Relating the Distribution of Humpback Whales to Environmental Variables and Risk Exposure

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Abstract

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Humpback whales (*Megaptera novaeangliae*) have been increasing in abundance globally since they faced near-extinction in the 1900s. As the species recovers, it is returning to areas it historically occupied. The Salish Sea in Washington state and British Columbia is an area where humpback whale sightings are increasing and is an important summer feeding ground. Here, I examined the dramatic increase in sightings in the Salish Sea since 1989. To better understand where the whales are going and why, I related whale sightings to chlorophyll-a (a proxy for primary productivity) and bathymetry. To understand the potential interactions with vessels, I analyzed the overlap of sightings with ship traffic and ferry routes in the region. Whale sightings were associated with increased chlorophyll-a in coastal waters and in Puget Sound during portions of the year and with depths generally shallower than the bathymetric averages. Humpback whales appeared to be using habitats with substantial traffic in commercial vessels and car ferries, suggesting an increasing risk of ship strikes as humpback numbers rebound. Sightings data indicate that the humpback whale critical habitat proposed by the National Marine Fisheries Service (NMFS) in 2019 appears to cover the area of highest use by the whales. While

this study indicates associations, there may be a sighting bias caused by the opportunistic public sightings in areas closer to developed population hubs.

Introduction

Humpback whales (*Megaptera novaeangliae*) are found throughout the oceans of the world. They historically were abundant, with a worldwide population estimate of approximately 125,000 individuals (National Marine Fisheries Service, 1991), and were known to occur in the Salish Sea. During the 1800s and 1900s, humpback whales, along with other cetacean species, were heavily hunted by the whaling industry, with the result that their populations were sharply reduced.

The pre-exploitation (before 1905) population of humpback whales in the North Pacific was around 15,000 whales (Rice, 1978), which was reduced to 1,200-1,400 by 1966 (Gambell 1976; Johnson and Wolman 1984). The Pacific Whaling Company was founded in 1905 with two stations operating from Vancouver Island. A third whaling station, located at Page's Lagoon in the Strait of Georgia near Nanaimo, operated from 1907-1909 and specialized in taking humpback whales. The protected nature of this station allowed whaling to occur during the winter in the inland waters while the coastal stations were forced to close due to foul weather. The whales were so numerous in the Strait of Georgia that five humpback whales were harvested from this station within one weekend (Webb 1988). Whalers at Page's Lagoon took an estimated 97 individuals during the two-year period of operation (Merilees 1985). In 1908, whaling operations removed an estimated 462 humpback whales from British Columbia, mainly from waters outside of the Strait of Georgia (Tønnessen and Johnson 1982; Webb 1988). Nearby, the American Pacific Whaling Company took approximately 1,933 individuals out of their Bay City station in Grays Harbor during this period (Scheffer and Slipp 1948). Humpback whales compromised 72 percent of the total catch of all species at this station. Whaling of humpbacks and other species continued along the West Coast, with the profit from whale products greatly decreased by the end of the 1950s (Webb 1988).

Declines in the proportion of humpback whales harvested in the Pacific Northwest led to fears of overharvesting and extirpation, causing the International Whaling Commission (IWC) to enact a one-year ban on the commercial take of humpback whales in 1965. A similar ban on non-subsistence hunting of humpback whales in the North Atlantic was issued by the IWC in 1955 (NMFS, 1991). This ban was renewed for a second year in 1966 and effectively ended commercial whaling of this species (Webb 1988). Humpback whales have been recovering since the ban was enacted and following their listing as endangered under the Endangered Species Act (ESA) in 1973. The National Oceanic and Atmospheric Administration's (NOAA's) Humpback Whale Recovery Team released a Recovery Plan in 1991 for use by the National Marine Fisheries Service (NMFS) in managing this protected species. The recovery plan established a goal of returning the global humpback whale population to 60 percent of its historic level. In 2016, NMFS revised the ESA listing, dividing the international humpback whale population into 14 distinct population segments (DPSs). Of these, nine were determined to not warrant listing. The remaining five DPSs include four that are listed as endangered (Central America DPS, Western North Pacific DPS, Arabian Sea DPS, and Cape Verde Islands/Northwest Africa DPS) and one that is listed as threatened (Mexico DPS). The majority of individuals visiting the Salish Sea are believed to be from the Hawaii DPS (not listed) and the Mexico DPS (listed as threatened), with a small number from the Central America DPS (listed as endangered) (Wade 2017).

Although humpback whales were common in Washington's inland waters prior to the whaling period, since then few sightings had been reported in this area until recently, as more humpback whales have started returning to the Salish Sea (Calambokidis et al. 2017). The Salish Sea is part of the Northern Washington/Southern British Columbia biologically important area (BIA) as an important summer feeding ground for a portion of humpback whales in the California/Oregon/Washington stock (Calambokidis et al. 2015). Humpback whales show strong maternal fidelity to feeding grounds (Baker et al. 2013), suggesting that humpback whales will continue to return to the Salish Sea.

The environmental conditions of the Salish Sea have changed substantially since the whaling industry was active. The human population of Washington State has increased by 550 percent since the whaling era (1910), with approximately 62 percent of the current population living near the coast (Washington Office of Financial Management, 2018; NOAA 2013; U.S. Census Bureau 1910). British Columbia is similarly experiencing continued positive population growth, increasing by over 1,186 percent during the same time period (IP and Lavoie, 2020; MacDonald 1970). Population growth has led to changes in shoreline development and use and to a dramatic increase in vessel use of the inland waters. Moreover, the number of large ships passing through the Salish Sea has sharply risen. The Port of Seattle was founded in 1911 (Port of Seattle 2019) while the Port of Tacoma was founded in 1918 (Port of Tacoma 2018). Prior to the development of these ports the majority of the transportation of goods to and from the area was by the Northern Pacific Railroad. The Port of Vancouver was founded in 1962 and is the same size as the next five largest Canadian ports combined (Vancouver Fraser Port Authority 2020a). These three ports are within the top seven container inbound ports in North America (JOC 2019). The

Department of Ecology reported 5,906 cargo, passenger ship, and tanker vessels entered the Salish Sea (via the Strait of Juan de Fuca and the Strait of Georgia; does not include exit numbers) and 6,805 transits to the Salish Sea and other Washington Ports in 2019 (Washington State Department of Ecology 2020). These transits were conducted by 2,663 individual vessels. The number of ferry trips has increased by 57.9 percent since 1993, increasing from 69,978 trips to approximately 170,000 trips annually (Washington State Department of Ecology 2020). During the period from 2015-2017, the U.S. Coast Guard handled approximately 60,000 non-ferry transits annually (Washington State Department of Ecology 2019).

Rockwood et al. (2017) determined that vessel strikes are the second greatest cause of death for humpback whales along the U.S. west coast. Between 2007 and 2019, there were 27 reported ship strikes on humpback whales along the West Coast, four of which were within Washington waters (NMFS stranding data, unpublished). Humpback whales spend the majority of their time within 30 meters of the sea surface (90 percent at night and 69 percent during daytime), increasing their risk of vessel strike (Calambokidis et al. 2019). The western portion of the Strait of Juan de Fuca is a relatively high-risk area for humpback vessel strikes due to the large number of vessels transiting the area at high speeds, as are areas near the west coast of Vancouver Island (Nichols et al. 2017). This risk may extend into other portions of the Salish Sea given the large number of vessels and humpback whale sighting reports. Two vessel strikes in 2008 in Clallam County, WA were presumed to be fatal (NMFS stranding data, unpublished). In 2018, a humpback whale carcass was found near Neah Bay and a necropsy confirmed that the death was due to a vessel strike (NMFS stranding data, unpublished). Most recently, there were two occurrences of juvenile humpback whales being struck by Washington State ferries in May 2019 and July 2020. Given the speeds of the ferry and the witnessed injuries, the strikes were both presumed to be fatal despite no recovery of either carcass (NMFS Stranding Data, unpublished).

A number of studies have examined the fatalities associated with a vessel strike at different speeds. Generally, strikes of large whales at speeds greater than 10 to 12 knots are considered to be fatal (Nichol et al. 2017; NMFS, 2012; Vanderlaan and Taggart, 2006). Rockwood et al. (2017) modeled vessel strikes along the west coast and determined that from 2006 to 2016, there were an average of 1.4 humpback whale mortalities cause by ship strikes per year, with a minimum of 8.2 and a maximum of 28 deaths depending on carcass buoyancy. Humpback whale carcasses display negative buoyancy, making it difficult to determine the true number of fatal vessel strikes. Many of the large shipping vessels enter the Salish Sea at high speeds, increasing the risk of a fatal strike.

In October 2019, NMFS proposed critical habitat pursuant to the ESA to protect the listed DPSs in the Pacific Ocean. This proposal includes portions of critical habitat for three listed DPSs and spans the majority of the West Coast of the United States. Unit 11 of the critical habitat proposal includes the outer coast of Washington State along with the first few miles past the entrance of the Strait of Juan de Fuca (NMFS, 2019a).

To better understand the distribution of humpback whales within the Salish Sea and along the outer coast of Washington and southwestern Vancouver Island, and the implications of these distributions, I sought to answer four research questions:

- The degree to which humpback whales in the Salish Sea are increasing?
- Is there a relationship between the sighting locations and environmental characteristics?
- What is the exposure of humpback whales to vessels?
- To what degree does NOAA's proposed critical habitat cover areas of high use by humpback whales?

I used public opportunistic sightings paired with a smaller number of scientific surveys to identify where humpback whales have been sighted within the Salish Sea and the outer coastal areas. This type of data is widely used to represent presence-only information to estimate species abundance and distributions. I used bathymetry and chlorophyll-a to represent environmental characteristics because 1) the spatial coverage for these two variables was most complete and 2) both are potentially linked to the abundance of prey. I estimated exposure to vessels by examining three types of information: 1) the boundaries of the traffic separation scheme within the Salish Sea, 2) the ferry routes within the Salish Sea, and 3) Automatic Identification System (AIS) data for large vessels moving along the outer coast into the western portion of the Strait of Juan de Fuca. I then considered how well the proposed critical habitat corresponds with the humpback whale sightings to understand the extent of protection of the species within the Salish Sea.

Methods

Humpback Whale Sightings Data

I partnered with Cascadia Research Collective (CRC) to obtain and analyze sightings data. CRC is a research non-profit dedicated to studying cetaceans and other marine mammals. The organization maintains a database of public opportunistic sighting reports that include sightings from the CRC call log, CRC public sighting reports, Orca Network reports, and sighting reports to the Whale Museum. Orca Network is non-profit dedicated to raising awareness to the presence of whales in the Pacific Northwest. Members of the public submit sighting reports to the Orca Network, which then publishes the reports on their website. The Whale Museum is a non-profit museum located in Friday Harbor on San Juan Island focused on education and supporting research on cetaceans in the Salish Sea. This dataset was combined with sightings from the BC Cetacean Sightings Network (BCCSN) from 2000 to 2019. The BCCSN is a research and conservation program that receives sighting reports from the public, researchers, and mariners. These public sightings are not effort corrected or associated with systematic surveys. The use of public sighting data is common and is used for a variety of species, especially cetaceans. Public sightings have been used to better understand the distributions and population dynamics of humpback whales in Australia and Maui (Bruce et al. 2014; Tonachella et al. 2012).

