz calls that considers multiple temporal scales is further examined in Chapter 5. Fin whale 20 Hz calls were more common overnight offshore and the considerable quantity and the patterning present in 20 Hz calls at Clayoquot Slope allowed for further examination of this call type and is the subject of Chapter 6.

This comparison analysis indicates fin whale vocalizations associated with long range communication and reproductive behaviour are concentrated along the continental slope in BC, but those associated with foraging are used over a larger spatial scale that includes the peripheral coastal areas. Besides providing predictable foraging opportunities, the continental slope may also serve to address other needs for fin whales here, such as social interactions and reproductive behaviours. There are still many unknowns about fin whale distribution, behaviour, and population dynamics in the eastern North Pacific, but monitoring long-term trends of fin whale call use and timing could help narrow some of these knowledge gaps.

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CHAPTER 4

A Detailed Analysis of Fin Whale Call Types and the Variation Within the 40 Hz Call Classification

Abstract

Marine species rely on the effective exchange of acoustic information for essential life processes, such as navigation, prey location and capture, and retaining conspecific contact. However, determining the full vocal repertoire of a species, and the corresponding function of each call, is challenging. Clues can be garnered from call structure and context. Here, long-term passive acoustic recordings from an offshore hydrophone on the west coast of Vancouver Island, British Columbia, Canada, are examined for the acoustic presence of fin whales. Call categorisation was initially guided by previously described 20 Hz and 40 Hz call types. These were thought to reflect breeding and foraging behaviour respectively. However, high variability in the 40 Hz call type led to further analysis for the potential for sub-categorization. Cluster and Random Forest analyses, used in conjunction with manual analysis notations, determined the possibility of re-classification based on call features. Hierarchical clustering first confirmed the strength of the 20 Hz and 40 Hz call distinction, and then five sub-categories within the 40 Hz call type. The Random Forest showed that peak frequency dominated the definition of the call clustering, with this and a decision tree analysis showing that frequency range and duration of the call were also influential in classifying calls to a sub-group. The clustering agreed with notations from the manual analysis, indicating clusters in frequencies both higher and lower than have previously been reported. This analysis suggests that, while the distinction between the 20 Hz and 40 Hz call types was still strongly apparent in the data, call structure of 40 Hz call types is more varied than previously recognized, or its name suggests. Based on these findings, more

data analysis and the consideration of sub-categories or gradients in calls as more species' repertoires are described is suggested.

Introduction

Vocalizations and the acoustic senses underlie all cetacean behaviours. Their perception of surroundings is principally driven by sound. The reception, interpretation and exchange of both active and passive acoustic cues is critical to all stages of a cetacean's life. The full vocal repertoire for many species is still being determined, with even less known about the function underlying the calls. Behavioural clues can be garnered from social or geographical settings, or from seasonal and diurnal patterns of call presence (Wiggins et al. 2005, Oleson et al. 2007, Baumgartner and Fratantoni 2008, Širović et al 2013). Call structures and use differ between species and populations (e.g., Ford 1991, Musser et al. 2014, Whitehead and Weilgart 1990, Weilgart and Whitehead 1997, Garland et al. 2013, Širović et al. 2013, 2017). Vocalizations convey complex information including the signaller's location, behavioural and physiological state, and group membership to conspecifics (e.g., Markl 1985, Maynard-Smith and Harper 2003, Wiley et al. 2013). This may be through the use of different or modified call types to incorporate behavioural, functional, or identification signals (Smith 1981, Rendall et al. 2009, King and Janik 2015). This information may be interpreted by the analysis of variation in calls and the context of their production.

Cetacean vocalizations are often classified to reflect behaviours most critical to their success. Typically, the strongest division in call types is the distinction between foraging and calls linked to reproductive displays (e.g., Clark 1983, Mellinger et al. 2007, Baumgartner and Fratantoni 2008, Parsons et al. 2008, Parks et al. 2011, Vu et al. 2012). 'Food calls' may be used to convey prey information to conspecifics, or aid synchronised prey capture or sharing (e.g., Thompson et al. 1986, Gong et al. 2014, Parks et al. 2014, Ellis et al. 2017, Matkin et al. 2017). Calls used in social interaction and group dynamics include, for example, vocalizations used during conflict resolution, competition, or hierarchy and territory establishment (e.g., Tyack 1981, Norris et al. 1991, Oleson et al. 2007 a,b, Dunlop et al. 2008, Smith et al. 2008, Chloewiak et al. 2018). Calls linked to breeding or 'song' displays, have also been noted for several whale species. Reproductive acoustic displays can vary from highly complex, as seen in humpback whale song (Payne et al. 1983, Payne and Payne 1985), to relatively simple song displays such as those of the fin whale (Koot 2015, Širović et al. 2013, Burnham 2019). However, this dichotomous approach of categorising call types may underestimate the complexity of the calls and the messages they carry. Indeed, it has been shown that a small repertoire can be modified and restructured to give rise to a rich 'vocabulary' (Dunlop et al. 2008, McCordic et al. 2016). Also, it may not simply be the distinction of call type and structure but could also be patterns in call use or timing that reinforces functionality (e.g., Clark 1983, Mellinger et al. 2007, Baumgartner and Fratantoni 2008, Parsons et al. 2008, Parks et al. 2011, Vu et al. 2012).

The reproductive-foraging dichotomy is most strongly applied to baleen whales. It has long been applied to the low frequency (<100 Hz) vocalizations described for fin whales (Watkins 1981, Edds-Walton 1997, Širović et al. 2013, Burnham 2019). Calls have typically been described as either 20 Hz breeding or 40 Hz feeding calls (Watkins 1981). The research has typically focussed on the 20 Hz call type, thought to be used for long-distance communication and, when produced in regularly timed patterns, as song produced by males to attract females (Clark 1983). The 40 Hz call was first described and distinguished qualitatively from the 20 Hz call by Watkins (1981). However, few studies have followed to better describe the structure or use of this call type. Work by Širović et al. (2013) showed annual patterns in 40 Hz calling, reflective of foraging periods, which furthered the distinction from the 20 Hz calls. More recently, 40 Hz calls have been linked to fin whale prey abundance and social feeding aggregations, further suggesting a foraging function for these calls in social aggregations (Burnham et al. 2021, Romagosa et al. 2021). Moreover, the early work by Watkins (1981) described the variability in this call, which has not been replicated in subsequent studies. Only very recent work shows these 40 Hz calls include variability in structural parameters that could differentiate between individuals (Wiggins and Hildebrand 2020).

Here, long-term passive acoustic recordings from the west coast of Vancouver Island, British Columbia (BC), Canada, are examined for fin whale calls. The aim is two-fold: First, to identify fin whale calls over a year of recordings as an acoustic indicator of their presence and habitat use patterns. In this initial stage, call classification is in accordance with the established 20 Hz and 40 Hz grouping and descriptions in previous studies. Second, to examine the calls for the variability described in the early research, perhaps suggestive of the social, behavioural, or physiological context of the calling whales. Whether the broad categorisation of calls is sufficient to capture the variability and nuanced nature of whale acoustics use is considered.

Methods

Acoustic data collection

Passive acoustic recordings were made by an offshore cabled device located at Clayoquot Slope, about 45 nautical miles (nm) west of Vancouver Island on the west coast of BC, Canada (48.700° N, -126.872° W) (Figure 1) at a 1255 m depth. The recordings were made continuously by an Ocean Sonics icListen AF hydrophone with a sensitivity of -159 dB re 1 V/μPa and a frequency range of 1 Hz to 12 Hz (± 3 dB bandwidth). This recorder is part of the Ocean Networks Canada Neptune Observatory network which has been in place since 2009. This study focused on recordings made between July 1, 2018, to July 1, 2019 (see Ocean Network Canada Oceans 3.0 Data portal for more details, https://data.oceannetworks.ca/home).

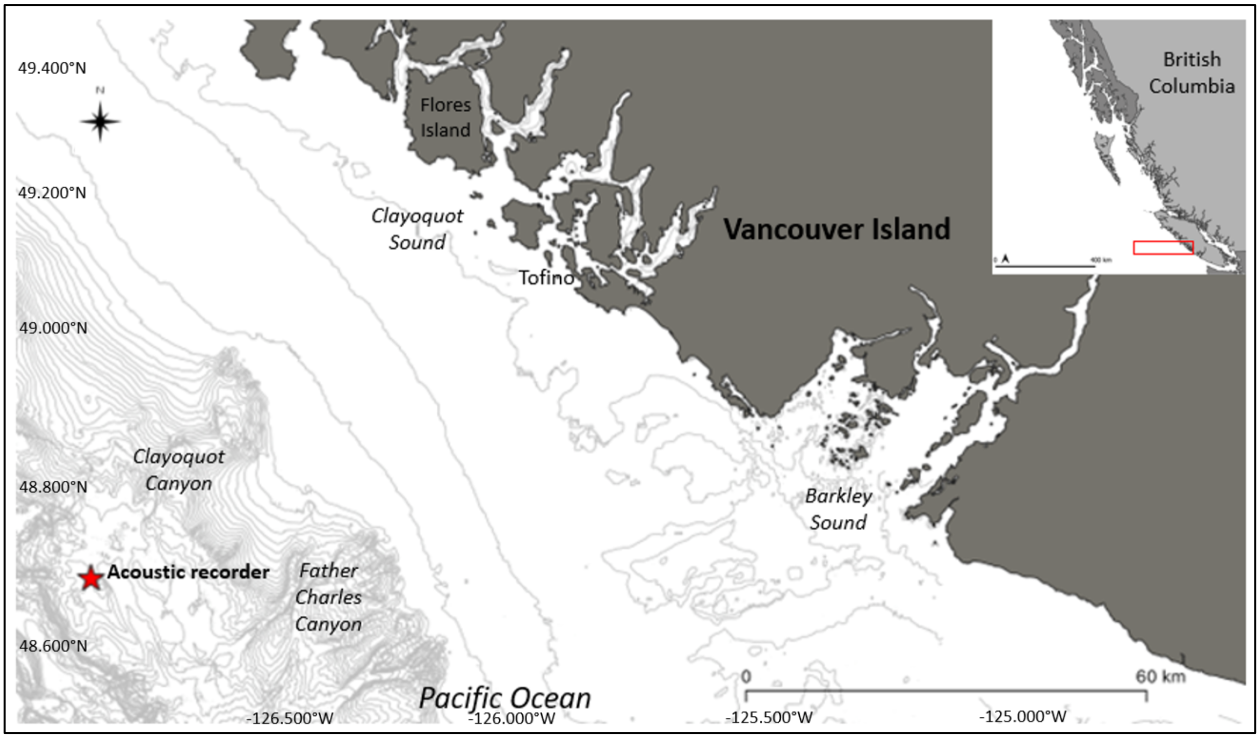

Figure 1: Location of stationary hydrophone at Clayoquot Slope on the west coast of British Columbia, Canada, used to record fin whale vocalizations.

Fin whale call presence

Recordings were subject to manual aural-visual (AV) verification using spectrograms generated using a 256-point Hann window 1s FFT with 50 % overlap in Raven Pro Interactive Analysis Software (Version 1.6.4; Center for Conservation Bioacoustics, 2014). A systematic sampling method was used to manually analyze in excess of 10% of the total recordings made during the year, by analyzing every second five-minute recording of every fifth day of the recordings. Calls were identified and classified by referencing descriptions from the literature (Table 1 in Chapter 3). For each call, structural parameters derived using Raven Pro Software

(Charif et al. 2010, Center for Conservation Bioacoustics 2014) from manual selection of each call in the recording. Parameters included the highest and lowest frequency extent, peak frequency (the frequency where most of the call energy was focused, measured in Hertz), call duration (measured in seconds), and peak power density (highest received level of call energy in selection, measured in dB FS/Hz). Calls were categorised based on these parameters, as well as patterns in calling and inter-call intervals to discern call type (Širović et al. 2013). If patterning was apparent in the calling, with calls regularly spaced in time, or in clusters, this was noted. In addition, comments on the relative amplitude of the call and the presence of any masking noise sources such as vessels, earthquakes, or other calling whales were noted.

Call classification

Variability in the structure of the parameters collected for each call was measured by standard deviation and variance. This considered the variation of all calls, and within the 20 Hz and 40 Hz groupings. The strength of the call type distinction between these call classes, and the possibility for sub-classification or a new class of calls, was explored through hierarchical and K-means cluster analyses (IBM SPPS). Cluster analysis inputs were call duration (in seconds), peak frequency, and frequency range (highest-lowest call frequency). The maximum number of clusters considered in the hierarchical cluster analysis was ten as an exploratory measure. The result of the hierarchical clustering, and intra-cluster variation in the results, were used to guide the number of clusters considered for the K-means cluster analysis. As this is an initial foray into potential sub-classification, all calls identified in the recordings were included in the analysis using the parameters as they were received, without correction for potential propagation losses. Including all calls eliminated any biases in the call type or structuring that might be present if we were to use, for example, the loudest calls (absolute or signal-to-noise ratio) and allows the possibility that the amplitude of a call may be manipulated by the whale as a variable open to modification when calling. However, without visual confirmation of whale's proximity to the recorders, this is not able to be substantiated, or completely ruled out.

The initial aim of the cluster analysis was to confirm the dual categorisation of call types for fin whales, 20 Hz and 40 Hz calls, and to determine the strength of the partitioning of calls in our data. If the distinction between 20 Hz and 40 Hz calls was confirmed, focus would shift to the variability in the 40 Hz calls to refine that call type description, as it is the more sparsely reported. If the separation between call types was less distinct, all call types would remain aggregated for further analysis. Any clustering found using the statistical analyses would be compared to notes made during the manual analysis that commented on the qualities of the call. This initial cluster analysis was performed on individual calls, and did not consider temporal patterning of the calls, as described for 20 Hz calls used during song, as this can differ between location and time of the mating season (see Oleson et al. 2014, Širović et al. 2017). If patterning was present, it was denoted using binary coding.

