ABUNDANCE AND DISTRIBUTION OF HUMPBACK WHALES (*MEGAPTERA NOVAEANGLIAE*) ALONG THE OUTER COAST OF WASHINGTON AND OREGON
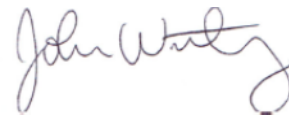
By
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A Thesis
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This Thesis for the Master of Environmental Studies Degree
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ABSTRACT

Abundance and distribution of humpback whales (*Megaptera novaeangliae*) along the
outer coast of Washington and Oregon

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Humpback whales (Megaptera novaeangliae) are highly migratory marine mammals
whose migratory corridors overlap with human activities, making them susceptible to
potentially fatal human interactions. To mitigate the negative impacts anthropogenic
threats are having on humpbacks' long-term survival, it is vital to understand what
specific threats they face. Along the US West Coast, their biggest threats are
entanglement in derelict fishing gear (i.e., crab pots) and fatal collisions with vessels.
Effective conservation management strategies rely on the continual update of species
abundance and density estimates in a given geographic area. These estimates provide our
best insight into the severity of specific threats and can be used by a multitude of
agencies to develop more effective conservation management practices. Marine mammal
abundance surveys are vital for determining high density areas and detecting changes in
populations. Seasonal estimates provide more detailed look at when and how long these
animals are spending in a particular area during a given time of the year. Distance
sampling is the mostly widely used technique for estimating abundances of wild animal
populations. It allows for estimation of abundance in an area without needing to count
every animal within the area of interest. Cascadia Research Collective and Washington
Department of Fish and Wildlife jointly designed and implemented Distance sampling
surveys off the coast of Washington State and Oregon from 2011 – 2013 to obtain
seasonal abundance and density estimates humpback whales. Humpback whale sightings
data collected during these surveys were analyzed using the software Distance following
'conventional distance sampling' and 'multiple covariate distance sampling'
methodologies. Hazard-rate with visibility as covariate was determined the model of best
fit of the detection function over distribution of perpendicular sightings for large whales
based on lowest ΔAIC. In total, 2,044 nmi were surveyed for whales between 2011 –
2012. Data from 2013 was omitted due to inconsistent survey coverage. Modeled results
estimate the total abundance to be 2,205 (CV=0.26) humpbacks and an estimated density
of 6 (CV=0.26) humpbacks per 100 nmi2. Seasonal effort was variable, with a range of
224-1,061 nmi surveyed. It was estimated that there were 276 (CV=0.6) humpbacks in
the spring, 1406 (CV=0.32) in the summer, and 524 (CV=0.6) in the fall. Although
estimates appear to differ by season, the 95% CI for abundance and density estimates
overlap, therefore there is no significant difference in seasonal estimates. Although there
have been numerous studies estimating humpback abundance and density estimates along
the US West Coast, this is the first to assess seasonal trends. These results provide
general insight in the probable seasonal distribution trends and can aid in the
understanding of humpback whale seasonal variations within this study area.

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Chapter 1 : **Introduction**

Humpback whales are highly mobile marine mammals, migrating seasonally and traveling up to 10,000 km per year (Baker *et al.*, 1990). Humpbacks were once abundant throughout the Pacific, Atlantic, Indian, and Arctic Oceans, but commercial whaling drastically reduced their populations. In the North Pacific (NP), it is estimated that humpbacks were reduced to 10% of their historic population size by commercial whaling (Teerlink *et al.*, 2015).

Currently, humpbacks are separated globally into 14 distinct population segments (DPS), as defined by the National Marine Fisheries Service (NMFS) under the U.S. Endangered Species Act (ESA). Each DPS has their own conservation status under the ESA. Their breeding and feeding areas, as well as their migratory routes, often position them in close proximity to humans. Inhabiting coastal waters, whether for feeding or breeding, puts them at an increased risk of ship strikes, risk of negative impacts from noise pollution, and potential for entanglement in fishing gear. Also, habitat degradation through coastal development and over-fishing can cause a decrease in prey availability. Recently, it has been observed that microplastics are increasingly becoming a serious threat to humpbacks as well (Besseling *et al.*, 2015).

Abundance and density estimates of humpback whales aids in the identification of seasonal high-density areas as well as detecting changes in the population over time. The continual update of these estimates is crucial for creating and implementing effective conservation management strategies. A common method of obtaining theses estimates is through the conduction of systematic line-transect surveys, which allows for the

collection of sighting data that is used to assess status, detect trends, and predict habitat use (Barlow, 2010; Barlow & Forney, 2007; Rone *et al.*, 2017).

For the outer coast of Washington State (WA) and Oregon (OR), abundance estimates are necessary to implement effective regulation and management strategies to mitigate the negative effects of anthropogenic activities on their populations. Here, humpbacks are highly susceptible to entanglement in crab pots nearshore and along the coasts (Carretta *et al.*, 2016). The shipping channels entering the Strait of Juan de Fuca and the mouth of the Columbia River are a major site for cetacean vessel collisions due to the amount of shipping traffic they experience throughout the year (Douglas *et al.*, 2008). The Strait of Juan de Fuca is suggested to be an area of especially high-risk for ship strikes because it is the only entrance into the Puget Sound for vessels, creating a 'bottleneck' area for whales and ships (Williams & O'Hara, 2010). There is similar concern for vessel strikes of large whales at the mouth of the Columbia River on the border of Washington and Oregon. This, coupled with expected increase of vessel traffic as amount of exported cargo increases, can make humpbacks traveling near coasts of WA and OR highly susceptible to fatal ship strikes (BST Associates, 2017).

Accurate abundance estimates are extremely important, making it necessary to analyze new line-transect data to ensure policy decisions are being made on the most current data available. According to NMFS, abundance estimates are considered outdated after eight years (NMFS, 2005). Analyzing line-transect survey data in a timely manner should be of the utmost importance because it allows for performance of rigorous statistical analyses to keep these estimates as current as possible. While there are citizen

science data available on presence of whales (i.e., whale watch tours), this data is unstructured and tends to be biased towards where people are (Kamp *et al.*, 2016).

Density and abundance estimates are significant because they can be used to understand and potentially predict human impacts on cetaceans. Unfortunately, it is not possible to fully understand the negative impact of anthropogenic activities on humpback whale populations as there is no way to track every death attributed to human activities. Therefore, abundance estimates provide our best insight into these impacts and can be used by a multitude of agencies to develop more effective conservation management practices. The U.S. Navy, for example, utilizes cetacean abundance estimates to identify potential impacts their training can have on specific species (U.S. Department of the Navy, 2015). Meanwhile, Feist *et al.* (2015) used abundance estimates to quantify impacts of fishing fleets on cetaceans in the California Current. Similarly, density and abundance estimates have been used in determining high risk area of cetacean-vessel collisions (Rockwood *et al.*, 2017).

Surveys have been carried out periodically to estimate cetacean abundances along the US West Coast (Barlow, 1997; Barlow, 2003; Calambokidis & Barlow, 2004; Calambokidis *et al*., 2004; Zerbini *et al*., 2007; Moore & Barlow, 2015), however, these studies focused on obtaining yearly estimates. This study used methods to determine seasonal and yearly distribution of humpbacks along Washington and Oregon coasts from surveys conducted between 2011 and 2012. Results presented here provide a novel look at seasonal abundance and density of humpbacks in this area, which is valuable when creating conservation management action plans.

Chapter 2 : **Literature Review**

This literature review will explore the historical and current conservation status of humpback whales in the North Pacific Ocean, issues related to their overall recovery, the use of systematic line-transect surveys in conjunction with distance sampling to generate abundance and density estimates, and the importance of these estimates for effective conservation management strategies. The review will start with a general overview of humpback whales in the North Pacific, including information about their biology, range, and taxonomy. The review will next cover the history of their conservation status, to include their recent separation into distinct population segments globally. It will then synthesize current anthropogenic threats to their populations, followed by an examination of one of the most popular methods for collecting data to generate abundance and density estimates -- line transect surveys.

2.1 Humpback Whales (*Megaptera novaeangliae*)

2.1.1 Evolutionary History

Cetaceans are an order of mammals that originated during the Eocene epoch about fifty million years ago (MYA; Thewissen *et al.*, 2009). Cetaceans are comprised of whales, dolphins, and porpoises. Fossil records, morphological, and molecular evidence support the hypothesis that cetaceans evolved from land mammals (Luo, 2000). After becoming fully aquatic, their evolutionary diversification accelerated.

The evolutionary history of cetaceans is one of the best-understood examples of macro-evolutionary change (Bajpai *et al.*, 2009). Currently, the most widely supported hypothesis is the cetacean-artiodactyl hypothesis, due to recent findings that cetaceans

and artiodactyls share specific ankle bones called astralagi (Thewissen and Madar, 1999; Thewissen *et al*. 2009). It is suggested that the closest extant artiodactyl relative of cetaceans are the hippopotomids (Gingerich *et al*., 2001). Analyses of the fossil record have discovered five families from the Eocene, believed to have led to the modern-day cetaceans: Raoellidae, Pakicetidae, Ambulocetidae, Remingtonocetidae, Protocetidae, and Basilosauridae (Figure 2.1; Bebej, 2011). Neocetes are considered to be modern day whales that consist of two suborders, Odonotceti and Mysticeti.
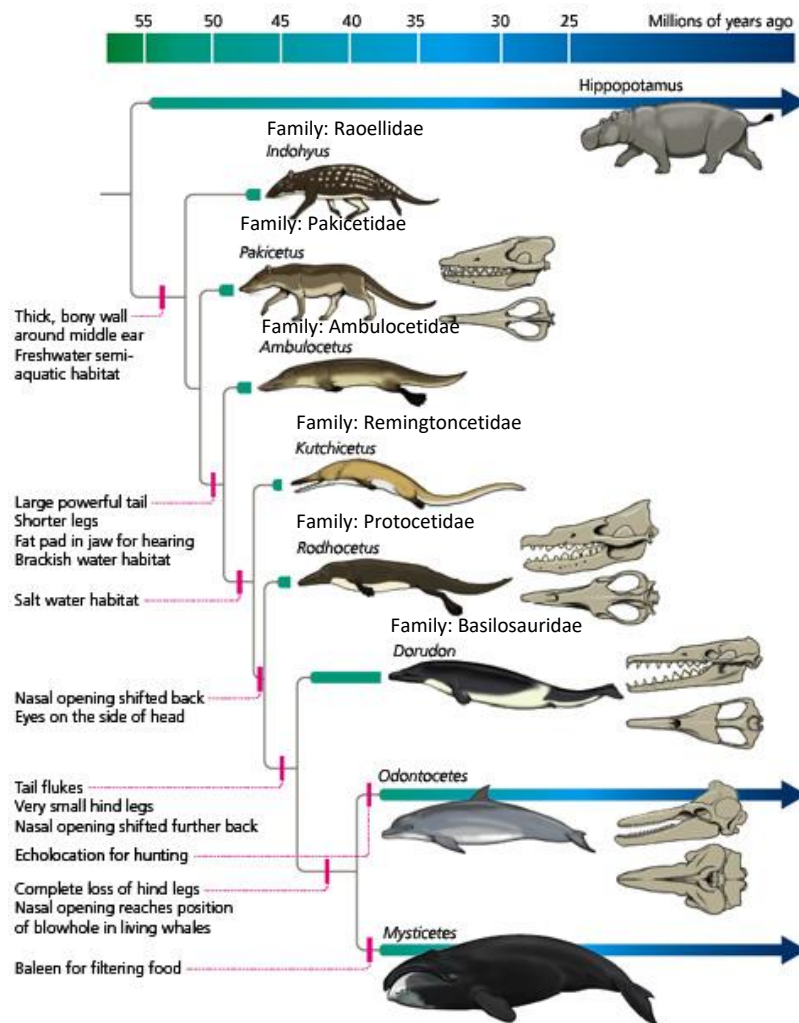
Figure 2.1: Evogram detailing evolutionary history and important morphological adaptions of whales dating back 55 MYA. (Image adapted from Zimmerman, C. (2009). The Tangled Bank: An Introduction To Evolution. Roberts and Company Publishers.)

2.1.1.1 Morphological Adaptions

Cetaceans have gone through extreme morphological adaptations to become giants of the sea. Starting in the Early Eocene, the osterosclerotic cortex (a thickening and hardening of specific bones) was found in cetaceans' closest extinct relative from the genus *Indohyus* of the Raoellidae family. The finding of osterosclerotic limb bones in this family has been suggested as a critical piece in understanding cetacean evolution from terrestrial life to aquatic (Cooper *et al*., 2012). The function of osteosclerosis is to counteract buoyancy and allow for stability while wading in the water. It was also found in Pakicetids and Ambulocetids, two families of extinct cetacean ancestors (Bajpai *et al*., 2009). This adaptation permitted late cetaceans to spend more time in the water and less time on land, initiating the gradual transition of a mainly terrestrial life to a fully aquatic life.

As late cetaceans spent an increased amount of time in the water, more adaptations are found in their fossils that supported suitability to aquatic life. The large size of the bulla found in Pakicetid fossils from the Early Eocene is interpreted as an adaptation for underwater hearing and since has been a characteristic found in all cetaceans (Uhen, 2007). Modern day cetaceans have a pad of fat in their lower jaw that is connected to the middle ear, allowing the transfer of underwater sounds (Thewissen *et al* 2009). This was present in Remingtoncetids (a fully aquatic family), suggesting that underwater sound transmission was an important aquatic adaptation (Thewissen *et al*., 2009). These adaptations have helped cetaceans hear directionally underwater, thus increasing underwater survivability (Uhen, 2007).

Studies of the Ambulocetids have significantly contributed to our understanding of the evolution of cetacean locomotion (Madar *et al.*, 2002). They demonstrate a means of locomotion that lies between a land mammal and a modern whale, and provides the link between cetaceans' terrestrial ancestors to modern cetaceans (Thewissen and Bajpai, 2001). Based on the morphology of their hind limbs and tail, their means of locomotion was a mix between pelvic paddlers and caudal undulators (Thewissen and Bajpai, 2001). They had hip flexors, extensors, and adductors, which are important for both walking on land and stabilization in the water (Madar *et al.*, 2002). Following the Ambulocetids, Remingtoncetid morphology shows movement by caudal locomotion, indicated by the location of the adductor muscles of the thigh (Bajpai *et al.*, 2009). In Protocetids we start to see a decrease in limb size, indicating slower land locomotion due to decreased ability to support their weight (Bajpai and Thewissen, 2001). Their swimming style also changes to a combination of hind limb paddling and dorsoventral undulations of the tail (Thewissen *et al.*, 2009). With the Basilosaurids, we see the emergence of a fluke and caudal swimming (Bajpai *et al.*, 2009).

A change in the position of the eye orbits is first seen in the Ambulocetids, moving towards the side and higher up on the skull resembling those of modern-day hippopotamus (Thewissen *et al.*, 2009). The eyes of Protocetids become large, face laterally, and are set farther from the midline of the skull under a supraorbital shield (Thewissen *et al.*, 2009). Modern cetaceans today have eye orbits placed widely apart under broad supraorbital processes (Fordyce and Barnes, 1994). Starting with the Protocetids, the nasal opening has started to move further posterior on the snout, starting the formation of the blowhole we see in modern day cetaceans (Thewissen *et al.*, 2009).

The blowhole is an important adaptation because it allows for breathing while submerged in water (Thewissen *et al*., 2009). In Basilosaurids, the nasal opening has shifted far back on the snout toward the eyes and is now considered a blowhole (Thewissen *et al*., 2009). For Protocetids the emergence of osmoregulation of saltwater appears through stable isotope records taken from fossils (Clementz *et al*., 2006). With the ability to osmoregulate saltwater, Protocetids gain the ability to travel across the open marine waters and increase their geographic distribution to areas including the Pacific and Atlantic Oceans (Clementz *et al*., 2006).

2.1.1.2 Cetaceans Today

There are currently two different extant suborders of cetaceans that originated from Basilosaurids near the Eocene and Oligocene boundary that took off and spread all over the globe: Odontoceti and Mysticeti (Uhen, 2010). Mysticetes are distinguished by baleen plates and a dual opening in their blowhole, while Odontocetes are distinguished by their distinct teeth, ability to echolocate, and a single opening in their blowhole (Uhen, 2007). The Odontocetes are composed of many different subfamilies that include dolphins, pilot whales, melon-headed whales, and narwhales. Known as the toothed whales, they developed echolocation to locate prey to make up for their loss of their sense of smell (Gatesy *et al*., 2012). Odontocetes have a unique mechanism to locate their prey that is not found in any other animal (Mckenna *et al*., 2012). They have an organ called the melon that is located at the front of their skull that produces the sound energy used to echolocate prey (Mckenna *et al*., 2012). Echolocation appeared around the Early Oligocene as a result of changing food resources, changing oceans, and continental rearrangement (Fordyce and Barnes, 1994). All fossils have been found with the

structures used in modern cetaceans for echolocation and both is past and the present been widely used in navigation and hunting (Fordyce, 2003).

The Mysticetes are composed of subfamilies that include humpback whales, grey whales, blue whales, and right whales. Mysticetes have baleen plates instead of teeth and have retained their sense of smell (Gatesy *et al*., 2012). Baleen is a keratinous strainer that enables filter feeding which is an important that enables the intake of huge energy resources (Demere *et al*., 2007). Filter feeding can be seen in majority of the fossils of Mysticetes (Fordyce and Barnes, 1994). It has been found that early Mysticetes were toothed but that these teeth had the basic genetic structure for baleen (Demere *et al*., 2007). A nutrient of baleen was present in animals from the late Oligocene that led to the present-day baleen (Demere *et al*., 2007). The evolution from teeth to baleen may have emerged from its increased efficiency to capture prey (Demere *et al*., 2007).