I updated the database to include public sighting reports from Orca Network for the years 2017 through 2019. A script extracted the sighting report information into a spreadsheet that was then processed by hand to enter information on the reporting party, location, species, and number of whales reported. This generated a dataset of public opportunistic sightings of humpback whales from 2000 to 2019. Lastly, the public sightings were combined with the CRC survey sightings, including surveys with partners such as Sealife Response, Rehab and Research (SR3), for years 2017 through 2019 to create a dataset comprising all sightings from all sources, including opportunistic surveys made aboard Island Adventures Whale Watching (IA) cruises throughout the summer in recent years. All of the sighting sources combined created a dataset of 10,096 sighting reports.

Once combined, the dataset was loaded into RStudio (RStudio Team, 2020) and cleaned. This involved removing sightings that did not include a longitude and latitude entry, converting the dataframe into a simple features object, assigning a coordinate reference system (CRS) of 4326, and cropping the spatial extent to only include sightings within the Salish Sea and along the outer coast of Washington State and west Vancouver Island. This resulted in a total of 8,509 humpback whale sighting reports (Table 1).

Table 1. Humpback Whale Sightings Data by source and timeframe.

Public Opportunistic Sightings					Survey Sightings	
BCCSN (2000 - 2019)	Orca Network (2001 - 2019)	Whale Museum (2008-2015)	CRC Public Sightings (1983-2007)	CRC Call Log (2009, 2016, 2017)	CRC and SR3 Surveys (2017-2019)	Island Adventures Whale Watching (2019)
4759	3032	222	76	13	359	48

Figure 1 shows the distribution of the sighting report locations based on the public data source. The public opportunistic sightings represent presence-only data and do not necessarily indicate that humpback whales are not found in areas that lack or have a limited number of sighting reports. Additionally, no attempt was made to correct for a possible sightings bias associated with the ease of viewing humpback whales in certain portions of the inland waters. For instance, the small number of sightings located in the coastal waters does not imply that there are few humpback whales found in those areas. In fact, some CRC and SR3 sightings indicate groups of up to 50 whales in these waters. Instead, the limited number of sightings may imply a sighting bias towards reporting in areas that are more accessible to the public. This bias may skew understandings of relationships between humpback whales and areas of use. It may indicate areas of use based on ease of access and not a larger number of whales visiting an area. To try to mitigate for the sightings bias, analyses were also compared with CRC and SR3 track data for they surveys for 2017 through 2019 (Figure 2).The CRC and SR3 survey sightings were further divided into two categories: systematic surveys (295 sightings) and sightings collected aboard IA cruises (114) that do not systematically cover areas and are for this reason are included in Figure 1 instead.

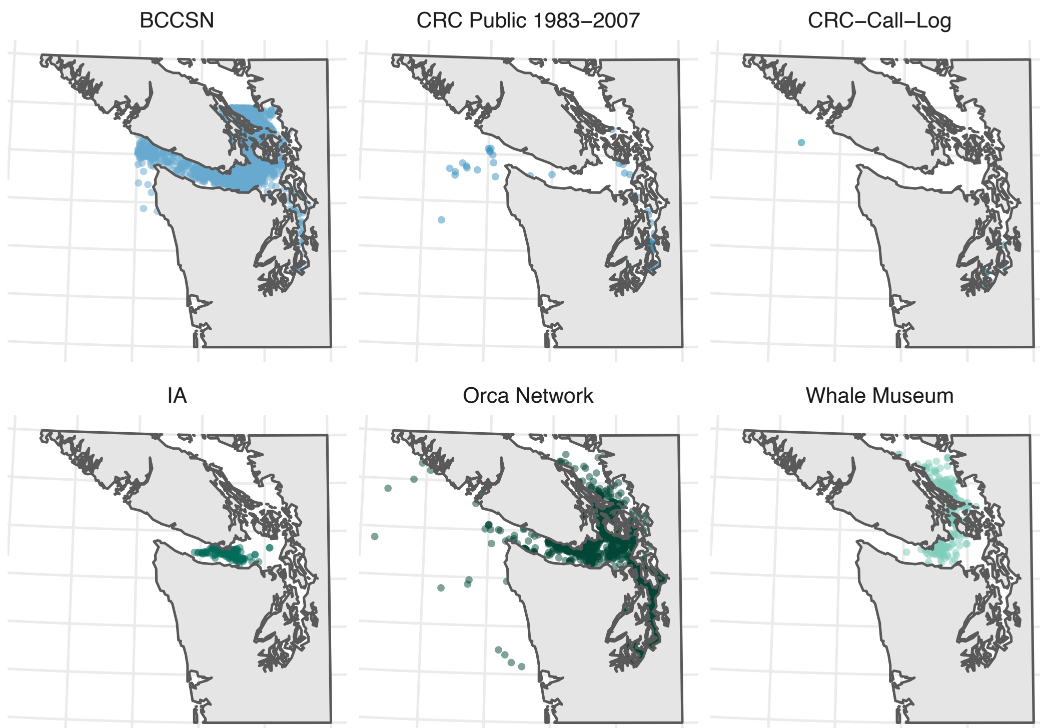

Figure 1. Distribution of sighting report locations based on data source spanning 2000 through 2019.

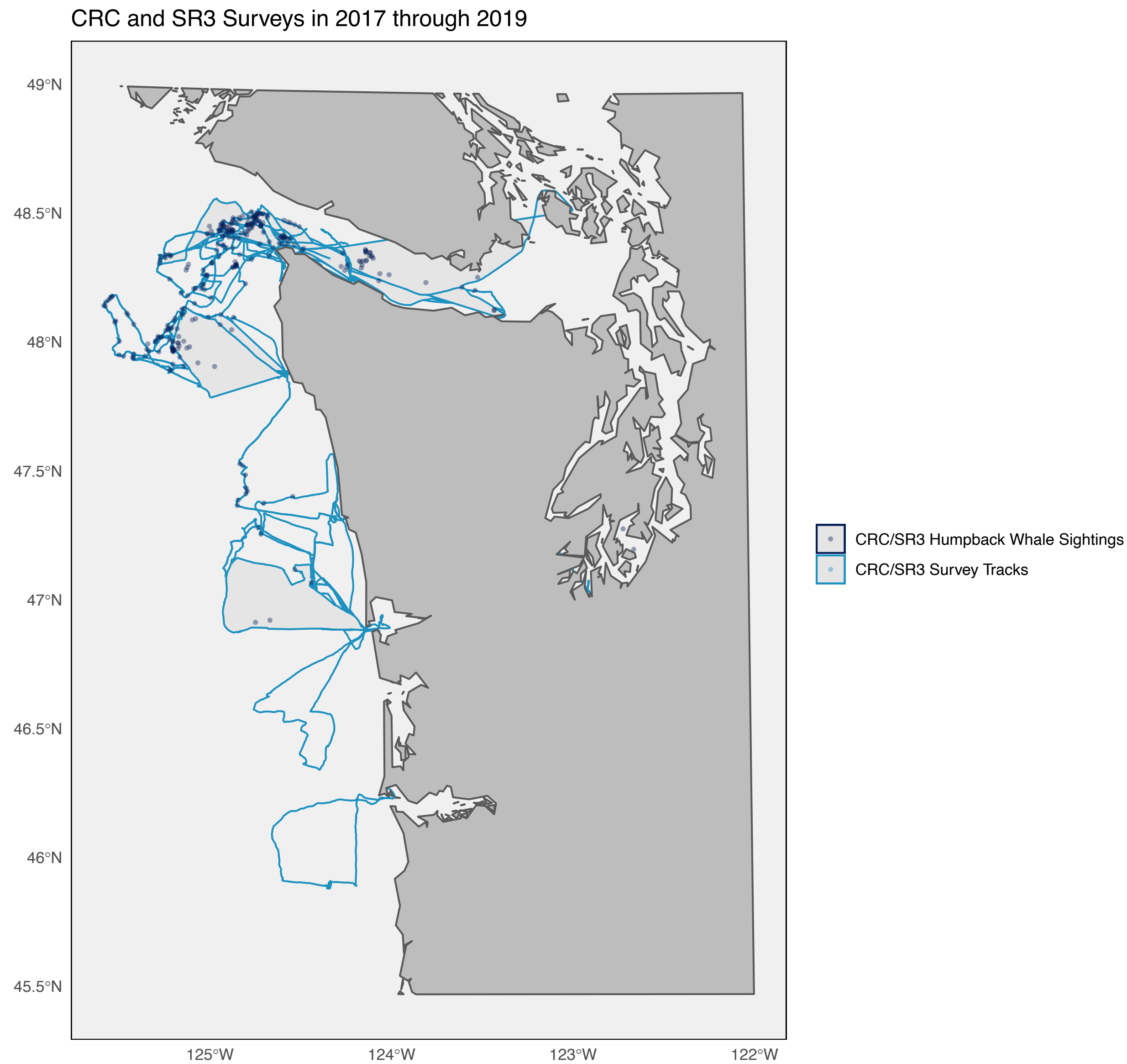

Figure 2. Cascadia Research Collective (CRC) and Sealife Response, Rehab and Research (SR3) survey tracks and the associated humpback whale sightings for 2017 through 2019.

Increases in population

To determine if the increased number of sightings reflects an increase in the number of whales or is a result of duplicate sightings, I normalized the public sightings data (excluding the CRC and IA surveys) by date and latitude. Using RStudio[1], latitudes of sightings were rounded to the

[1] R script for analyses in this thesis may be made available upon request.

nearest decimal using the dplyr package (Wickham et al. 2020). All sightings with the same rounded latitude from the same date were grouped and considered a single sighting. The changes in the annual number sightings from this normalized dataset were then compared with the changes in sighting reports from the full dataset.

Chlorophyll-a

Chlorophyll-a data from the NOAA Chlorophyll-a dataset (NOAA, 2019a) was used as a proxy for humpback whale prey maps. These data provide near-surface concentrations of chlorophyll-a in mg per m^3 from in situ measurements and remote sensing reflectance in the blue-to-green portion of the visible spectrum. The data represent monthly mean climatologies for a 10-year period from 2007 to 2016. An annual climatology for the same time period was also analyzed. These data were loaded into RStudio and the spatial extent was cropped to match that of the sightings. The monthly means were averaged for each of the four seasons (Fall, Winter, Spring, and Summer). Additionally, the monthly means were averaged for May through September to create a "long summer" raster. The month of the humpback whale sightings was extracted from the sighting dates and turned into objects for each calendar month. The chlorophyll-a measurements at each sighting location were extracted from the monthly rasters for each corresponding month (i.e., the sightings in January extracted chlorophyll-a values from the January climatology), except for December which did not have enough satellite data to extract values from. In a two-sample t-test, the mean chlorophyll-a values for each sighting month was compared to the mean chlorophyll-a measurement of the Salish Sea for that month (i.e. January sighting average chlorophyll-a vs. January Salish Sea average chlorophyll-a). This was also done for the four seasons and the long summer raster.

Additionally, the Salish Sea was divided into three geographic areas (Puget Sound, Coastal, and the Straits) to prevent chlorophyll-a measurements in one area from influencing the relationship between chlorophyll-a and the humpback whale sightings for the rest of the Salish Sea. The Puget Sound geographic area was classified as portions of Puget Sound south of Point Wilson at Admiralty Inlet (latitudes of less than 48.15 degrees and longitudes greater than -122.752). The Coastal area included sightings located west of the most western edge of Tatoosh Island (latitude of approximately -124.747 degrees). The Straits includes sightings within the Strait of Juan de Fuca and the Strait of Georgia; any sightings not included in the Puget Sound or Coastal areas were included in the Straits area. The average chlorophyll-a value extracted for the humpback whale sightings within each of these areas per month and season was compared with the average chlorophyll-a value of the corresponding geographic area (i.e., the average chlorophyll-a for the sightings with the Puget Sound area in March was compared to the average chlorophyll-a measurement for the Puget Sound area in March) through a two-sample t-test.