Call classification, defined by the K-means cluster analysis, was then added as a category to the call parameters for each call. To examine how widely applicable the statistically derived call classes were, these categories were used as an output variable first in a decision tree model, where the class is defined by a series of binary questions, and then in a Random Forest (RF) machine learning model (Breiman 2001). The decision tree was the initial look at the criteria that formed the clusters, whereas the RF model determined the relative influence of each of the input variables, identifying the most influential in the classification, especially in the case that new call types or sub-groups were defined in the cluster analysis. The decision tree and RF algorithm was performed using Scikit learn Python library in Jupyter notebooks (RandomForestClassifier from sklearn.ensemble (https://scikit-learn.org/stable/modules/ensemble.html) and DecisionTreeClassifier from sklearn.tree (https://scikit-learn.org/stable/modules/generated/sklearn.tree.DecisionTreeClassifier.html). The input variables for both the decision tree and the RF matched those used in the cluster analysis, and included call duration (sec), the low and high frequency extents (Hz), the frequency range calculated from these extents, the peak frequency, and the power at that peak. Sklearn.tree and Pyplot from matplotlib libraries were used to create visualisations of the decision trees.

The RF model combined all the input call parameters in 150 (3 folds, 50 iterations) random selections to form decision trees, selecting from a minimum of 1 and a maximum of 7 variables (call duration, high- and low-frequency extent, frequency range, peak frequency, peak power and if the calls were part of a pattern defined by inter-call interval). Cross-validation and model tuning via Scipy was used to find the best fitting parameters and maximum tree depth. One thousand iterations were run from bootstrap samples to form an unpruned tree. From these trees the results were aggregated to form an ensemble. The model was trained on 70% of the call data, with the remaining 30% percent remained unseen by the model to act as a test data set from which to calculate the accuracy and predictive power for novel calls. Again, the predictions from the RF model were compared to initial classification and call quality notes, as well as the class assigned by the cluster analysis. In addition to the call parameters, parameters reflecting the temporal patterns between calls were also included in the RF model via an input variable that indicated if the call was part of a pattern (as a binary input), whereby the inter-call intervals were consistent between adjacent calls. Such temporal patterns have not been previously described for 40 Hz calls. Also, the year, month, day and year day (number of days elapsed from January 1) hour call was made, and if that was morning or afternoon-evening (midnight-noon, or noon-midnight) were also included to examine if the cluster formation was temporally driven.

Results

Call presence

Manual analysis for the year of data at Clayoquot Slope identified 108,879 fin whale calls in 747 hours of data analysed. Of these, 92,618 were 20 Hz (85.07%) and 16,261 (14.93%) were 40 Hz calls. The recordings from Clayoquot Slope showed that fin whales were acoustically present throughout the year, with both call types present in all months (Figure 2). Calls in the winter were predominantly the 20 Hz type. The number of calls/hr analysed was greatest for this call type in February. Calls classified as 40 Hz calls, typically considered to be foraging calls, were more prominent in the late summer and spring (Figure 2), and most frequently heard (calls/hr analysed) in September and April, with the latter being concurrent to the spring transition to ocean upwelling (Boldt et al. 2020).

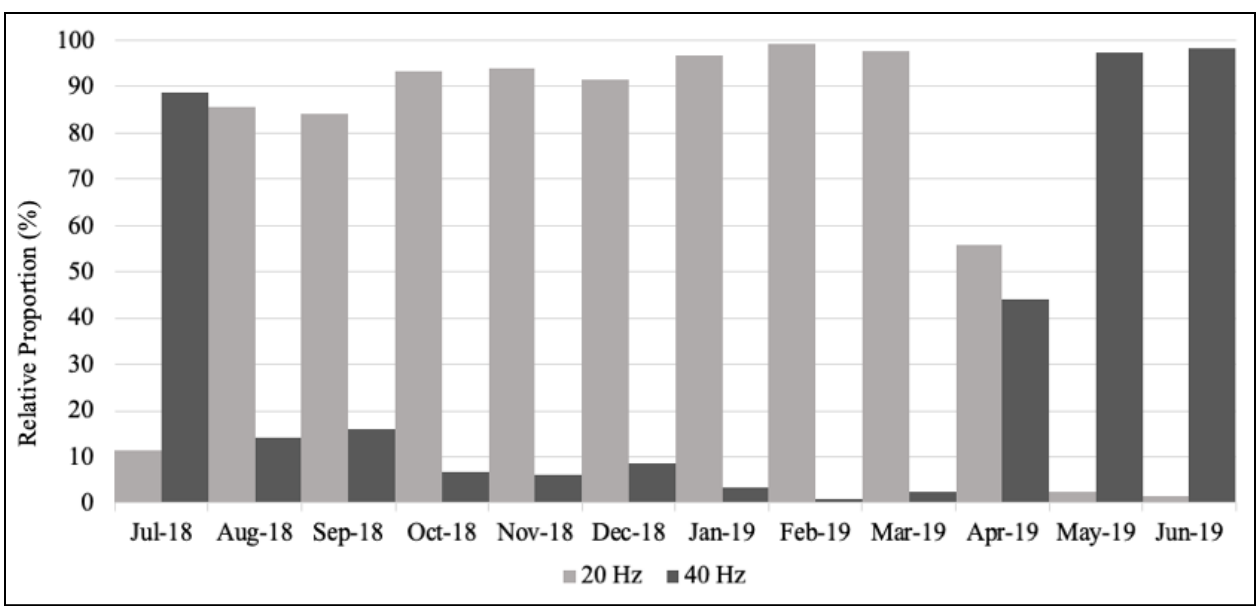

Figure 2: Call distribution of 20 Hz and 40 Hz calls from July 2018 to July 2019 at Clayoquot Slope, represented as relative percentages of recordings with fin whale calls observed per month.

The 20 Hz calls were similar to those reported in previous studies, with a portion of the calls showing inter-pulse intervals consistent with song patterning (see Oleson et al. 2014, Širović et al. 2017). However, the 40 Hz calls here did not show obvious patterning and inter-pulse intervals were not considered for this call type. Details of the presence and use of the 20 Hz calls, including the timing of use, the song patterning and changes in the temporal spacing between the component notes forming the song patterns are discussed in greater detail in Chapter 6. Variability in the 40 Hz calls was compared to descriptions from previous studies. Therefore, the focus of the current analysis was to further refine the description of the 40 Hz call type if the 20 Hz to 40 Hz call distinction was confirmed.

A comparison of peak frequencies of the 20 Hz and 40 Hz vocalizations showed higher variability in the 40 Hz calls (50.48 ± 17.64 Hz) than in the 20 Hz calls (20.80 ± 2.67 Hz). Qualitative notations and the call parameters collected for each call suggest that the 40 Hz calls extend further into both lower and higher frequencies than previously reported (Table 1 in Chapter 3).

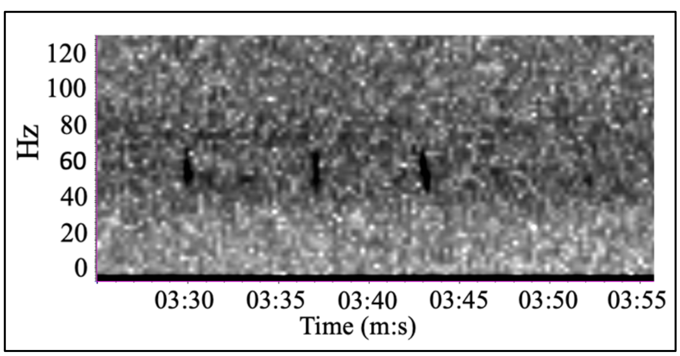

Figure 3: Spectrogram of examples of "typical" 40 Hz fin whale calls, as reported in the literature (see Table 1 in Chapter 3) found in this study. Spectrogram was generated using a 256-point Hanning-window FFT with 50% overlap.

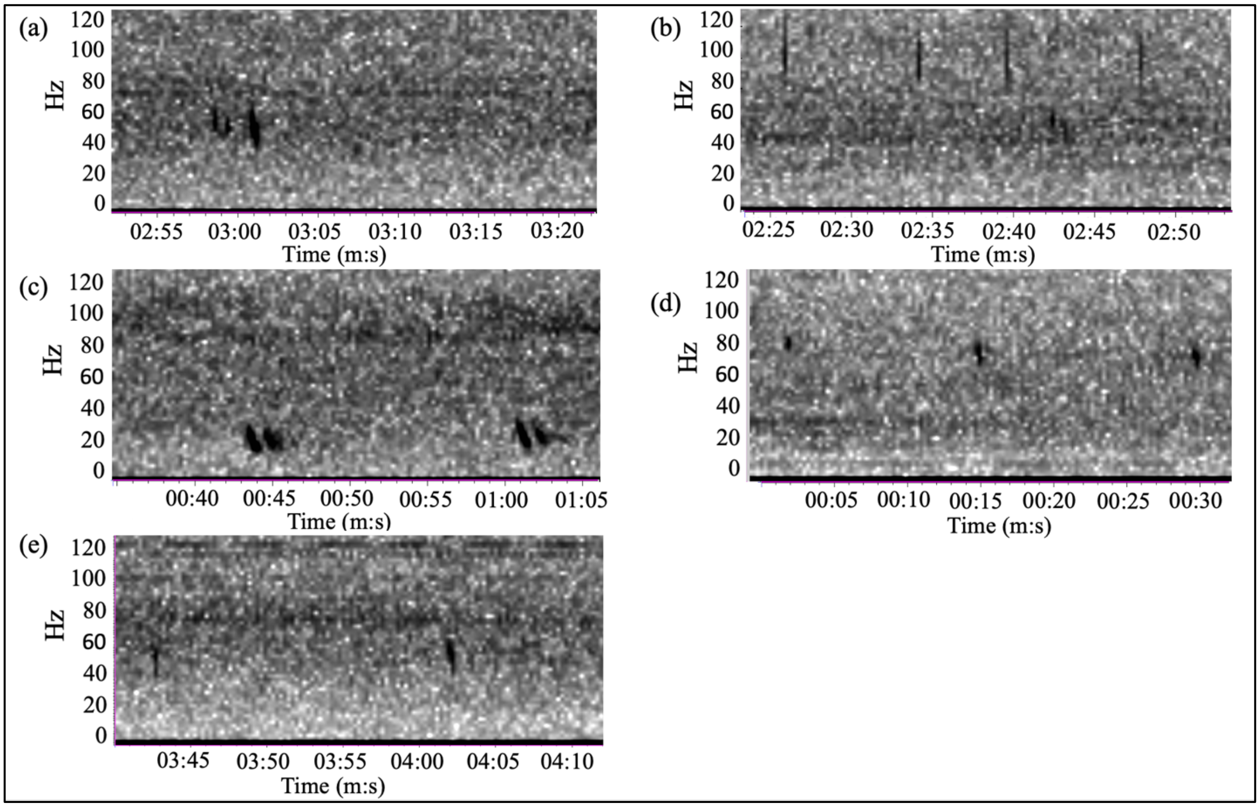

Figure 4: Spectrograms of the variety of 40 Hz fin whale calls found in this study, separated into examples from each call cluster. (a) cluster 1, (b) cluster 2, (c) cluster 3, (d) cluster 4, (e) cluster 5. Note the same frequency scales to demonstrate relative frequency of each call cluster type. Spectrograms were generated using a 256-point Hanning-window FFT with 50% overlap.

The greatest variability in the 40 Hz calls, compared to those reported in the literature, was present in parameters of frequency extent and call duration (see Table 1 in Chapter 3). Calls in the 40 Hz category ranged from a minimum low-frequency of 11.3 Hz up to a high-frequency of 202.4 Hz (see Table 1 in Chapter 3). Despite the overlap with the 20 Hz call class, the lower frequency calls here were determined to not belong to this class due to the inflection and timbre of the call. These calls were also found to be grouped in the 40 Hz call clusters by the statistical analyses, confirming the initial classification.

The average of the call parameters showed low frequency extent for all 40 Hz calls to be 43.20 ± 17.02 Hz, high frequency was 58.88 ± 17.91 Hz, and the peak frequency of all calls classified as 40 Hz was 50.48 ± 17.64 Hz. These are all higher than the 40 Hz call designation suggests (see Table 1 in Chapter 3). The parameters of frequency were consistent through time for the calls identified in this study. They also showed some consistency with previous work in this area (see Burnham 2019, Burnham et al. 2021). However, call duration showed more variation. The longest calls were recorded in September (3.15 ± 0.29 s) and the shortest calls were recorded in March (0.08 ± 0.32 s), although average call duration was less than that previously reported for this area for both 20 Hz and 40 Hz calls (Figure 5, Table 1 in Chapter 3). Work is ongoing to establish if this difference with previous studies may be representative of a change in calling over time, such as the seasonal changes in song note parameters reported for fin whale calls (Oleson et al. 2014, Weirathmueller et al. 2017) or perhaps similar in nature to the downward frequency shift in song calls over a decadal timeframe that has been reported for blue whales (McDonald et al. 2009).

Call classification of 40 Hz calls

The cluster analysis for all calls confirmed the strong distinction between 20 Hz and 40 Hz calls. Five groupings were indicated to be the maximum needed to capture the variability in the calls by the hierarchical cluster analysis for the 40 Hz calls. Five clusters were therefore considered in the K-means cluster analysis. These clusters were formed on the input values of peak frequency, frequency range, and call duration.