2.1.2 Species Description

Humpback whales (*Megaptera novaeangliae*), like other whales, dolphins, and porpoises, are part of the order Cetacea (Box 1). Humpbacks are classified under the suborder Mysticeti, which

Box 1. Taxonomic Classification	
Order:	Cetacea
Suborder:	Mysticeti
Family:	Balaenopteridae
Genus:	*Megaptera*
Species:	*Megaptera novaeangliae*

represents the baleen whales that rely on filter feeding using baleen plates instead of teeth. Megaptera, their scientific name meaning "large-winged", comes from their long, wing-like flippers that can measure up to one-third of their body length. Humpback dorsal body coloration is black, and their underside pigmentation varies between black, white, or mottled (**Error! Reference source not found.**, Clapham, 2018). Flipper dorsal c

oloration varies depending on population and individual (i.e., North Atlantic populations tend to be white and North Pacific populations tend to be black) (Clapham, 2018). Like all whales in their family, they have pleats that run along their jaw, but a distinguishing feature of this species are tubercles (knobs) that cover their head and jaw (Clapham, 2018). Their flukes also have features unique to this species that are used for identification of individuals within populations. Fluke ventral coloration patterns range from all white to all black and the fluke trailing edge is prominently serrated (Clapham, 2018). Adults range in size from 14 – 17 m. It is not easy to discern between males and females, but females are reported to be about 1 – 1.5 m longer than males and they have a lobe the size of a grapefruit towards rear of their genital slit (Clapham, 2018).

Humpbacks are considered generalists when it comes to feeding, preying on euphausids and small schooling fish (Clapham, 2018). A unique feeding behavior they display is bubble netting, the act of trapping schooling fish in a net of bubbles near the surface and then lunge feeding into the center of the trapped fish (Clapham, 2018). It is unclear how humpbacks find their food, but it is suggested that they rely on their sense of smell. Socially, they form short-term groups associated with feeding and breeding, with long term associations only occasionally recorded. It is believed that the main purpose of males' long and complex songs is to attract females but could also be used to assert dominance or initiate cooperative behavior (Clapham, 2018). Humpbacks have been dubbed as charismatic megafauna due to their tendencies to display spectacular aerial behavior, such as breaching and lobtailing.

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Figure 2.2: Northern Hemisphere (top) and Northern Hemisphere (top) and Southern Hemisphere Humpback whale. (Image adapted from Clapham, P. J. (2018). Humpback whale: *Megaptera novaeangliae*. In Encyclopedia of marine mammals (pp. 489-492), Academic Press.)

2.2 Policies, Conservation Status, and Management

Humpbacks can be found inhabiting all major oceans around the world. Being seasonal migrators that can travel over 10,000 km a year, no surprise this species has extensive ranges (Baker *et al.,* 1990). In the North Pacific (NP), their winter breeding areas extend throughout the western NP Ocean, the Hawai'ian Islands, and along coasts of Mexico down through Central America (**Error! Reference source not found.**; C alambokidis *et al.,* 2015). During spring and summer months, they migrate along coastal feeding areas, ranging from California, Alaska, and Russia (Calambokidis *et al*., 2015).

Genetic and photo-identification data indicate that humpback whales have strong site fidelity towards specific feeding and breeding areas, with six feeding and six breeding areas identified in the NP (Barlow *et al*., 2011; Calambokidis *et al*., 2015). The National Marine Fisheries Service (NMFS) has divided the global population of humpbacks into 14 distinct population segments (DPS) based on breeding areas, with each DPS having their own conservation status under the Endangered Species Act (ESA) (**Error! Reference source not found.**; 81 FR 62259; NOAA, 2016a). Under the Marine M ammal Protection Act (MMPA), there are four identified humpback whale stocks based on breeding areas, each assigned their own protection status independent of the ESA (16 U.S.C. §§ 1361 *et seq*.).
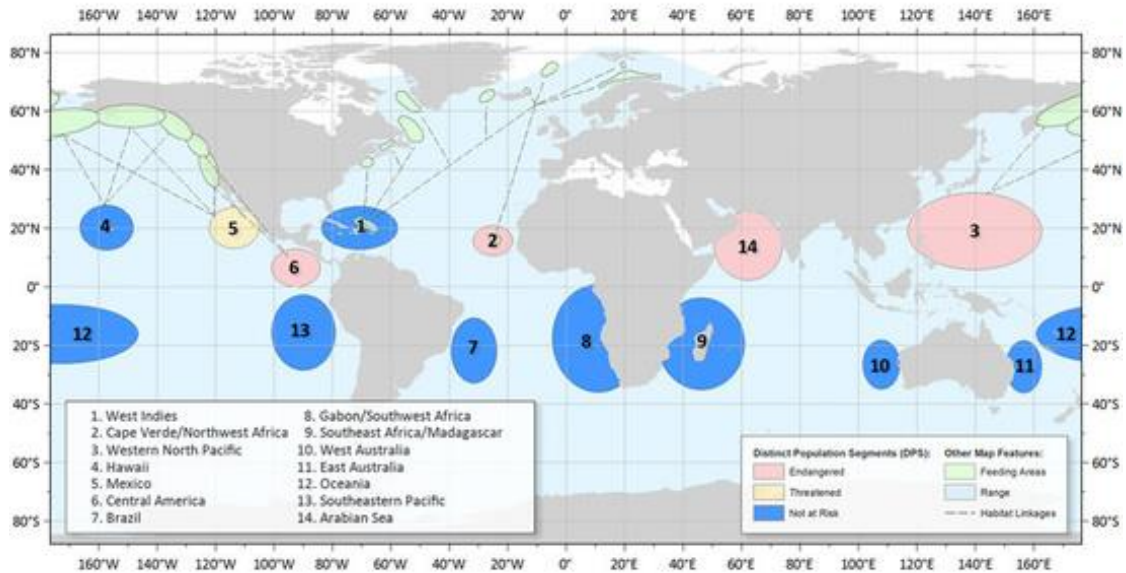
Figure 2.3: Identification, location, and current conservation status of the 14 identified distinct population segments of humpback whales (numbered circles) and their associated feeding areas (green circles). (Image adapted from NOAA Fisheries https://www.fisheries.noaa.gov/species/humpback-whale).

2.2.1 Policy and Conservation Status

There are numerous acts and policies dedicated to directly protecting marine mammals within the U.S. implemented by various federal, state, and native tribe entities. Their main sources of protection nationally come from the MMPA and ESA, and internationally through the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the International Whaling Commission (IWC). Under the MMPA, marine mammals are protected through prohibition of hunting, harassing, capturing, or killing any marine mammal species in U.S. waters as well as the prohibition of importing or exporting marine mammals and their parts as products (16 U.S.C. §§ 1361 *et seq.*) Humpbacks were listed as an endangered species under the ESA in 1973. They were also classified as 'endangered' on IUCN's Red List in 1988. Marine mammal species that are given a conservation status of 'endangered' or 'threatened' are allocated

additional protection under the ESA (16 U.S.C. § 1531 *et seq*.). MMPA provides marine

mammal species protections regardless of conservation status under ESA. CITES and

IWC provide avenues for international collaboration to protect and conserve marine

mammal species.

Their population has increased since the world-wide embargo on commercial

whaling established by the International Whaling Commission (IWC) in 1966 and

protections under the MMPA and ESA (Fleming & Jackson, 2011; Wedekin *et al*., 2017).

As of 2008, humpbacks are classified as 'least concern' on IUCN's Red List (Reilly *et

al*., 2008). The IUCN serves to classify species at high risk of global extinction and does

not provide any management recommendations. They currently have nine categories,

ranging from extinct to least concerned, a taxon can be classified into based on a species

extinction risk (IUCN Standards and Petitions Committee, 2019). To determine if a

species falls under a threatened category, they are assessed by a panel of experts based on

five criteria: population decline measured longer than 10 years, reduction in geographic

range occurrence and/or occupancy, abundance, and quantitative estimates of the direct

risk of extinction (IUCN Standards and Petitions Committee, 2019). A species' listing is

based on the highest category of threat within any given criteria. According to IUCN,

humpbacks were down-listed because of their overall increasing population numbers and

population reaching 60,000 individuals world-wide, excluding them from criteria that

would qualify for a higher classification of concern.

2.2.1.1 Marine Mammal Protection Act (MMPA)

The MMPA was enacted on October 21, 1972 in response to Congress identifying

that marine mammals have economic, recreational, international, and ecological

significance, realizing that certain species and population stocks are at risk of extinction due anthropogenic activities and require federal protections to prevent loss of species (16 U.S.C. §§ 1361 *et seq.*). The main purpose of the MMPA is to provide policies of resource management with the primary objective to maintain healthy and stable marine ecosystems to prevent unsustainable species population decline (16 U.S.C. §§ 1361 *et seq.*). It is implemented by the National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service (FWS), and the Marine Mammal Commission. MMPA defines 'take' similarly to the ESA, to mean to harass, hunt, capture, kill, or any attempts thereof to any marine mammal. Its fundamental objectives are to maintain marine mammal stocks at optimal sustainable populations (OSP) and as functioning elements of their ecosystems.

Under the MMPA, humpback whales are categorized into stocks based on geographic location within U.S. waters and EEZ. Along the U.S. west coast there are four stocks: 1) American Samoa (Hawai'ian Islands area), 2) Western North Pacific, 3) California/Oregon/Washington, and 4) Western North Pacific. All west coast stocks are classified as deleted except for the American Samoa stock.

Title I of the MMPA covers the conservation and protection of marine mammals, providing specifics on taking, importing, prohibitions, exceptions, penalties, regulations, enforcement, cooperation with states, and conservation plans. Title 1 of the MMPA is extensive and beyond the scope of this literature review. Of relevance, section 101 of Title I of the MMPA explicitly prohibits the taking and importing of marine mammals and their products, with exceptions for scientific research, public display, photography for educational or commercial purposes, or enhancing survival of a species or stock. Important specific exceptions are the permitted and authorized incidental takes by

commercial fishery industries, oil and gas development, military activities, renewable energy projects, construction projects, and research (16 U.S.C. §§ 1361 *et seq.*). All exceptions require permits before taking or importing any marine mammal.

Title II describes the establishment of the Marine Mammal Commission. The commission is composed of three members chosen by the President of the U.S. who exhibit knowledge of the field of marine ecology and resource management (16 U.S.C. §§ 1361 *et seq.*). The commission is responsible for providing "independent, science-based oversight of domestic and international policies and actions of federal agencies addressing human impacts on marine mammals and their ecosystems." Title III describes the purpose of the International Dolphin Conservation Program. The main goal of this program is to reduce the amount of dolphin and marine mammal mortalities from intentional encirclement in tuna purse sein fisheries (16 U.S.C. §§ 1361 *et seq.*). Title IV establishes the purpose of marine mammal health and stranding response program. It also provides guidelines for the collection and distribution of data relating to health of marine mammals and coordinate effective responses to unusual mortality events (16 U.S.C. §§ 1361 *et seq.*). And finally, Title V deals specifically with polar bears (*Ursus maritimus*) and their conservation and protections.

Overall, the MMPA serves to provide rules and regulations to prevent marine mammal populations from depleting due to anthropogenic activities. It requires NMFS and FWS to prepare yearly stock assessments of marine mammals that occur in US waters and the Exclusive Economic Zone (EEZ). These assessments must contain information on stock distribution and abundance, population growth rates and trends, estimate annual deaths from anthropogenic activities, known fishery interactions, and

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stock status. Stocks are assigned a status of strategic or non-strategic based on their

listing under the ESA, if the number of human-caused deaths exceeds their estimated

PBR, and if the population is declining and will be listed under the ESA in the near future

(Carretta *et al*., 2019).

2.2.1.2 Endangered Species Act (ESA)

The main purpose of the ESA is to protect and recover threatened and endangered

species along with the ecosystems they depend on. Humpback whales were listed

globally as an endangered species under the ESA from 1970 - 2016 (Fleming & Jackson,

2011). Currently, the smallest taxonomic unit identified under the ESA is subspecies

(Rosel *et al*., 2017b). A distinct population segment is a grouping of individuals within a

species that differ from other individuals in the same species; however, these differences

are not significant enough to warrant separation of this grouping into a full subspecies.

Designation of a species into DPS is determined based on criteria established by the FWS

and NMFS. First, either a population segment must be considered discrete from other

groups, being bound by a physical barrier that does not allow interaction between

populations, or noticeably distinct based on physical factors such as different

pigmentation, physiological factors such as differences in bodily functions, or ecological

factors such as feeding/breeding area preferences (16 U.S.C. 1531 *et seq*.). For this,

measures of genetics can be used to provide supporting evidence of these differences.

Second, loss of the population would create a significant gap in the species' range,

(Grunwald *et al*., 2008).

The NMFS and National Oceanic and Atmospheric Administration (NOAA)

began a status review for humpbacks in 2009. Reviewing petitions from the Hawaii

Fishermen's Alliance for Conservation and Tradition, Inc. and State of Alaska ultimately led to the division of humpback whales into distinct population segments (DPS) (50 CFR 224). The purpose of separating individuals into these distinct population segments is to allow FWS and NMFS "to protect and conserve species and the ecosystems upon which they depend before large-scale decline occurs that would necessitate listing a species or subspecies throughout its entire range" (16 U.S.C. 1531 *et seq.*, p. 4725). The theory is conserving and protecting DPS is more cost and time effective than conserving a whole species within its entire range (16 U.S.C. 1531 *et seq.*).

Humpback DPS identification was based on extensive genetic studies that demonstrate humpbacks have strong site fidelity to specific feeding and breeding areas, with rare instances of intermingling (Calambokidis *et al.*, 2008; Barlow *et al.*, 2011; Baker *et al.*, 2013; Calambokidis *et al.*, 2015). In the NP, Mexico is listed as threatened, and Western North Pacific and Central America are listed as endangered (Figure 2.3; 16 U.S.C. 1531 *et seq.*). With the designation of endangered or threatened, protective measures that go beyond those established by the MMPA are provided to each DPS.

The implementation of the ESA for marine mammals falls under the responsibility of NOAA Fisheries. Marine mammals that are identified as endangered or threatened have similar protections as depleted stocks under the MMPA. NOAA Fisheries is required to carry out various management actions for species listed under the ESA including, but not limited to, designate critical habitat, monitor and evaluate species status, and develop and implement recovery plans (16 U.S.C. 1531 *et seq.*).

2.2.2 Management

The main goal of management plans is to prevent populations from depleting, but it is a challenge to predict how severe of an impact anthropogenic threats will have on populations. Universally, there are several methods used to assess/manage whale populations in efforts to prevent populations from going extinct including IUCN Red List Criteria, European Union's (EU) Habitats Directive, US Marine Mammal Protection Act (MMPA) & Potential Biological Removal (PBR), and International Whaling Commission's (IWC) Revised Management Procedure. The EU's Habitats Directive aims to conserve rare, threatened, and endemic species as well as rare and characteristic habitat types, encompassing over 1000 animal and plant species and 200 habitat types (Council of the European Commission, 1992). Member states of the EU are required to enforce laws, regulations, and administrative provisions needed to comply with the Directive. The Revised Management Procedure developed by IWC, serves to estimate sustainable catch limits for commercial whaling of baleen whales by maintaining populations at 72% of their carrying capacity and prohibits commercial whaling of populations who are below 54% of their pre-exploitation levels (IWC, 1994). In the US, an animal's potential biological removal is used to determine the amount of animals that can be removed from a population, excluding natural deaths, without having a negative impact on the species survival.

2.2.2.1 Potential Biological Removal

The MMPA and ESA require the investigation of population structure, estimate population size and trends in abundance, identify and mitigate anthropogenic threats, and designate critical habitat to maintain populations at optimum sustainable population

levels to prevent the extinction of species. According to the NMFS, a population is considered depleted if they are estimated to be 50-70% below their historic population size (Wade, 1998). Determining if a population is declining to 50-70% below their historic population size requires a great deal of monitoring encompassing many years to determine abundance trends. Often times, by the time a declining trend is detected, it is too late, and the population is already at "depleted" levels (Wade, 1998). A robust management strategy takes into account precision and bias of estimated abundance and mortality and the uncertainty of population growth rate (Wade, 1998). If the source of mortality is known, the level of human caused mortality can be estimated (Wade, 1998).

The Potential Biological Removal (PBR) level is the number of animals that can be removed every year from a stock due to reasons other than natural mortalities while allowing the stock to maintain optimal sustainable population levels (NOAA, 2018). It is calculated by the following equation:

$$PBR = Nmin * \tfrac{1}{2} Rmax * Fr$$

Where:
$Nmin$ = minimum population estimate = 20th percentile of a log-normal distribution of the population abundance estimate

$Rmax$ = the maximum theoretical or estimated net productivity rate of the stock at a small population level. The default values are 0.04 for cetaceans and 0.12 for seals.

Fr = a recovery factor that is between 0.1 and 1. The default values are 0.1 for endangered stocks and 0.5 for depleted and threatened stocks and stocks of unknown status.

Generally, the maximum growth rate and total population size are near impossible to be measured directly, so approximations of these variables from readily available data is used when estimating PBR. It is easy to implement when assessing the impact for situations where mortalities are directly observed, like bycatch in fisheries, but

challenging when cause of death is unknown or for instances that just increase the risk of mortality, such as microplastic ingestion or noise pollution (Lonergan, 2011). Despite its limitations, PBR is used to gauge how much of an impact anthropogenic activity are having on populations. If certain anthropogenic activities are causing more mortalities than the PBR allows, that helps to focus where management efforts should be targeted. Currently, the PBR for the California/Oregon/Washington stock of humpback whales as identified by MMPA within U.S. is calculated to be 16.7 whales per year, meaning that 16.7 whales can die due to anthropogenic activities each year without having a negative impact on their population (Carretta *et al*., 2019).

2.3 Monitoring Methods

The effective conservation and management of whales, including humpbacks, relies on rigorous and sound scientific research. The scope and amount of funding typically dictates which monitoring method can be implemented. Whales can be difficult to locate and track throughout the world's oceans, so a variety of research technologies and techniques are used to study their movements, behaviors, and population trends. Most popular methods include passive acoustic monitoring, satellite tagging, photo identification, and vessel-based line-transect surveys. Often, multiple techniques and methods are used together. Data acquired from marine mammal monitoring projects are then used in calculating abundance and density for populations in each area.