Bathymetry

I used the Northern California 36 arc-second MSL Coastal Digital Elevation Model from the NOAA National Centers for Environmental Information (2005) to map the bathymetry of the Salish Sea, the outer coast of Washington state, and the west coast of Vancouver Island. The bathymetry netCDF was loaded into RStudio and then cropped to match the spatial extent of the total humpback whale sightings dataset. I extracted the corresponding depth of each sighting report location from the bathymetry raster. To prevent the deeper depths of the outer coast from masking a relationship between sightings and the shallower waters in the Salish Sea, the sightings dataset was divided into two components: coastal and inland water datasets. Sightings that were located west of the most western edge of Tatoosh Island (latitude of approximately

-124.747 degrees) were considered coastal and any sighting reports located east of that boundary were considered inland. The bathymetry raster was cropped and saved into two objects that matched either the coastal or inland water spatial extents. I then ran a two-sample t-test to determine if the mean bathymetry of the area was the same or significantly different than the mean of the corresponding sightings dataset.

Ferries

To assess the potential risk associated with ferries in the Salish Sea, I examined the degree of overlap between routes and humpback while sighting locations. The Washington State Department of Transportation (WSDOT) published a shapefile with all of the vehicular ferry routes along with some of the passenger-only ferries (WSDOT 2017). I created a 30-meter buffer around the ferry route simple features lines and the humpback whale sightings to create objects with a space to be able to intersect in R. I used 30 meters to represent two body lengths based on the average length of a humpback whale (Bettridge et al. 2015). Then, I used the st_intersection function (Pebesma, 2018), to create a new geometry that included all of the sighting reports that overlapped with the geometry of a ferry route. To establish a buffer around the objects, I re-projected the ferry route data and the humpback whale sighting report data into CRS 32610.

Traffic Separation Scheme

To assess the risk humpback whales may be exposed to by ship traffic within the inland waters, I examined the degree of spatial overlap between the sightings and the traffic separation scheme (TSS) in the Salish Sea (NOAA 2015). The TSS is managed by the United States and Canadian Coast Guards and dictates the location of vessels as they move through the Salish Sea. The TSS shapefile was cropped to match the spatial extent of the Salish Sea and then re-projected to CRS

32610. I removed the “Area to be Avoided” polygon from the TSS object because vessels are requested to avoid transit through the area, reducing the risk of vessel strikes for humpback whales in that region. I used the st_intersection function to create a new object with the geometry of the sighting reports that fell within the bounds of the TSS.

Large Vessel Traffic

The Salish Sea has three major ports and supports a substantial amount of shipping traffic. To examine the risk posed by large vessels, I used AIS data from the Olympic Coast National Marine Sanctuary (OCNMS) for vessels transiting through the sanctuary and Washington outer coast along with the western portion of the Strait of Juan de Fuca[2] in 2017 (OCNMS 2018a). This included 17,209 transits by 6 vessel classes. Three vessel classes (cargo vessels, tankers, and passenger ships) were used to assess the potential overlap between humpback whale distribution and shipping traffic. Similar to the ferry routes, I added a 30-meter buffer to the shipping tracks.

Critical Habitat

NMFS published a shapefile for its proposed critical habitat in the Federal Register (NMFS, 2019b). This was used to assess the extent of spatial overlap between the proposed critical habitat and humpback whale sighting reports. The critical habitat file was cropped to the extent of the Salish Sea and the outer coast and transformed into CRS 32610. A new geometry was created using the st_intersection function (Pebesma, 2018) with the humpback whale sighting reports that were located within the critical habitat boundary. A column for the country the sighting report was located in was created to distinguish between sightings within the U.S. and

[2] The area runs 46°45’ N to 48° 45’ N Latitude and 124° to 127° West Longitude (https://nmsolympiccoast.blob.core.windows.net/olympiccoast-prod/media/docs/2017_atba.pdf)

Canada. I used a function to erase the sightings located within the critical habitat from the larger dataset to remove duplication (Pebesma, 2017) and allow for comparisons of sightings inside and outside of the critical habitat. To examine areas with higher use, the sighting reports were subsetted to create a dataset consisting only of reports that observed 3 or more humpback whales and again used the st_intersection function to determine which sightings with 3 or more whales were located within the critical habitat boundaries. The sightings within the critical habitat were also erased from the larger dataset to remove duplicates and facilitate comparison.

Results

Sightings

The public sightings dataset includes sightings from 2,216 days between 1989 and 2019. The majority of sighting reports occurred between May and October, with a peak in July. Normalizing the sightings by date and latitude led to 4,922 unique sightings. Both the full dataset and the normalized dataset show an increase in the number of sighting reports of humpback whales in the Salish Sea beginning in 2011 (Figure 3). With the exception of 2016, the number of sighting reports has increased every year.

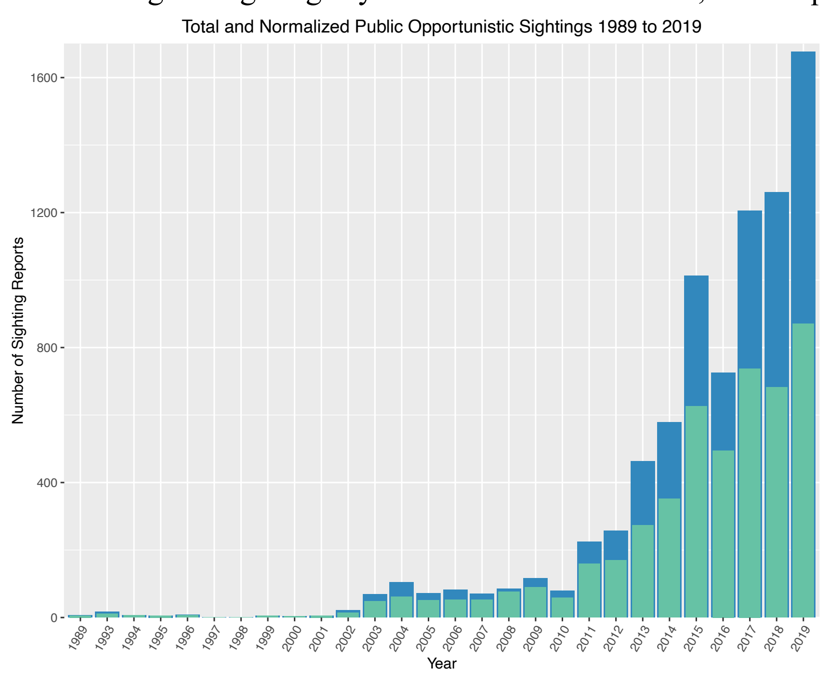

Figure 3. Public sighting reports from the BCCSN, Orca Network, CRC-logs, and the Whale Museum from 1989 to 2019. The blue bars are the total sighting reports per year and the green bars are the normalized sighting reports per year.

Chlorophyll-a

Within the Salish Sea, the humpback whale sightings during the long summer season were associated with areas of higher chlorophyll-a measurements compared with the regional average (Figure 4). This association existed for all months analyzed (Table 2) and for all four seasons (Table 3).

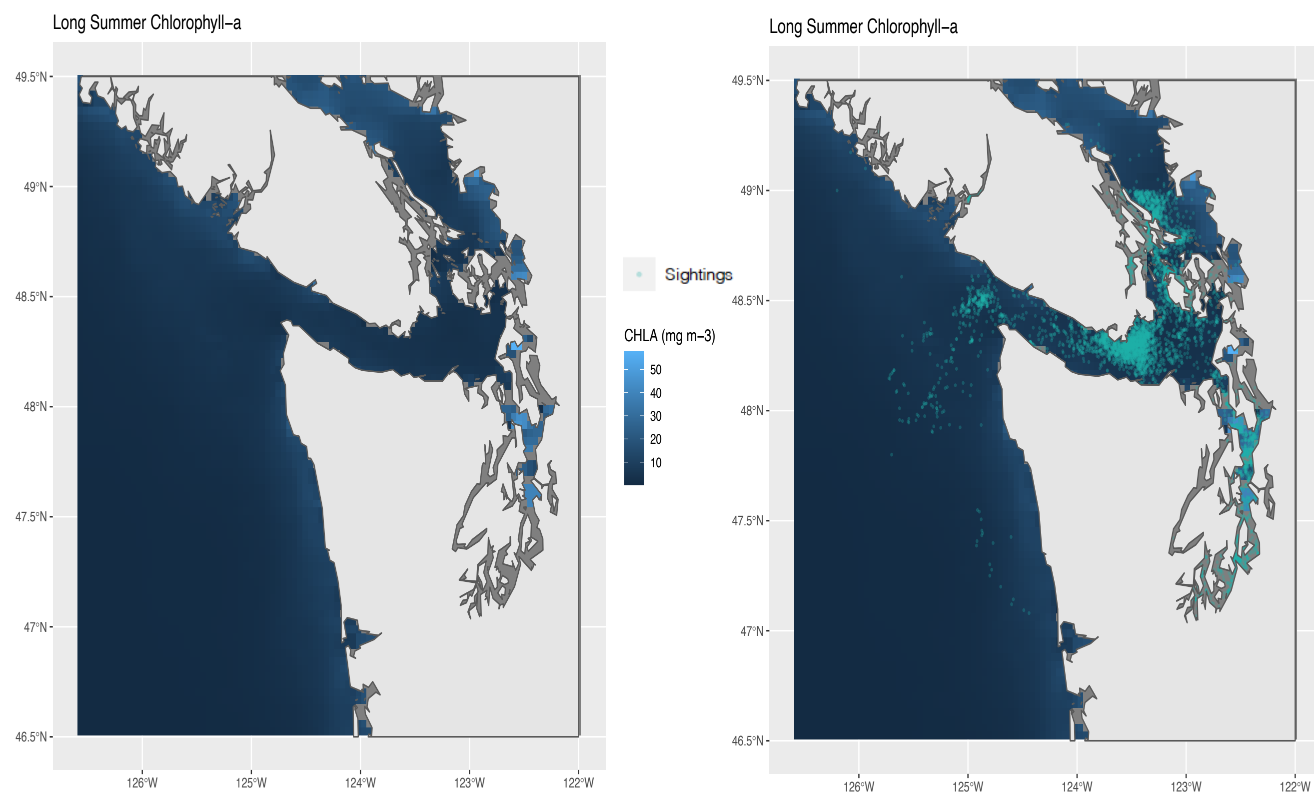

Figure 4. a) Chlorophyll-a measurements for the long summer months (June through September) and b) the humpback whale sighting report locations for those months. The teal dots represent the location of a humpback whale sighting report during the long summer month.

Table 2. Two sample t-test results for all months (except for December).

Month	Chlorophyll-a mean measurement		
	Sightings	Salish Sea	p-value
January	13.99973	2.574616	1.35E-13
February	15.104364	2.729151	< 2.2e-16
March	6.10265	3.248586	0.001806

April	8.430038	4.469324	< 2.2e-16
May	9.870987	5.946826	< 2.2e-16
June	8.665074	4.805873	< 2.2e-16
July	6.923854	5.420639	7.65E-11
August	5.616995	4.854156	3.64E-05
September	8.338294	4.640969	< 2.2e-16
October	8.225665	3.966124	< 2.2e-16
November	6.147759	3.342164	1.27E-10

Table 3. Two sample t-test results for all seasons.