This clustering corroborated the initial classification of calls, and qualitative notations, noting calls could be separated into three call or sub-types representing a 'typical', 'high frequency' and 'low frequency' 40 Hz call type. Indeed, the hierarchical cluster first showed a split of calls to three clusters, with one further sub-divided to give the final five clusters. These represented the calls that were consistent to previous descriptions of 40 Hz calls in the literature, and those that displayed higher or lower frequency extents and peak frequencies respectively. The first split in the hierarchical cluster was to separate those that were more 'typical' of the previous descriptions in the literature, or slightly higher in frequency, and those that had been noted during the manual analysis as being more centered on 30-Hz. The initial subjective classification of calls contained 11,359 'typical' calls (50 – 100 Hz, 69.82% of the 40 Hz calls), 4,698 low-frequency calls (30 - 50 Hz, 28.92% of 40 Hz calls), and 204 'high-frequency' calls (>100 Hz, 1.26% of 40 Hz calls). These distinctions were principally based on their frequency range, peak frequency and cadence. Comments from the manual analysis did not recognize the further subdivision of the 'typical' 40 Hz call since they were within previously reported ranges. However, it was clear there were both low and high 'typical' calls that challenged the limits of their classification. This would corroborate a potential sub-division of this cluster, as determined by the hierarchical clustering analysis.

The cluster analyses determined calls initially classified as 'typical' calls were the most numerous. This matched the division of calls into two clusters (1 and 5), which accounted for 16.4 % and 32.2 %, respectively (n = 2669 and n = 5233, respectively). Although the division of these two clusters initially went unnoticed due to their similar frequency parameters, differences in average peak frequency (cluster 1 = 57.83 ± 5.20 Hz and cluster 5 = 51.50 ± 5.10 Hz) and average frequency range (cluster 1 = 22.50 ± 5.40 Hz and cluster 5 = 12.98 ± 3.60 Hz) were enough to form two separate clusters. The higher frequency component of the 'typical' calls was represented by cluster 4 accounting for 20.0 % (n = 3249) of calls. Cluster 3 contained the 'low frequency' calls accounting for 29.4 % (n = 4771) and cluster 2 contained the 'high frequency' calls accounting for only 1.7 % of all the calls examined. Discrepancies between the initial subjective classification of calls and the cluster categorisation was from calls that were at the extremes of the frequency range for that grouping.

Call parameters were compared between clusters (Figures 5 and 6) and considered over time on a coarse level. Greater analysis of the presence of each cluster, and the variability of the call parameters between and within clusters over time is the subject of Chapter 5. The frequency parameters were consistent when considered monthly, however, call duration varied over time. All clusters had their highest call durations in April.

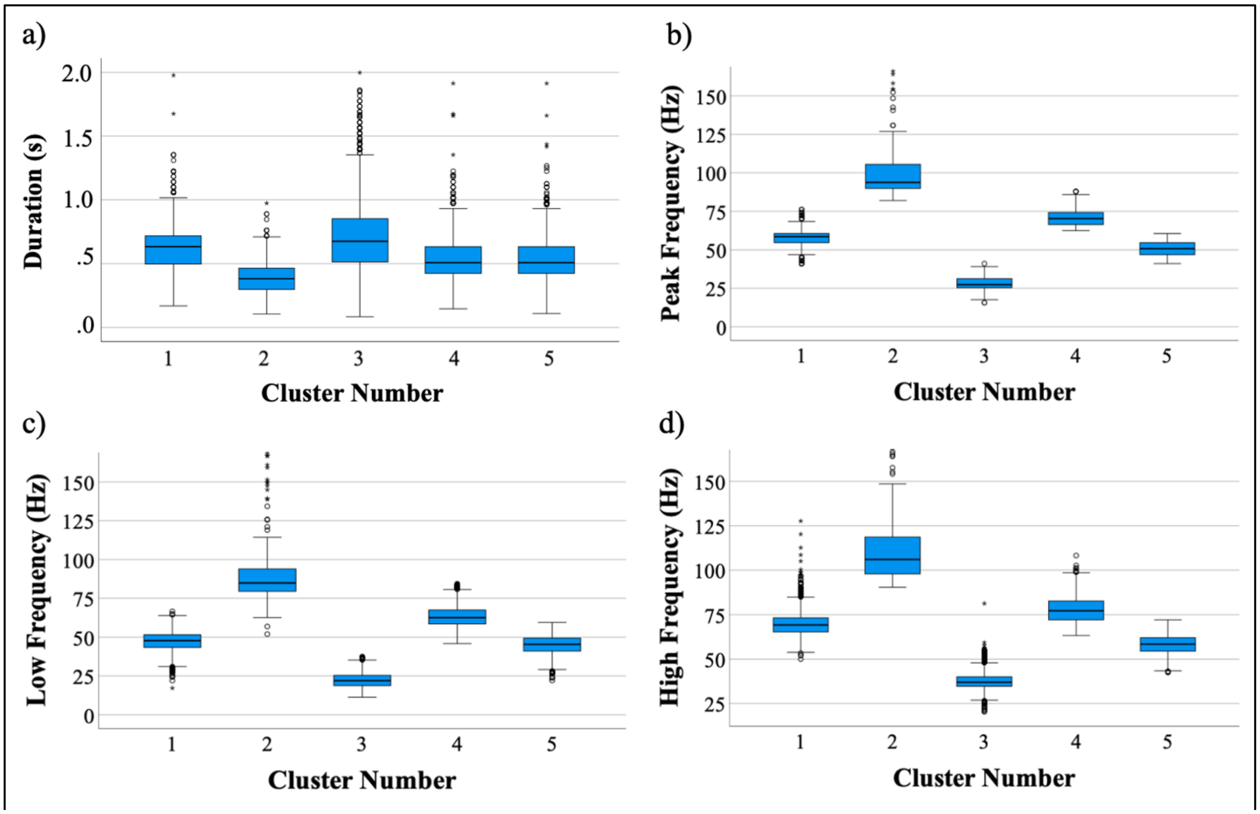

Figure 5: Box plots representing parameters within each cluster for 40 Hz calls identified at Clayoquot Slope. a) 40 Hz call duration, b) 40 Hz call peak frequency, c) 40 Hz call low frequency extent, and d) 40 Hz call high frequency extent. Note: some outliers of cluster 2 are not shown here for clarity purposes.

Cluster 2 showed the shortest call duration and least variation, whilst cluster 3 showed the highest call duration (Figure 5). Cluster 2 showed the highest peak frequency and greatest frequency extents, whereas cluster 3 showed the lowest values (Figure 5). All but cluster 2 showed relatively normal distributions in their low and high frequency extents. This was in the range of 52.0 Hz to 202.4 for cluster 2. Although not considered directly as a call parameter, the measured peak power density (PPD) of calls for each call class was within 3 dB of each other, except for cluster 3 which had just less than 7 dB standard deviation from the mean value. Work on the transmission properties of fin whale calls through time and space along the coast of BC is ongoing.

The call classification resulting from the cluster analysis was examined using a machine learning decision tree and Random Forest (RF) models. The RF was able to predict the call cluster classification to an accuracy of 98.75%. Input values of call parameters (call duration, high and low frequency extents, frequency range, and peak frequency) and timing variables (year, month, day, year day, hour, AM/PM) were used. The model showed that the cluster classification was predominantly defined by the peak frequency. The decision tree model, with the same input variables, also showed peak frequency to be the principal decision in the call categorisation (Figure 6). This was followed by frequency range and then call duration. The decision tree again highlighted the differences in the parameters between clusters 1 and 2 and clusters 3 and 4 (Figure 6). The use of frequency extent and duration did not feature highly in the decision tree, with classification centered on the peak frequency and frequency range of calls (Figure 6).

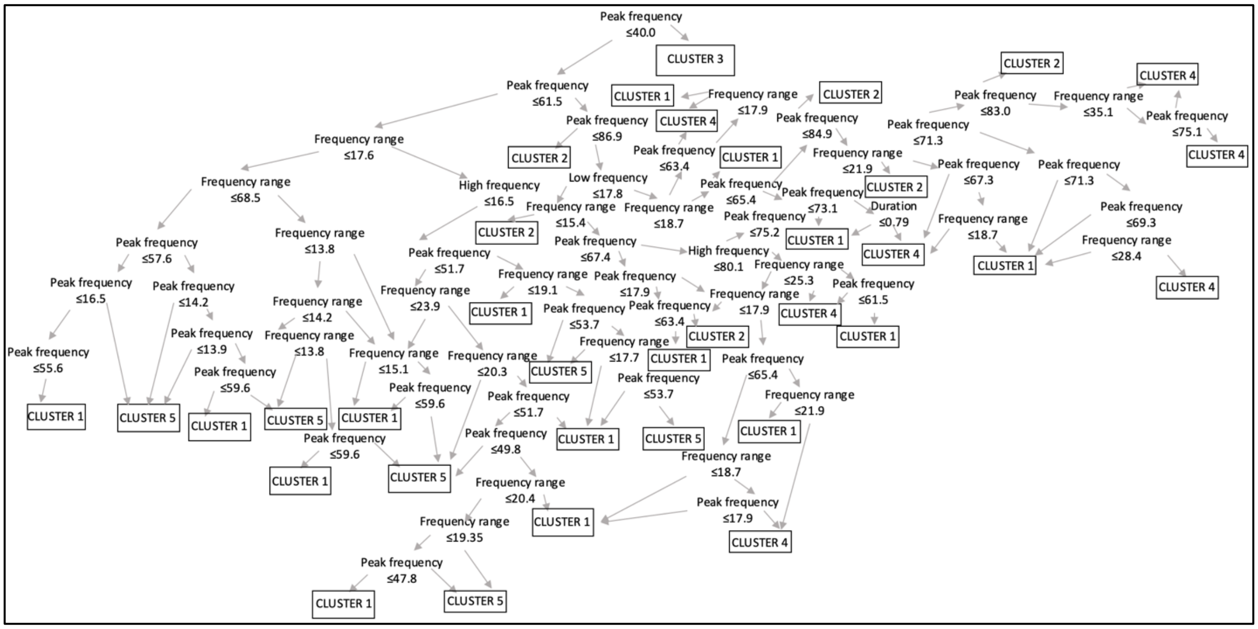

Figure 6: Dendrogram from the decision tree model to predict the cluster classification.

The decisive feature, described by the decision tree model is whether the peak frequency is greater or lesser than 40.0 Hz. This agrees with the hierarchical clustering results. Below this value was cluster 3. The next defining feature was a threshold value in peak frequency of 61.5 Hz, below which was clusters 1 and 5, and above 2 and 4 (Figure 6). It is cluster 1 that is most like the more traditional description of the 40 Hz call, with this featured most frequently as a terminal node (Figure 6).

Discussion

Fin whales were acoustically present in all months of the data analysed from Clayoquot Slope. The cluster analysis confirmed the 20 Hz to 40 Hz call type distinction, with the timing of their presence (Figure 2) also supporting their separation in type and potential function. The 20 Hz call type was most frequent in the winter and spring months, with song patterning found during this period also, supporting the idea that the use of this call type is part of a reproductive display. The 40 Hz calls were most frequent in the late summer and spring, with the latter timing being consistent with the previous conclusion that they are used during foraging (Širović et al. 2013, Burnham 2019). However, analyzing 40 Hz calls over an annual period here shows that, although this call type is reduced during winter breeding periods, it is still produced by fin whales throughout the year. This suggests the calls heard were not purely those of whales transiting the offshore waters of Vancouver Island, but that this area supports key life history stages of fin whales year-round.

A cluster analysis of all calls identified from the recordings from July 2018 to July 2019 first confirmed the broad distinction between 20 Hz and 40 Hz call types previously established in the literature and applied throughout the manual verification process (see Table 1 in Chapter 3). Without matching observational data, the behavioural context of the calls was not fully substantiated to confirm the breeding-feeding dichotomy. However, song patterns found in the 20 Hz calls suggests a reproductive function (Chapter 6). Also, the seasonal patterning found in calling prevalence and the rate of calls heard (calls/hr) of the 40 Hz calls indicates their use in foraging.

Previous work by Watkins (1981) noted greater variation in the 40 Hz call than the 20 Hz call type, which was further substantiated by this study. However, the variability in the calls identified in this study were greater than that described previously. In particular, there was more variability in the range of minimum low and maximum high frequencies, with the calls in this study falling within the range of 11.3 to 202.4 Hz. Since early descriptions by Watkins (1981) and other works (e.g., Širović et al. 2013, Burnham 2018, 2019, Wiggins and Hildebrand 2020, Table 1 in Chapter 3) have shown calls to be more restricted in their frequency extents than determined here. However, the mean peak frequency of calls in this study are similar to that reported by Burnham (2019). The calls reported in by Burnham (2019) were recorded in the same area but an earlier time period. Work is ongoing to look at longer-term trends in fin whale call presence and structure, alongside work to determine call transmission properties and likely detection ranges. The work presented here is the most extensive study of fin whale 40 Hz calling to date in the northeast Pacific, and definitely in the Canadian Pacific. The variability in calls, therefore, may be more apparent due to the high number of calls examined compared to earlier works. However the cluster analysis suggests that the variability could form part of a sub-categorisation, or nuanced application of this call type.

The clustering, using parameters of call duration (in seconds) and frequency (range and peak), matched the initial manual analysis notes, which were based on the structural and auditory qualities for each of the calls identified. The call clusters that best aligned with previous descriptions of the 40 Hz call type in the literature were clusters 1 and 5, which were designated as “typical 40 Hz” calls by the analyst. Cluster 1 had a slightly higher peak frequency and a larger frequency range than cluster 5. These “typical” clusters, however, still showed a higher peak frequency than descriptions from other fin whale calling studies (Table 1 in Chapter 3). Calls from cluster 4 were also initially designated as ‘typical 40 Hz’ calls, being within previously reported frequency ranges but typically being towards the higher frequencies of the more typical range. In addition, call clusters 2 (peak frequency = 100 Hz) and 3 (peak frequency = 28 Hz) validated comments initially made as a ‘high 40 Hz’ call and a ‘low 40 Hz’ call, respectively.

