Agenda Item G.4.a
NMFS Report 4
June 2021

Estimated Humpback Whale Bycatch in the U.S. West Coast Groundfish Fisheries, 2002 - 2019

M. Bradley Hanson[1], Thomas P. Good[1], Jason E. Jannot[2], and Jason Eibner[2]
Northwest Fisheries Science Center National Marine Fisheries Service,
NOAA 2725 Montlake Blvd. E. Seattle, WA 98112

2021-05-24

Table of Contents

[1] Conservation Biology Division

[2] Fishery Resource Analysis Monitoring Division

Executive Summary

In accordance with the National Marine Fisheries Service (NMFS) Biological Opinion (BiOp) on Continuing Operation of the Pacific Coast Groundfish Fishery, this document provides a summary of observed bycatch of U.S. Endangered Species Act (ESA)-listed humpback whales (*Megaptera novaeangliae*; Borowski, 1781) in sectors of the west coast groundfish fishery from 2002–2019.

There have been two documented takes of a humpback whale in the Pacific Coast groundfish fisheries – one in the Limited Entry (LE) sablefish pot fishery sector in 2014 and one in the Open Access Fixed Gear pot fishery sector in 2016. Despite the low numbers reported in federally-observed West Coast groundfish fisheries, pot and trap fisheries in general represent the majority of documented fishery interactions with humpbacks along the U.S. West Coast. We used Bayesian procedures to estimate mean annual fleet-wide bycatch and a running 5-year fleet-wide average in two West Coast groundfish pot sectors. The estimated fleet-wide entanglements/takes in the combined LE Sablefish and Open Access Fixed Gear pot sectors were not above the 5-year running average threshold (2.34/year). While the estimate for the OA Fixed Gear pot sector is higher than the estimate for the LE Sablefish pot sector, neither sector alone nor combined exceeded this threshold in recent years,.

Acknowledgements

The authors gratefully acknowledge the hard work and dedication of observers from the West Coast Groundfish Observer Program and the At-Sea Hake Observer Program, as well as contributions from observer program staff. This document was a joint effort of the Marine Mammal Bycatch Reporting Team, which included at various times and in various roles, Jason Jannot (NWFSC, WCGOP), Vanessa Tuttle (NWFSC, ASHOP), Brad Hanson (NWFSC, CBD), Eric Ward (NWFSC, CBD), Jim Carretta (SWFSC, MMTD), Karin Forney (SWFSC, MMTD), Robyn Angliss (NMML), Teresa Mongillo (WCRO, PRD), and Strandings Network Coordinators: Kristin Wilkinson, Brent Norberg, Justin Viezbicke, and Justin Greenman.

Introduction and Background[3]

In accordance with the National Marine Fisheries Service (NMFS) Biological Opinion Regarding the Effects of the Continued Operation of the Pacific Coast Groundfish Fishery (NMFS 2012a, 2020) as governed by Pacific Coast Groundfish Fishery Management Plan, this document provides a reporting of observed takes of U.S. Endangered Species Act-listed humpback whales (*Megaptera novaeangliae*; Borowski, 1781) in U.S. west coast groundfish fishery sectors. This report updates assessments submitted in accordance with the Biological Opinion requirement, which reported on bycatch in the fisheries for 2010-2013, 2014-15, and 2016-2017 (Hanson et al. 2015, 2017, 2019).

Humpback whales are baleen whales of the family Balaenopteridae. Humpback whales are found in all oceans of the world with a broad geographical range from tropical to temperate waters in the northern hemisphere and tropical to arctic waters in the southern hemisphere. All populations migrate seasonally between winter calving and breeding grounds and summer feeding grounds within ocean basins. Despite this potential for dispersal, interbreeding of individuals from different major ocean basins is extremely rare. Whales from the major ocean basins are differentiated by reproductive seasonality, behavior, color patterns, and genetics.

Humpback whales were listed worldwide as endangered under the ESA in 1970, and a Recovery Plan was finalized for this species in 1991 (NMFS 1991). Under the MMPA, humpback whales are classified as a strategic stock and considered depleted. In 2009, NMFS initiated an ESA status review of humpback whales ("Endangered and Threatened Species; Initiation of a Status Review for the Humpback Whale and Request for Information (Notice)". Federal Register 74: 154 (Aug. 12, 2009) p.40568) and produced a status review (Bettridge et al. 2015) that identified distinct population segments (DPS) of humpback whale and evaluated their risk of extinction. In September 2016, NMFS issued a final rule revising the listing status of the species (81 FR 62259), in which 14 distinct population segments were identified. Of these, nine did not warrant listing under the ESA, four were listed as endangered, and one was listed as threatened. In the North Pacific, there are four discrete and significant DPS, identified by breeding location: *Hawaii*, *Central America*, *Mexico*, and *Western North Pacific*. Humpback whales found off the Oregon, Washington, and California coast are from the Central America, Mexico and Hawaii DPS (Barlow et al. 2011). Only the Mexico DPS and Central America DPS are listed, as threatened and endangered, respectively.