Passive acoustic monitoring utilizes sounds produced by whales to understand migration and distribution patterns, acoustic behavior and movement, and in conjunction with visual survey, deriving abundance and density estimates (Stanistreet *et al.*, 2013; Risch *et al.*, 2014; Davis *et al.*, 2017). Satellite tagging of whales has provided insight

into whale movement and behaviors, shedding light on migration routes and feeding

locations and behavior with the addition of time-depth sensors (Kennedy *et al*, 2013;

Owen *et al.*, 2015; Cerchio *et al.*, 2016). Whales can be identified based on distinct body

markings on either underside of the fluke or markings on dorsal fin area. Long term

tracking of individuals with photo-ID has shed light on migratory patterns and habitat

usage (Stevick *et al.*, 2004; Gabriele *et al.*, 2017). The most commonly used method to

study whales is through vessel based systematic line-transect surveys within an

established study area. These methods often follow standardized distance sampling

protocols, with resulting data used to generate abundance and density estimates.

2.3.1 Distance Sampling

Distance sampling was historically referred to as "line transect sampling"

(Burham *et al*, 1980). Now known as Distance sampling, it is the mostly widely used

technique for estimating abundances of wild animal populations (Buckland *et al.*, 2004)

Distance sampling is a group of methods that are widely used to estimate abundances of

biological populations, by providing a rigorous framework for estimating detectability

(Burnham *et al.*, 1980; Buckland *et al.*, 2004, 2015; Thomas *et al.*, 2010, 2014). Distance

sampling allows for estimation of abundance in an area without needing to count every

animal within the area of interest. Standardized methods are detailed in Buckland *et al.*

(2001). Distance sampling blends together model-based and design-based statistical

methods, using the modeled detectability of surveyed transects or plots estimate

abundance of animals outside the surveyed area (Buckland *et al.*, 2004). Distance

sampling helps to guide the placement of transects to cover a proportion of the study area,

which allows for the estimation of detection probability. In this way, one can estimate abundance and density without having to count every animal.

Accurate abundance and density estimates rely on obtaining exact numbers of animals within a certain area. This is achieved by plot, quadrat, or strip sampling methods where all animals of interest are counted in an established plot, quadrate, or strip (Burnham *et al.*, 1980). With these methods, random strips or plots with a certain area, *a,* are assigned within a large survey area of size *A*, and all animals of interest are counted, *n,* along the strips (transects) or in the plot (Marques, 2009). We can then calculate the density, or number of animals per unit area, as well as estimate animal abundance for the entire survey area because it is assumed that all animals that are in the sampling plots or strips are counted (Marques, 2009).

Density is calculated by the formula:

$$D = \frac{n}{a'}$$

And abundance by the formula:

$$\overline{N_a} = A\frac{n}{a'}$$

These standard methods of estimating abundance and density are difficult to implement when studying wildlife populations because not all animals are counted. When studying whales, it is especially difficult to count them all because they spend majority of their time below the surface of the water. This will result in inaccurate and impractical estimates. To improve accuracy of estimates, we need to account for the proportion of whales missed during surveys.

2.3.1.1 Distance Practices

For vessel-based line transect distance sampling, a vessel navigates along systematically spaced transect lines with a random starting point (Thomas *et al.*, 2010). Observers perform a standardized survey while the vessel follows a linear transect searching for animals or clusters of animals (Thomas *et al.*, 2010, 2014). When an animal, or cluster of animals, is detected, the distance that the animal is from the line is recorded (Figure 2.4). A major assumption of distance sampling is that all animals on the transect line are detected (Thomas *et al.*, 2010, 2014). It is expected that objects become harder to detect the farther away they are from the line, thus observations decrease with increasing distance (Thomas *et al.*, 2010, 2014). The distribution of recorded distances is used to estimate the proportion of animals missed during the survey (Buckland *et al.*, 2015; Thomas *et al.*, 2010, 2014). From here, abundance and density estimates of animals can be obtained for the survey area (Thomas *et al.*, 2010, 2014). Distance sampling has three assumptions: 1) objects on the line are detected with certainty, 2) objects do not move, and 3) measurements are exact (Thomas *et al.*, 2010).
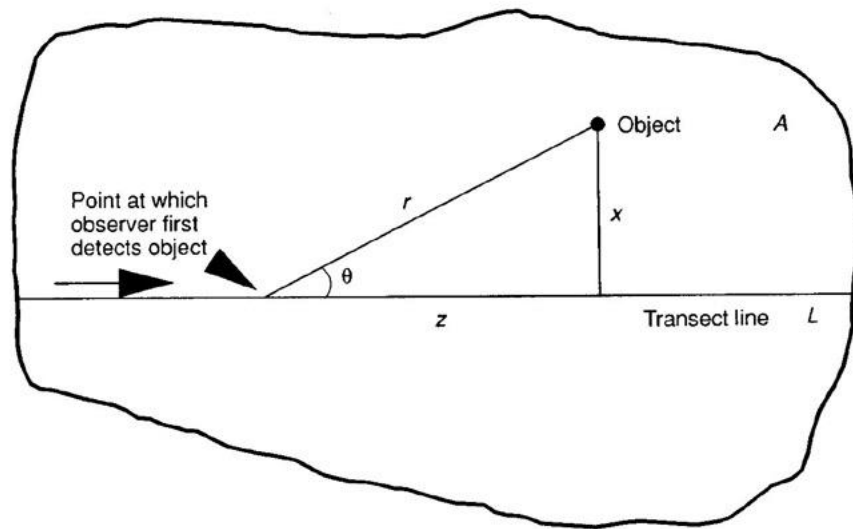
Figure 2.4: Measurements that are recorded during line transect surveys. An area size A is sampled by following along a line of length L. An objected is detected at distance r from observer and sighting angle θ is measured to calculate perpendicular distance x. The distance the object is from observer parallel to transect at detection is z = r * cos (θ). (Image adapted from: Buckland, S.T., Anderson, D.R., Burnham, K.P. and Laake, J.L. (1993) Distance Sampling: Estimating Abundance of Biological Populations. Chapman and Hall, London. 446 pp.).

2.3.1.2 Distance: Abundance and Density Calculation

The key component in obtaining abundance and density in distance sampling is the estimation of a detection function. The detection function describes the relationship between distance and probability of detection (Buckland *et al.*, 2001). A major assumption in distance analyses is that the detection function ($g(y)$) at distance 0 ($y=0$) is 100%: $g(0) = 1$ (Buckland *et al.*, 2001). In many instances, especially in cetacean research, $g(0) < 1$, due to availability bias (failure to detect an animal due to diving) and perception bias (observers failing to detect animals that are at the surface) (Pollock *et al.*, 2006). Various methods can be implemented to reduce these biases but require more effort, time, and personnel (Buckland and Turnock, 1992; Laake *et al.*, 1997; Hiby and

Lovel, 1998). Distance rescales the detection function $g(x)$ to integrate unity so that we are now estimating the probability density function, $\hat{f}(0)$, of perpendicular distances to detected objects (Thomas *et al.*, 2002). The probability density function (pdf*)*, $\hat{f}(0)$, describes the relationship between distance and probability of detection (Buckland *et al.*, 2001). The following formulas are used to estimate density and abundance from data collected from Distance sampling:

$$\text{Density: } \hat{D} = \frac{n\hat{f}(0)}{2L}$$

$$\text{Abundance: } \hat{N} = \frac{n\hat{f}(0)A}{2L}$$

Where:
n = number of animals or clusters detected
L = total length of transects surveyed
A = size of survey region
$\hat{f}(0)$ = f(x) evaluated at 0 distance; f(x) = probability density function (pdf) of observed distances

The surveys provide us values for *n, L,* and *A,* and Distance will estimate $\hat{f}(0)$ through fitting parametric 'key' functions onto histogram of recorded perpendicular distances of sightings (Thomas *et al.*, 2002). Each 'key' function uses a different formula to estimate $\hat{f}(0)$ ((Buckland *et al.*, 2015). Distance assigns each model an Akaike Information Criterion (AIC) value based on how well the key function fits the data (Akaike, 1973). The model with the lowest AIC value is determined to fit the histogram of perpendicular distances the best and use that model's estimated $\hat{f}(0)$ value into the abundance and density formulas to give estimates.

This can be done by using one of three different analysis engines in the software Distance: 1) conventional distance sampling (CDS), 2) multiple covariate distance sampling (MCDS), and 3) mark-recapture distance sampling (MRDS). This thesis used CDS and MCDS to generate abundance and density estimates. CDS operates under the

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assumption that detection probability of an animal only decreases with increasing perpendicular distance from the transect line (Buckland *et al.*, 2004). MCDS assumes the detection function is influenced by a number of factors, or covariates, other than distance (Buckland *et al.*, 2004). MCDS allows the inclusion of various covariates when estimating detection function (Buckland *et al.*, 2004). MCDS can potentially yield more efficient estimates of abundance, depending on whether exploratory analyses indicate something other than distance is influencing the detection probability.

2.4 Line-Transect Surveys and Abundance and Density

Effective conservation management relies on the continual update of species abundance estimates. These population estimates are vital for determining seasonal high-density areas and detecting changes in the population in order to implement more effective conservation management strategies. Results from line-transect surveys utilizing distance sampling protocols have been frequently used to generate density and abundance estimates. New surveys and analyses are needed to understand population fluctuation, which in turn drive better understanding and management. Systematic line-transect surveys provide information on whale species, allowing us to assess status, detect trends, and predict habitat use (Rone *et al.*, 2017).

Previous studies have utilized line-transect surveys following distance sampling protocols (LTS) to establish population abundance estimates and aid in conservation of numerous animals, especially in whale research. Studies by Rone *et al* (2017), Barlow & Moore (2017), and Bradford *et al.* (2017) employed LTS in their research. Rone *et al.* (2017) conducted three LTS in offshore waters of the Gulf of Alaska, a region previously unsurveyed due to various environmental factors, to determine baseline density,

distribution, and abundance estimates of six species of cetaceans. Other studies have used LTS to update trend abundance estimates for various species of cetaceans including beaked and sperm whales (Bradford *et al.*, 2016; Barlow & Moore, 2017).

A popular method of analyzing LTS data to obtain abundance and density estimates is through the creation of habitat-based density models, a type of species distribution model (SDM) (Figure 2.5; Becker *et al.*, 2017**;** Roberts *et al.*, 2016; Forney *et al.*, 2015; Forney *et al.*, 2012) For example, Becker *et al.* (2017) used data from 20 LTS to develop seasonally-explicit habitat-based density models for three whale species in the California Current. Also, Forney *et al.* (2012) developed habitat-based density models that displayed species density maps for 22 whale and dolphin species from 15 LTS in the temperate and tropical eastern Pacific Ocean. Analyses are also performed to update existing habitat-based density models. Forney *et al.* (2015) updated habitat-based density models for whale and dolphin densities around Hawai'i and other central pacific islands from 15 LTS. From these updated estimates, they were able to produce high-use areas for each of the ten documented species and estimate monthly cetacean abundance by incorporating satellite-derived environmental data. Such studies have shown the value of LTS and their accompanying analyses, which is the focus on this thesis.
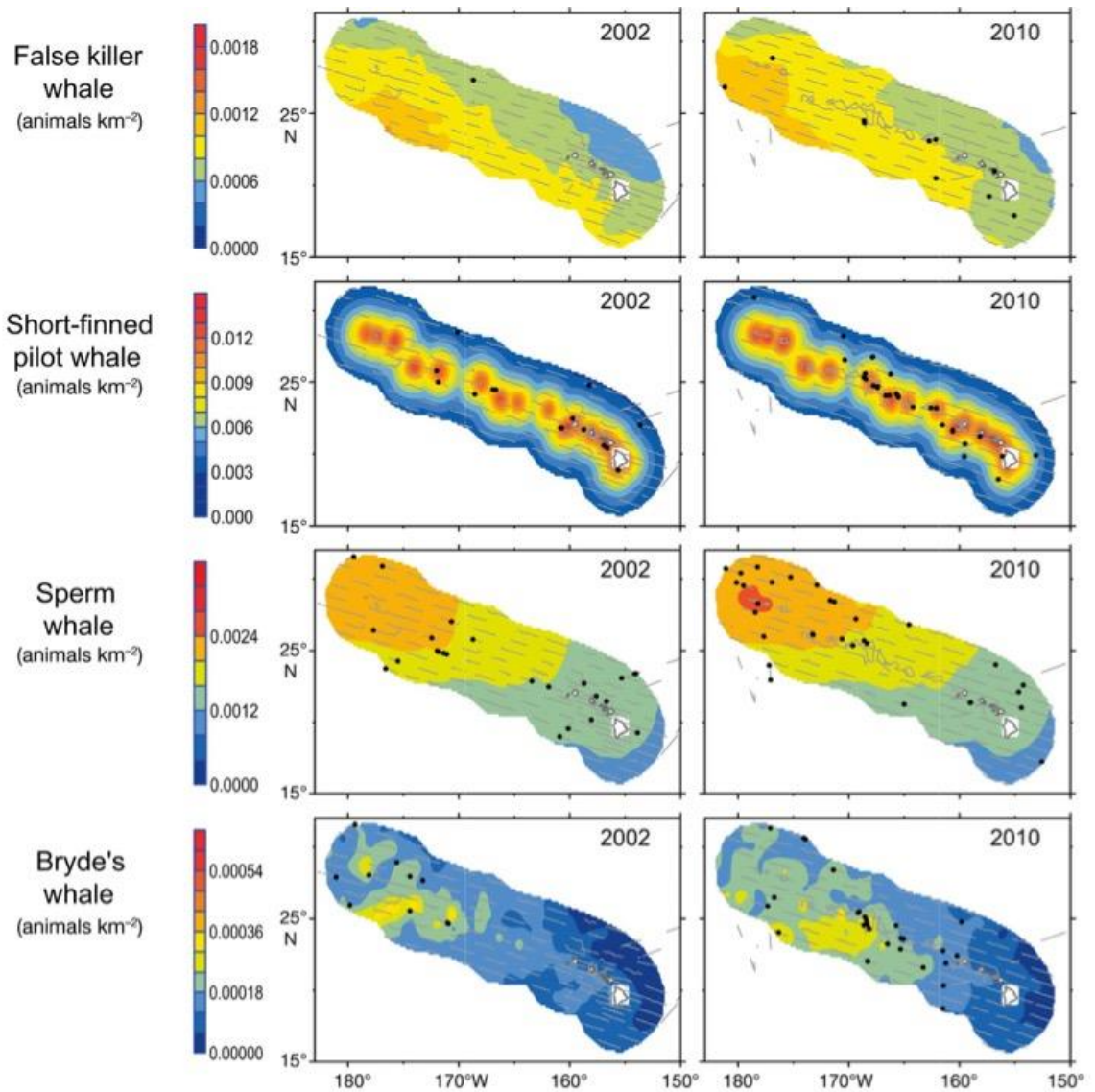
Figure 2.5: Updated model-based densities for false killer whale, short-finned pilot whale, sperm whale, and Bryde's whale from line-transect surveys (grey lines) for years 2002 and 2010 from 15 systematic line-transect ship surveys conducted by National Oceanic and Atmospheric Administration (NOAA) Southwest Fisheries Science Center and the Pacific Islands Fisheries Science Center between 1997 and 2012. Black dots represent locations of sightings. (Figure adapted from Forney, K. A., Becker, E. A., Foley, D. G., Barlow, J., & Oleson, E. M. (2015). Habitat-based models of cetacean density and distribution in the central North Pacific. *Endangered Species Research, 27*(1), 1-20.)

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2.5 Current Threats

Humpback whales are susceptible to negative impacts from anthropogenic activities and having abundance and density estimates allows researchers to monitor and assess how much of an impact they are having on populations. When large migration routes overlap shipping channels, then risk for ship strikes and entanglement in fishing gear increases. Increase in vessel traffic throughout the oceans causes negative impacts from noise pollution by interfering with communication and breeding. Overfishing by commercial fisheries is leading to a decrease in prey availability. Climate change is also a potential threat to humpback whales and many marine species, as it is unclear when and how available prey will shift and how the apex predators will adapt. Understanding their current threats is necessary for implementing effective conservation management strategies.

2.5.1 Ship Strikes

Humpback whales, being slow moving, large marine mammals, are highly susceptible to ship strikes. Their migration routes and feeding areas often overlap with shipping lanes, resulting in increases of ship strikes that can lead to serious injury or death. The National Marine Fisheries Service (NMFS) has established that the human-caused mortality limit (Potential Biological Removal, PBR) is 11 for humpback whales (Carretta *et al*., 2017). Rockwood *et al*. (2017) suggests that the number of whales struck and killed by cetacean-vessel collisions are greater than previously suspected, and significantly greater than the established PBR counts. Whale carcasses, in general, tend to sink before the bodies can be beached, which results in low carcass recovery rates. This contributes to challenges in quantifying accurate numbers of whale mortalities caused by

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collisions (Laist *et al*., 2001). Based on recent models of ship strike effects on cetacean populations, fatal cetacean-vessel collisions are one of the leading causes of human-related death for large cetaceans in the U.S. and around the world (Rockwood *et al*., 2017; Redfern *et al*., 2013; Williams & O'Hara, 2010).

Humpbacks are especially susceptible to ship strikes near the entrance to the Strait of Juan de Fuca and within the Salish Sea because there is one main entry from the Pacific Ocean utilized by both cetaceans and vessels. Williams & O'Hara (2010) noticed a pattern in their modeled results of cetacean-vessel collisions that suggested these 'bottleneck' areas had highest relative risk for cetacean-vessel collisions. A report from Washington State Department of Ecology from 2016 stated that, on average, the daily commercial vessel traffic density in the Puget Sound is 27 vessels per day. Vessel traffic in the Salish Sea is expected to increase due to increases in amount of cargo exported (BST Associates, 2017; Cascadia Research Collective, n.d.). The Northwest Seaport Alliance is the gateway for marine cargo for the ports of Tacoma and Seattle and claims that the Pacific Northwest is one of the most trade dependent regions of the US. According to their September 2019 cargo report, in the last five years grand total containerized volumes (twenty-foot equivalent units, TEUs) have increased 5.8% and grand total cargo volume (metric tons) have increased 5.5% (Northwest Seaport Alliance, 2019). Also, their international imports are up by 4.5% and exports are up by 8.5% from the previous year (Northwest Seaport Alliance, 2019). In 2017, it is estimated that $17 billion worth of goods were exported and it's estimated that 10.5 million metric tons of containerized cargo are exported yearly with a worth of $12.4 billion (Northwest Seaport Alliance, 2019). They are also accepting proposal for cargo operations at Terminal 46 in

Seattle to support further marine cargo operations with the intent to increase cargo volumes (Northwest Seaport Alliance, 2019).