The clusters were strongly based on frequency parameters of the calls. The RF model results suggested that call cluster classification could be predicted to a very high degree of accuracy by considering the peak frequency and the frequency range of the call. Although call time and frequency parameters measured can be affected by ambient noise and acoustic propagation to varying degrees, this was not taken into account in this initial foray. However, the peak frequency is where most of the energy of the call is focused, and is likely the parameter least influenced by variables impacting the received call (e.g., propagation loss from variable propagating distances of the calling whale to the acoustic recorder) or during the manual selection process of extracting call parameters. Further to this, the decision tree model suggested the strongest feature defining the clusters was peak frequency and whether the value sat above or below a threshold value of 40 Hz (Figure 6). That the first binary decision step is centered on this frequency suggests that a review of the call classification and perhaps naming convention is needed for fin whale calls.

The application of the machine learning models in predicting the categorisation of calls in these new classes showed that the features defining the clusters are distinct enough to result in classes that can be reliably and repeatedly used to describe calls (e.g., Figure 5 and 6). This suggests more nuanced calling by fin whales than has been so far appreciated, and that the categorisation of calls to the 40 Hz type so broadly needs to be reconsidered.

The variability in fin whale 40 Hz calls has been suggested as a means for identification between conspecifics foraging in the same area (Wiggins and Hildebrand 2020). The strength of the clusters, however, suggests that the variability, although possibly produced on the individual level, may also be a reflection of spatially separated populations or sub-groups using different call characteristics. Variability could also arise from the social situation, behavioural context, or physiological condition of the caller, factors that were not able to be considered in this study. These factors would, however, presumably co-occur rather than show temporal separation in use that was shown provisionally here and further examined in Chapter 5. The sub-categories of the calls also suggest different aspects of foraging may rely on subtle differences in calls. These hypotheses can only be substantiated with concurrent visual observations and further temporal analysis.

Sound transmission properties of a location may also have some effect on the call parameters as they are received at the recorder and when they are being extracted as part of the analysis phase. Amplitude or power at the peak frequency during the cluster were not considered, or further decision tree analyses due to this being possibly as much an indicator of the relative distance of the calling whale from the acoustic recorder as it might be a defining call-type parameter. In the RF model, this was not found to be a feature influential in cluster determination.

Without visual means to express behaviour, whales rely primarily on subtleties in communication that express specific intent and motivation through sound. Fin whale vocalizations are seemingly simple. However, their use of distinct types of 40 Hz calls emphasizes that a more complex vocal repertoire may be more at play here than previously acknowledged. Further research in the temporal and spatial aspects of the sub-categories suggested by the cluster analysis, and an understanding of the drivers of this variability is necessary for further interpretation of these call types. The relative presence of the five sub-groupings of the 40 Hz call category over time are examined in Chapter 5.

This study also shows that both the 20 Hz and 40 Hz call descriptions form a reliable acoustic indicator to fin whale presence and potential habitat use (also see Burnham 2018). Further, the temporal separation between the use of 20 Hz and 40 Hz calls as described by Burnham (2019) is confirmed, but greater sub-division in the call type descriptions is suggested. The results presented here show that analysis of acoustic data and demarcation of calls may be done on too coarse a scale. Here, the frequency parameters dominated call categorisation, and perhaps use. For 20 Hz calls the inter-call interval and patterning of calls through time may also be an indicator of behaviour, group identity and call function. However, at least in the calls analysed here, this same manipulation of call timing was not found for 40 Hz calls. Knowledge of whale acoustics and the application of acoustic data to their ecological study is still undervalued and over-simplified. The recognition of a more varied repertoire of calls, and calls extending to frequencies not previously described, highlights the acoustic sensitivity of a species that has, up until now, been noted as having fairly simplistic call use. Recognising this can increase our awareness of the potential impact of anthropogenic noise and make us more conscious of how changing soundscapes impact this already endangered species.

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CHAPTER 5

Seasonal and Diurnal Call Patterns Within Fin Whale 40 Hz Call Types at an Offshore Site in British Columbia Waters

Abstract

Fin whale 40 Hz calls that are associated with group foraging activity are still an understudied vocalization; most research on fin whale calls focus on the 20 Hz song display, largely due to the potential of this call type to form song. Here, acoustic methods are used to consider the relative presence of fin whale 40 Hz calls in 2018/2019 recordings from an offshore site over daily, monthly and seasonal time periods, as well as the relative presence of the newly established five sub-groupings of the 40 Hz call category. The analysis of recordings showed both seasonal and diurnal temporal patterns for 40 Hz calls overall, with the highest relative acoustic presence during the late summer and spring and higher call presence during the daytime than during night or twilight. However, further analysis considering the five call subcategories within this call type showed variable seasonal and diurnal temporal patterns between subcategories, which may suggest higher variability in form and function of the 40 Hz call than has previously been recognized.

Introduction

Industrial whaling in British Columbia (BC) targeted fin whales and decimated their population numbers. As they recover, establishing knowledge of their abundance, habitat use, ecology and phenology in northeastern Pacific waters is critical for the preparation of successful management plans. Few dedicated vessel-based surveys have been commissioned to this task, with inherent logistical and financial constraints. Instead, passive acoustic monitoring (PAM) systems are being employed to try to fill these knowledge gaps.

Fin whales have two main call types. The 20 Hz downsweep is thought to be used predominantly while traveling, socializing and for mate attraction (McDonald et al., 1995; Edds-Walton, 1997; Watkins et al., 1987; Širović et al., 2013, Watkins et al., 2000; Croll et al., 2002; Koot, 2015; Širović et al., 2013; Burnham, 2019). The 40 Hz call, in contrast, is used during foraging (Širović et al., 2013; Burnham et al., 2021; Romagosa et al., 2021), and has been associated with group communications during feeding, suggesting a cooperative group function (Watkins 1981, Ramp 2016, Romagosa et al. 2020). Acoustic evidence shows fin whales use BC waters throughout the annual period and 40 Hz calls are present in all months examined (Frouin-Mouy et al. 2022, Chapter 2), although concentrated during the late summer and spring (Chapter 3). Changes through the year could indicate periods of more concentrated feeding behaviours, that may be correlated to oceanographic properties, seasonal upwelling, and prey abundance (Zerbini et al. 2016, Burnham 2019, Romagosa et al. 2021, Oestreich et al. 2022). Increased call presence in the acoustic record might indicate a greater abundance of whales, considering calling rate and concurrent call presence. On finer scales, call timing could be suggestive of temporal patterns in feeding activities. Diurnal patterns, for example, may provide clues to the targeted prey species and foraging tactics used, with many zooplankton species known to exhibit a diel vertical migration. Active feeding may be most prevalent at times when prey swarms are aggregated to maximize prey capture and minimize energy expenditure (e.g., see Stafford et al. 2005, Calambokidis et al. 2007, Baumgartner and Fratantoni 2008).

Fin whales feed on a wide variety of prey, such as squid, schooling fish, herring, euphausiids (Flinn et al. 2002, Mizroch et al. 2009). Foraging patterns have been seen to follow the presence of prey resources (e.g., Panigada et al. 2003, Nottestad et al. 2013), with previous PAM data preliminarily showing that the 40 Hz call peaks in spring and early summer, following the transition to an upwelling system (Širović et al. 2013, Koot 2015, Burnham 2019, Chandler et al. 2017). There has been little consistent evidence of diel patterning; daytime increases have been suggested for waters off the west coast of Vancouver Island (Burnham 2019), but patterns were not noted in other northern BC waters (Pilkington et al. 2018). In addition, analysis of the 40 Hz call used during foraging has found this call type to be much more varied than previously reported (Chapter 4).

Here, recordings from an offshore site at Clayoquot Slope on the west side of Vancouver Island, were examined for temporal patterning in the presence of 40 Hz calls. The relative presence over daily, monthly and seasonal time periods were examined, as was the relative presence from the newly established five sub-groupings of the 40 Hz call category (Chapter 4) to examine the drivers of variation within this call type. Together this may suggest the call structure and timing may be much more nuanced to the feeding behaviours than previously described.

Methods

Acoustic recordings from an offshore stationary hydrophone off the coast of Vancouver Island were used. The hydrophone was located at Clayoquot Slope on the continental shelf-break about 45 nm west of Vancouver Island at the base of Clayoquot Canyon (48.700° N, -126.872 W, Figure 1) at a depth of 1255 m. The recordings here were made continuously by an Ocean Sonics icListen AF hydrophone at a maximum sampling rate of 32 kS/sec and with a sensitivity of -159 dB re 1 V/μPa and a frequency range of 1 Hz to 12 kHz (± 3 dB bandwidth). This recorder is part of the Ocean Networks Canada, Neptune Observatory network and has been in place since 2009; here the focus was data between July 2018, to July 2019 (Ocean Network Canada Oceans 3.0 Data portal, https://data.oceannetworks.ca/home).

Figure 1: Map of the British Columbia coast, with the source of acoustic recordings for this study at Clayoquot Slope indicated by red star.

Analysis

A manual aural-visual analysis of the recordings was undertaken to identify call presence in the recordings. Each call was classified into one of five sub-groups of the 40 Hz call, described previously through a cluster analysis (see Chapter 4). Categorization was done in reference to previous work which distinguished five clustered groups of call types which were statistically and audibly distinct from each other (Chapter 4). The groupings were primarily based on peak frequency and frequency range parameters of calls, where Group 1 calls had an average peak frequency of 57.8 Hz and average frequency range of 22.5 Hz, group 2 was 100.9 Hz and 21.5 Hz, group 3 was 28.5 Hz and 15.2 Hz, group 4 was 70.9 Hz and 14.5 Hz, and finally group 5 calls was 51.5 Hz and 13.0 Hz.

The temporal presence of calls was considered. Each call was assigned to a season, month and time of day. Seasons were defined as: fall (September 23 to December 20), winter (December 21 to March 20), spring (March 21 to June 20), and summer (June 21 to September 22). Calls within subcategories were examined for hourly patterns and diurnal periodicity in different light conditions by allocating each call to a period of nautical twilight (two hours before sunrise to two hours after sunrise as dawn, and two hours before sunset to two hours after sunset as dusk), day (two hours after sunrise to two hours before sunset), or night (two hours after sunset to two hours before sunrise). Standard times of solar rise and set were calculated at deployment location using the National Research Council of Canada's Sunrise/Sunset Calculator (http://www.nrc-cnrc.gc.ca/eng/services/sunrise/advanced.html). Timing of peaks in call presence of each call type group was established, and the relative presence of each of all the calls identified was established. Chi-square goodness of fit tests using a 95% confidence level were utilized to determine if calls were evenly distributed among different time periods.

The number of calls per month and per hour were calculated and expressed as a call presence rate. This was done to have a standardized measure for comparison but does not account for the number of calling whales present at any one time.

Results

A total of 16,261 fin whale 40 Hz calls identified in the sample of recordings from Clayoquot Slope, each categorized to one of the five sub-groups within this call type. Group 1, which had an average peak frequency of 57.8 Hz, had 2,669 calls, group 2 had an average peak frequency of 100.9 Hz and had the lowest number of calls at 275, group 3 with an average peak frequency of 28.5 Hz had 4,771 calls, group 4 had an average peak frequency of 70.9 Hz and

3,249 calls, and finally group 5 had an average peak frequency of 51.5 Hz had the highest number of calls at 5,233. Considerable differences in annual, seasonal, and daily call rate peaks were evident between the five subcategories within this call type. Overall, 40 Hz calls were most present in the summer to late fall, with low call presence through the winter (Figure 2). The late summer also showed the highest call rates (number of calls/hour), with the higher-frequency group 2 calls most prevalent at this time (Figure 3, Table 1). Calls categorized as 40 Hz were present in every month, with Groups 3, 4, and 5 present in low numbers through the winter (Figure 3, Table 1).

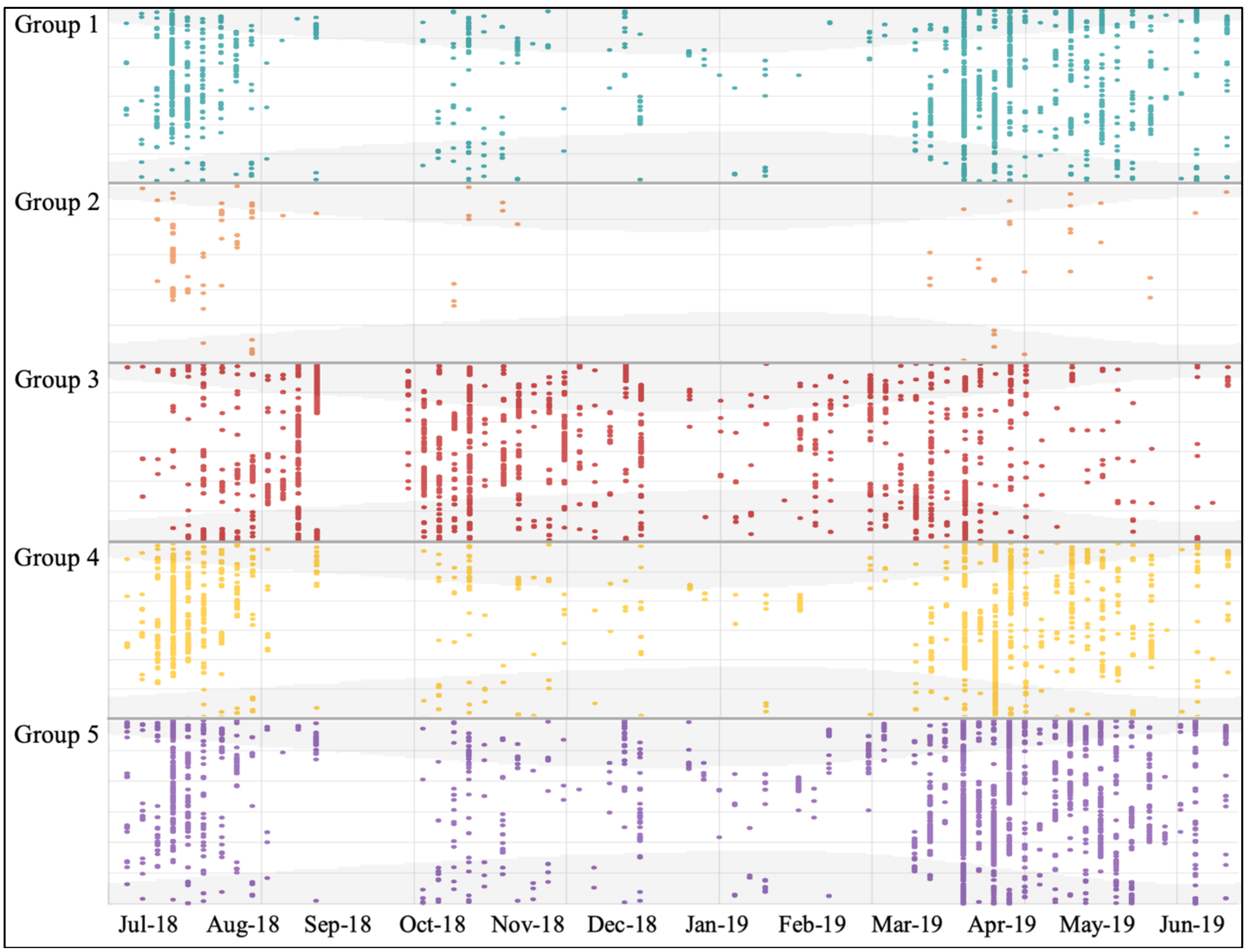

Figure 2: Fin whale 40 Hz calls as they occur in varying light conditions over the study period between July 2018, and July 2019. White and light gray backgrounds represent daytime and nighttime, respectively. Calls are represented as colored dots.