Breeding locations in the North Pacific are more geographically separated than feeding areas and include regions offshore of Hawaii, Central America; the west coast of Mexico, and the Ogasawara and Okinawa Islands and the Philippines. Feeding areas in the North Pacific range from California, USA to Hokkaido, Japan, with most feeding occurring in coastal waters. Humpback whales in the North Pacific rarely move between these breeding

---

[3] This section is adapted from the NOAA Fisheries Humpback Whale Status Review; for details, see Bettridge et al. (2015).

regions. Strong fidelity to both feeding and breeding sites has been observed but movements are complex (Calambokidis et al. 2008; Barlow et al. 2011). In general, Asia and Mexico/Central America are the dominant breeding areas for humpback whales that migrate to feeding areas in lower latitudes and coastal California and Russia. The Revillagigedo Islands and Hawaiian Islands serve as wintering areas for humpback whales that feed in the more central and higher latitude areas (Calambokidis et al. 2008). Exceptions to this pattern exist, and complex population structure and strong site fidelity appear to coexist with lesser known, but potentially high, levels of plasticity in the movements of humpback whales (Salden et al. 1999).

The Hawaii DPS is composed of humpback whales that breed within the main Hawaiian Islands. Whales from this DPS use most known feeding grounds in the North Pacific; half migrate to feeding grounds in southeast Alaska and northern British Columbia, with many also using northern Gulf of Alaska and Bering Sea feeding grounds. The Central America DPS is composed of humpback whales that breed along the Pacific coast of countries in Central America. Whales from this DPS feed almost exclusively offshore of California and Oregon in the eastern Pacific, with a few individuals in the northern Washington-southern British Columbia feeding grounds. The Mexican DPS is composed of humpback whales that breed along the Pacific coast of mainland Mexico, Baja California, and the Revillagigedo Islands. Whales from this DPS feed across a broad geographic range from California to the Aleutian Islands, with concentrations in California-Oregon, northern Washington-southern British Columbia, northern and western Gulf of Alaska and Bering Sea feeding grounds. The Western North Pacific DPS is a combined DPS composed of humpback whales that breed/winter around Okinawa and the Philippines (Okinawa/Philippines DPS) and a second population that transit the Ogasawara area but breed in an unknown location (Second West Pacific DPS). Whales from the Okinawa/Philippines DPS portion migrate to feeding grounds in the northern Pacific, primarily off the Russian coast, while whales from the Second West Pacific DPS are linked to the Aleutian Islands feeding grounds.

A recent analysis of genetic variation in >2000 humpback whales found support for DPS designation in substantial level of genetic divergence among breeding areas at the mtDNA control region (Baker et al. 2013). For example, humpback whales in Central America have a unique mtDNA signature (Baker et al. 2008a; Baker et al. 2008b). The Hawaii population is separated from distant but neighboring populations in both frequencies of mtDNA haplotypes and nDNA (microsatellite) alleles (Baker et al. 2013). In Mexico, mtDNA haplotype frequencies in mainland and Revillagigedo Islands humpback populations were not significantly different (Baker et al. 2013) and were thus considered a single population.

Recent population and abundance estimates for the west coast are summarized in Carretta et al. (2018b). Recent humpback whale abundance estimates for the entire North Pacific and have ranged from 18,302 (Calambokidis et al. 2008) to 21,808 individuals (Barlow et al. 2011); the latter estimate may still be an underestimate of actual humpback whale abundance. For the lower estimate, whale populations in breeding areas have been estimated at 10,000 individuals in Hawaii, 500 for Central America, 6,000-7,000 animals in Mexico, and 1,000 for the Western Pacific, for a total of 17,500-18,500. Barlow et al. (2011) did not apportion the 21,808 individuals to breeding areas, but the proportions are likely to be similar to those estimated by Calambokidis et al. (2008). Barlow (2016) recently estimated 3,064 (CV= 0.82) humpback whales from a 2014 summer/fall ship line-transect survey of California, Oregon, and Washington waters.