Season	Chlorophyll-a mean measurement		
	Sightings	Salish Sea	p-value
Fall	7.507107	4.068358	< 2.2e-16
Winter	9.153553	2.909366	< 2.2e-16
Spring	8.027125	4.616007	< 2.2e-16
Summer	6.922374	5.123029	< 2.2e-16
Long Summer	7.622695	5.106866	< 2.2e-16

The relationship between chlorophyll-a and humpback whale sightings varied by location when broken into the three geographic areas (Puget Sound, Coastal, and Straits). The difference in means between the Puget Sound and the associated humpback whale sightings was only significant in September and October, where the mean chlorophyll-a measurement for the humpback whale sightings was greater than that of the Puget Sound (Table 4). Interestingly, when chlorophyll-a was broken down by seasons in the Puget Sound, the difference in means was significant only for the summer and the long summer (June through September) seasons, again with the humpback whales associated with a higher average chlorophyll-a level than the Puget Sound (Table 5).

Table 4. Two-sample t-test results for the Puget Sound Area. Gray lines indicate a significant p-value.

Month	Chlorophyll-a mean measurement		
	Sightings	Puget Sound	p-value
January	16.18955	17.32673	0.2973
February	17.70317	16.14053	0.1324
March	11.30241	12.65085	0.5205
April	11.53976	12.64172	0.6694
May	26.54725	24.70638	0.5271
June	27.87138	26.01143	0.5898
July	31.07598	28.32607	0.2517
August	22.90005	20.41075	0.1784
September	35.22871	28.55405	0.01608
October	35.71653	31.36877	0.03356
November	18.92517	21.78442	0.2882

Table 5. Two-sample t-test results for Puget Sound in all seasons. Gray lines indicate a significant p-value.

Season	Chlorophyll-a mean measurement		
	Sightings	Puget Sound	p-value
Fall	28.01327	26.69673	0.4058
Winter	16.51201	16.90352	0.6546
Spring	15.84304	15.35066	0.717
Summer	28.16311	24.96105	0.04988
Long Summer	31.07489	27.0795	0.02338

There were not enough humpback whale sightings in the Coastal area to run a two-sample t-test for February through April. For January and May through November the tests indicate a significant positive association of humpback whales and greater chlorophyll-a measurements than the average for the Coastal area (Table 6). Again, there were not enough humpback whale sightings in the Coastal area to run a two-sample t-test for the winter season. This positive association occurred for the remaining four seasons (Table 7). Humpback whales appear to be associating with areas of higher chlorophyll-a quantities in the coastal waters.

Table 6. Two-sample t-test results for the Coastal area in all months (except for December).

Month	Chlorophyll-a mean measurement		
	Sightings	Coastal	p-value
January	2.40853	1.451077	< 2.2e-16
May	12.848164	4.555094	7.64E-10
June	5.956817	3.545573	4.03E-09
July	4.739687	4.026857	1.14E-07
August	4.666038	3.508996	0.02495
September	3.859576	2.861998	1.20E-15
October	4.435512	2.628884	8.75E-08
November	3.044389	2.062092	1.93E-06

Table 7. Two-sample t-test results for the Coastal area in all seasons (except for winter).

Season	Chlorophyll-a mean measurement		
	Sightings	Coastal	p-value
Fall	3.769415	2.54843	< 2.2e-16
Spring	7.898403	3.572805	2.46E-10
Summer	4.622488	3.710003	8.17E-14
Long Summer	4.359336	3.511016	2.40E-16

The Straits (the Strait of Juan de Fuca and the Strait of Georgia) was the only area where humpback whale sightings were not associated with a greater chlorophyll-a level than the surrounding area. The difference in mean chlorophyll-a measurements between the humpback whale sightings and the Straits was significant for all months, except for March and April, and for all seasons, with the sightings consistently associated with lower levels of chlorophyll-a (Table 8 and 9).

Table 8. Two-sample t-test results for the Straits and all months. Gray coloring indicates a significant p-value where the mean sightings chlorophyll-a measurement was greater.

Month	Chlorophyll-a mean measurement		
	Sightings	Straits	p-value
January	3.156458	4.461733	< 2.2e-16
February	2.399093	4.059857	4.57E-09
March	3.857541	5.090015	0.1741
April	8.156489	8.205864	0.9006

May	8.734602	10.548999	4.05E-08
June	6.014771	8.579677	< 2.2e-16
July	5.737081	8.919013	< 2.2e-16
August	4.464019	7.063936	< 2.2e-16
September	4.275265	7.509531	< 2.2e-16
October	3.964497	5.879119	1.27E-15
November	3.872	5.997816	< 2.2e-16

Table 9. Two-sample t-test results for the Straits and all seasons.

Season	Chlorophyll-a mean measurement		
	Sightings	Straits	p-value
Fall	4.148178	6.569471	< 2.2e-16
Winter	2.831303	4.35137	8.73E-15
Spring	7.276942	7.892766	0.006967
Summer	5.285196	8.490288	< 2.2e-16
Long Summer	5.022357	8.342179	< 2.2e-16

Bathymetry

There was a significant relationship between the humpback whale sightings and bathymetry (Table 10). Sightings in the Salish Sea were not randomly distributed with respect to bathymetry (Figure 5a) and were significantly associated with shallower depths compared to the average depth of the study area. Similarly, coastal sightings were significantly associated with shallower depths (Figure 5b). A few sighting reports were located in the deeper waters off the coast, however the majority of the coastal sighting locations are on the continental shelf, closer to shore.

Table 10. Mean depth for humpback whale sightings and the inland and coastal waters.

Location	Mean Depth of Humpback Sightings	Mean Depth of Area	p-value
Inland Waters	111.89	145.29	<2.2e-16
Coastal Waters	174.17	876.83	<2.2e-16

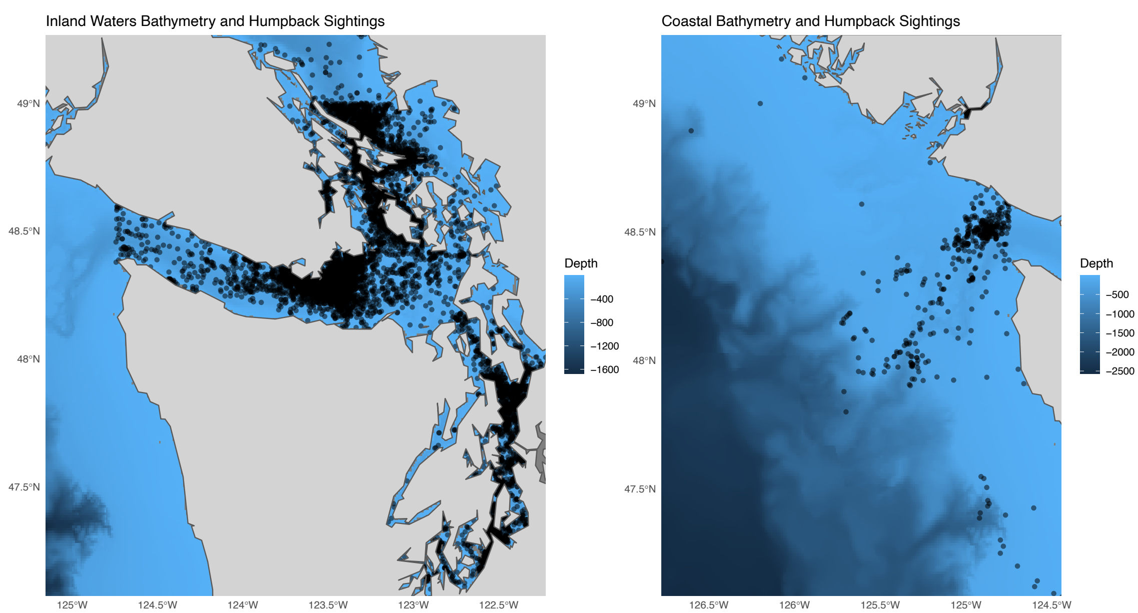

Figure 5. (a) Inland Salish Sea sighting reports and bathymetry and (b) Coastal sighting reports and bathymetry. The sighting reports are each of the dark gray dots. Darker colored dots signify overlap of multiple sighting report points.

Ferries

Twenty-two ferry routes exist within the area of interest in the Salish Sea. Of these, 17 routes overlapped with one or more humpback whale sighting. A total of 127 sightings intersected with 17 routes (Figure 6). Approximately 68.5 percent of the overlap in routes and sighting locations occurred between 2016 and 2019. The Tsawwassen, B.C - Swartz Bay, B.C route in the Strait of

Georgia resulted in the largest number of overlaps with 32 intersections, followed by the Port Angeles, WA to Victoria, B.C. route with 17 intersections. The 5 ferry routes that did not intersect a humpback whale sighting location are all short routes that have few humpback whale sightings nearby.

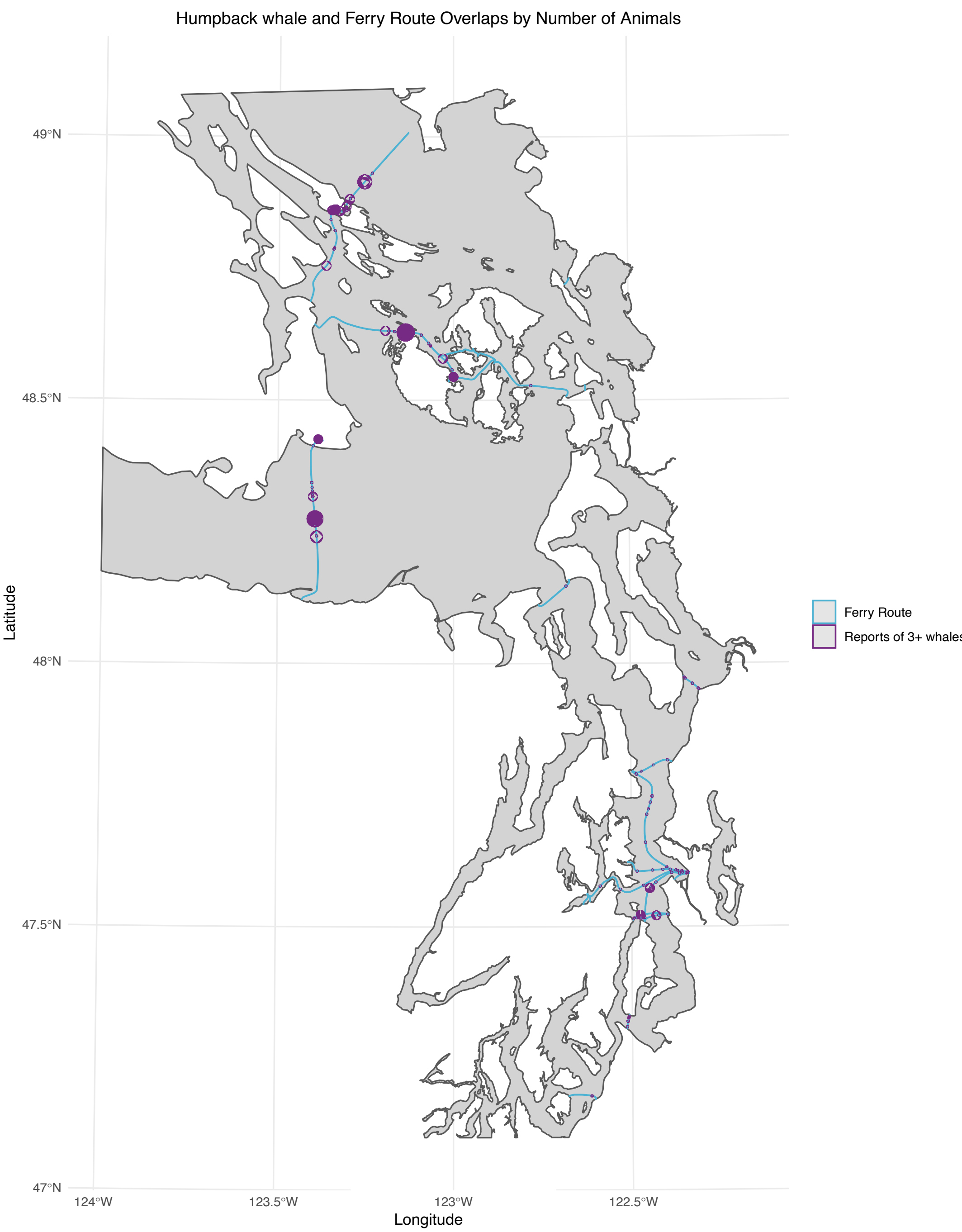

Figure 6. Ferry Route and humpback whale intersections. The purple dots represent a humpback whale sighting that overlapped with the geometry for a ferry route and are size proportionately based on the number of individual humpback whales included in the report.