Projected increases in vessel traffic increase the risk of vessel collisions in the Strait of Juan de Fuca and surrounding waters. This coupled with documented increase and now stabilization of numbers of humpback whales found seasonally along the US west coast including Washington (Calambokidis *et al*., 2004; Calambokidis and Barlow, 2004), there are ever more opportunities for vessels and whales to come into conflict. Humpback whales have made a dramatic return to the Salish Sea in recent years (Steiger *et al*., 2015; Calambokidis *et al*., 2018; Falcone *et al*., 2005). Understanding factors that increase probability of ship strikes and establishing high-risk areas of collisions will be vital for conservation management practices that want to reduce number of humpback whale and vessel collisions near the entrance to the Strait of Juan de Fuca and the Salish Sea.

2.5.1.1 Contributing Factors

Understanding factors that contribute to increased probability of fatal cetacean-vessel collisions in necessary for implementing effective management practices to mitigate fatal cetacean-vessel collisions. Determining a significant relationship between seasonal whale abundances and vessel strikes will help in evaluating if current mitigation efforts would be more beneficial if implemented year-round or having seasonal restrictions. Knowing the effect sea state has on probability of boat operators and/or observers to detect cetaceans in the water can be beneficial when developing management practices to decrease cetacean-vessel collisions. If sea state has a negative effect on probability of whale detection, then that will decrease a boat operator's ability

to avoid collision. If a boat operator or observer cannot detect a whale, then they cannot reduce speed and change course to avoid collision. It is important to understand if there are differences in cetacean-vessel collisions between different age classes of cetaceans, i.e. are juveniles more prone compared to adults, mothers with calf more prone than those without. This goes along with seasonal variation. Presence of calves coincides with seasonal variation so this could strengthen the need for either seasonally restricted or year-round mitigation efforts. Finally, understanding what effect vessel speed has on the probability of fatal cetacean-vessel collisions. If we know how speed, along with the other stated factors, affects probability of fatal collisions, it will help in analyzing overall how effective current management practices are for mitigating cetacean-vessel collisions in the Salish Sea.

2.5.1.2 Seasonal Variation

Humpbacks traveling along the west coast of North America have wide migratory ranges—from waters around Central America and Mexico to the coast of California to southern British Columbia (Calambokidis *et al*, 2000, Calambokidis *et al* 2001). Their migration routes in summer and fall months range from Central America and Mexico to coast of California to southern British Columbia (Calambokidis *et al*, 2000, Calambokidis *et al* 2001). Peak humpback abundances along the west coast of the North America are estimated to be between summer and fall, depending on geographic region. The literature suggests that there is an increased chance of humpbacks encountering vessels during these months of peak abundances. Numerous studies find a positive relationship between seasonal abundance and risk of collisions on humpback whales. For example, in an analysis of historical humpback whale and vessel collision data from

Hawai'i during 1975-2011, 75% of reported collisions happened between February and March, peak whale season for Hawai'i, suggesting a relationship between whale density and frequency of collisions (Lammers *et al*., 2013). In addition, Currie *et al*. (2015) found that risk of vessels encountering humpbacks varied month to month, with an increase during Hawai'i's peak whale season. Similarly, Neilson *et al*. (2012) found seasonal trends in their summary of 108 cetacean-vessel collisions in Alaska from 1978-2011, with 91% of the humpback related collisions occurring May-September. Together, these various studies demonstrate that humpback whale abundances vary seasonally and suggest that high abundances of collisions can be predicted during peak whale season.

2.5.1.3 Sea State and Age Class

Sea state refers to wave condition at sea and is typically classified using the Beaufort scale. This is an important measure that is considered by boatmen/sailors when maneuvering ships at sea. The Beaufort scale ranges from 0, indicating the sea surface is smooth and mirror-like, to 12 indicating hurricane like conditions, with waves over 45 feet (NOAA, n.d.). Research documents that an increase in Beaufort scale decreases one's ability to detect cetaceans (Demaster *et al*., 2001; Teilmann, 2003; Dolman *et al*., 2006; Barlow & Taylor, 2005; Williams *et al*. 2016). One study demonstrated a 15-20% reduction in ability to detect a humpback 300m away when sea state increased from 0 to 4 on the Beaufort scale (Currie *et al*., 2015). Understanding the effect of sea state on boat operators' or on-board observers' ability to detect whales is crucial to invoke measures of avoidance (Williams *et al*., 2016).

Cetacean age classes are classified as 1) calves who rely on their mother for milk, 2) sexually immature juveniles, and 3) sexually mature adults. In the literature, there is

evidence suggesting that the age class of a cetacean can determine an individual's susceptibility to a ship strike (Carrillo & Ritter, 2010; Currie *et al*., 2015; Lammers *et al*., 2013). Scientists hypothesize that calves and juveniles are more susceptible due to traits such as spending more time at surface to breath compared to adults, being less visible than adults, and being naïve to interactions with vessels (Laist *et al*., 2001; Paniganda *et al*., 2006). For example, Carrillo & Ritter (2010) found that 44% of cetacean carcasses documented (59 total) from vessel collisions between 1991-2001 in the Canary Islands were either calves or juveniles, compared with only 25% being adults. In another study conducted on Hawai'ian humpback whales, calves and juveniles were found to be more vulnerable to cetacean-vessel collisions (Currie *et al*., 2015). In an analysis of historical Hawai'ian cetacean-vessel collision records from 1975-2011, ~64% of 52 collisions involved either a calf or juvenile (Lammers *et al*., 2013). Neilson *et al*. (2012) found in their summarized report of 108 cetacean-vessel collisions on seven different whale species in Alaskan waters from 1978-2011 that calves and juveniles appeared to be at higher collision risks than adults. Knowlton & Kraus (2001) found that calves and juveniles accounted for 53% of documented severe injuries from fishery interactions and vessel collisions on Atlantic right whales.

2.5.1.4 Vessel Speed

The speed at which a vessel is traveling can influence the whale's ability to perform evasive maneuvers to avoid a ship strike. Numerous studies have been conducted to analyze the relationship between vessel speed and probability of a fatal cetacean-vessel collision. Silber *et al*. (2010) found a direct relationship between vessel speed and severity of injury in relation to cetacean-vessel collisions. Transect surveys, carried out

monthly during the winter in Hawai'i from 2013-2015, suggest that vessels moving at speeds over 12-13 knots (kts) increase the likelihood of cetacean-vessel collisions (Currie *et al*., 2015). Wiley *et al*. (2011) modeled lethal risk reductions of cetaceans; specifically, humpback, fin, and wright whales, with overall findings suggesting that restricting speeds to 10 kts reduced probability of lethality by 56.7%. Lammers *et al*. (2013) suggests that vessel speeds above 12 kts decrease whale's ability to avoid vessels and collisions above this speed increase probability of a fatal cetacean-vessel collision. Based on models of humpback and fin whale sighting data and environmental covariates, the western portion of the Strait of Juan de Fuca is a high-risk area of fatal cetacean-vessel collisions because the Strait has higher than average vessel speeds (>12 knots) and high-density marine traffic (Figure 2.6; Nichol *et al*., 2017). Understanding relationship of vessel speed and probability of fatal collisions is important when analyzing current mitigation practices for reducing cetacean-vessel collisions.
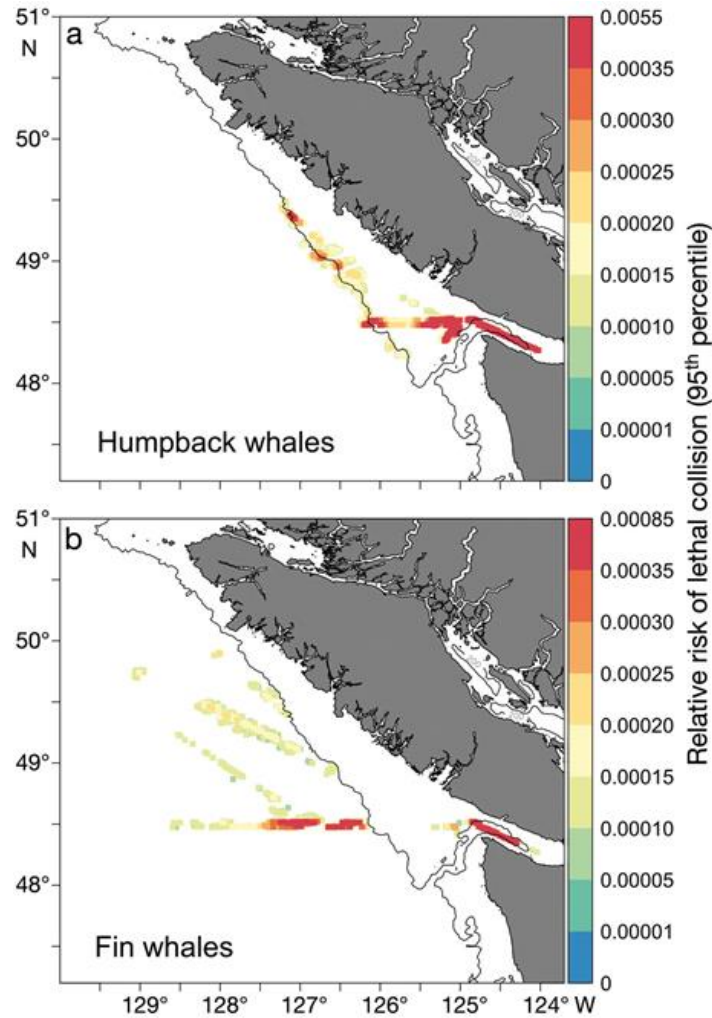
Figure 2.6: Map showing highest risk areas of a lethal collision for humpback (top) and fin whales (bottom) along coast of Vancouver Island, BC and at the mouth of the Strait of Juan de Fuca from GAM model estimates. Whale sighting data obtained from aerial surveys from 2012 – 2015 and shipping data was obtained from 2013 AIS ship traffic data. (Image adapted from: Nichol, L.M., Wright, B.M., Hara, P.O., & Ford, J.K. (2017). Risk of lethal vessel strikes to humpback and fin whales off the west coast of Vancouver Island, Canada. *Endangered Species Research, 32,* 373-390.)

2.5.1.5 Ship Strike Conclusion

The major findings have determined that there are multiple factors that come into play when trying to determine the probability of a fatal cetacean-vessel collision: seasonal variation, sea state, age class, and vessel speed. While certain factors have a

greater effect than others on the probability of a fatal collision, it is important to take each

into consideration. A high sea state paired with high vessel speed is suggested to have a

greater negative effect on detecting a cetacean in time for avoidance measures like

altering route and slowing down (Wiley *et al.*, 2011; Teilmann, 2003). The susceptibility

of calves and juveniles in relation to seasonal variation should be considered because

calves and juveniles are likely to be present during peak migration periods, increasing the

probability of cetacean-vessel collisions (Neilson *et al.*, 2012). In April of 2017, a gray

whale from the North Puget Sound Feeding Group was struck, and survived, by a

recreational vessel off the coast of Whidbey Island (Lewis, 2017). A whale watching boat

struck a humpback whale, who survived, near Race Rocks Ecological Reserve, Canada

while traveling between 24-28 knots (Lawrence, 2017). These incidences, though not

fatal, further strengthen how necessary it is to evaluate current mitigation practices that

are in place to reduce cetacean-vessel along the coast of Washington and

Northern/Central Oregon. In the most recent marine mammal stock assessment for

humpbacks along the west coast, over a five-year period (2012-2016) it is estimated that

2.1 whales on average are taken each year due to ship strikes (Carretta *et al.*, 2019).

2.5.2 Entanglement

Entanglement has dire and lasting consequences to whales, with the main cause of

death from entanglement being drowning due to asphyxiation (Moore & Hoop, 2012;

Dolman & Moore, 2017). Entanglement has the potential to prevent the whale from rising

to the surface to breath, resulting in death. A study by Cassoff *et al.* (2011) suggests that

age class may predispose a whale to drowning, with younger age classes being more at

risk. If the whale manages to survive initial entanglement, they suffer from a variety of

internal and external injuries. Gear that is entangled around or near the mouth can disrupt feeding, thus leading to starvation (Kot *et al*., 2009; Cassoff *et al*., 2011; Moore & Hoop, 2012; Dolman & Moore, 2017). Lacerations leave the body open to bacteria that can lead to infection which then leads to a weakened immune system and opens them up for more infections, and eventually death (Cassoff *et al*., 2011; Moore & Hoop, 2012). Entanglement can trigger behavioral and physiological stress responses. Exposure to prolonged chronic stress can weaken their immune system, making them prone to fatal infections and diseases (St. Aubin & Dierauf, 2001; Cassoff *et al*., 2011). Exposure to prolonged entanglement also causes severe tissue damage, leading to continual chronic pain until subsequent death (Cassoff *et al*., 2011).

Alaska, California, Idaho, Oregon, and Washington are part of an interstate compact agency, The Pacific States Marine Fisheries Commission (PSMFC) that assists in resource management of various agencies and the fishing industry to prevent unsustainable use of Pacific Ocean resources. Each state is represented by three commissioners and the PSMFC is required to meet at least once a year. Yearly meetings provide an opportunity for each state to identify priority issues and vote for resolutions. PSMFC received a NOAA Bycatch Reduction Engineering Program grant to use towards testing the most promising innovations that could reduce entanglements of marine mammals, with particular focus on humpbacks in crab pot gear.

2.5.2.1 Current Trends

In 2017, NOAA Fisheries reported that there were 76 confirmed entanglement cases of large whales. Humpback whales were the number one whale species entangled (n=49) in 2017 (NOAA Fisheries, 2017). Since 2007, humpbacks represent 68% of large

whales reported entangled (NOAA Fisheries, 2017). The confirmed cases of

entanglement reports occurred along all U.S. coasts except the Gulf of Mexico and more

than half of all reports occurred off waters of two states: California (32.9%) and

Massachusetts (26.6%) (NOAA Fisheries, 2017). A high number of confirmed

entanglements for humpbacks occurred off the coast of the main Hawai'ian Islands

(14.3%) (NOAA Fisheries, 2017). It is estimated that 70% of the entanglements were

from fishing gear and 24% in line of unknown origin. Along the US West Coast

specifically, NOAA Fisheries – West Coast Region, report 31 whales confirmed

entangled off the coast of Washington, Oregon, and California. Of the 31 confirmed

reports, humpbacks made up roughly half (n=16) (NOAA Fisheries, 2018). The number

once source of entanglement along coasts of Washington, Oregon, and California was

entanglement in commercial and recreational Dungeness crab traps (NOAA Fisheries,

2018). More than half the confirmed reports were off central and southern California

(80%) and the rest occurring off Oregon and Washington (19%) (NOAA Fisheries,

2018). In the most recent marine mammal stock assessment for humpbacks along the

west coast, over a five-year period (2012-2016) it is estimated that 15.7 whales on

average are taken each year due to entanglement in fishing gear (Carretta *et al*., 2019).

2.5.3 Other Threats

Along with facing threats from ship strikes and entanglement in fishing gear, they

also face negative impacts from other threats with anthropogenic origins like ingestion of

microplastics and noise pollution. Microplastics are generally defined as plastic particles

smaller than 5mm and are a unique threat because of their ability to absorb and

concentrate various toxic pollutants (Fendall and Sewell, 2009; Betts, 2008; Moore,

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2008, Andrady, 2011). The Great Pacific Garbage Patch, located in the NP, is estimated to be twice the size of Texas and contain an estimated 7 million tons of trash (Craens, 2012). Eighty percent of trash in the garbage patch is estimated to be plastic, contributing to the threat of microplastics (Craens, 2012). Microplastics are associated with persistent, bioacculmulative, and toxic organic contaminants (PCBs, PAHs, PBDEs) which are known to have adverse effects on organisms such as reduced growth rate, decreased reproductive output, and reduced offspring viability, which can all result in population declines (Galloway & Lewis, 2016). Deaths at sea and natural decay of organisms before necropsies can be performed decreases opportunities to document microplastics in baleen whales (Besseling *et al*., 2015). Due to difficulties of directly observing plastic ingestion by whales, many scientists are looking at their prey source, and determining the potential a whale species has of ingesting plastics based on prey source (Au *et al*., 2017; Egbeocha *et al*., 2018; Burkhardt-Holm & N'Guyen, 2019). It has been theorized that baleen whales were ingesting plastics, but it was not confirmed until 2012 (Besseling *et al*., 2015). After necropsying a juvenile female humpback whale, Besseling *et al* (2015) found 45 plastic particles, ranging in size from 0.04 mm – 5.8 mm. They only examined a fifth to a tenth of the total length of the humpback's intestine, and therefore estimate that the total amount of plastic consumed could be five to ten times higher than what they found. Due to potential to cause population decline if there is enough plastic accumulation within populations, management efforts should also focus on ways to reduce the number of plastics entering the oceans.

Whales are dependent on sound for various behaviors such as communication, navigation, and foraging and the impact anthropogenic noise can have on these vital

behaviors has been a topic of increasing concern as human activity increases in the oceans. Sources of ocean noise include military sonar, commercial shipping, marine geophysical surveys, marine construction, whale watching, and aircraft, with increased ocean noise suggested to have negative behavioral, acoustic, and physiological responses (Todd *et al*., 1996; Croll *et al*., 2001; Williams *et al*., 2006; Nowacek *et al*., 2007; Miller *et al*., 2009; Rolland *et al*., 2012; Sivle *et al*., 2015; Isojunno *et al*., 2016; Dunlop, 2016). Due to the difficulty to track the number of deaths a year by these other anthropogenic threats, there is no estimate available on how many deaths a year are caused by noise pollution or plastic ingestion. This, in turn, effects the total number of whales killed each year by anthropogenic activities, thus reducing accuracy of how many whales are killed each year due to humans.