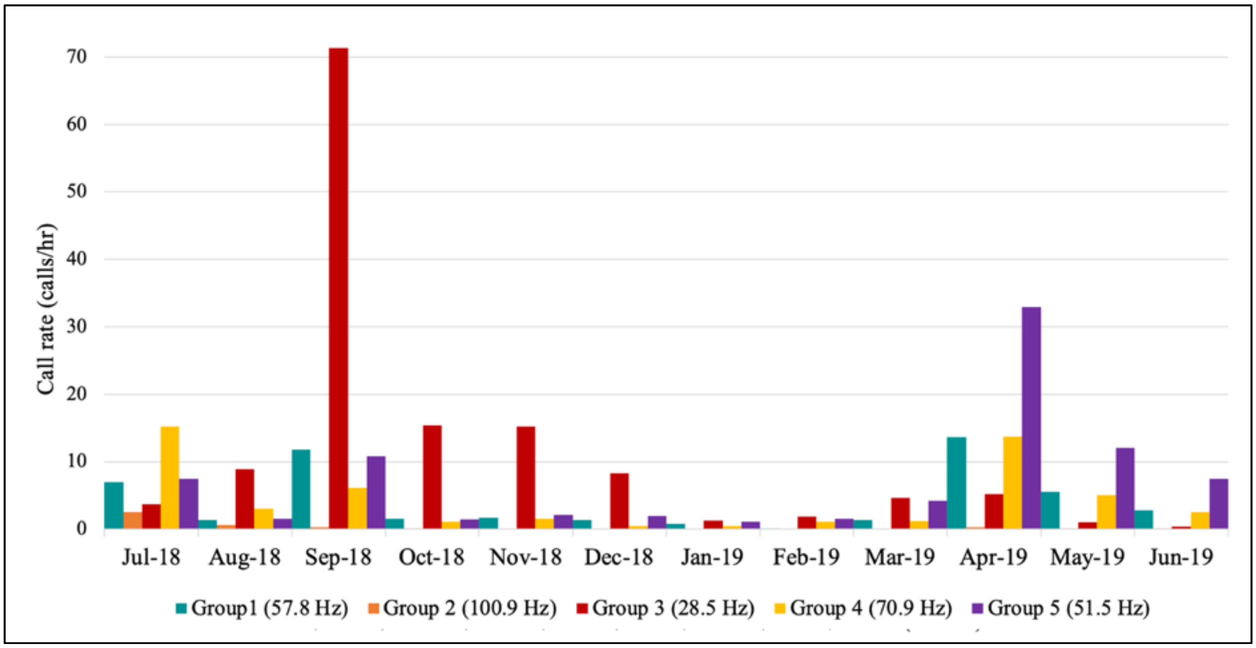

Figure 3: Monthly call rates of the fin whale 40 Hz call type groups identified in recordings from July 2018 to June 2019 at Clayoquot Slope, represented as number of calls per hours analyzed in each month.

Table 1: Monthly call use of five subcategories within the 40 Hz call type, expressed as the number of calls found in each month (n), the monthly call rate (calls/hour), and as the monthly proportion of 40 Hz calls (%).

Month		n	Call Rate (n/hr)	Proportion (%)
July 2018	Group 1	503	7.0	19.5
	2	184	2.6	7.1
	3	256	3.7	9.9
	4	1,100	15.3	42.7
	5	535	7.4	20.8
August	Group 1	94	1.3	8.8
	2	42	0.6	3.9
	3	619	8.9	57.9
	4	211	3.0	19.7
	5	104	1.5	9.7
September	Group 1	50	11.8	11.7

	2	1	0.2	0.2
	3	303	71.3	71.1
	4	26	6.1	6.1
	5	46	10.8	10.8
October	Group 1	110	1.5	7.9
	2	6	0.1	0.4
	3	1,098	15.4	78.8
	4	79	1.1	5.7
	5	101	1.4	7.2
November	Group 1	123	1.7	8.3
	2	6	0.1	0.4
	3	1,097	15.2	73.7
	4	113	1.6	7.6
	5	150	2.1	10.1
December	Group 1	66	1.4	11.5
	2	0	0.0	0.0
	3	394	8.3	68.6
	4	23	0.5	4.0
	5	91	1.9	15.9
January 2019	Group 1	53	0.7	20.7
	2	0	0.0	0.0
	3	95	1.3	37.1
	4	30	0.4	11.7
	5	78	1.1	30.5
February	Group 1	6	0.1	2.4
	2	0	0.0	0.0
	3	100	1.8	39.8
	4	59	1.1	23.5
	5	86	1.6	34.3
March	Group 1	97	1.3	11.7
	2	3	0.0	0.4

	3	335	4.6	40.4
	4	89	1.2	10.7
	5	306	4.2	36.9
April	Group 1	985	13.6	20.7
	2	19	0.3	0.4
	3	377	5.2	7.9
	4	991	13.7	20.9
	5	2,375	32.9	50.0
May	Group 1	394	5.5	23.4
	2	8	0.1	0.5
	3	71	1.0	4.2
	4	356	5.0	21.2
	5	856	12.0	50.8
June	Group 1	188	2.8	21.0
	2	6	0.1	0.7
	3	26	0.4	2.9
	4	172	2.5	19.2
	5	505	7.4	56.3

Annual patterns

A bimodal peak in call presence and calling rates were seen through the year of data analyzed. Overall, the 40 Hz calls were most prevalent in the fall and spring (Figure 3). Timing of the peaks differed between groups; Groups 1, 4 and 5 calls comply more closely to the typical 40 Hz call description and are most prevalent in the spring. Group 2 calls peaked in number of calls per hour in the summer, and group 3 in the fall, although the lowest rates of calling were present during winter months for all 40 Hz call types (Figure 3).

Group 3 had the highest call rate overall and was present in all months. This contrasted to Group 2 that had the lowest call rate and was absent in the winter months. Group 3 and 5 had a similar pattern of presence, where calling peaked in the late summer-early fall but was less present during the summer months. Group 4 followed the pattern that might be most expected for a call representing foraging; it was most prevalent during the summer, peaking in July, and showed comparatively low numbers of calls from October to February.

The proportional presence of each call group through time was also examined (Figure 3). This showed the use of group 3 calls to be distinct, with the monthly presence of this call type contrasting with the other four groups. Its highest presence was in September, a month with only one day of data availability (September 5, 2018), and was proportionally the most frequently heard call type in October, during a period of relatively low proportional use of other subcategory calls. Conversely, Group 3 calls are proportionally lowest in June, during a period of relatively high proportions of most other subcategory call use. The other call groups peaked in call rate and in their proportional presence in late spring and summer months (Figures 2 and 3), which might be more in line with the use of a call thought to be correlated with foraging activities. Group 2 was the only call sub-group not present in the winter months.

Daily patterns

Testing for periodicity showed significant diurnal patterning within subcategories (Table 2), although this was not consistent throughout the year analyzed. When examined over the full year of data, all groups except for group 3 had significantly more calls during the day than during night and twilight (Table 2). Within the groups that showed higher calling during the day periods, this diurnal pattern was most strongly seen for Group 4. Group 3 calls were more present during the twilight periods than during the day or overnight, and specifically more prevalent in dusk compared to dawn ($n = 1830$, $p < 0.001$ in chi-squared test). Groups similar to each other in structure, such as Groups 1 and 5, which have similar average peak frequencies (57.8 Hz and 51.5 Hz, respectively) but different average frequency ranges (22.5 Hz and 13.0 Hz, respectively), differed in their daily presence in the strength of significance that this pattern held.

Table 2: Diurnal significance test results for fin whale 40 Hz call type groups identified in recordings at Clayoquot Slope using t-tests.

Group	Average Peak Freq. (Hz)	$\chi2$ value	p-value	Diurnal call period
1	57.8	117.492	< .001	day
2	100.9	189.913	< .001	day
3	28.5	149.629	< .001	twilight (dusk)
4	70.9	467.825	< .001	day
5	51.5	13.285	.0013	day

Diurnal periodicity was considered seasonally for each call group (Table 3), although was limited for Group 2 due to the lack of calls in the fall and winter and low numbers in the spring (Figures 2,3). No consistent diurnal pattern between seasons was seen for any of the call groups (Table 3). In the fall and winter seasons, all groups showed significantly higher call use during the dusk or night than during day. In the spring, Groups 1, 4, and 5 changed to show significantly higher call use during the day than night and twilight, while Group 3 maintained more calls at night. During the summer period, Groups 1 - 4 all had higher call use during the day than night and twilight, while Group 5 changed to show significantly higher call use at night.

Table 3: Diurnal significance test results for fin whale 40 Hz call type groups for each seasonal period, using t-tests. Months marked with an asterisk indicate the period of peak call rate(s) (unimodal or bimodal) for each group.

Group	Season	$\chi2$ value	p-value	Diurnal call period
1	summer*	165.356	< .0001	day

	fall	105.679	< .0001	night
	winter	21.000	< .0001	twilight (dusk)
	spring*	120.418	< .0001	day
2	summer*	215.852	< .0001	day
	fall			
	winter			
	spring			
3	summer*	19.513	< .0001	night
	fall	88.373	< .0001	twilight (dusk)
	winter	83.186	< .0001	twilight (dusk)
	spring	91.379	< .0001	night
4	summer*	942.839	< .0001	day
	fall	75.47	< .0001	twilight (dusk)
	winter	31.294	< .0001	twilight (dusk)
	spring*	30.686	< .0001	twilight (dawn/dusk) and day
5	summer	12.24	.0022	night
	fall	79.00	< .0001	night
	winter	37.406	< .0001	night
	spring*	71.415	< .0001	day

Discussion

Calls classified as 40 Hz, and noted as foraging calls, were present year-round along the continental slope at the base of Clayoquot Canyon. The analysis of recordings showed both seasonal and diurnal temporal patterns in the five subcategories previously determined for the 40 Hz call (Chapter 4). Four of the five call subcategories were present in all months of the study period. Testing for significance in diurnal periodicity for the entire study period showed significantly higher daytime presence than during night or twilight conditions. However, this was not consistent when considered on a seasonal basis. The variability in timing of use combined with the variability found within the parameters of the fin whale 40 Hz calls highlighted in previous chapters (Chapters 3 and 4) suggest the function of the call may be nuanced and, with further study, may give greater insight into fin whale feeding behaviours.

Overall, the 40 Hz calls showed two peaks in annual presence: the strongest presence was in the late summer with a second peak in spring (Figure 3, Chapter 3). The strongest peak in presence was driven principally by the elevated presence of Group 3 calls in September, the group with the lowest frequency 40 Hz calls included in this analysis. Group 3 calls may represent a transition from the dominant use of 40 Hz calls to 20 Hz calls in the winter. However, a similar transitional use of calls was not seen in the spring. This call pattern may indicate an anticipatory function for Group 3 calls prior to 20 Hz call production and the fin whale breeding season. It was also considered that Group 3 calls are 20 Hz pulse calls that have been previously described in the literature (Watkins 1981, McDonald et al. 1995, Edds-Walton 1997) but now produced in slightly higher frequencies. The diurnal patterning determined here, with more calls at night than day or dusk during its call rate peak, is more consistent with the 20 Hz call type (Koot 2015, Širović et al. 2013). However, this call is concentrated during the period when 20 Hz calls are rare in the data stream and, although Group 3 calls are produced during the winter, their use declines over this period. Additionally, these calls were higher in average peak frequency than other 20 Hz calls (20.8 Hz, Chapter 2) produced as irregular pulses with the inflection and timbre of typical 20 Hz calls at the same time at Clayoquot Slope. These differences, therefore, separated these calls from the 20 Hz type. Also considered was the possibility of Group 3 calls to be produced by sei whales, based on the combination of the structural and temporal differences from both fin whale 20 Hz and 40 Hz calls. Similar calls produced by sei whales were identified by Rankin and Barlow (2007) near the Hawaiian Islands, which the authors note had a longer duration (1.2 s) than fin whale calls (0.8 s) with the same frequency characteristics. Group 3 calls identified in this study had a mean call duration of 0.7 s, which more closely resembles fin whale calls. Although endangered in Canadian waters, a large aggregation of sei whales has recently been sighted in offshore BC waters (T. Doniol-Valcroze, personal communication, December 8, 2021), so this consideration cannot be ruled out without paired observational data. Further research that examines the use and behavioural context of this newly described call for this region may help to determine the source and if there are any functional differences for this call.