Traffic Separation Scheme

A total of 2,131 humpback whale sightings were within the TSS, which represents almost a quarter of all sightings included in the dataset (Figure 7). Almost half of these overlaps occurred within the lanes themselves (1,013 or 47.5 percent of overlaps) reflecting a potential risk of vessel strike for humpback whales within the lanes. There were 506 sightings located with the Precautionary Areas and 379 sightings located within the Traffic Separation Schemes which is the area between the traffic lanes that larger vessels are supposed to avoid using, but may be used by smaller vessels.

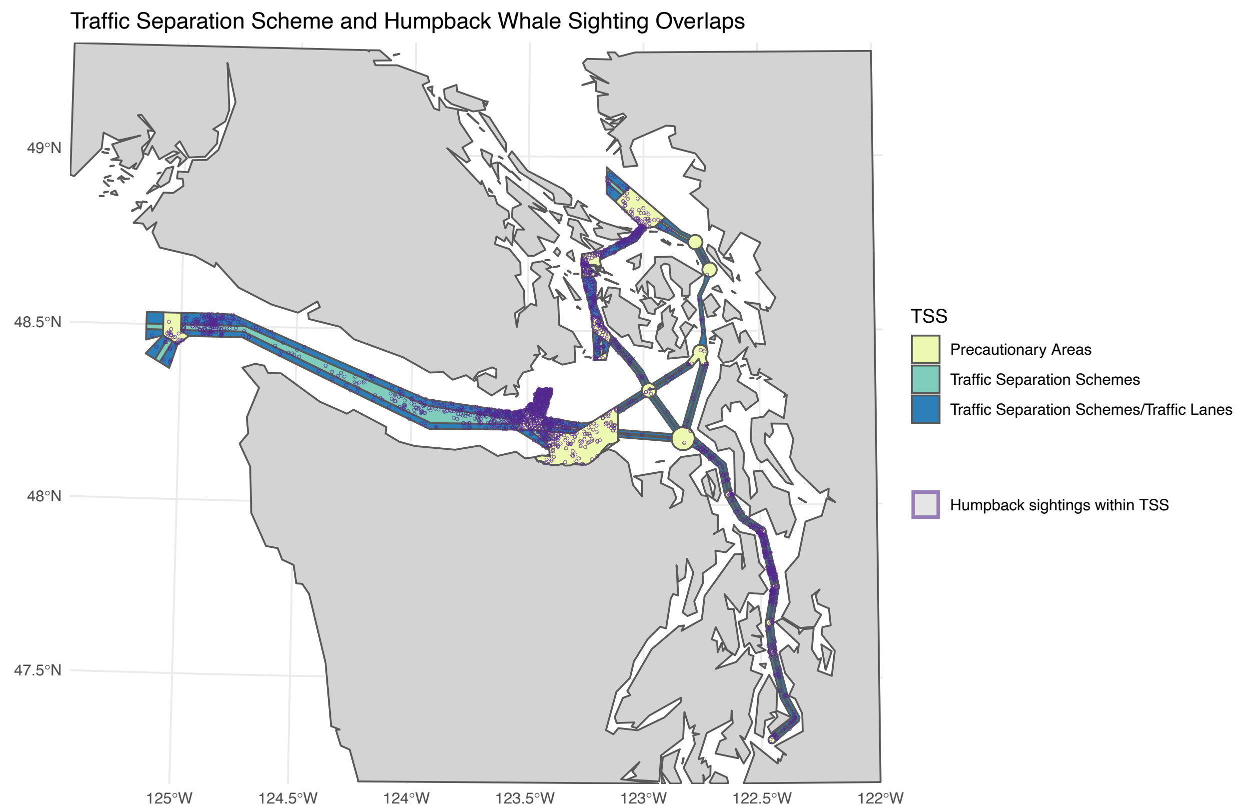

Figure 7. Traffic Separation Scheme (TSS) and humpback whale sightings within the Salish Sea. The purple dots are the locations of the humpback whale sighting reports.

Large Vessel Traffic

Transits by cargo ships represented 42.4 percent (7,299 transits) of all vessel transits through the OCNMS in 2017 (Figure 8a) and 81.6 percent of the transits of the three vessel types (cargo vessels, tankers, and passenger ships). The number of cargo vessel transits is relatively constant throughout the year with an average of approximately 1,144 trips per month. Approximately 5,312 of the cargo vessel transits in 2017 resulted in a total of 13,728 overlaps with a humpback whale sighting location (Figure 8b). The maximum number of overlaps a single transit had with humpback whale sighting locations was 13. The average speed of cargo ship transits that intersected with sightings was 13.38 knots with a median of 12.6 knots and a maximum speed of 24 knots. The number of intersections where the transit speed was 10 knots or greater was 12,498 (91.0 percent of all intersections with a cargo vessel track).

There was a total of 1,186 unique transits by Tankers in 2017 (Figure 8C). The number of tanker vessel transits is relatively constant throughout the year with an average of approximately 99 trips per month. Of these transits, 925 transits resulted in a total of 2,626 overlaps with humpback whale sightings from that year or other years (Figure 7D). The number of overlaps per Tanker transit ranged from 1 to 12. The average speed of tanker vessels that overlapped with sightings was 13 knots and a maximum speed of 17.6 knots. The number of overlaps where the transit speed was 10 knots or greater was 2,487 (94.7 percent of all overlaps by tanker transit tracks).

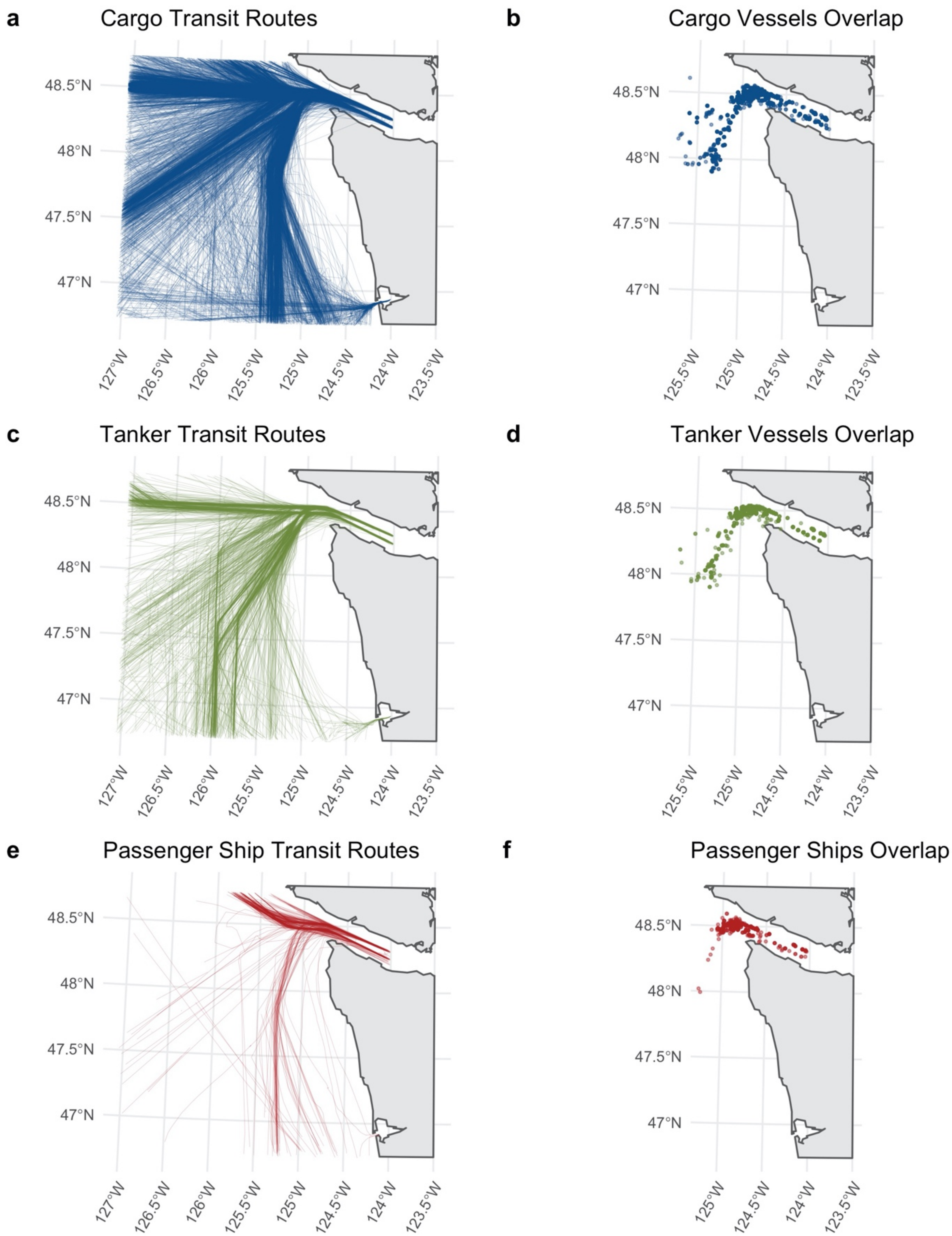

Figure 8. AIS data for cargo, tanker, and passenger vessels. The lines represent the tracks for each of the three vessel types transiting through the Sanctuary and into the Strait of Juan de Fuca. The dots represent sighting reports that overlapped with a vessel track line.

Passenger ships conducted 460 transits through the area in 2017, with 261 of these transits resulting in 557 overlaps with a humpback whale sighting location (Figures 8E and 8F). The maximum number of route overlaps with a sighting location was 6 and the average number of overlaps was approximately 2 sighting reports. The average speed of passenger vessels that intersected with a sighting location was 18.85 knots with a median speed of 19.9 knots and a maximum speed of 24.4 knots. The number of transits with a speed of 10 knots or greater was 538. Unlike cargo and tanker transits, passenger ship traffic is highly seasonal with the number of transits per month ranging from 0 in January to 92 in September. I attempted to correct for seasonality by matching the month of the sighting with the month of the passenger ship transit. This correction caused the number of overlaps to decrease to 88 intersections from 68 unique transits and may be a more representative estimate. However, the peak months of passenger ship traffic occurs during the summer months, which also correspond with the peak in humpback whale sightings. Matching for the long summer months (June through September), the number of overlaps is 298 with 165 unique passenger ship transits. The average number of overlaps per transit was approximately 2, with a maximum of 5. Of these, 162 transits (98.2 percent) were at speeds of 10 knots are greater. The average speed of the passenger ships during these overlaps was 19.4 knots with a median of 20.3 knots and a maximum of 24.4 knots.