Chapter 3 : **Methods**

Cascadia Research Collective and Washington Department of Fish and Wildlife (WDFW) jointly designed and implemented vessel-based line-transect surveys for the west coast of Washington State and Northern/Central Oregon from 2011 – 2013. The project was part of a WDFW Section 6 Grant with overall objectives to conduct research on Endangered Species Act (ESA)-listed marine mammals. The project aimed to determine abundance, distribution and habitat use, gather information on stock structure, and identify areas of human interaction including ship strikes, entanglements, and other fishery interactions for the California/Oregon/Washington stock of humpback whales along the US West Coast. To achieve the Section 6 Grant objective, surveys were planned to sample the study area every spring, summer and fall from 2011 to 2013. Transect design and placement were determined to specifically include deep and shallow waters, with focus on overlapping shipping lanes and surveying over the continental shelf and various underwater canyons (**Error! Reference source not found.**). Access to o vernight harbors and distance from Greys Harbor, WA, in conjunction with weather windows dictated how far south the survey area could extend.

This thesis compiles and analyses data from these line-transect surveys to address the following species-specific objectives for humpback whales:

1. Examine the distribution of sightings of humpback whales along the outer coast of Washington and Northern/Central Oregon
2. Determine density and abundance estimates
3. Examine if these estimates of abundance display any seasonal trends or differences with estimates obtained in other surveys

3.1 Survey Area

Survey lines were numbered from north to south beginning at Neah Bay, Washington and ended at Newport, Oregon with western boundaries of the survey area varying from 31 to 43 nmi from shore, encompassing a total area of 9967 nmi^2 (Figure 3.1). Within this survey region is the Olympic Coast National Marine Sanctuary (OCNMS), one of North America's most productive marine regions and a vital area for numerous ecologically and commercially important species, including humpback whales (Basta, 2011). Transect lines were specifically created to cover the continental shelf and major submarine canyons. It has been suggested that whales congregate to submarine canyons and continental shelves, seasonally and year-round, due to oceanographic mechanisms that occur within these underwater features (Moors-Murphy, 2014). The transect lines traversed major shipping lanes accessing the Puget Sound on the northern end of the study area and the Columbia River at the border of Washington and Oregon. The northernmost part of the study area encompasses the entire OCNMS, 2408 nmi^2. It includes most of the continental shelf and parts of three major submarine canyons, Nitinat Canyon, the Quinault Canyon, and the Juan de Fuca Canyon (Figure 3.1). The southern portion of Oregon extends to include another major submarine canyon, Stonewall Bank.
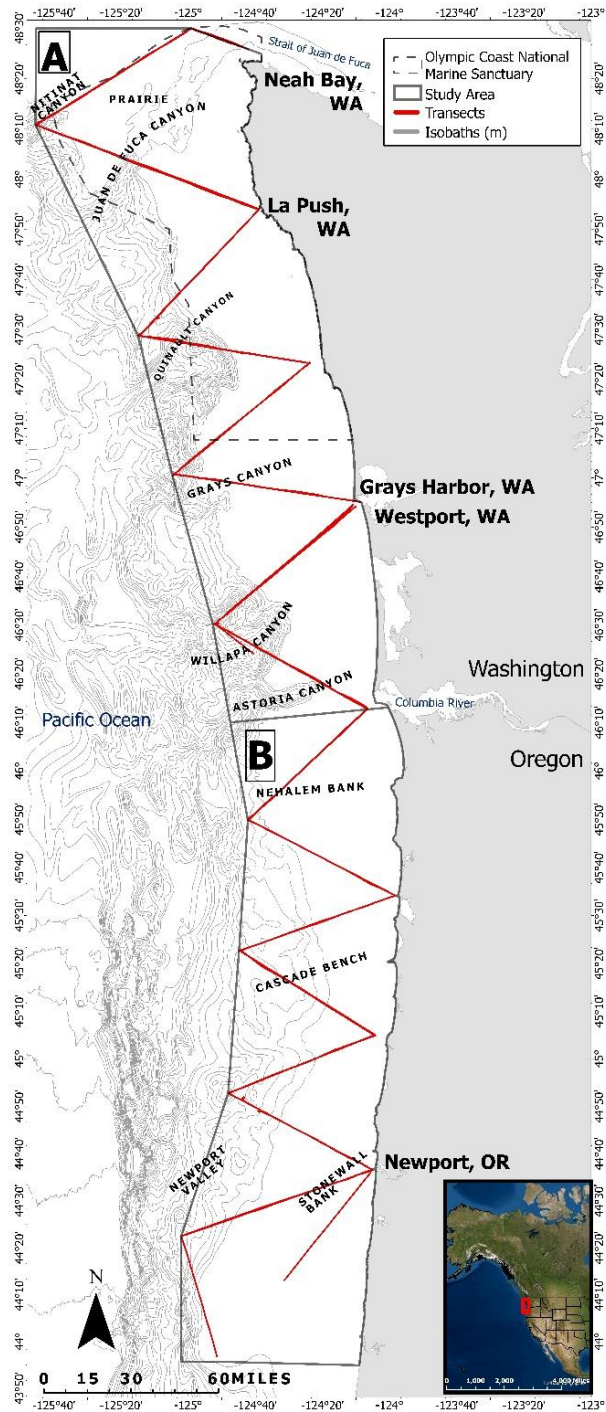
Figure 3.1: Designated survey area outlined in black for systematic line-transect surveys by Cascadia Research Collective and WDFW on vessel G.H. Corliss from 2011 – 2012. Regions are identified as [A]: Washington; [B]: Northern/Central Oregon. Dashed box outlines the Olympic Coast National Marine Sanctuary. Red lines are the navigated transect lines and their corresponding transect number. Major submarine canyons are identified. Major cities labeled. Light grey lines represent bathymetric contours.

3.2 Data Collection

The same survey protocol was followed for the 18 established transects, starting from Neah Bay, WA and ending at Newport, Oregon (Figure 3.1). Each survey consisted of four personnel: 2 observers, 1 data recorder, and the captain. Environmental conditions (Beaufort, visibility, swell height) were recorded every half hour or more often if conditions changed during surveys. The program WinCruz was used during the first half of the project to record effort, environmental conditions, and sighting data, then switched to Access database. To be considered on-effort, two observers needed to be actively searching with a combination of naked eye and 7x50 fujinon binoculars, the vessel had to be traveling on the established survey lines at > 5 knots and weather conditions had to be acceptable. Acceptable weather conditions were considered Beaufort 5 or less, visibility greater than 0.5 nautical miles, and no rain. While on-effort, observers continually scanned from the boat to horizon looking for marine mammals. If the vessel slowed below 5 knots or if observers experienced drastic weather change such as dense fog, the survey would go off-effort. To address observer fatigue, observers would rotate with data recorder, spending one hour observing on portside, one hour observing on star board side, and then one hour as data recorder. On-effort observations were made until they ran out of daylight, conditions worsened, or made it into the harbor.

When a marine mammal sighting was made, the time, latitude/longitude, ship heading, angle from angle board, and reticle from binoculars or estimated distance in meters was recorded. Marine mammals were identified to the species level if possible, and cluster size was estimated. If the species could not be identified, all observations were recorded in the comments section that could aid in species identification later.

3.3 Data Analysis

The survey area was digitized using ArcGIS Pro 2.2.3. The survey GPS points used for navigating from transect to transect were connected to create a polygon feature. The eastern boundary of the survey area was traced and snapped to the west coast shoreline layer obtained from the ESRI Online data portal. Because of inconsistent survey coverage, data was post-stratified by region, either Washington (WA) or Northern/Central Oregon (OR). The data were analyzed using the software Distance following methods outlined in Buckland *et al*. (2001) for 'conventional distance sampling' (CDS) and 'multiple covariate distance sampling' (MCDS; Distance version 7.2; Thomas *et al*., 2010). The analysis was divided into three parts: 1) fitting the probability density function f(x), 2) estimating mean cluster size based on observed cluster sizes, and 3) estimating abundance and density in Distance with the following formulas as mentioned in section 3.2.2 of the Literature Review:

$$\text{Density: } \widehat{D} = \frac{n\hat{f}(0)}{2L}$$

$$\text{Abundance: } \widehat{N} = \frac{n\hat{f}(0)A}{2L}$$

A global f(x) (the probability density function) was fitted for large whales that included sightings from fin and humpback whales. Initially, if a cetacean could not be identified to the species genus level it was identified to the group level (i.e., large whale, small whale, etc.). To increase sample size, unidentified large whale counts were prorated into fin whale or humpback whale counts. This was only used in distance analyses and not in reporting of raw sighting data nor mapping of humpback whale distributions. They

were included in estimating large whale's detection function and included in species-specific abundance and density estimates.

Due to small sample size, stratified abundance and density was only estimated for humpback whales once an appropriate detection function was selected. Humpback whale sightings were pooled across regions, seasons, and years to generate an overall abundance and density estimate for the study area from April – December. Estimates were generated for four levels of stratification: 1) pooled, 2) regional, 3) region and year, and 4) region and season.

3.3.1 Estimating Probability Density Function and Cluster Size

The probability density function (pdf), f(x), describes the relationship between distance and probability of detection (Buckland *et al*., 2001). CDS and MCDS was used in Distance to estimate best fit of f(x) following methods described in Buckland *et al*. (2001). Hazard-rate and half-normal key functions with no series expansions were fit to the distribution of observed distances. These functions often provide a good fit when modeling f(x) (Buckland *et al*., 2001, 2004; Thomas *et al*., 2010).

Visual exploration of the data suggested that the data should be truncated to 1.5 nmi to improve ability to fit f(x) (**Error! Reference source not found.**). For MCDS, e xploratory analyses indicated that Beaufort and visibility had the most substantial effect on detecting a whale. Beaufort was used as a continuous variable (on a scale of 0-6) and as a four-factor variable (0, low, medium, high) (**Error! Reference source not found.**), w hile visibility was used just as a continuous variable. When looking at the distribution of recorded Beaufort as a continuous variable, it is unusual for there to be a spike in

sightings after Beaufort 3. Visibility and Beaufort were analyzed using 1-way ANOVA in R to determine if seasonal averages varied significantly.

In the final modeling of pdf(0), hazard-rate and half-normal key functions with no series expansions were fit to the distribution of observed sighting distances. The covariates of Beaufort continuous, categorized Beaufort, and visibility continuous were used for MCDS models. Model of best fit was chosen based on AIC values and examining detection plots. This provided the f(0) value necessary for Distance to estimate abundance and density, and thus provided final regional and seasonal abundance and density.
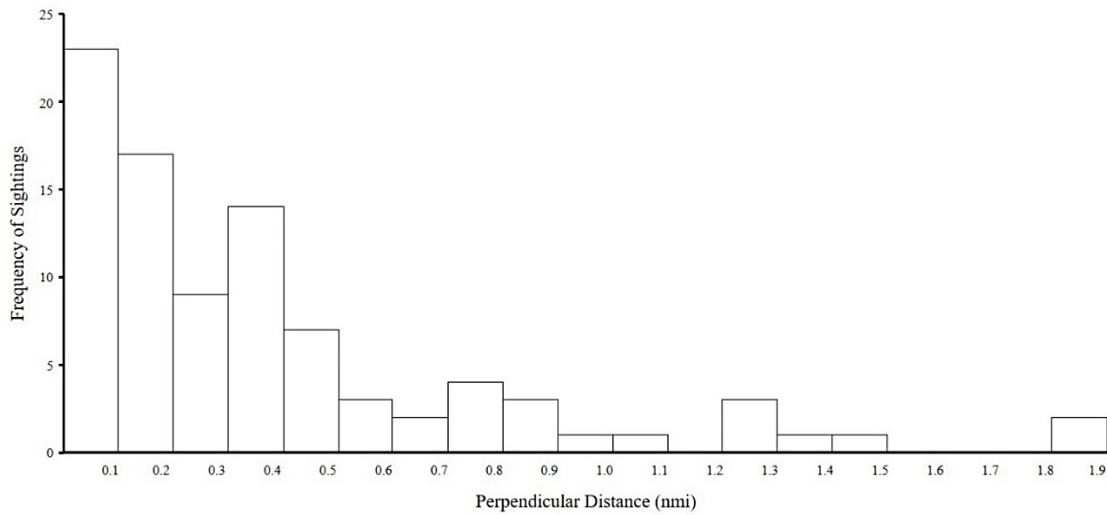
Figure 3.2: Histogram of perpendicular distances of large whales sighted during G.H. Corliss line-transect surveys by Cascadia Research Collective and WDFW from 2011 – 2012 along coast of Washington and Northern/Central Oregon.
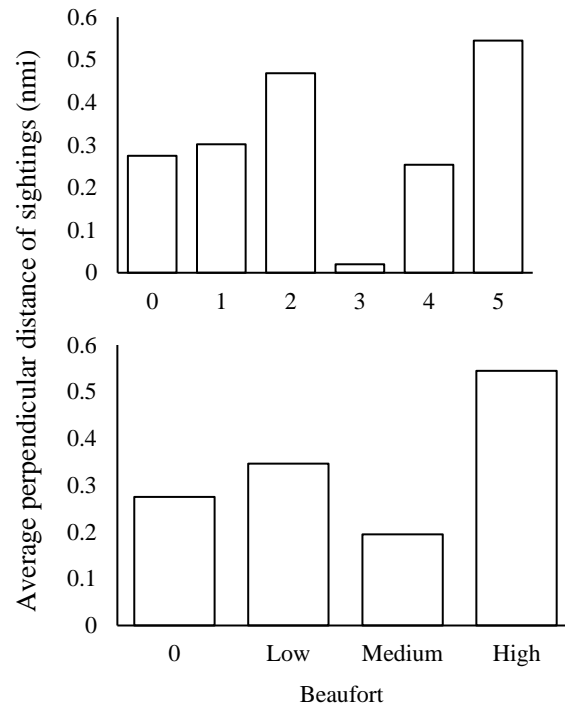
Figure 3.3: Perpendicular distances of large whale sightings by beaufort categorized as (top) continuous variable, and (bottom) as a four-factor variable as used in MCDS analyses.

Chapter 4 **Results**

4.1 Survey Effort and Model of Best Fit

4.1.1 Survey Effort

Regional effort varied by season and year, with Washington having the most consistent survey coverage by season and year (Table 4.1). Between 2011 and 2012 five systematic line-transect surveys, broken up into 12 cruises covering over 2,044 nmi of transects and an area of 9,967 nmi^2, were conducted from the WDFW patrol vessel *G. H. Corliss*. Surveys done in spring 2011, summer 2011, and spring 2012 had complete survey coverage whereas surveys done in fall 2011 and summer 2012 failed to fully survey the entire study area. For fall 2011 and summer 2012, weather, personnel, and boat availability prevented the survey being conducted down into Oregon. The 2013 survey data was omitted because of inconsistent survey coverage.

Table 4.1: Summary of on-effort surveys conducted from *G.H. Corliss* line-transect surveys by Cascadia Research Collective and WDFW from 2011 – 2012 along coast of Washington (WA) and Northern/Central Oregon (OR).

Region	Year	Season	Effort (nmi)	# of transects	Area (nmi^2)
WA	2011	Spring	282.4	9	5,204
	2011	Summer	263.3	10	
	2011	Fall	223.7	8	
	2012	Spring	298.1	10	
	2012	Summer	199.9	7	
OR	2011	Spring	222.4	7	4,763
	2011	Summer	296.3	9	
	2011	Fall	-	-	
	2012	Spring	257.9	7	
	2012	Summer	-	-	
		Total	**2,044.1**		**9,967**

Table 4.2: Summary of total effort (nmi), number of transects covered, and average of environmental variables measured for each survey from *G.H. Corliss* line-transect surveys by Cascadia Research Collective and WDFW from 2011 – 2012 along coast of Washington and Northern/Central Oregon.

Survey Dates	Season/Year	# transects	Effort nmi	Beaufort	Visibility nmi
30Apr-01May. 04-06May	Spring 2011	16	504.8	2.95	8.2
06-07May. 29-31May	Spring 2012	17	556.1	1.50	8.1
23-24Aug. 14-16Sept,	Summer 2011	18	559.6	1.28	8.5
19Jul. 16-18Aug	Summer 2012	7	199.9	0.54	4.0
06-08Dec	Fall 2011	8	223.7	2.33	7.5

Environmental variables have an impact on an observer's ability to detect an animal at sea. As Beaufort increases or visibility decreases, the ability to detect a whale decreases. These variables are often used as covariates in multiple-covariate distance sampling (MCDS) analyses to generate abundance and density estimates. Beaufort and visibility were continually recorded throughout all surveys. Visual exploration of the data suggested that the data should be truncated to 1.5 nmi to improve ability to fit f(x), as noted in the previous section (Figure 3.2). For MCDS, exploratory analyses indicated that Beaufort and visibility had the most substantial effect on detecting a whale. Beaufort was used as a continuous variable (on a scale of 0-6) and as a four-factor variable (0, low, medium, high), while visibility was used just as a continuous variable. When looking at the distribution of recorded Beaufort measurements as a continuous variable, it is unusual for there to be a spike in sightings after Beaufort 3 (Figure 3.3). A one-way ANOVA was conducted on seasonal Beauforts to determine if season had significant impact on average beaufort, and thus an impact on observer's ability to detect a whale. There was significant difference in average Beaufort by season at the $p<0.05$ level (1-way ANOVA, $F_2=579.12$, $P<0.0001$). Post hoc comparisons using the Tukey HSD test indicated seasonal averages varied significantly across all seasons ($p<0.01$), with spring 2011 having the highest average beaufort of 2.9 and summer 2012 having the lowest average beaufort of 0.53 (Table 4.2). Examining humpback encounter rate by beaufort, we see an increase in encounter rate at beaufort 5, but with less effort (Table 4.3).

Table 4.3 Number of humpback whale sightings, effort, encounter rate, mean cluster size, and average perpendicular distance by sea state from G.H. Corliss line-transect surveys by Cascadia Research Collective and WDFW from 2011 – 2012 along coast of Washington and Northern/Central Oregon.