Growth rates have been calculated on regional scales and include ~8%/year for the U.S. West Coast (1991-2008; Calambokidis 2009), 6.6%/year for the Alaskan Peninsula and Aleutian Islands (2001-2003; Zerbini et al. 2010), and 10.6%/year in southeast Alaska (1991-2007; Dahlheim et al. 2009), 5.5-6.0%/year for Hawaii and 6.7%/year in the western Pacific (1990- 1993, NPAC and 2004-2006, SPLASH; Calambokidis et al. 2008). More recent estimates show a possible leveling-off of the population, depending on the choice of model and time frame used (Calambokidis et al. 2017).

Humpback whales face a variety of threats, depending on the region in which they occur. Threats listed in the Recovery Plan include entrapment and entanglement in fishing gear, collisions with ships, acoustic disturbance, habitat degradation, and competition for resources with humans (NMFS 1991). Climate change and ocean acidification are also global threats to marine ecosystems that could indirectly affect humpback whales via trophic dynamics and available prey. Globally, entrapment and entanglement in fishing gear and collisions with ships represent most of the reported and observed serious injuries and mortalities for the species (review in Carretta et al. 2014b). The number of human-related deaths and injuries for each humpback whale feeding group are unknown, but based on the proportion of the overall abundance (2,900 whales) belonging to the California-Oregon (82%) and Washington and southern British Columbia (18%) feeding groups, a majority of cases likely involve whales from the California- Oregon feeding group that includes nearly all of the Central American DPS (Carretta et al. 2018b). Entanglement data are available for most stocks of humpback whales worldwide. These entanglements result from humpback whale interactions with a variety of fisheries and gear types and generally result in some level of serious injury and mortality. The absolute number of humpback whale entanglements is likely under-represented by these data, in part because observer programs and stranding networks do not exist in many parts of the world.

Threats from Fishing Gear Entanglements

Humpback whales may break through, carry away, or become entangled in fishing gear. Whales carrying gear may later die, become debilitated or seriously injured, or have normal functions impaired, all without having been recorded. Of nations reporting to the IWC, 64.7% (n=11) reported humpback whale bycatch from 2003-2008 (Mattila and Rowles 2010). Some countries (e.g., U.S., Canada, Australia, South Africa) have well-developed reporting and response networks collecting information on entanglements. Still, <10% of humpback whale entanglements in the Gulf of Maine are reported, despite strong outreach and a response network (Robbins and Mattila 2004). For whales off the U.S. East Coast, 89% of removed gear was pots/traps or gillnet gear, although other gear types were observed (Johnson et al. 2005). A wide range of entangling gear has also been reported in the South Pacific (Neilson 2006; Lyman 2009), Newfoundland (Lien et al. 1992) and by the IWC (Mattila and Rowles 2010). In the North Pacific, entanglement is pervasive but highest among coastal populations (Robbins et al. 2007a; Robbins 2009).

Entanglement may result in only minor injury, or potentially may significantly affect individual health, reproduction or survival. Studies of the fate of entangled whales in the Gulf of Maine suggest that juveniles are less likely than adults to survive (Robbins et al. 2008), and observed entanglement deaths and serious injuries in that region are known to exceed what is considered sustainable for the population (Glass et al. 2009). Most deaths likely go unobserved and preliminary studies suggest that entanglement may be responsible for 3-4% of total mortality, especially among juveniles (Robbins et al. 2009).

Much more is known about fishing gear entanglement in the Northern Hemisphere than in the Southern Hemisphere. Off Japan, an entangled whale is legally allowed to be killed and sold on the market (Lukoschek et al. 2009), so entanglement often leads to death for humpback whales in this region. While the number of reported bycaught animals is not large, the number of reports has been increasing and may underestimate the actual number caught. The Mexico population has one of highest scar rates from nets and lines in the North Pacific, indicating a high entanglement rate (Bettridge et al. 2015). Based on this information, the severity of the threat of fishing gear entanglements varies among regions and ranges from low to high.

Entnanglement Threat for Hawaii DPS

Studies indicate that the Hawaii DPS experiences a high rate of interaction with fishing gear (20-71%), with the highest rates recorded in southeast Alaska and northern British Columbia (Neilson et al. 2009). Fatal entanglements of humpback whales in fishing gear have been reported in all areas, and observed fatalities are almost certainly under-reported. Studies in another humpback whale feeding ground, which has similar levels of scarring, estimate that the actual annual mortality rate may be as high as 3.7% (Angliss and Outlaw 2008). The level of threat from fishing is considered medium and is not expected to significantly diminish population growth.

Entnanglement Threat for Central America DPS

Vessel collisions and entanglement in fishing gear pose the greatest threat to this population, especially off Panama, southern California, and San Francisco. Between 2004 and 2008, there were 18 reports of humpback whale entanglements in commercial fishing gear off California, Oregon, and Washington (Carretta et al. 2010), and the actual number of entanglements may be higher. Effective fisheries monitoring and stranding programs exist in California, but are lacking in Central America and much of Mexico. Levels of mortality from entanglement are unknown, but entanglement scarring rates indicate a significant interaction with fishing gear. The Central America DPS is therefore considered to be at moderate risk of extinction over the next three generations.