Proposed Critical Habitat (U.S.)

The proposed critical habitat covers approximately 3,441 nmi^2 of marine habitat in U.S. coastal waters and into the U.S. side of the Strait of Juan de Fuca. A total of 451 sighting reports fell within the bounds of the proposed critical habitat while 8,058 reports were located outside of the proposed boundaries, including 4,598 in Canadian waters (Figure 9). To better compare sightings data between areas inside and outside of the proposed critical habitat, I examined only those sighting reports that reported 3 or more whales. This adds confidence to the analysis by focusing on comparisons of high-use areas that may be of greatest importance to humpback whales. Because NMFS can propose critical habitat only within U.S., waters, I removed all sighting reports located within Canadian waters. Within U.S. waters of the Salish Sea and the Washington coast, there were 126 sighting reports with 3 or more humpback whales within the proposed critical habitat compared to the 244 sighting reports with 3 or more humpback whales in the rest of U.S. waters in the Salish Sea (Figure 10). Summing the whales sighted in each of these U.S. multiple whale reports, more humpback whales were sighted outside of the critical habitat (1,348) than within the boundaries of the critical habitat (945). The proposed critical habitat had a mean number of sightings per report of approximately 8 whales and a median of 5 whales (ranged 3 to 55). The U.S. portion of the Salish Sea with multiple sightings reports had a mean of approximately 6 humpback whales per report and a median of 3 whales per report.

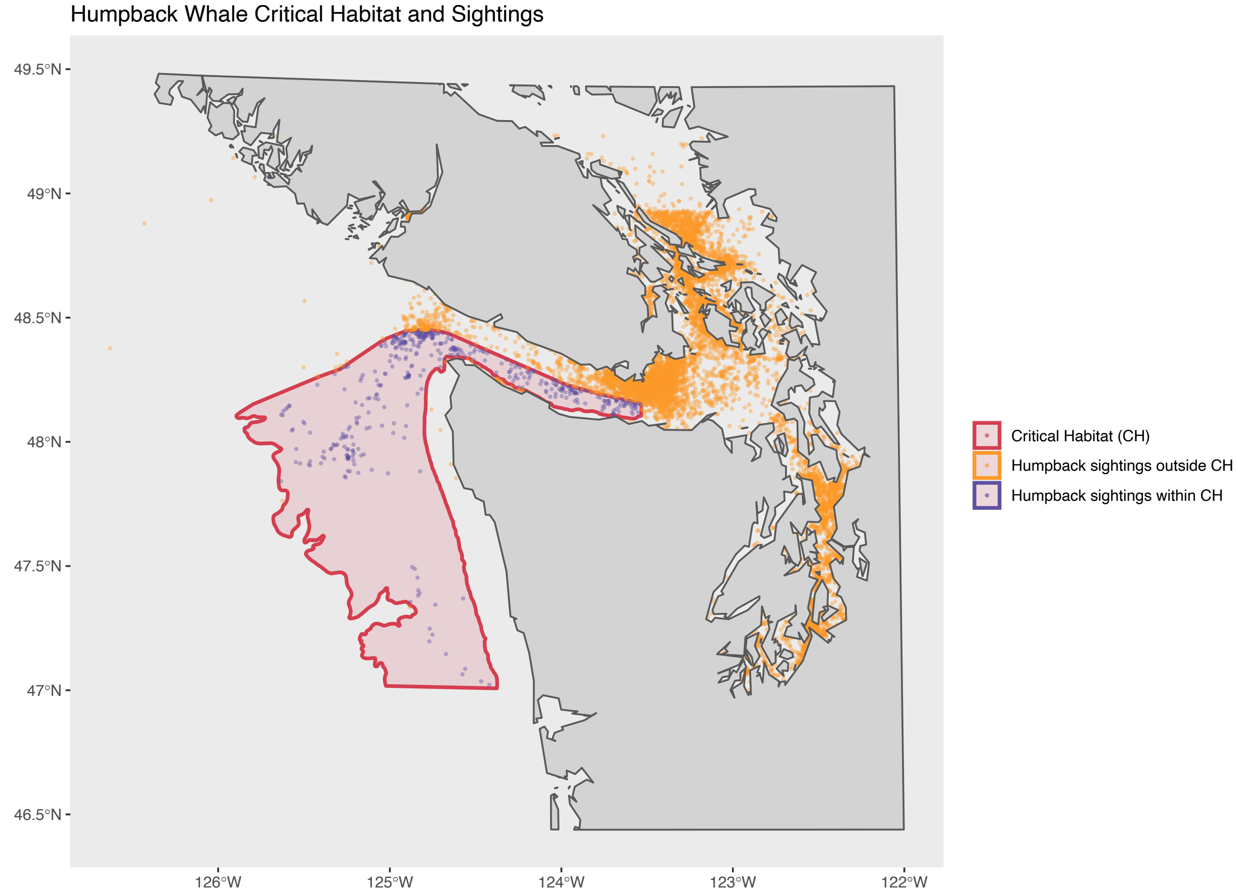

Figure 9. NMFS's Proposed Critical habitat overlaid on humpback whale sighting report locations. The area in red shows the proposed critical habitat. The blue dots show all of the humpback whale sightings located outside of the critical habitat (including sightings located within the U.S. and sightings within Canadian waters) while the purple dots are the sighting reports located within the critical habitat bounds.

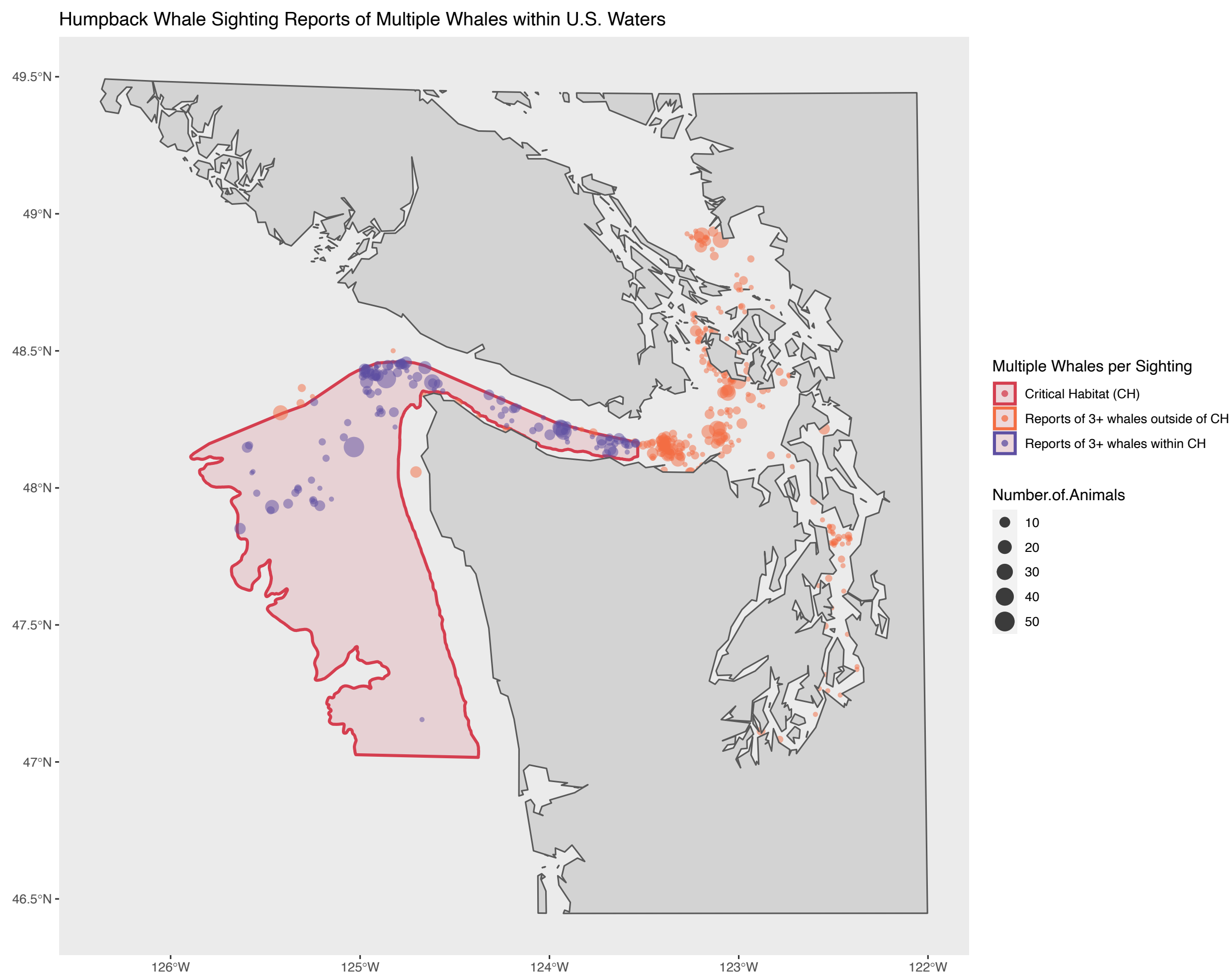

Figure 10. NMFS's proposed critical habitat and sighting reports of multiple whales. The red area is the proposed critical habitat. The orange dots are the sighting reports outside of the critical habitat that included 3 or more whales, scaled proportionately to the number of whales reported. The purple dots are the reports located within the critical habitat for 3 or more whales.

I examined the sightings from CRC and SR3 surveys to better understand how the sightings bias from the more accessible areas may influence the distribution of sightings within and outside of the proposed critical habitat. The surveys provide a more systematic coverage of areas and are more reliable and precise. The proportion of CRC/SR3 humpback whale sightings within U.S. waters that were within versus outside the proposed critical habitat 237 to 14; that is, 94.4 percent of CRC/SR3 sightings fell within the bounds of the proposed critical habitat (Figure 11 a and b). The majority of the CRC/SR3 sightings that were not within the bounds of the proposed habitat were just outside the bounds of the proposed area. In looking at sighting reports with three or more whales per report, 61 CRC/SR3 multiple-whale sightings were within the proposed critical habitat while only one sighting was located outside of the proposed critical habitat. In comparison, only 196 non-survey sightings (public sightings and sightings from IA vessels, including those collected by CRC) were located within the proposed critical habitat bounds while 3,446 of those sightings were located outside of the critical habitat in the U.S. There were 64 of these opportunistic sightings with three or more whales within the critical habitat and 243 sighting reports in the rest of the U.S. waters in Washington (Figure 11c and d).