Beaufort	L nmi	n	n/L per 100nmi	mean cluster size	Avg. Perp Distance nmi
0	230.8	17	7.4	1.5	0.3
1	746.7	32	4.3	1.5	0.2
2	530.4	15	2.8	1.4	0.7
3	293.4	1	0.3	1.0	0.0
4	213.6	6	2.8	1.8	0.3
5	28.9	11	38.1	1.3	0.6
6	0.2	0	-	-	-

4.1.2 Model of Best Fit

Distance 7.3 was used to determine model of best fit of the detection function over distribution of perpendicular sightings for large whales. The key component in obtaining abundance and density in distance sampling is the estimation of a detection function. The detection function describes the relationship between distance and probability of detection (Buckland *et al.*, 2001). The model of best fit based on lowest ΔAIC was the hazard-rate with visibility as covariate and thus used to determine estimates for the four different levels of stratification of humpback whales (Table 4.4; Figure 4.1). The estimated effective strip width (ESW) for large whales is 0.43 nmi.

Table 4.4: Summary of model selection statistics and parameter estimates for models proposed to fit perpendicular distance data for large whale sightings from *G.H. Corliss* line-transect surveys by Cascadia Research Collective and WDFW from 2011–2012 along the coast of Washington and Northern/Central Oregon. Model of best fit (hr + *vis*) chosen by lowest AIC value (ΔAIC = 0).

Model + covariates	ΔAIC	# par	Model Parameters					
			ESW	CV	pdf (0)	P	CV	GOF K-S p
hr + *vis*	0	3	0.43	0.09	2.33	0.29	0.09	0.641
hr	2.26	2	0.44	0.15	2.29	0.29	0.15	0.641
hr + *bft cat*	5.24	5	0.54	0.09	1.85	0.36	0.09	0.204
hr + *bft cat* + *vis*	6.43	6	0.53	0.09	1.88	0.36	0.09	0.192
hr + *bft*	8.69	3	0.57	0.08	1.75	0.38	0.08	0.235
hr + *vis* + *bft*	10.1	4	0.56	0.09	1.79	0.37	0.09	0.334
hn	12.1	1	0.61	0.06	1.64	0.41	0.06	0.026

hr hazard rate, *hn* half normal, *vis* visibility (nmi), *bft cat* beaufort category (0, low, med, high), *bft* beaufort numerical, *ΔAIC* delta Akaike Information Criterion, *# par* number of parameters, *ESW* effective strip width, *CV* coeffecient of variation, *pdf (0)* probability density function at 0, *GOF K-S p* Goodness-of-fit Kolmogorov Smirnov test probability.
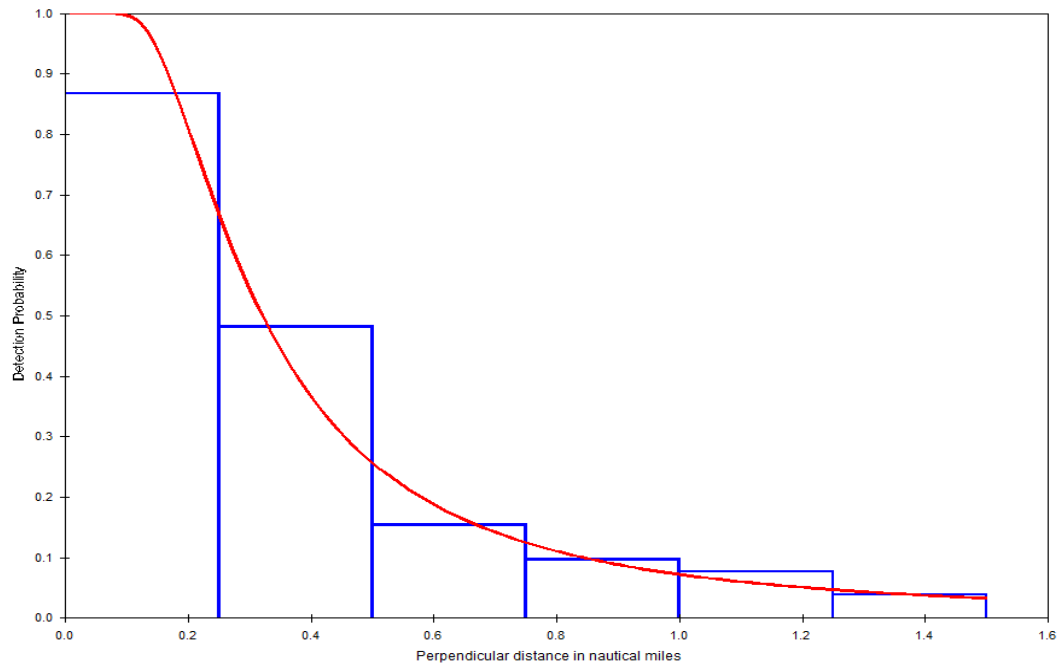
Figure 4.1: Fitted hazard rate with visibility as covariate MCDS model (red curve) to distribution of large whale perpendicular distances (histogram).

4.2 Humpback Abundance and Density Estimates

4.2.1 Raw Data

Within the entire study area, humpback whales were the most seen of the large whale group, consisting of 68 sightings of 100 individuals during all surveys without truncating the sightings by distance from boat. After prorating sightings of unknown large whales, there are an estimated 82 humpback whale sightings consisting of 119 individuals (Table 4.5). These prorated estimates are used in Distance to estimate abundance and density. Group size ranged from 1 to 7 (mean = 1, SD = 2). The largest number of sightings was made during the summer 2011 survey, with 37 sightings of 57 individuals.

Table 4.5: Summary of raw large whale sightings made during on-effort before truncation for surveys conducted from *G.H. Corliss* line-transect surveys by Cascadia Research Collective and WDFW from 2011 – 2012 along coast of Washington and Northern/Central Oregon. Before includes unidentified large whales and after shows

Species	*N* sightings (total indvs.)	
	Before	*After*
Fin whale, *Balaenoptera physalus*	5 (10)	9 (14)
Humpback whale, *Megaptera novaeangliae*	68 (100)	82 (119)
Unidentified large whale	18 (23)	
TOTAL		**91 (133)**

Sightings were concentrated around various submarine canyons throughout the entire study area. An area termed "the Prairie", the area between Juan de Fuca Canyon and outer edge of the continental shelf identified by Calambokidis *et al*. (2004), had consistent sightings each survey and highest concentration of sightings overall (Figure 4.2). Farther south, there was a high concentration of sightings around Stonewall Bank

during summer 2011. Summer 2011 had the most sightings, concentrated around the Prairie, Juan de Fuca Canyon to the north and Stonewall Bank to the south, with few sightings in between. Fall 2011 appears to have the most even distribution of sightings compared to other seasons and years. Spring 2012 had the least number of sightings, and uneven distribution of sightings, all of them occurring to the north near the Prairie and Juan de Fuca Canyon or further south near Willapa Canyon and Seachannel. There were no sightings of humpbacks in spring 2011 despite surveys being conducted in good weather conditions and covering almost all 18 transects.
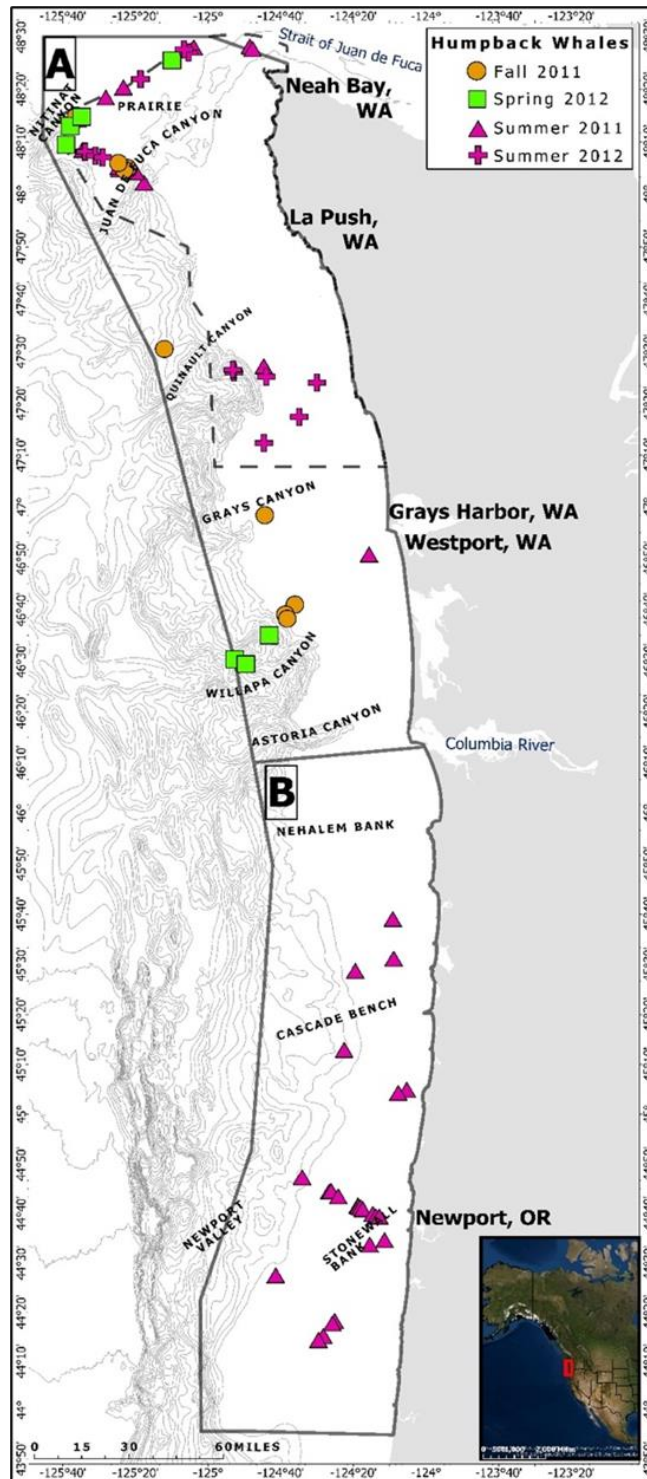
Figure 4.2: Distribution of raw sightings of humpback whales made during line-transect surveys from 2011 – 2012 and important underwater canyons identified. Geographic strata include: (A) Washington and (B) Northern/Central Washington. Dashed outline represents boundary for Olympic Coast National Marine Sanctuary.

4.2.2 Abundance and Density Estimates

For the entire study area from 2011-2012, it is estimated 82 humpback whales were sighted over 2,044 nmi of effort. Modeled results estimate the abundance for the survey area to be 2,205 (CV=0.26) humpbacks with an estimated density of 6 (CV=0.26) humpbacks per 100 nmi^2 (Table 4.5). Seasonal effort was variable, with a range of 224-1,061 nmi surveyed. Summer had the most humpbacks sighted, with an estimated density of 4 (CV=0.23) humpbacks per 100 nmi2 and an estimated abundance of 1406 (CV=0.32) throughout the entire area. Although abundance and density estimates appear to differ by season, the 95% CI for abundance and density estimates overlap; therefore, there are no significant difference in seasonal estimates for abundance and density (Table 4.5).

Regional effort for Oregon was inconsistent throughout the study period with no effort conducted in the fall 2011 nor summer 2012. Humpbacks were only sighted in 2011, despite having 258 nmi of effort in the spring of 2012. Even though there was comparable effort between spring 2011, summer 2011, and spring 2012 (ranging from 222 – 296nmi of survey effort), only summer 2011 had sightings, with a modeled abundance estimate of 689 (CV=0.51) whales and a density of 2 (CV=0.51) humpbacks per 100 nmi^2 throughout the study period (2011-2012) (Table 4.5).

Regional effort for Washington was comparable across all surveys ranging from 200 – 298nmi of effort, with a combined total of 1267.431 nmi surveyed. Washington had a modeled abundance estimate of 1516 (CV=0.3) whales and a density of 4 (CV=0.29) humpbacks per 100 nmi^2 throughout the study period (2011-2012) (Table 4.5). Modeled seasonal abundance estimates range from 276-524 (CV=0.65, 0.59)

humpbacks, with an average of 303 humpbacks per season. Spring 2011 had the lowest

estimate of 0 whales sighted, followed by spring 2012, which had an estimated

abundance of 276 (CV=0.65) humpbacks. Fall 2011 had the highest modeled estimate of

524 (CV=0.59) humpbacks. Modeled density estimates range from 0.79-1.49 (CV=0.65,

0.59) humpbacks per 100 nmi^2.

Table 4.5: Number of sightings with associated total survey effort and summary of modeled results using hazard-rade MCDS model with visibility as covariate and truncation distance of 1.5 nmi. Results separated by the different levels of stratification used when modeling results for humpback whales along coast of Washington and Oregon from 2011-2012.

Stratification			Survey Effort			Model Estimates				
			n	# transects	Lnmi	n/L per 100 nmi	D/100nmi^2(CV)	95%CI	N(CV)	95%CI
Region		WA	57	44	1267	4.5	4.3(0.29)	2.4-7.8	1516(0.3)	848-2710
		OR	25	23	777	3.2	2.0(0.51)	0.8-5.1	689(0.5)	265-1794
Region, Year	WA	2011	34	27	769	4.4	2.6(0.42)	1.2-5.8	910(0.4)	405-2042
		2012	23	17	498	4.6	1.7(0.40)	0.8-3.7	606(0.4)	280-1314
	OR	2011	25	16	519	4.8	2.0(0.51)	0.8-5.1	689(0.5)	265-1794
		2012	0	7	258	-	-	-	-	-
Season		Spring	10	33	1061	0.9	0.9(65)	0.2-2.6	276(0.6)	85-898
		Summer	51	26	760	6.7	4.0(0.32)	2.2-7.4	1406(0.3)	757-2611
		Fall	19	8	224	8.5	1.5(0.59)	0.1-4.4	524(0.6)	176-1556
Region, Season	WA	Spring	10	19	580.5	1.7	0.8(0.64)	0.2-2.6	276(0.6)	85-898
		Summer	26	17	463.2	5.6	2.0(0.40)	1.0-4.3	717(0.4)	334-1537
		Fall	19	8	223.7	8.5	1.5(0.59)	0.5-4.4	524(0.6)	176-1556
	OR	Spring	0	14	480.4	-	-			
		Summer	25	9	296.3	8.4	2.0(0.51)	0.8-5.1	689(0.5)	265-1794
		Fall					not surveyed			
Pooled	**Total**	WA&OR	82	67	2044.1	4.0	6.3(0.26)		2205(0.3)	

n number of sightings, *L* total length of transect lines nmi, *n/L* encounter rate, D density, N abundance, CV coefficient of variation

Chapter 5 : **Discussion**

5.1 Humpback Whale Abundance & Density

A number of researchers have generated abundance and density estimates for the California/Oregon/Washington stock of humpback whales along the US West Coast (Barlow, 1994; Calambokidis *et al*., 1999, Calambokidis *et al*., 2003; Barlow *et al*., 2011; Barlow, 2016; Wade *et al*, 2016; Calambokidis *et al*., 2017). This is the first study to perform surveys specifically to examine sighting data to estimate multiple seasonal trends (see Barlow, 2016; Calambokidis *et al*., 2004). This discussion will focus mainly on results generated for Washington because this region had more data and thus able to draw more conclusions. In this study, it is estimated that there are a total of 2,205 humpback whales migrating through the area between 2011-2012. If we compare that to the annual marine mammal stock assessment reports generated by NOAA Fisheries in 2018, which used data collected during a similar time period (2011-2014) as this study (2011-2012), they estimated abundance of the California/Oregon/Washington stock to be 2,900 (CV=0.048) animals. This is comparable to the estimates generated here of 2,205 (CV=0.26) animals.

Overall, the distribution of whales was not uniform throughout the study area, with sightings tending to aggregate at specific submarine canyons (the Prairie, Juan de Fuca Canyon, Stonewall Bank, etc., Figure 4.2). This is not surprising because it is well documented in the literature that deep sea canyons can serve as important feeding habitats for whales (Benson *et al*., 2002; Calambokidis *et al*., 2004; Rosa *et al*., 2012; Moors-Murphy, 2014).

Whales are seasonal migrators, so it is expected to see them occupying different habitats throughout the year as they migrate from their southern breeding grounds in warmer waters to their northern feeding grounds in colder, productive waters. Where they are spending time in the interim is a topic of importance for management and conservation purposes. Seasonal estimates aid in identification of abundance and density fluctuations within a particular area of interest, highlighting instances of variations. There were statistically significant differences in humpback whale abundances between seasons, with the highest estimate in summer and the lowest in spring. Having dedicated seasonal survey effort, it can further be determined a range of specific dates we can expect humpbacks to be in an area. It is established in the literature that humpbacks are in this area starting in May. Spring 2011 had no sightings of humpback whales despite being done in early May, having good survey coverage, and overall good weather conditions. If we compare the spring 2011 survey to the spring 2012 survey, we see that spring 2012 was conducted later in May, suggesting that the spring 2011 survey was conducted too soon in the season thus potentially explaining why there were no humpbacks sighted during spring 2011 survey. This suggests that whales are not in this area until later in May. The latest surveys were conducted was December 6-8, with an estimated abundance of 524 humpbacks. This suggests that humpbacks are still present in this area until at least the middle of December.

Marine mammal abundance surveys are vital for determining high density areas and detecting changes in populations. Seasonal estimates provide more detailed look at when and how long these animals are spending in a particular area during a given time of the year. For example, off the Coast of Virginia, it has been discovered that North

Atlantic Right Whales (*Eubalaena glacialis*) occupy this area between November 1st –

April 30th (Mallette *et al*., 2018). This led to the implementation of a seasonal

management area, where vessels that are larger than 65 ft are required to reduce their

vessel speed to less than 10 kts while traveling through the area to reduce likelihood of

injury to these animals (Mallette *et al*., 2018).

Along the Pacific Coast of the United States, fatal collisions with vessels and

entanglement with trap and pot line fishing gear is the most common source of injury

(Carretta *et al*., 2016). Current entanglement reduction efforts are focusing mainly on

fishing line modifications that ether reduce the amount of time a line is in the water

column (galvanic time released devices, acoustic buoy releases) or altering composition

of the line so that it breaks easier when a whale does become entangled (changing line

color, changing line material/strength, adding weak links, timed tension-line cutters)

(Lebon & Kelly, 2019). The biggest hurdle here is identifying ways to reduce

entanglement while avoiding unnecessary repercussions to the fishing community.