The second annual peak in 40 Hz call rates was during the spring. Spring presence was predominantly from the subgroups considered more typical for the 40 Hz call type, with higher proportional use of Group 1 (57.8 Hz), Group 4 (70.9 Hz), and Group 5 (51.5 Hz) calls (Figure 3, Table 1). During this period, calls were mostly produced during the day (Table 2). Examined call patterning of the call groups within this three-month timeframe corroborates with previous acoustic studies in the northeast Pacific Ocean showing similar temporal results of 40 Hz calls with comparable average frequencies (Burnham 2019, Širović et al. 2013). Acoustic behaviour in the daytime during a period that coincides with the spring bloom (Chandler et al. 2017) may suggest fin whales concentrate feeding efforts during the day to capitalize on dense prey aggregations at depth during periods with high biological productivity and increased prey availability. The lack of consistency in subcategory composition between the two annual peaks may suggest different feeding behaviours or prey targeting are present during these two periods.

The increased 40 Hz call presence in July was driven by the presence of calls from Groups 2 and 4. These higher frequency fin whale calls have yet to be described by other studies, and so we can only speculate as to their function without further study. The acoustic differences between fin whale calls during the spring bloom and summer may suggest different aspects of foraging, which may rely on subtle differences in call use or structure. Further research to determine the behavioural context in call production of these 40 Hz call groups with peak frequencies outside of what is considered more typical for this fin whale call type may help determine what drives the production of these calls.

The winter months marked another shift in fin whale acoustic behaviour. Although 20 Hz calls clearly dominated their sound production (Chapter 3), fin whales continued to produce 40 Hz calls year-round, although at relatively low calling rates through the winter season (Figure 3). The presence of fin whale calls associated with foraging behaviour during their winter breeding season is consistent with previous research which found at least some of the fin whale population remain in BC waters year-round instead of migrating to warmer breeding locations (Burnham 2019, Frouin-Mouy et al. 2022). The diurnal periodicity during the winter for all subcategories were found to be extremely significant during the dusk or night (Table 3), which parallels the diel patterning found for 20 Hz calls here (Chapter 3), and so may be a more general calling pattern, not specific to foraging. The functional use of 20 Hz call and song production during the night is largely unknown but has so far been understood as the period when whales are not focused on foraging (Aulich et al. 2023). It also may be to take advantage of lower ambient sound levels, presuming that vessel noise might be reduced during this time particularly from non-commercial vessels.

Most research on fin whale vocalizations has focused on the 20 Hz call variety, largely due to the potential of this call type to form song; little information is available on their 40 Hz calls (but see Širović et al. 2013, Burnham 2019). In many cases, the absence of 20 Hz calls in acoustic recordings during the day is presumed to indicate the presence of fin whale foraging behaviour and a switch to the production of 40 Hz calls (Simon et al. 2010, Pilkington et al. 2018, Burkhardt et al. 2021). However, this research shows this to be an erroneous assumption and that these call types are not mutually exclusive. The variation found in the 40 Hz calls here adds support to this and suggests that call structure might be more nuanced and refined based on the behaviour the whale is engaged in, as well perhaps the social or physiological context when calling. It may also represent adaptive measures in response to changes in ambient noise and sound propagation conditions, not considered in this analysis.

The variability in frequency parameters of fin whale 40 Hz calls has also been suggested as a means for identification between conspecifics foraging in the same area (Wiggins and Hildebrand 2020). Following this suggestion, the 40 Hz call sub-groups used here may be reflective of populations or sub-groups that use different call characteristics when using Clayoquot Slope and the surrounding offshore waters as a foraging location. Although there is some overlap in the temporal distribution of the sub-groups, the annual peak timing properties differ for each sub-group and may then reflect the presence of these population groups arriving at and using these foraging grounds during different periods.

This research suggests fin whales in BC waters optimize the seasonal window of higher foraging opportunities during the spring and summer at Clayoquot Slope, while seasonal increases in fin whale foraging intensity are coincident with periods of increased ocean productivity (Panigada et al. 2003, Širović et al. 2013, Burnham 2019, Burkhardt et al. 2021). There may be more flexibility in foraging patterns throughout the year than has been previously recognized. Findings here also underscore the variability within the fin whale vocal repertoire and highlights the limitations of categorizing call types that may underestimate the complexity of the calls and the messages they carry.

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CHAPTER 6

Fin Whale Song Presence and Pattern Analysis in British Columbia

Abstract

Regular patterning of 20 Hz fin whale calls forms 'song', thought to represent males' reproductive display calls. Patterns are defined by regular sequences of calls, and repetition of a note or notes, separated by a consistent inter-pulse (IPI) interval. In British Columbia (BC) the presence of a doublet song has been described as the dominant pattern since 2007, comprised of two note types and two alternating IPIs. This pattern is widely observed in the North Pacific. Here, analysis from acoustic recordings from 2018-2019 at a site on the west coast of Vancouver Island confirmed the continued prevalence of this song type, but also described a previously undocumented singlet song for this area. Song patterns were present in all months except June, but were prevalent over the winter, consistent with previous descriptions from BC. Fin whale song suggests the use of BC waters for courtship, breeding and calving and the difference in song structures may represent at least two populations using these waters.

Introduction

Fin whales make a variety of low-frequency calls of which the most commonly described is the 20 Hz downsweep, used predominantly when travelling and socializing (McDonald et al. 1995, Edds-Walton 1997, Širović et al. 2013). These can be produced as single calls or arranged in repeated patterns. If these stereotyped calls are produced in a regular pattern, with consistent intervals between calls, they are referred to as "notes" and the sequence represents song thought to be used by males as part of their reproductive display (Watkins et al. 2000, Croll et al. 2002, Koot 2015, Širović et al. 2013, Burnham 2019, King-Nolan et al. 2024). Several fin whale song structures have been observed worldwide, each with different note and timing properties, and may reflect distinct populations (Mellinger and Barlow 2003, Hatch and Clark 2004, Delarue et al. 2009, Koot 2015, Castellotte et al. 2012, Širović et al. 2017, Burnham 2019). Song notes consist of lower frequency “A” notes (<15 Hz; sometimes referred to as the “backbeat” note) and/or slightly higher frequency “B” notes (>15 Hz; sometimes referred to as the “classic” note because it is similar in frequency to other 20 Hz fin whale calls). The structure of each song refers to how the IPIs are organized; singlets consist of a single repeated IPI, doublets alternate between two different IPIs, and triplets repeat the pattern of three different IPIs between 20 Hz pulses. It is typical for a singlet song pattern to consist of one repeated note of the same frequency (i.e. A or B). For doublet patterns the note types in the pattern may differ, with a B note and an A note often forming the pattern (Širović et al. 2013, Burnham 2019), but could also include phrases of A-A or B-B providing the timing between notes have two different IPIs. Fin whale songs can be repeated for hours or longer and show seasonal peaks that coincide with their annual breeding period. Like the songs of humpbacks, patterns change over multiple temporal scales, with subtle changes identified over a singing season (Oleson et al. 2014) and song evolutions over decades (Weirathmeuller et al. 2017).

In British Columbia (BC) waters fin whale song has been analyzed from passive acoustic recordings spanning the last 15-years. Currently, the dominant song pattern noted here has a doublet structure that alternates between a B and an A note (see Koot 2015, Burnham 2019). This pattern is consistent with other song notations in the eastern north Pacific (see Soule and Wilcock 2013, Oleson et al. 2014, Širović et al. 2017, Weirathmueller et al. 2017). Studies predating 2007 suggest that a singlet pattern may have dominated in BC waters, with a documented transition over approximately 10 years to the doublet-dominant song currently present (Weirathmueller et al. 2017). Although similar in structure, the IPI durations between notes in this doublet have shown variation over time, as high as 24/30 s in 2003/2004 as reported by Soule and Wilcock (2013) and as reduced as 10-15 s in 2007 noted by Weirathmueller et al. (2017). Despite the prevalence of song observations in BC waters, our understanding of fin whale song here is still limited.

Recent recordings from offshore west coast Vancouver Island report a doublet pattern with consistent temporal presence and IPI with recordings made in southern California (Širović et al. 2017, Burnham 2019). As song patterning has been linked with population structures and sub-grouping (Hatch and Clark 2004, McDonald et al. 2006, King-Nolan et al. 2024), the consistency in the presence of this pattern suggests a far-ranging population and/or highly connected population group that spans the west coast of North America (Širović et al. 2017, Burnham 2019). Here, I identify the presence and temporal patterns in fin whale song, building on findings from Burnham (2019), in BC waters and particularly offshore of Vancouver Island. Changes in song structure over various time scales will be examined; it is known that fin whale song characteristics and the IPI can change over a season (Oleson et al. 2014, Širović et al. 2017, Burnham 2019), but changes over longer time scales are also beginning to be noted (Weirathmueller et al. 2013). Comparison to patterns known to the region, and north Pacific more generally, will help clarify aspects of population structure and dynamics, as well as the phenology of breeding and migration. This may stimulate discussion on the drivers of these changes and what this might imply for fin whale population structures in BC.

Methods

Passive acoustic recordings

Continuous recordings were made from a bottom-stationed hydrophone, located at the base of Clayoquot Canyon, offshore west coast Vancouver Island at a depth of 1255 m (48.700° N, -126.872° W; Figure 1). This location is consistent with previous works by Burnham et al. (2019) in describing fin whale presence and song pattern (Burnham 2019). The acoustic data were collected by an Ocean Sonics icListen AF hydrophone that recorded continuously at a maximum sampling rate of 32 kS/sec and with a sensitivity of -159 dB re 1 V/μPa and a frequency range of 1 Hz to 12 kHz (± 3 dB bandwidth). This hydrophone is one of several acoustic nodes that form part of the Ocean Networks Canada Neptune Observatory network. Recordings were retrieved from the Ocean Network Canada Oceans 3.0 Data portal (https://data.oceannetworks.ca/home). Data from July 2018 to July 2019 were used for this analysis.

Figure 1: Location of the acoustic recorder (red star) at the base of Clayoquot Canyon, west coast Vancouver Island, British Columbia.

Acoustic Analysis

Manual aural-visual verification was undertaken by generating spectrograms using a 256-point Hann window FFT with 50% overlap in Raven Pro Interactive Sound Analysis software (Version 1.6.4; Charif et al. 2010, Center for Conservation Bioacoustics 2014). A systematic sampling regime was undertaken, whereby a full day of recording was analyzed every fifth day of recording throughout the year. Notes on the presence of fin whale calls were made, along with details of call parameters, including the highest and lowest frequency extents (Hz), peak frequency (the frequency where most of the call energy was focused, Hz), call duration (s), and peak power density (highest received level of call energy in selection, dB FS/Hz), and structure and timing of note patterning (IPI). During the manual aural-visual analysis comments were made on whether the calls appeared to form a pattern of singlet, doublet or triplet structure. Within these initial song structure groupings IPI calculations were made, which were calculated as the time between the start of a note, to the start of the subsequent note. If multiple IPI forms were identified within the same song structure (i.e. singlet, doublet, triplet) these were noted, but the modal IPI was considered predominant. Each apparent pattern was compared to those recorded in the eastern North Pacific, with reference to call structures and timing documented in previous studies (Table 1). In this comparison call parameters and IPI were used. To be conservative and to account for possible errors in call selection, average values were rounded to the nearest Hertz (for frequency) or second (call length, IPI).

Table 1: Fin whale song patterns previously reported from acoustic recordings in BC waters. The study location, period of study, and the song patterning observed (including the note type, pattern type, and the IPI, in seconds) are given. These are compared to the results of this study.

Reference	Location	Study period	Song pattern
Soule and Wilcock 2013	Endeavour	2003-2004	A singlet (25 s)
			AB doublet (24/30 s)
Koot 2015	Brooks Peninsula	2010-2011	AB doublet (13/17 s)
			AB doublet (12/16 s)
Weirathmueller et al. 2017	Endeavour	2003-2013	A singlet (25-30 s)
			AB doublet (10-15 s)
Burnham 2019	Clayoquot Canyon	2016-2017	AB doublet (16.5/17 s)
This study	Clayoquot Canyon	2018-2019	AB doublet (19/21 s)
			B singlet (20 s)

The relative presence of song, and song types, were noted through time and considered on a monthly basis. This helped examine patterns through the year, including seasonal peaks that had been noted in previous works.

Results

Over 92,000 20 Hz calls were identified from 747 hours of the sample of recordings from the base of Clayoquot Canyon. Of these, 16% of the 20 Hz pulses identified were in a discernable song pattern with regularly repeating notes. In some sections of the recordings, more than one song type may have been present. Due to the uncertainty of possible patterns and potential overlap of song sequences, these sections of the acoustic data were not analyzed further for their IPIs and structuring. Only sequences of 20 Hz notes that were clearly in a repeated pattern were subject to further analysis.

Two song patterns dominated. The first was similar to that reported by Burnham (2019) from recordings made in the same location (Table 1), forming an AB doublet from 20 Hz and backbeat notes that were separated by a regular IPI of 19/21 s (Table 1, Figure 2). Overall, this accounted for 91% of all the song structures that were further analyzed for timing properties and accounted for 69.2% of all song patterns. The other prevalent pattern was a repeated B note singlet separated by a regular IPI of 20 s (Table 1, Figure 3). This was present in 7.1% of the recordings with song patterns. The remaining patterns were identified as ABA triplets (0.2%) (Figure 4) and a further 23.5% of calls that were suggestive of song, but the patterning was unclear due to multiple callers or concurrent call structures.