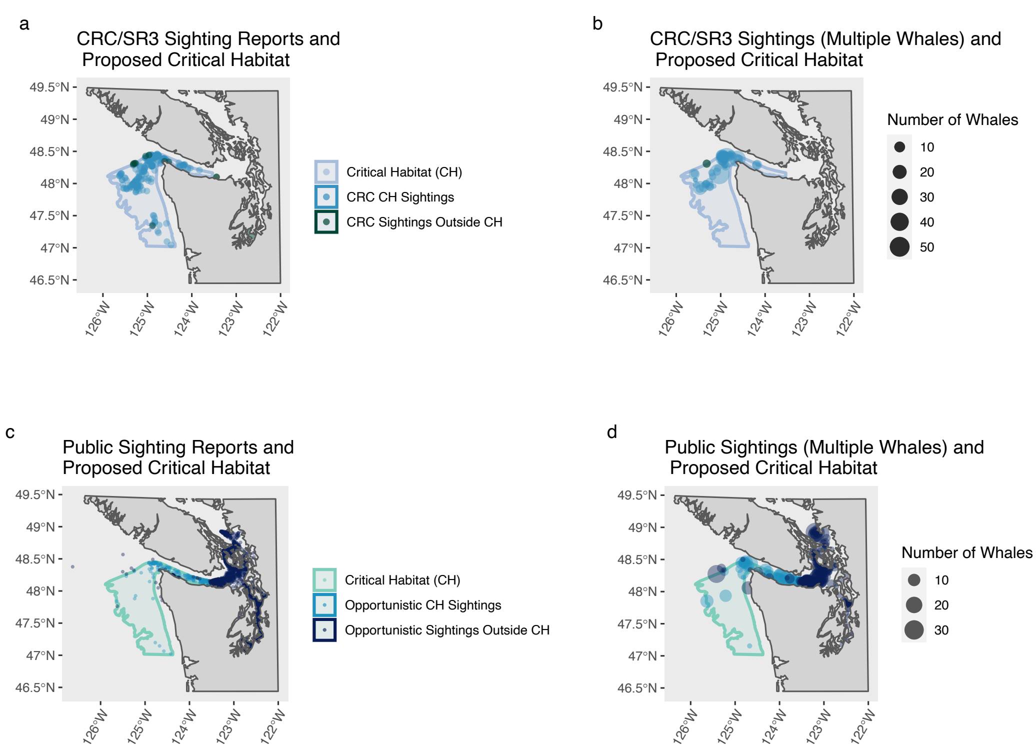

Figure 11. Overlap of humpback whale sightings and proposed critical habitat: a) All of CRC/SR3 sightings from their 2017-2019 surveys and the proposed; b) CRC /SR3 sightings of multiple humpback whales per report during their 2017-2019 surveys; c) all public sightings located within the U.S. waters; and d) Public sightings were 3 or more whales were reported. The sighting reports with multiple whales are sized proportionally based on the number of whales include in the report.

Discussion

Increases in sighting reports and population

Both the full dataset and the normalized dataset of humpback whale sightings indicate that the number of whales returning to the Salish Sea is increasing. Approximately 87 percent of all reported sightings have occurred since 2011.

The number of public sighting reports has increased as the interest in viewing whales has grown. Whale-watching in the Salish Sea emerged in the early 1900s with designated whale watching boats by the Terminal Steamship Company in Vancouver (Webb 1988). This growing industry was in direct conflict with the successful and more lucrative whaling operations at Page's Lagoon. As the whales were largely removed from the Salish Sea, interest in viewing whales lagged until 1986 as trips from San Juan Island (O'Connor et al. 2009) began to watch killer whales. Whale watching has become a $40-50 million industry in the Salish Sea with an estimated 500,000 people going out on commercial or private vessels to observe whales annually (Seely et al. 2017). While viewing of southern resident killer whales (SRKW) in the Salish Sea has been the primary focus for the last couple of decades, this has shifted in recent years to viewing gray whales in the spring and humpback whales during the summer as SRKW have become less reliable visitors.

The increase in the number of people looking for whales likely contributes to the increase in sightings. Overall public interest in whales has increased during this time with public reporting centers such as the Orca Network and the BCCSN being established in 2001 and 1999, respectively. Land-based viewing has also become popular during this time with the creation of the Whale Trail in 2008 to promote viewing of SRKW from land. This increased interest has led to more eyes on the water, searching for whales of all types. While this has led to an increase in the number of reports made by the public, it is clear from the normalized sightings and from the full public dataset that the number of humpback whales utilizing the Salish Sea is growing and is not simply a function of increasing public effort.

Chlorophyll-a

The humpback whale sightings appear to be correlated with higher levels of chlorophyll-a compared to chlorophyll-a measurements averaged over the Salish Sea. However, the relationship becomes less clear when the three geographic areas (Puget Sound, Coastal, and the Straits) are examined. Humpback whale sightings were only associated with a significantly higher average chlorophyll-a level in the Puget Sound in September and October and during the summer and long summer seasons. For the remainder of months and seasons the differences in means was not statistically significant. In the Straits geographic area, humpback whale sightings were never associated with a greater chlorophyll-a measurement. This association, or lack thereof, may be caused in part by a sightings bias. The western portion of the Strait of Juan de Fuca and the northern boundary of the Strait of Georgia included in study area tended to have higher chlorophyll-a than the Eastern Basin. The number of sightings in the Eastern Basin may be partially caused by the ease of viewing and therefore reporting sightings since it is closer to the places that people live. In contrast, the humpback whale sightings in the Coastal area were associated with higher chlorophyll-a in all months and seasons for which there were enough sighting reports to compare. This may also be associated with a sighting bias where the areas closer to shore are easier for people to access. The nearshore areas tend to have higher chlorophyll-a than the deeper areas off the coast. Without more surveys of the Straits and the

Coastal areas it may be difficult to determine the extent of the relationship humpback whales have with chlorophyll-a.

I used chlorophyll-a as a proxy for humpback whale food availability. Common prey items include euphausiids and various schooling fishes, including but not limited to herring, capelin, sand lance, and mackerel (Clapham 2009). Pacific herring populations appear to be declining (Sandell et al. 2019), but no assessment of Northern anchovy or Pacific sand lance abundance in the Salish Sea has been conducted (Penttila 2007). Some studies do indicate an increase in sand lance catch and abundance (Greene et al. 2015). Higher levels of chlorophyll-a signify a higher abundance of phytoplankton, which is a food source for the fish species humpback whales consume. The association between humpback whale sighting locations and chlorophyll-a suggests that prey availability could influence the distribution of whales in this region, although the spatial scale of the analysis is coarse. Specifically, while the satellite data were able to provide chlorophyll-a measurements for the vast majority of sighting locations, the data coverage and resolution was not at a scale fine enough to provide chlorophyll-a estimates for narrow portions of the Salish Sea, such as Hood Canal. A chlorophyll-a dataset with a more complete coverage would help to further elucidate the association between humpback whales and chlorophyll-a in the region. Similarly, humpback whale sightings with effort recorded or corrected would be necessary to determine the strength of an association with humpback whale distributions and chlorophyll-a and remove any associations caused by a sightings bias. Prey mapping would provide a more direct measure of the association between whale distribution and food availability and could help advance our understanding of habitat use by humpbacks in the Salish Sea.

Bathymetry

Humpback whale sighting reports tended to be in water shallower than the average depth of the study areas. This suggests that humpback whales are less commonly found in the deepest areas of the Salish Sea or the outer coast. This association could be a reflection of prey distribution. A sightings bias from the ease of accessing the shallower waters may be impacting this association. The difference in mean depths between sightings locations compared with the total study area for the coastal datasets is statistically significant. However, this result is likely skewed by relatively small numbers of sightings and low survey effort, combined with the difficulties of reaching the deeper waters to survey. The outer coast represents a large area that is quite difficult to comprehensively cover. Only 359 of the sighting reports are the result of scientific surveys in which observers have the ability to access more remote waters. Because of this, we know that the outer coast sightings are underreported and that humpback whales may be found in deeper waters, but have not be observed there due to the difficulty and resource intensity (money, time, etc.) to reach the deeper areas.

Santora et al. (2020) found that during periods of increased sea surface temperatures humpback whales moved to shallower, nearshore waters, creating habitat compression. Portions of the Pacific Ocean, including the Salish Sea, have experienced warmer ocean conditions over the last 5 years, which has been hypothesized to be causing an atypical community of zooplankton (such as krill) in the North Pacific (DFO 2018). Changes in oceanographic conditions may influence the association between humpback whales and bathymetry on both a short-term and long-term scale.

Ferries

While the total number of sighting reports that were intersected by a ferry route represents a small proportion of the total sightings, the proportion of ferry routes that did intersect with a sighting is substantial (approximately 77 percent). Consistent with this finding, many of the public sightings were reported by Washington State ferry staff or passengers. The overlap between whale distribution and ferry routes suggest an increasing potential for collisions between ferries and humpback whales. One such collision occurred in May 2019 involving a juvenile humpback whale and a Washington State ferry in Elliot Bay. This collision was presumed to be fatal based on the vessel speeds and the observed injury (NMFS Stranding Data, unpublished). A humpback whale was struck by a Washington State Ferry near Whidbey Island in July 2020. The whale was seen with injuries at the surface, but was not re-sighted since the incidence and the whale it was traveling with has been relocated alone, indicating that the strike was likely fatal (CRC 2020).

This dataset does not include all of the private or passenger-only ferry routes in the study area. Nor does it distinguish between the slower moving ferries and the Kitsap "fast ferries". These ferries can travel at speeds of up to 38 knots compared with automobile and passenger ferries that travel at top speeds of 16 to 18 knots (Friedrich, 2017; WSDOT, no date). A collision at these faster speeds would likely cause a serious injury or a fatality. As the human population in the Salish Sea continues to grow and the ferry system expands to meet increasing demand, it will be important to continue to and further examine the potential for overlap between humpback whales and ferry routes. Washington State Ferries, in an effort to avoid collision with any of the many cetaceans that occupy the inland waters, has adopted the Whale Report Alert System that provides operators with real time updates on cetacean sightings (WSDOT, 2019). While this effort was driven by the desire to avoid impacts to SRKW, it has the potential to help avoid collisions with humpback whales, too. However, it will still be difficult for operators to avoid striking humpback whales when it is dark or when weather limits visibility. The ferry involved in the July 2020 strike responded to notifications of the presence of humpback whales by decreasing its speed to approximately 7 knots. However, even at this slow speed the ferry was unable to avoid striking the whale as it surfaced suddenly in front of the ferry. It appears that even at this slower speed the strike was fatal.

Traffic Separation Scheme

Previous studies have focused on the risk of vessel strikes in coastal waters (Nichol et al. 2017; Rockwood et al. 2019) and at the mouth of the Strait of Juan de Fuca, but have not focused on the inland waters. The sightings bias towards inland waters may also cause the risk at the mouth of the strait to be underrepresented in the overlap analysis. In 2019, NMFS consulted on the renewal of the TSS by the U.S. Coast Guard and determined that the renewal did not pose a risk for humpback whales (NMFS, 2019c). However, the degree of overlap between the sightings and the traffic lanes indicates that vessels transiting in the lanes may pose a risk to the species. As the ports in the Salish Sea seek to expand operations, such as the expansion project at the Port of Vancouver (Hixson, 2020), vessel traffic is likely to continue to increase. Regulators, managers, and vessel operators may need to extend the use of the Whale Report Alert System that the ferries use or create their own reporting and alert system.

In 2017, the Port of Vancouver implemented the ECHO Project, a voluntary vessel slowdown trial in Haro Strait to minimize the noise impacts to SRKW. This voluntary program has been implemented again for each following summer since the trial in Haro Strait and the Boundary Pass with a high participation rate (approximately 87 percent of transits) (Vancouver Fraser Port Authority, 2019). While this program is aimed at reducing noise impacts on SRKW, the speed reduction to 11 knots or less also decreases the risk of serious or lethal vessel strikes to humpback whales that utilize these areas. In June 2020, the Vancouver Fraser Port Authority implemented a voluntary lateral displacement program for tugboats in the Strait of Juan de Fuca to move vessels outside of the enhanced management area (EMA) that runs along the shoreline (Vancouver Fraser Port Authority, 2020b). It is not clear at this time if the movement of tugboats towards the center of the Strait will increase the risk of vessel strike of humpback whales.