Continuing research efforts should focus on identifying effective methods of reducing

entanglements that will not negatively impact fishermen's livelihoods from financial

constraints. To reduce the risk fatal vessel collisions, studies suggest reducing vessel

speed or location restrictions to be the most effective methods to implement is areas of

high overlap between vessels and whales (Calambokidis *et al*., 2019; Lammers *et al*.,

2013; Wiley *et al*., 2011). No major action has been taken to implement any of the

suggested measures recommended to reduce fatal vessel collisions on the West Coast of

the US. Efforts should still be made to understand an animal's seasonal use of a particular

geographic region to encourage and aid in development of the most effective

conservation management strategies as well as providing valuable information on movement patterns, habitat use, and population demographics.

Inconsistencies in the survey coverage led to small sample size with large coefficient of variations, thus results should be interpreted as conservative and limit the amount of regional and seasonal comparisons that can be made. The results do provide general insight in the probable seasonal and yearly abundance and density trends. Surveys only happened in Oregon for three seasons, and only one season had any sightings, thus severely limiting any conclusions that can be made about yearly or seasonal abundance and density estimates in this area.

5.2 Conclusion

Accurate abundance estimates are vital for understanding where mitigation efforts will be most effective for reducing anthropogenic threats such as cetacean-vessels collisions and entanglement in derelict fishing gear. The abundance and density estimates calculated in this thesis helps contribute to general understanding of humpback whale seasonal variations within this study area. These estimates can aid future comparisons in identifying changes in seasonal and yearly trends in distribution. While this study had its limitations due to small sample size, I was able to generate conservative seasonal abundance and density estimates of humpback whales off the coast of Washington and Northern/Central Oregon between 2011-2012. Future studies should continue conducting seasonal surveys along the US West Coast to obtain more sighting data, thus leading to more robust estimates to determine seasonal use of this geographic region.

Literature Cited

16 U.S.C. 1531 *et seq.* Policy Regarding the Recognition of Distinct Vertebrate
Population Segments Under the Endangered Species Act. (February 7, 1996).

50 CFR 224 Endangered and Threatened Species; Identification of 14 Distinct Population
Segments of the Humpback Whale *(Megaptera novaeangliae)* and Revision of
Species-Wide Listing. (October 11, 2016).

Au, S. Y., Lee, C. M., Weinstein, J. E., van den Hurk, P., & Klaine, S. J. (2017). Trophic
transfer of microplastics in aquatic ecosystems: identifying critical research needs.
Integrated Environmental Assessment and Management, 13(3), 505-509.

Bajpai, S, J.M. Thewissen, and A. Sahni. 2009. The Origin and Early Evolution of
Whales: Macroevolution Documented On The Indian Subcontinent. *Journal of
Biological Science, 34* 673–686.

Baker, C. S., Palumbi, S. R., Lambertsen, R. H., Weinrich, M. T., Calambokidis, J., &
O'Brien, S. J. (1990). Influence of seasonal migration on geographic distribution
of mitochondrial DNA haplotypes in humpback whales. *Nature, 344*(6263), 238.

Baker, C. S., D. Steel, J. Calambokidis, J. Barlow, A. M. Burdin, P. J. Clapham, E.
Falcone, J. K.B. Ford, C. M. Gabriele, U. Gozález-Peral, R. LeDuc, D. Mattila, T.
J. Quinn, L. Rojas-Bracho, J. M. Straley, B. L. Taylor, U. R. J., M. Vant, P. R.

Wade, D. Weller, B. H.Witteveen, K. Wynne, and M. Yamaguchi. (2008a). geneSPLASH: An initial, ocean-wide survey of mitochondrial (mt) DNA diversity and population structure among humpback whales in the North Pacific. Final report for Contract 2006-0093-008 to the National Fish and Wildlife Foundation.

Baker, C. S., Steel, D., Calambokidis, J., Falcone, E., González-Peral, U., Barlow, J., ... & Mattila, D. (2013). Strong maternal fidelity and natal philopatry shape genetic structure in North Pacific humpback whales. *Marine Ecology Progress Series*, *494*, 291-306.

Barlow, J. (1997). Preliminary estimates of cetacean abundance off California, Oregon and Washington based on a 1996 ship survey and comparisons of passing and closing modes. Administrative Report LJ-97-11, Southwest Fisheries Science Center, National Marine Fisheries Service, P.O. Box 271, La Jolla, CA 92038. 25pp.

Barlow, J., & Taylor, B. L. (2005). Estimates of sperm whale abundance in the northeastern temperate Pacific from a combined acoustic and visual survey. *Marine Mammal Science, 21(3),* 429-445.

Barlow, J., & Forney, K. A. (2007). Abundance and population density of cetaceans in the California Current ecosystem. *Fishery Bulletin, 105(4),* 509-526.

Barlow, J. (2010). Cetacean abundance in the California Current estimated from a 2008

   ship-based line-transect survey. NOAA Technical Memorandum NOAA-TM-

   NMFS-SWFSC-456. 19pp.

Barlow, J., Calambokidis, J., Falcone, E. A., Baker, C. S., Burdin, A. M., Clapham, P. J.,

   ... & , T. J. (2011). Humpback whale abundance in the North Pacific estimated by

   photographic capture-recapture with bias correction from simulation

   studies. *Marine Mammal Science*, *27(4),* 793-818.

Basta, D. J. (2011). Olympic Coast National Marine Sanctuary final management plan

   and environmental assessment. U.S. Department of Commerce, National Oceanic

   and Atmospheric Administration, Office of National Marine Sanctuaries, Port

   Angeles, WA. https://repository.library.noaa.gov/view/noaa/4153.

Bebej RM. 2011 Functional morphology of the vertebral column in Remingtonocetus

   (Mammalia, Cetacea) and the evolution of aquatic locomotion in early

   archaeocetes. PhD dissertation, The University of Michigan, Ann Arbor, MI,

   USA.

Besseling, E., Foekema, E. M., Van Franeker, J. A., Leopold, M. F., Kühn, S., Rebolledo,

   E. B., ... & Koelmans, A. A. (2015). Microplastic in a macro filter feeder:

humpback whale Megaptera novaeangliae. *Marine Pollution Bulletin*, *95(1),* 248-252. Doi:http://dx.doi.org/10.1016/j.marpolbul.2015.04.007

Best, B., Fox, C., Williams, R., Halpin, P., & Paquet, P. (2015). Updated marine mammal distribution and abundance estimates in British Columbia. *J Cetacean Res Manage*, *15*, 9-26.

Bettridge, S., Baker, C., Barlow, J., Clapham, M., Gouveia, D., Mattila, D., Pace, R., Rosel, P., Silber, G., Wade, P., (2015). Status Review of the Humpback Whale (*Megaptera novaeangliae)* Under the Endangered Species Act. NOAA Technical Memorandum NMFS. U.S. Department of Commerce.

Bowen, W. D. (1997). Role of marine mammals in aquatic ecosystems. *Marine Ecology Progress Series,* 267-274.

Bradford, A. L., Forney, K. A., Oleson, E. M., & Barlow, J. (2017). Abundance estimates of cetaceans from a line-transect survey within the US Hawaiian Islands Exclusive Economic Zone. *Fishery Bulletin*, *115(2),* 129-142.

BST Associates. (2017). Washington State Marine Cargo Forecast Draft Report. Olympia: Washington Public Ports Association.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and
Thomas, L. (editors) 2004. Advanced Distance Sampling. Oxford University
Press, London.

Burkhardt-Holm, P., & N'Guyen, A. (2019). Ingestion of microplastics by fish and other
prey organisms of cetaceans, exemplified for two large baleen whale species.
Marine Pollution Bulletin, 144, 224-234.

Calambokidis, J., G. H. Steiger, K Rasmussen, J. Urban, K. C. Balcomb, P. Ladron, de
Guevara P., M. Salinas Z., J. K. Jacobsen, C. S. Baker, L. M. Herman, S. Cerchio
and J. D, Darling. (2000). Migratory destination of humpback whales that feed off
California, Oregon and Washington. *Marine Ecology Progress Series, 192*, 295-
304

Calambokidis, J., G.H Steiger, J.M Straley, L.M. Herman, S. Cerchio, D.R. Salden, J.
Urbán R., J.K. Jacobsen, O. von Ziegesar, K.C. Balcomb, C.M. Gabriele, M.E.
Dahlheim, S. Uchida, G. Ellis, Y. Miyamura, P. Ladrón de Guevara P., M.
Yamaguchi, F. Sato, S.A. Mizroch, L. Schlender, K. Rasmussen, J. Barlow and
T.J. Quinn II. (2001). Movements and population structure of humpback whales
in the North Pacific. *Marine Mammal Science 17,* 769-794.

Calambokidis, J., Steiger, G. H., Ellifrit, D. K., Troutman, B. L., & Bowlby, C. E. (2004).
Distribution and abundance of humpback whales (*Megaptera novaeangliae*) and

other marine mammals off the northern Washington coast. *Fishery Bulletin,*
102(4), 563-580.

Calambokidis, J., & Barlow, J. (2004). Abundance of blue and humpback whales in the
eastern North Pacific estimated by capture-recapture and line-transect methods.
Marine Mammal Science, 20(1), 63-85.

Calambokidis J., Falcone E.A., Quinn T.J., Burdin A.M., Clapham P.J., Ford J.K.B.,
Gabriele C.M., LeDuc R., Mattila D., Rojas-Bracho L., Straley J.M., Taylor B.L.,
Urba´n R.J., Weller D., Witteveen B.D., Yamaguchi M., Bendlin A., Camacho D.,
Flynn K., Havron A., Huggins J., Maloney N., Barlow J., Wade P.R. (2008).
SPLASH: structure of populations, levels of abundance and status of humpback
whales in the north pacific. Final report for Contract AB133F-03-RP-00078
prepared by Cascadia Research for U.S. Dept of Commerce.

Calambokidis, J., Steiger, G. H., Curtice, C., Harrison, J., Ferguson, M. C., Becker, E., ...
& Van Parijs, S. M. (2015). 4. Biologically important areas for selected cetaceans
within US waters-west coast region. *Aquatic Mammals*, *41(1),* 39.

Calambokidis, J., Flynn, K, Dobson, E., Huggins, J. L., and Perez, A. (2018). Return of
the Giants of the Salish Sea: Increased occurrence of humpback and gray whales
in inland waters. Salish Sea Ecosystem Conference. 593.
https://cedar.wwu.edu/ssec/2018ssec/allsessions/593

Calambokidis, J., Fahlbusch, J. A., Szesciorka, A. R., Southall, B. L., Cade, D. E., Friedlaender, A. S., & Goldbogen, J. A. (2019). Differential vulnerability to ship strikes between day and night for blue, fin, and humpback whales based on dive and movement data from medium duration archival tags. *Frontiers in Marine Science*, *6,* 543.

Carretta, J. V., Forney, K. A., Lowry, M. S., Barlow, J., Baker, J., Johnston, D., ... & Ralls, K. (2017). US Pacific marine mammal stock assessments: 2016. U.S. Department of Commerce, NOAA Technical Memorandum. NOAA-TM-NMFS-SWFSC-577. doi:10.7289/V5/TM-SWFSC-577

Carretta, J. V., Forney, K. A., Oleson, E. M., Weller, D. W., Lang, A. R., Baker, J., Muto, M. M., Hanson, B., Orr, A. J., Huber, H., Lowry, M. S., Barlow, J., Moore, J. E., Lynch, D., Carswell, L., and Robert L. Brownell Jr. (2019). U.S. Pacific Marine Mammal Stock Assessments: 2018. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-617.

Carrillo, M., & Ritter, F. (2010). Increasing numbers of ship strikes in the Canary Islands: proposals for immediate action to reduce risk of vessel-whale collisions. *Journal of Cetacean Research and Management, 11(2),* 131-138.

Cassoff, R. M., Moore, K. M., McLellan, W. A., Barco, S. G., Rotstein, D. S., & Moore, M. J. (2011). Lethal entanglement in baleen whales. *Diseases of Aquatic Organisms, 96(3),* 175-185.

Cerchio, S., Trudelle, L., Zerbini, A. N., Charrassin, J. B., Geyer, Y., Mayer, F. X., ... & Rosenbaum, H. C. (2016). Satellite telemetry of humpback whales off Madagascar reveals insights on breeding behavior and long-range movements within the southwest Indian Ocean. *Marine Ecology Progress Series, 562,* 193-209.

Clapham, P. J. (2018). Humpback whale: *Megaptera novaeangliae*. In Encyclopedia of marine mammals (pp. 489-492). Academic Press.

Clementz, M.T., Anjali Goswami, P.D. Gingerich, and P.L Koch. (2006). Isotopic Records from Early Whales and Sea Cows: Contrasting Patterns of Ecological Transition. *Journal of Vertebrate Paleontology, 26*, 355-370

Cooper, Lisa Noelle, J.M. Thewissen, S. Bajpai, and B.N. Tiwari. (2012). Postcranial Morphology And Locomotion Of The Eocene Raoellid Indohyus (Artiodactyla: Mammalia). *Historical Biology*, *24*, 279-310

Council of the European Commission. (1992). Council Directive 92/43/EEC of 21 May

    1992 on the conservation of natural habitats and of wild fauna and flora. *Official*

    Journal of the European Communities, 206(7), 1-9.

Craens, A. (2012). Facts. *Garbage Patch – The Great Pacific Garbage Patch and Other*

    Pollution Issues.

Croll DA, Clark CW, Calambokidis J, Ellison WT, Tershy BR. (2001). Effect of

    anthropogenic low-frequency noise on the foraging ecology of *Balaenoptera*

    whales. *Anim. Conserv. 4,* 13–27. doi:10.1017/S1367943001001020

Currie, J.J., Stack, S.H., Easterly, S.K., Kaufman, G.D., & Martinez, E. (2015). Modeling

    whale-vessel encounters: the role of speed in mitigating collisions with humpback

    whales (*Megaptera novaeangliae*). International Whaling Commission Scientific

    Committee. Report Number: SC/66a/HIM/3.

Currie, J. J., Stack, S. H., Easterly, S. K., Kaufman, G. D., & Martinez, E. (2017).

    Modeling whale-vessel encounters: the role of speed in mitigating collisions with

    humpback whales (*Megaptera novaeangliae*). *Journal of Cetacean Research and*

    Management, 17, 57-63.

Davis, G. E., Baumgartner, M. F., Bonnell, J. M., Bell, J., Berchok, C., Thornton, J. B., ...

    & Clark, C. W. (2017). Long-term passive acoustic recordings track the changing

distribution of North Atlantic right whales (*Eubalaena glacialis*) from 2004 to 2014. *Scientific reports, 7(1),* 13460.

Dolman, S., Williams-Grey, V., Asmutis-Silvia, R., & Isaac, S. (2006). Vessel collisions and cetaceans: what happens when they don't miss the boat. A WDCS Science Report. 25pp.

Dolman S.J., Moore M.J. (2017) Welfare Implications of Cetacean Bycatch and Entanglements. In: Butterworth A. (eds) Marine Mammal Welfare. Animal Welfare, vol 17. Springer, Cham. https://doi.org/10.1007/978-3-319-46994-2_4

Dunlop RA. (2016). The effect of vessel noise on humpback whale, Megaptera novaeangliae, communication behaviour. *Anim. Behav. 111*, 13–21. doi:10.1016/j.anbehav.2015.10.002

Egbeocha, C. O., Malek, S., Emenike, C. U., & Milow, P. (2018). Feasting on microplastics: ingestion by and effects on marine organisms. *Aquatic Biology, 27*, 93-106.

Falcone E., Calambokidis, J., Steiger, G.H., Malleson, M. and Ford, J. (2005). Humpback whales in the Puget Sound/Georgia Strait Region. Proceedings of the 2005 Puget Sound Georgia Basin Research Conference, 4 pp.

Feist, B., Bellman, M. A., Becker, E. A., Forney, K. A., Ford, M. J., & Levin, P. S. (2015). Potential overlap between cetaceans and commercial groundfish fleets that operate in the California Current Large Marine Ecosystem. NOAA Professional Paper NMFS 17, 27 p. doi:10.7755/PP.17

Fleming, A., & J. Jackson. (2011). Global Review of Humpback Whales (*Megaptera novaeangliae*). NOAA Technical Memorandum NMFS-SWFSC-474.

Ford, J. K., Ellis, G. M., Barrett-Lennard, L. G., Morton, A. B., Palm, R. S., & Balcomb III, K. C. (1998). Dietary specialization in two sympatric populations of killer whales (*Orcinus orca*) in coastal British Columbia and adjacent waters. *Canadian Journal of Zoology, 76(8),* 1456-1471.

Fordyce, R.E. (2003). Cetacean Evolution And Eocene-Oligocene Oceans Revisited. From greenhouse to icehouse : the marine Eocene-Oligocene transition. edited by Donald R. Prothero, Linda C. Ivany, and Elizabeth A. Nesbitt. New York : Columbia University Press, 154-170.

Fordyce, R. E., and L.G. Barnes. (1994). The Evolutionary History Of Whales And Dolphins. *Annual Review Of Earth And Planetary Sciences*, *22*, 419-455.

Forney, K. A., & Barlow, J. (1998). Seasonal patterns in the abundance and distribution of California cetaceans, 1991–1992. *Marine Mammal Science, 14(3),* 460-489

Forney, K. A., Ferguson, M. C., Becker, E. A., Fiedler, P. C., Redfern, J. V., Barlow, J., ... & Ballance, L. T. (2012). Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. *Endangered Species Research*, *16*(2), 113-133.

Forney, K. A., Becker, E. A., Foley, D. G., Barlow, J., & Oleson, E. M. (2015). Habitat-based models of cetacean density and distribution in the central North Pacific. *Endangered Species Research, 27(1),* 1-20.

Fossi, M. C., Marsili, L., Baini, M., Giannetti, M., Coppola, D., Guerranti, C., ... & Rubegni, F. (2016). Fin whales and microplastics: The Mediterranean Sea and the Sea of Cortez scenarios. *Environmental Pollution*, *209*, 68-78.

Gabriele, C. M., Neilson, J. L., Straley, J. M., Baker, C. S., Cedarleaf, J. A., & Saracco, J. F. (2017). Natural history, population dynamics, and habitat use of humpback whales over 30 years on an Alaska feeding ground. *Ecosphere, 8(1)*.

Galgani, F., Hanke, G., Maes, T. (2015). Global Distribution, Composition and Abundance of Marine Litter. Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter, Springer International Publishing, pp. 29-56.