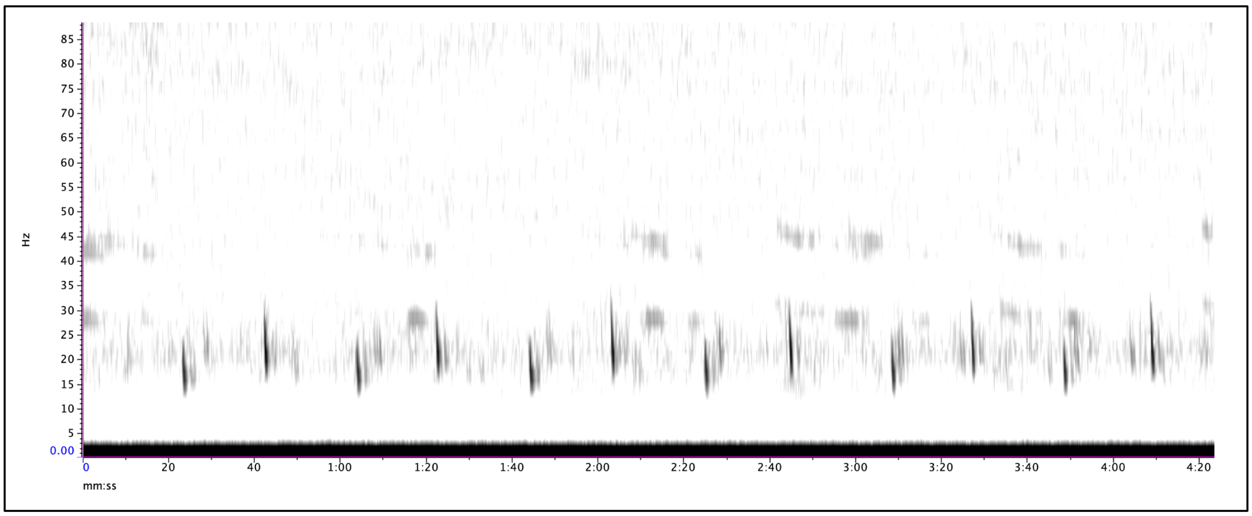

Figure 2: Example of fin whale doublet pattern (AB) observed at Clayoquot Slope from October 30, 2018. Blue whale B calls are also present in the background. Spectrograms were generated using a 256-point Hanning-window FFT with 50% overlap.

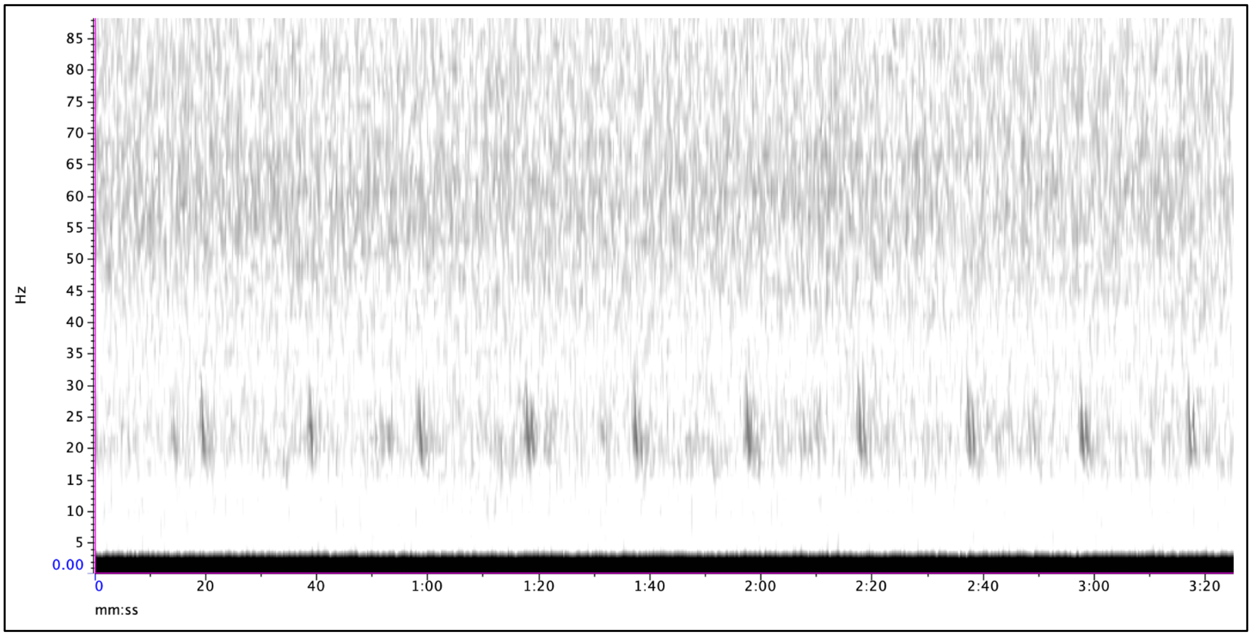

Figure 3: Example spectrogram of fin whale singlet pattern (B) observed at Clayoquot Slope from January 15, 2019. Spectrograms were generated using a 256-point Hanning-window FFT with 50% overlap.

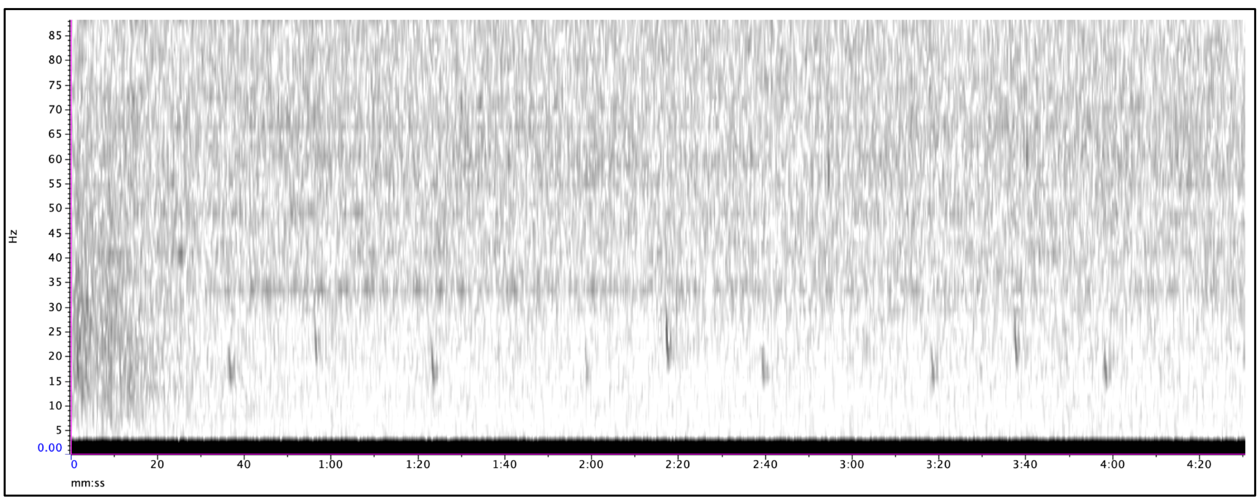

Figure 4: Example spectrogram of fin whale triplet pattern (ABA) observed at Clayoquot Slope from April 10, 2019. Spectrograms were generated using a 256-point Hanning-window FFT with 50% overlap.

Song patterns were found in every month, except June. The presence of the two dominant types differed over time. The prevalence of the doublet pattern notes was greatest in October, followed by a second peak in March. This contrasted with the presence of the singlet pattern which increased from October until February, and then was mostly absent (Figure 5). Switching between the use of singlet and doublet song types occurred during 23 song sequences, which has been reported previously elsewhere (see Soule and Wilcock 2013, Helble et al. 2020). However, this switching was on short-time scales, within hours.

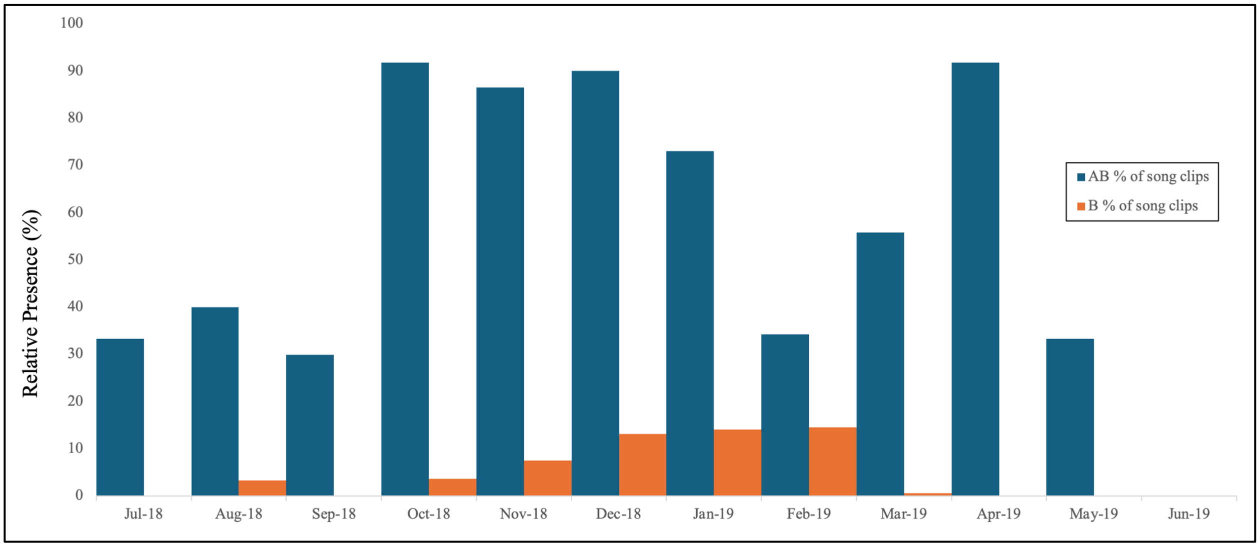

Figure 5: The monthly distribution of the two dominant fin whale song types identified in recordings from July 2018 to June 2019 at Clayoquot Slope, represented as relative percentages of recordings analyzed with song patterning present.

Through the analysis some deviation from the average IPI in the pattern was occurring. Overall, eight AB doublets with different IPIs were calculated, including those with IPIs of 18/20, 18/21, 18/22, 19/20, 19/21, 19/22, 19/23, 20/22 s (Figure 6). However, the most predominant IPI within the doublet structures was 19/21 s. Two AB singlets were calculated including those with IPIs of 19 and 20 s, but in consideration of the deviation seen in IPIs for the AB doublet pattern, were considered deviant forms of the doublet song structure. Four B singlets were found, including those with IPIs of 18, 19, 20, 21 s, and the predominant IPI within the singlet structures was 20 s (Figure 7). Koot (2015) argued these differences in IPI could be indicative of separate population groups, even with differences in IPIs of only one second. The analysis here showed overlapping temporal presence of the ten AB doublet variations throughout the annual period (Figure 6), which was also evident for the four B singlet variations (Figure 7).

Consistency with the analysis Koot (2015) presented would indicate the two dominant song types could represent as many as 14 population groups or sub-groups.

Previous analysis by Oleson et al. (2014) and Burnham (2019) has shown IPIs to increase as the breeding season progresses, which was not evident for song patterns identified in this study. Song variations were sometimes identified simultaneously within recordings, with instances of pattern changes also present within songs.

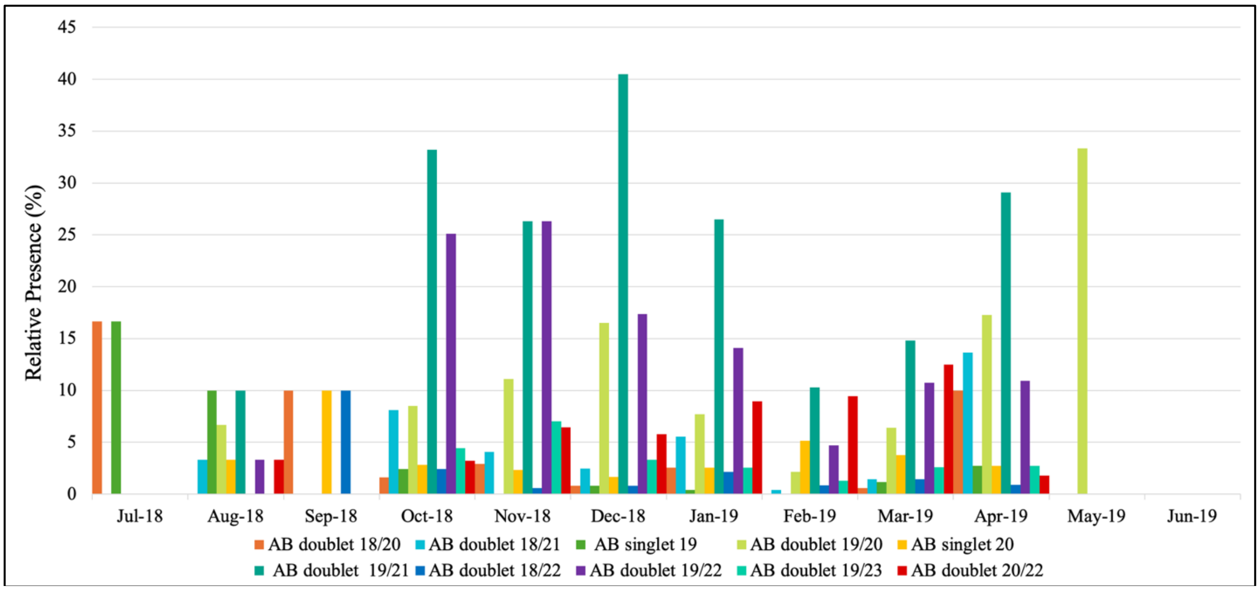

Figure 6: The monthly distribution of the ten forms of the AB doublet song pattern identified in recordings from July 2018 to June 2019 at Clayoquot Slope, including eight AB doublets and two AB singlets with different calculated IPIs. These are represented as relative percentages of recordings analyzed with song patterning present.