Large Vessel Traffic

Shipping traffic has been increasing and will continue to increase as the Salish Sea ports expand. It is clear that humpback whales and shipping vessels both transit the continental shelf as they move along the Washington coast. This overlap may result in an increase in vessel strikes as the numbers of vessels and humpback whales continue to rise in the area. Based on models, Nichol et al. (2017) found the western portion of the Strait of Juan de Fuca to be a relatively high-risk area for humpback vessel strikes, along with areas near the shelf edge off Vancouver Island, and within the Strait itself. The large number of vessel transits examined support the finding of Nichol et al. (2017), with a concentration of vessel track intersections at the mouth of the strait. For cargo and tanker vessels, the area of risk extends south into the Washington coastal waters.

Cargo ships represent the largest portion of the shipping traffic in the region and travel at faster speeds than some other vessels, with only 147 out of the 7,299 transits traveling at speeds of less than or equal to 10 knots. Previous studies have found a positive relationship between vessel speed and the lethality of vessel strikes, although collisions at slower speeds of 2 to 5.5 knots may still cause serious injuries (Conn and Silber, 2013). Vanderlaan and Taggart (2007) found that strikes at or above 15 knots have a greater than 80 percent chance of resulting in a fatality. Only when speeds drop below 11.8 knots does the chance of a lethal strike drop below 50 percent. The average speed of vessels as they transit along the Washington coast and into the Strait of Juan de Fuca may be putting humpback whales at increased risk of a serious or fatal strike. The three vessel types examined in this study had a combined speed range between the first and third quartile of 11.2 to 15.2 knots, with a median speed of 12.7 knots. These vessels had a maximum transit speed of 24.4 knots. Given these speeds and the large number of transits, managers of the Salish Sea may need to look into strategies to reduce vessel speeds and the associated risk of lethal vessel strikes.

One attempt to slow vessel speeds to prevent whale strikes was made by NMFS in the Northeast to protect the North Atlantic Right Whale (NARW). There were only 300 NARW in 2004, with ship strikes causing one third of all NARW mortalities (Bone et al. 2016). To address this, NMFS promulgated a ship speed rule for all vessels 65 feet or greater, limiting vessel speed to 10 knots or less when within areas of NARW seasonal use (NMFS 2012). Initial compliance with the regulation was low but following increased enforcement and communication efforts, including publicly identifying entities that did not comply with the speed regulation, compliance increased substantially. NMFS issued fines up to $25,000 to 26 operators/companies for violating the speed regulation (Silber et al. 2014). The average delay for vessels that slowed down was 22 minutes and the regulation had a $19.6 million direct impact on the shipping industry due to delays and vessel operating costs (Nathan Associates Inc. 2012). The rule resulted in an 80-90 percent decrease in the number of fatal strikes on NARW (Conn and Silber 2013).

Another approach at reducing vessel strikes was implemented in the Santa Barbara Channel to protect a variety of large whale species, especially endangered blue whales. In 2014, the Channel Islands National Marine Sanctuary (CINMS), National Marine Sanctuary Foundation (NMSF), the Santa Barbara County Air and Pollution Control District (SBCAPCD), and the Environmental Defense Center (collectively all called the partners) conducted a vessel speed reduction trial that provided a subsidy for vessel trips that participated in a voluntary slowdown. Companies applied to participate before the season began and 27 vessels traveled through the channel at a speed of 12 knots or less without incident (Bone et al. 2016). The partners were able to provide an incentive payment of $1,500 to $2,500 for each participating trip, with an additional incentive of $1,250 if the speed was reduced to 10 knots or less and the vessels helped to report sightings of whales on their transit (NMSF 2017). The trial was implemented again for 2016 through 2019. In 2018 and 2019 a change was made to divide speed reductions into three categories with incentive payouts ranging from $5,000 to $75,000 to participating companies. The program resulted in a total payout of $242,000 to participating companies in 2018 (SBCAPCD 2019). While participation has increased and vessels have slowed, it is not clear yet what impact the voluntary program has had on reducing vessel strikes due to the rarity of documenting strikes.

The most effective conservation measures may require more severe changes, such as altering the shipping lanes and routes to avoid areas of whale concentrations. The OCNMS already has a designated Area to be Avoided along the Washington coast to protect marine resources and monitors for vessel compliance. This area had an average compliance rate of 96.1 percent for 2016 through 2018 (OCNMS 2018b). In areas where it may not be possible to relocate the shipping lanes, such as the entrance to the Strait of Juan de Fuca, vessel speed reductions may be necessary to reduce the risk of strike. Implementing a reporting system, such as Whale Spotter, or expanding the Whale Report Alert System to the outer coast, may help by allowing vessel operators to report sightings of humpback whales, or other large cetaceans, so that other vessels transiting through the area are aware. Another option may be to place a marine mammal observer on these vessel transits to help prevent strikes (Flynn and Calambokidis, 2019). As the number of whales utilizing the area continues to increase, so does the need to take preventative measures. On July 29, 2020 a juvenile humpback whale carcass washed up at Ocean Shores with injuries consistent with a vessel strike[3]. It is clear that vessel strikes are occurring, but we may be unaware of the extent of the problem given the low likelihood that a carcass is discovered.

Proposed Critical Habitat

The critical habitat proposed for Washington covers an area of high use by humpback whales. While the area covers only 5 percent of the total humpback whale sighting reports in the Salish Sea and coastal waters, a large portion of the sightings not covered are located outside of NMFS's jurisdiction. Removing the sightings from Canadian waters and examining only sightings with 3 or more whales magnified the high use of the coastal waters and the western portion of the Strait. Generally, humpback whales are solitary individuals, but may be found in pairs especially within their summer feeding grounds. The vast majority of humpback whale

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[3] This was a difference whale than the one involved in the ferry strike in July 2020. Retrieved from https://www.cascadiaresearch.org/washington-state-stranding-response/humpback-whale-washed-near-ocean-shores-was-killed-apparent-ship

sighting reports in the Salish Sea report only 1 individual, but some reports may include up to 80 individuals. Of the multiple humpback whale reports located within the U.S., 34.1 percent were located within the proposed critical habitat. The data show clear grouping of the multiple whale reports within the proposed critical habitat, especially within the Strait of Juan de Fuca portion. The total number of whales reported in these multiple humpback whale reports is 2,293. Of these humpback whales, approximately 41.2 percent were sighted within the bounds of the critical habitat. This further confirms that the critical habitat proposed covers an area of importance to humpback whales. However, the analysis also showed that there was a smaller concentration of sightings with 3 or more whales per report in the Eastern Basin. The geographical analysis signals that NMFS's proposed critical habitat extent does capture large numbers of humpback whales, supported by the scientific surveys of the Straits and the outer coast, but it excludes some of the lower density areas where whale watch boats operate and where members of the public are more likely to view whales, which may become more important if humpback whale populations continue to expand into the Salish Sea. The high use area in the eastern part of the Strait of Juan de Fuca may be caused in part by a sightings bias as this area is the most popular portion of the strait for whale-watching vessels to visit.

NMFS addressed the exclusion of the eastern portion of the Strait of Juan de Fuca in the draft Biological Report citing a bias from whale watching vessels and recreational boaters reporting sightings within the Eastern Basin (NMFS, 2019a). The large number of sighting reports in the inland waters is partially due to a bias caused by the ease of viewing humpback whales there. Moreover, whale-watch operations will return to areas where they have previously seen whales that are as close to their port as possible to minimize transit times. The proposed critical habitat does cover areas of high use identified by models, such as that of Becker et al. (2016). However, the Strait of Juan de Fuca appears to be used by hundreds of humpback whales during the summer (NMFS, 2019a). The analysis of multiple whales per report is an attempt to limit the sightings bias and suggests that there may be high use areas in the Eastern Basin. Continued dedicated scientific surveys may help to further distinguish whether this high use area is related to a sighting bias and/or duplicate sightings of groups of whales. The boundaries of the proposed critical habitat strongly overlap with the CRC and SR3 survey tracks that resulted in the most humpback whale sightings (Figures 2 and 10). The few survey tracks that extent into the eastern portion of the Strait of Juan de Fuca and up to the San Juan Islands resulted in few humpback whale sightings. However, more survey efforts of the inland waters are necessary to understand how humpback whales are using these waters.

An additional issue with proposing critical habitat within the inland waters relates to which humpback whale DPSs are using the area. NMFS may only provide critical habitat for listed species. Because unlisted Hawaii DPS humpbacks represent approximately 63.5 percent of humpback whales using the area (Wade, 2017), critical habitat may not be needed for listed humpbacks in the inland waters. Further studies on humpback whale DPS use of the inland waters would be needed to determine the necessity of inland critical habitat.

While the proposed critical habitat would provide additional protections to humpback whales within the Salish Sea, the species is already protected under both the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA), requiring NMFS to consult on any federal action (actions taken by a federal agency including agency projects, project approvals, or project funding) to ensure that the action will not jeopardize the continued existence of protected species or harm marine mammals. Additionally, SRKW critical habitat already exists for the inland waters (79 FR 69054; November 29, 2006), which provides additional protections for the Salish Sea ecosystem through additional analysis of project impacts. While SRKW and humpback whales are differentially impacted by vessel actions, actions taken to protect SRKW may provide some protection for humpback whales.

Conclusion

Humpback whale populations are continuing to recover globally, with NMFS determining that the majority of DPSs are large enough to no longer require listing under the ESA. The increase in humpback whale sightings over the past decade show that humpbacks are returning to the Salish Sea and re-occupying areas they inhabited before they were harvested in large numbers. As humpbacks return to areas like the Salish Sea or the San Francisco Bay, they are exposed to new risks. Increases in human populations along the coast and especially surrounding bays and estuaries are changing the way shorelines are structured and how the waters are used. Nearshore development may alter the distribution of humpback prey species, leading to changes in how humpback whales use inland areas. Finer resolution mapping with better coverage of the Salish Sea and efforts to minimize potential sightings biases are needed to better predict where humpback whales may be found in the inland waters.

This analysis also examined the risk to humpbacks from various vessel interactions in the Salish Sea. As the shipping industry continues to expand, the number of interactions between large vessels and humpback whales will also increase, likely resulting in fatal vessel strikes, both in the coastal waters and within the inland waters. The increased traffic of several types of vessels within the Salish Sea will also likely result in dangerous interactions with humpback whales, as exemplified by the presumed lethal strikes by the ferries in 2019 and 2020. The inclusion of a larger portion of the Strait of Juan de Fuca in the proposed critical habitat may help to mitigate some of this risk, but is unlikely to eliminate it.

As humpback whales have returned to the area, the interest in viewing them by the public and commercial whale-watch companies has also greatly increased, especially as viewing opportunities of the SRKW have become scarce. There currently are no regulations on the distance vessels must keep between them and a humpback whale within the Salish Sea. The Be Whale Wise guidelines recommend maintaining a distance of 100 yards, transiting at speeds of 7 knots or slower, and limiting viewing of an individual to 30 minutes (Be Whale Wise, 2019). Commercial whale watching vessels have begun to use "whale warning" flags to signal to other vessels, especially recreational boaters, transiting through the area that there is one or more whale in the vicinity. NMFS has enacted a law requiring vessels to remain a minimum of 100 yards away from humpback whales in Hawaii and Alaska waters (NOAA Fisheries, no date). As the interest and reliability grows, NMFS may need to consider implementing similar regulations to protect humpback whales.

While the sightings data do indicate a high use area in the Eastern Basin, further research is needed to determine whether this is due to an increase in use by the whales or is the result of a public sightings bias due to proximity to more populous areas. Calambokidis and Barlow (2020) estimated that the Washington and Southern British Columbia feeding group includes at least

900 individuals. Continued scientific surveys of the inland and coastal waters are essential to determine which whales are using the waters and to further elucidate where the whales are going and what risks this exposes them to.

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