Galloway, T.S., Lewis, C.N. (2016). Marine microplastics spell big problems for future generations. *Proc. Natl. Acad. Sci. 113*, 2331–2333.

Gatesy, John, J. H. Geisler, Joseph Chang, Carl Buell, Annalisa Berta, R.W. Meredith, M.S. Springer, and M.R. McGowen. (2012). A phylogenetic blueprint for a modern whale. *Molecular Phylogenetics and Evolution*, 66.

Gingerich, P.D., M. ul Haq, I.S. Zalmout, I.H. Khan, and M.S. Malkani. (2001). Origin of Whales From Early Artiodactyls: Hands And Feet Of Eocene Protocetidae From Pakistan. *Science*, *293*, 2239-2242.

Grunwald, C., Maceda, L., Waldman, J., Stabile, J., & Wirgin, I. (2008). Conservation of Atlantic sturgeon *Acipenser oxyrinchus oxyrinchus*: delineation of stock structure and distinct population segments. *Conservation Genetics*, *9(5),* 1111.

Hammond, P. S., Macleod, K., Berggren, P., Borchers, D. L., Burt, L., Cañadas, A., ... & Gordon, J. (2013). Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation, 164,* 107-122.

Herrera Environmental Consultants, Inc. (2012). Puget Sound No Discharge Zone For Vessel Sewage: Puget Sound Vessel Population and Pumpout Facilities. WA Department of Ecology. Publication No. 12-10-031 Part 3.

Herrera Environmental Consultants, Inc. (2013). Phase 2 Vessel Population And

      Pumpout Facility Estimates: Puget Sound No Discharge Zone For Vessel Sewage.

      WA Department of Ecology. Publication No. 12-10-031 Part 4.

IUCN Standards and Petitions Committee. (2019). Guidelines for Using the IUCN Red

      List Categories and Criteria. Version 14. Prepared by the Standards and Petitions

      Committee. Downloadable from

      http://www.iucnredlist.org/documents/RedListGuidelines.pdf.

Isojunno S, Curé C, Kvadsheim PH, Lam FPA, Tyack PL, Wensveen PJ, Miller PJOM.

      (2016). Sperm whales reduce foraging effort during exposure to 1–2 kHz sonar

      and killer whale sounds. *Ecol. Appl. 26,* 77–93. doi:10.1890/15-0040.

IWC. 1994. The Revised Management Procedure (RMP) for baleen whales. Report of the

      International Whaling Commission, 44, 145–152.

Ivashchenko, Y., Clapham, P. and Brownell, R.L., Jr., (2011). Soviet illegal whaling: The

      devil and the details. *Mar. Fish. Rev. 73(3),* 1–19.

Ivashchenko, Y. V., Zerbini, A.N, & Clapham, P.J. (2015). Assessing the status and pre-

      exploitation abundance of North Pacific humpback whales. Paper SC/66a/IA/16

      Submitted to the Scientific Committee of the International Whaling Commission,

      May 2016, San Diego, California, USA.

James V. Carretta, Karin. A. Forney, Erin M. Oleson, David W. Weller, Aimee R. Lang,
Jason Baker, Marcia M. Muto, Brad Hanson, Anthony J. Orr, Harriet Huber,
Mark S. Lowry, Jay Barlow, Jeffrey E. Moore, Deanna Lynch, Lilian Carswell,
and Robert L. Brownell Jr. (2019). U.S. Pacific Marine Mammal Stock
Assessments: 2018. U.S. Department of Commerce, NOAA Technical
Memorandum NMFS-SWFSC-617.

Jensen, C. M., Hines, E., Holzman, B. A., Moore, T. J., Jahncke, J., & Redfern, J. V.
(2015). Spatial and Temporal Variability in Shipping Traffic Off San Francisco,
California. *Coastal Management*, *43(6),* 575-588.

Kamp, J., Oppel, S., Heldbjerg, H., Nyegaard, T., & Donald, P. F. (2016). Unstructured
citizen science data fail to detect long-term population declines of common birds
in Denmark. *Diversity and Distributions*, *22(10)*, 1024-1035.

Kennedy, A. S., Zerbini, A. N., Vásquez, O. V., Gandilhon, N., Clapham, P. J., & Adam,
O. (2013). Local and migratory movements of humpback whales (*Megaptera
novaeangliae*) satellite-tracked in the North Atlantic Ocean. *Canadian Journal of
Zoology, 92(1),* 9-18.

Knowlton, A. R., & Kraus, S. D. (2001). Mortality and serious injury of northern right

   whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. *Journal of*

   Cetacean Research and Management (special issue), 2, 193-208.

Kot B.W., Ramp C., & Sears R. (2009). Decreased feeding ability of a minke whale

   (*Balaenoptera acutorostrata*) with entanglement-like injuries. *Marine Mammal*

   Science 25, 706−713.

Laist, D. W., A. R. Knowlton, J. G. Mead, A. S. Collet, & Pod, M. (2001). Collisions

   between ships and whales. *Marine Mammal Science, 17*, 35–75.

Lammers, M. O., Pack, A. A., Lyman, E. G., & Espiritu, L. (2013). Trends in collisions

   between vessels and North Pacific humpback whales (*Megaptera novaeangliae*)

   in Hawaiian waters (1975–2011). *Journal of Cetacean Research and*

   Management, 13(1), 73-80.

Lawrence, J. (2017, August 9). Two injured after whale-watching vessel strikes

   humpback near Victoria. CTV News . Retrieved from

   http://vancouverisland.ctvnews.ca/two-injured-after-whale-watching-vessel-

   strikes-humpback-near-victoria-1.3537747.

Lebon, K. M., & Kelly, R. P. (2019). Evaluating alternatives to reduce whale

    entanglements in commercial Dungeness Crab fishing gear. *Global Ecology and*

    Conservation, *18*, e00608.

Lewis, M. (2017, April 26). Whale in vessel collision on 23 April 2017 identified.

    Retrieved from Cascadia Research Collective Website:

    http://www.cascadiaresearch.org/north-puget-sound-gray-whale-study/whale-

    vessel-collision.

Lonergan, M. (2011). Potential biological removal and other currently used management

    rules for marine mammal populations: A comparison. *Marine Policy, 35(5),* 584-

    589.

Luo, Z. (2000). In search of the whales' sisters. *Nature, 404*, 235–237.

Madar, S.I., J.M. Thewissen, and S.T. Hussain. (2002). Additional Holotype Remains of

    Ambulocetus natans (Cetacea, Ambulocetidae), and Their Implications for

    Locomotion in Early Whales. *Journal of Vertebrate Paleontology, 22*, 405-422.

Marques, T. (2009). Distance sampling: estimating animal density. *Significance, 6*, 136 –

    137.

McKenna, M.F., T.D. Cranford, A. Berta, and N.D. Pyenson. (2012). Morphology fo the

odontocete melon and its implications for acoustic functions. *Marine Mammal*

Science, 28(4), 690-713.

Miller PJO, Johnson MP, Madsen PT, Biassoni N, Quero M, Tyack PL. (2009). Using at-

sea experiments to study the effects of airguns on the foraging behavior of sperm

whales in the Gulf of Mexico. *Deep. Res. Part I Oceanogr. Res. Pap. 56*, 1168–

1181. doi:10.1016/j.dsr.2009.02.008

Moore, M. J., & Hoop, J. M. van der. (2012). The Painful Side of Trap and Fixed Net

Fisheries: Chronic Entanglement of Large Whales. *Journal of Marine Sciences,*

vol. 2012, Article ID 230653, 4 pages, https://doi.org/10.1155/2012/230653

Moore, J. E., & Barlow, J. (2017). Population abundance and trend estimates for beaked

whales and sperm whales in the California Current from ship-based visual line-

transect survey data, 1991-2014. NOAA Technical Memorandum NOAA-TM-

NMFS-SWFSC-585. 16pp. http://doi.org/10.7289/V5/TM-SWFSC-585.

Moors-Murphy, H. B. (2014). Submarine canyons as important habitat for cetaceans,

with special reference to the Gully: A review. *Deep Sea Research Part II: Topical*

Studies in Oceanography, 104, 6-19.

Neilson, J. L., Gabriele, C. M., Jensen, A. S., Jackson, K., & Straley, J. M. (2012).

Summary of reported whale-vessel collisions in Alaskan waters. *Journal of*

Marine Biology, *2012*. http://dx.doi.org/10.1155/2012/106282.

Nichol, L.M., Wright, B.M., Hara, P.O., & Ford, J.K. (2017). Risk of lethal vessel strikes

to humpback and fin whales off the west coast of Vancouver Island, Canada.

Endangered Species Research, 32, 373-390.

NOAA. (2015). Humpback Whale (*Megaptera Novaeangliae*). NOAA Fisheries, 15 Jan.

2015, www.nmfs.noaa.gov/pr/species/mammals/whales/humpback-whale.html.

NOAA. (2018). Potential Biological Removal (PBR). Retrieved July 18, 2019, from

https://www.nefsc.noaa.gov/psb/assessment/pbr.html

Northwest Seaport Alliance. (18 Sept 2019). Total YTD Container Volumes up Nearly 6

Percent through August." The Northwest Seaport Alliance, Date accessed: Sept

27, 2019. URL: www.nwseaportalliance.com/stats-stories/cargo-

stats/9182019/total-ytd-container-volumes-nearly-6-percent-through-august.

Nowacek, D. P., Thorne, L. H., Johnston, D. W., & Tyack, P. L. (2007). Responses of

cetaceans to anthropogenic noise. *Mammal Review, 37(2),* 81-115.

NMFS (National Marine Fisheries Service). 2005. Revisions to guidelines for assessing

    marine mammal stocks. 24p.

O'Connor, S., Campbell, R., Cortez, H., Knowles, T. (2009). Whale watching worldwide:

    tourism numbers, expenditures and expanding economic benefits, a special report

    from the International Fund for Animal Welfare. International Fund for Animal

    Welfare, Yarmouth, pp. 295.

Owen, K., Warren, J. D., Noad, M. J., Donnelly, D., Goldizen, A. W., & Dunlop, R. A.

    (2015). Effect of prey type on the fine-scale feeding behaviour of migrating east

    Australian humpback whales. *Marine Ecology Progress Series, 541*, 231-244.

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., & Weinrich, M. T.

    (2006). Mediterranean fin whales at risk from fatal ship strikes. *Marine Pollution

    Bulletin, 52(10),* 1287-1298.

Redfern, J. V., McKenna, M. F., Moore, T. J., Calambokidis, J., Deangelis, M. L.,

    Becker, E. A., ... & Chivers, S. J. (2013). Assessing the risk of ships striking large

    whales in marine spatial planning. *Conservation Biology, 27(2),* 292-302.

Reilly, S.B., Bannister, J.L., Best, P.B., Brown, M., Brownell Jr., R.L., Butterworth, D.S.,

    Clapham, P.J., Cooke, J., Donovan, G.P., Urbán, J. & Zerbini, A.N.

    2008. *Megaptera novaeangliae*. The IUCN Red List of Threatened Species 2008:

e.T13006A3405371. http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T13006A34 05371.en.

Renker, A. M. (2005). The Makah Tribe: People of the Sea and the Forest. *University of Washington Libraries Digital Collections*. http://content.lib.washington.edu/aipnw/renker.

Risch, D., Castellote, M., Clark, C. W., Davis, G. E., Dugan, P. J., Hodge, L. E., ... & Popescu, C. M. (2014). Seasonal migrations of North Atlantic minke whales: novel insights from large-scale passive acoustic monitoring networks. *Movement Ecology, 2(1)*, 24.

Roberts, J. J., Best, B. D., Mannocci, L., Fujioka, E., Halpin, P. N., Palka, D. L., ... & McLellan, W. A. (2016). Habitat-based cetacean density models for the US Atlantic and Gulf of Mexico. *Scientific Reports*, *6*, 22615.

Rockwood, R. C., Calambokidis, J., & Jahncke, J. (2017). High mortality of blue, humpback and fin whales from modeling of vessel collisions on the US West Coast suggests population impacts and insufficient protection. *PloS ONE, 12(8), e0183052.*

Rolland RM, Parks SE, Hunt KE, Castellote M, Corkeron PJ, Nowacek DP, Wasser SK, Kraus SD. (2012). Evidence that ship noise increases stress in right whales. *Proc. R. Soc. B 279,* 2363–2368. doi:10.1098/rspb.2011.2429

Rone, B. K., Zerbini, A. N., Douglas, A. B., Weller, D. W., & Clapham, P. J. (2017). Abundance and distribution of cetaceans in the Gulf of Alaska. *Marine Biology*, *164(1),* 23.

Rosel, P. E., Hancock-hanser, B. L., Archer, F. I., Robertson, K. M., Martien, K. K., Leslie, M. S., ... & Taylor, B. L. (2017b). Examining metrics and magnitudes of molecular genetic differentiation used to delimit cetacean subspecies based on mitochondrial DNA control region sequences. *Marine Mammal Science*, 33*(S1),* 76-100.

Rosel, P. E., Hancock-hanser, B. L., Archer, F. I., Robertson, K. M., Martien, K. K., Leslie, M. S., ... & Taylor, B. L. (2017b). Examining metrics and magnitudes of molecular genetic differentiation used to delimit cetacean subspecies based on mitochondrial DNA control region sequences. *Marine Mammal Science, 33(S1),* 76-100.

Silber, G.K., Slutsky, J., & Bettridge, S. (2010). Hydrodynamics of a ship/whale collision. *Journal of Experimental Marine Biology and Ecology, 391(1)*, 10-19.

Sivle, L. D., Kvadsheim, P. H., Curé, C., Isojunno, S., Wensveen, P. J., Lam, F. P. A., ...
& Miller, P. J. (2015). Severity of Expert-Identified Behavioural Responses of
Humpback Whale, Minke Whale, and Northern Bottlenose Whale to Naval Sonar.
Aquatic Mammals, 41(4).

Stanistreet, J. E., Risch, D., & Van Parijs, S. M. (2013). Passive acoustic tracking of
singing humpback whales (*Megaptera novaeangliae*) on a Northwest Atlantic
feeding ground. *PLoS ONE*, *8(4),* e61263.

Stevick, P., Aguayo-Lobo, A., Allen, J., Ávila, I. C., Capella, J., Castro, C., ... & Flórez-
González, L. (2004). A note on the migrations of individually identified
humpback whales between the Antarctic Peninsula and South America. *J
Cetacean Res Manage 6,* 109–113.

TCW Economics. 2008. Economic analysis of the non-treaty commercial and recreational
fisheries in Washington State. Sacramento, CA: TCW Economics.

Teerlink, S. F., von Ziegesar, O., Straley, J. M., Quinn, T. J., Matkin, C. O., & Saulitis, E.
L. (2015). First time series of estimated humpback whale (*Megaptera
novaeangliae*) abundance in Prince William Sound. *Environmental and
Ecological Statistics*, *22(2),* 345-368.

Teilmann, J. (2003). Influence of sea state on density estimates of harbour porpoises (*Phocoena phocoena*). *Journal of Cetacean Research and Management*, *5(1),* 85-92.

Thewissen, J.G.M., L.N. Cooper, J.C. George, and S. Bajpai. (2009). From land to water: The origin of whales, dolphins, and porpoises. *Evolution: Education & Outreach, 2,* 272-288

Thomas, L., Buckland, S. T., Burnham, K. P., Anderson, D. R., Laake, J. L., Borchers, D. L. & Strindberg, S., 2002. Distance sampling. *Encyclopedia of Environmetrics 1*, 544-552. ISBN 0471 899976.

Thomas, L., S.T. Buckland, E.A. Rexstad, J. L. Laake, S. Strindberg, S. L. Hedley, J. R.B. Bishop, T. A. Marques, and K. P. Burnham. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology 47*, 5-14. DOI: 10.1111/j.1365-2664.2009.01737.x

Todd S, Stevick P, Lien J, Marques F, Ketten D. (1996). Behavioural effects of exposure to underwater explosions in humpback whales (*Megaptera novaeangliae*). *Canadian Journal of Zoology, 74,* 1661–1672.

Uhen, M. (2007). Evolution of Marine Mammals: Back to the Sea After 300 Million Years. *The Anatomical Record, 290,* 514-5

Wade, P. R. (1998). Calculating limits to the allowable human-caused mortality of
  cetaceans and pinnipeds. *Marine Mammal Science, 14(1),* 1-37.

Wedekin, L. L., Engel, M. H., Andriolo, A., Prado, P. I., Zerbini, A. N., Marcondes, M.
  M. C., ... & Simões-Lopes, P. C. (2017). Running fast in the slow lane: rapid
  population growth of humpback whales after exploitation. *Marine Ecology
  Progress Series*, *575*, 195-206.

Weitkamp, L. A., Wissmar, R. C., Simenstad, C. A., Fresh, K. L., & Odell, J. G. (1992).
  Gray whale foraging on ghost shrimp (*Callianassa californiensis*) in littoral sand
  flats of Puget Sound, USA. *Canadian Journal of Zoology, 70(11),* 2275-2280.

Wiley, D.N., Thompson, M., Pace, R.M., & Levenson, J. (2011). Modeling speed
  restrictions to mitigate lethal collisions between ships and whales in the
  Stellwagen Bank National Marine Sanctuary, USA. *Biological Conservation,
  144(9),* 2377-2381.

Williams R, Lusseau D, Hammond PS. (2006). Estimating relative energetic costs of
  human disturbance to killer whales (*Orcinus orca*). *Biological Conservation, 133*,
  301–311. doi:10.1016/j.biocon.2006.06.010.

Williams R., O'Hara, P. (2010). Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. *Journal Cetacean Research Management, 11,* 1-8.

Williams, S.H., Gende, S.M., Lukacs, P.M., Webb, K. (2016). Factors affecting whale detection from large ships in Alaska with implications for whale avoidance. *Endangered Species Research, 30*, 209-223.

Zerbini, A. N., Waite, J. M., Durban, J. W., LeDuc, R., Dahlheim, M. E., & Wade, P. R. (2007). Estimating abundance of killer whales in the nearshore waters of the Gulf of Alaska and Aleutian Islands using line-transect sampling. *Marine Biology, 150(5),* 1033-1045.