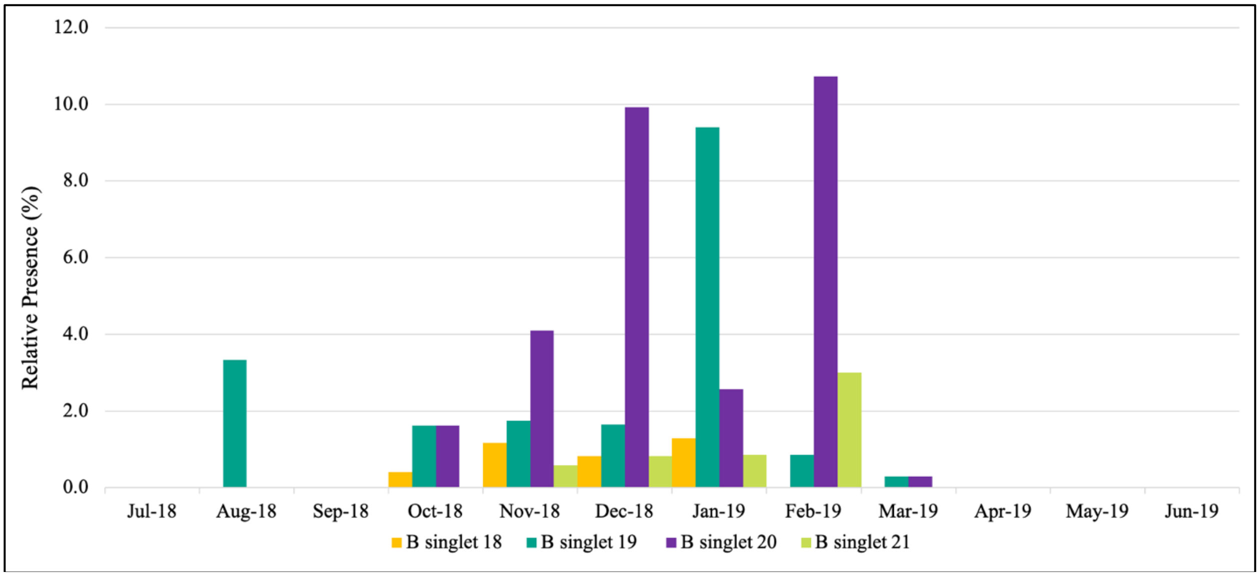

Figure 7: The monthly distribution of the four forms of the B singlet song pattern identified in recordings from July 2018 to June 2019 at Clayoquot Slope, including four B singlets with different calculated IPIs. These are represented as relative percentages of recordings analyzed with song patterning present.

Discussion

The presence of song patterns in the recordings confirms BC waters are an area of reproductive activity (courtship, mating and/or calving) for fin whales. This was first noted in whaling records (Gregr 2000) and the presence of song in these recordings from 2018/2019 over 50 years later suggests it remains true. Pregnant females were noted in the whaling records in northern BC from April to September (Gregr 2000) and with a gestational period of approximately a year, the song prevalence in the fall agrees with its use in reproductive displays. The presence of song in almost all months examined here suggests that courtship may occur over several months and that song may also serve a more general social function (Herman 2017), or aid in the locating of conspecifics (Mercado and Perazio 2021). Indeed, the use of song in humpback whales (*Megaptera novaeangliae*) is thought not only to attract females to individual males, but to have a broader role in the social matrix on the breeding grounds, facilitating hierarchical structuring and male-male affiliations as well as attracting females to an aggregation on males as part of a lekking system through communal singing (Herman 2017). In general, the breeding-feeding dichotomy in call behaviour has been observed to be more flexible than originally thought for some baleen whale species. For instance, humpback whale song has been observed on feeding grounds, with it more sporadically produced in the late summer and autumn months (Gabriele and Frankel 2002, Stimpert et al. 2012, Vu et al. 2012) as well as on migration (Norris et al. 1999, Ryan et al. 2019), indicating courtship may be a more prolonged process. The prevalence of the AB doublet song structure agrees with previous studies in the area (Koot 2015, Burnham 2019) and its dominance more generally in the northeast Pacific (Širović et al. 2013, Oleson et al. 2014, Weirathmueller et al. 2017, Burnham 2019). However, even given some flexibility to account for call selection errors and variation in IPI through a breeding season (see Oleson et al. 2014, Burnham 2019), the temporal structure of the doublet song in this study differs from those of similar patterns previously reported (Table 1). If these changes are considered as the same structure, but showing a long-term evolution, then there is a trend over the last 15 years or so of an increasing IPI in the doublet, whereby the report by Koot (2015) in 2010 of 13/17 s increased to 16.5/17 s in 2017 (Burnham 2019) and to 19/21 s in 2018 in this study. Comparing reports by Koot (2015) from 2010 to those by Burnham (2019) from 2017, the IPI lengthening seems to have only affected the short IPI of the AB doublet whereas the long IPI stayed the same (Table 1). However, the temporal change of the AB doublet from 2017 (see Burnham 2019) to 2018/2019 in this study, only a year later and at the same study site, was considerable and affected both the long and short IPI measures. This trend towards an increasing IPI over multiple years mirrors the changes in IPI observed over a decadal timeline, as described by Weirathmueller et al. (2017), and over a breeding season, as described by Oleson et al. (2014) and Burnham (2019) in their fin whale song analyses. This could be akin to humpback whale song, where singers adopt changes during the breeding season, while maintaining the same song structure but display song revolutions between seasons (Garland et al. 2011, Allen et al. 2018). These changes might also be indicative of population substructure and distribution, as well as perhaps a mechanism to overcome changes in ambient noise levels (see King-Nolan et al. 2024). Future research to examine fin whale song characteristics for this region that includes the period between 2010 and 2017, as well as years subsequent to this study, may help develop a finer-scale understanding of the evolution of the AB doublet over longer time periods for this region (see Weirathmueller et al. 2017).

Previous analyses by Oleson et al. (2014) and Burnham (2019) has shown a temporal progression in the IPI timing of fin whale song patterns over a single breeding season. This was not evident in song patterns identified in this study. Instead, the ten forms of the AB doublet song pattern and the four forms of the B singlet song pattern identified in recordings occurred with overlapping temporal presence over the winter breeding season and is thus not indicative of the same animals changing their song pattern as the season progressed. Previous song analysis has indicated at least two fin whale sub-populations in BC waters that are spatially segregated, with one of these using coastal and the other using offshore areas (Koot 2015). Koot (2015) reasoned that even song structures with IPI differences of 1 second is suggestive of separate fin whale populations. The presence of multiple variations of a similar song pattern would be more indicative of different groups of animals producing songs with different IPIs that are using the offshore area in BC throughout the winter breeding season. However, the variations within the similar song patterns co-occurred (Figures 6 and 7) and the significance of this is so far unknown. The detection ranges of calls were not estimated for this analysis, making it impossible to determine the spatial separation between calls produced. However, at least 23% of the recordings with song presence had such considerable song overlap that selecting individual notes could not be done with confidence. Further work to determine the spatial distribution of the song variations found in this analysis may help to determine the drivers behind the subtle differences in song patterns found for fin whales in BC waters and if these differences are indeed reflective of multiple subpopulations.

The B singlet song pattern found in this analysis is previously undocumented in this area and has not been described for fin whale song in BC. Prior to 2007, a singlet pattern was described as the most prevalent song structure in the Canadian Pacific (Weirathmueller et al. 2017), although the notes observed then are different to those reported here; the singlet pattern prior to 2007 consisted of repeating A notes, whereas a B singlet pattern was observed in this study. This is a much more substantial change in song presence and prevalence, exceeding within or between season shifts that have been documented elsewhere (see Morano et al. 2012, Oleson et al. 2014, Širović et al. 2017, Weirathmueller et al. 2017, Helble et al. 2020). This larger change may express something more than a change in social or behavioural context and show genetic changes, population divergence, or other changes in population distribution (Hatch and Clark 2004, McDonald et al. 2006, King-Nolan et al. 2024). A similar B singlet pattern was noted by Helble et al. (2020) for fin whales in waters off Hawaii between 2011 and 2017. At the time of reporting, Helble and colleagues (2020) suggested this song pattern was new for North Pacific fin whales and could be unique to whales using Hawaiian waters, as it had not been reported in previous studies (e.g., Oleson et al. 2014, Širović et al. 2017). Although differing in IPI, the similarity in song structure could represent connectivity between whales singing in Hawaii and Clayoquot Slope.

Although the ABA triplets observed here were rare (0.2% of recordings with song presence), this song structure has yet to be reported for fin whales in the North Pacific. Two triplet patterns were observed in acoustic recordings from southern California and the southern Gulf of California but were comprised of notes having the same frequency parameters (i.e. B notes) (Širović et al. 2017), whereas the triplet pattern observed here had both A and B notes. Long term monitoring of fin whale song types both in BC waters and across a broader geographical scale could indicate if this song type persists and is present elsewhere.

Acoustic recordings with overlapping song occurred in at least 23.5 % of the recordings with song presence. Although the song properties were ineligible for further analysis due to their lack of clarity, these recordings with multiple singers are notable. In 2010 acoustic recordings from an area north of the site examined in this study, Koot (2015) found song overlap to be rare, suggesting fin whale song is used as a spacing mechanism for defending territory. Singing fin whales have previously been reported to be spatially separated (Watkins 1981, Watkins et al. 1987, Soule and Wilcock 2003). Although it was not possible to know the distance between singing whales for this study, song overlap that was much more common than previously recorded in the North Pacific may indicate connectivity between singing fin whales is increasing and further study to determine this could be useful in our understanding of fin whale recovery here.

The differences in timing of the peaks of each of the dominant song type observed at Clayoquot Slope may further support the idea that song patterns are discrete in fin whale populations or subpopulations. If all variations in the timing of song structure were taken as indicators of a change in social structure or sub-populations, as suggested by Koot (2015), whereby distinct song patterns represent genetic diversity in populations, the offshore waters of

Clayoquot Sound could host up to, or exceed, 14 separate sub-populations annually based on the timing differences in song patterns noted here. However, the variation in IPI timing over the short-term was still considered here to represent the same song structure, leading to two dominant song structures (AB doublet and B singlet) and one song structure that was rarely found in the recordings (ABA triplet). Changes in song structure have previously been reported after extended periods of absence in calling, such as between breeding seasons (Širović et al. 2013) or having evolved over longer periods, such as over a decade (Weirathmueller et al. 2017). However, in recordings analyzed here, changes between song structures were noted within hours. This could suggest that although the peak presence of each population group differs, their presence overlaps (Figure 6). Indeed, in some cases this overlap made the differentiation of song structure difficult in the analysis, with both songs present for approximately 3 months of the year (Figure 6).

The long-term change in the doublet pattern and emergence of a singlet in song patterning in the offshore waters of Vancouver Island may give clues to repopulation and dynamics in demographics as fin whales recover from commercial whaling. There is still little observational evidence to draw on in this region currently, but passive acoustic records suggest this area, and BC waters more generally, are important for both foraging and breeding of fin whales (Koot 2015, Burnham 2019, Burnham et al. 2019, this thesis). Continued acoustic analysis of song presence and structure might further help us understand the connectivity between population groups and the repopulation of the northeast Pacific, as well as outline the areas that are critical in supporting fin whale recovery.

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CONCLUSION

A small minority of whale populations that were overexploited worldwide have recovered to pre-whaling numbers. Despite being the most heavily targeted species in BC waters, fin whales are beginning to increase their presence here and the variety of calls presented in this thesis indicates BC is an important critical habitat for recovering populations. The opportunity to record and analyze the acoustic behaviour of fin whales as they build their social and physical connectivity has provided some necessary baseline information on their ecology and habitat use.

Most studies on fin whale vocalizations have focussed on their 20 Hz calls; few examine the full fin whale vocal repertoire. This leads to an incomplete picture of the breadth of vocal communication produced and received by these whales and underestimates the importance of intraspecific communication in activities such as foraging. The manual review of acoustic data used to develop this thesis was time consuming and likely not replicable with the sizeable datasets being continuously collected for marine soundscapes. However, the detailed information presented on their ecology and habitat use was only accessible through this method as there is still no reliable autodetection system for the fin whale 40 Hz call. Using this method led to temporal findings previously unrealized for this call type, such as its use throughout the annual period and seasonal shifts in diel periodicity, indicating that erroneous results may come from assuming the presence of certain call types at any given time. Additionally, it led to the recognition of increased variation within this call type and highlights the acoustic sensitivity of a species that has, up until now, been noted as having fairly simplistic call use.

This thesis presents the most comprehensive review of data in terms of amount and depth of fin whale acoustics using manual techniques. However, much remains unknown about Pacific fin whales in BC waters. They are recovering into areas with changing oceanic regimes and prey availability, and into areas that increasingly overlap with anthropogenic disturbance. The findings in this thesis indicate fin whales concentrate acoustic behaviour associated with breeding and foraging activity in deeper offshore waters and areas along the continental slope should be further considered for protective measures for this species still recovering from decades of whaling. Long-term monitoring would be beneficial for fin whale management as distribution patterns may change over time and can help us better understand their flexibility and plasticity under changing ocean conditions, such as increased vessel noise, changing climates, and changing zooplankton species composition.