Entnanglement Threat for Mexico DPS

Of the 17 records of stranded North Pacific humpback whales in the NMFS stranding database, three involved fishery interactions, two were attributed to vessel strikes, and in five cases the cause of death could not be determined (Carretta et al. 2011). Specifically, between 2004 and 2008, 14 humpback whales were reported seriously injured in commercial fisheries offshore of California and two were reported dead. What proportion of these represent the Mexican breeding population is unknown, but the fishing gear involved included gillnet, pot, and trap gear (Carretta et al. 2010). The Mexico DPS is considered to be "not at risk" of extinction, although some voted for "moderate risk" reflect the threat of entanglement among other threats.

Entnanglement Threat for Western North Pacific DPS

Whales along the coast of Japan and Korea are at risk of entanglement related mortality in fisheries gear, although overall rates of net and rope scarring are similar to other regions of the North Pacific (Brownell et al. 2000). The threat of mortality from such entanglement is high given the incentive for commercial sale allowed under Japanese and Korean legislation (Lukoschek et al. 2009). The reported number of humpback whale entanglements/deaths has increased for Japan since 2001 due to improved reporting, although the actual number of entanglements may be underrepresented in both Japan and Korea (Baker et al. 2006). The level of confidence in understanding the minimum magnitude of this threat is medium for the Okinawa/Philippines DPS and low for the Second West Pacific DPS, given the unknown wintering grounds and primary migratory corridors.

Fishing gear entanglements are considered likely to moderately reduce the population size or the growth rate of the Hawaii, Central America, and Mexico DPSs and are likely to seriously reduce the population size or the growth rate of the Western North Pacific [Okinawa/Philippines] DPS.

U.S. West Coast Groundfish Fisheries

The west coast groundfish fishery (WCGF) is a multi-species fishery that utilizes a variety of gear types. The fishery harvests species designated in the Pacific Coast Groundfish Fishery Management Plan (PFMC 2011) and is managed by the Pacific Fishery Management Council. Over 90 species are listed in the groundfish FMP, including a variety of rockfish, flatfish, roundfish, skates, and sharks. These species are found in both federal (> 5.6 km off-shore) and state waters (0-5.6 km offshore). Groundfish are both targeted and caught incidentally by trawl nets, hook-&-line gear, and fish pots.

Under the FMP, the groundfish fishery consists of four management components:

- The Limited Entry (LE) component encompasses all commercial fishers who hold a federal limited entry permit. The total number of limited entry permits available is restricted. Vessels with an LE permit are allocated a larger portion of the total allowable catch for commercially desirable species than vessels without an LE permit.
- The Open Access (OA) component encompasses commercial fishers who do not hold a federal LE permit. Some states require fishers to carry a state-issued permit for certain OA sectors.
- The Recreational component includes recreational anglers who target or incidentally catch groundfish species. Recreational fisheries are not covered by this report.

- The Tribal component includes native tribal commercial fishers in Washington State that have treaty rights to fish groundfish. Tribal fisheries are not included in this report, with the exception of the observed tribal at-sea Pacific hake (*Merluccius productus*) (also known as whiting) sector.

These four components are further subdivided into sectors based on gear type, target species, permits and other regulatory factors (see Appendix 3). The analyses in this report focus on data from the Limited Entry (LE) fixed gear pot sector and the Open Access Fixed gear pot sector..

Northwest Fisheries Science Center Groundfish Observer Program

The NWFSC Groundfish Observer Program's goal is to improve estimates of total catch and discard by observing commercial sectors of groundfish fisheries along the U.S. west coast that target or take groundfish as bycatch. The observer program has two units: the West Coast Groundfish Observer Program (WCGOP) and the At-Sea Hake Observer Program (A-SHOP). The WCGOP Program was established in May 2001 by NOAA Fisheries (a.k.a., National Marine Fisheries Service, NMFS) in accordance with the Pacific Coast Groundfish Fishery Management Plan (50 CFR Part 660) (50 FR 20609). This regulation requires all vessels that catch groundfish in the US EEZ from 3-200 miles offshore carry an observer when notified to do so by NMFS or its designated agent. Subsequent state rule-making has extended NMFS's ability to require vessels fishing in the 0-5.6 km state territorial zone to carry observers.

The WCGOP and A-SHOP observe distinct sectors of the groundfish fishery. The WCGOP observes the following sectors: IFQ shore-based delivery of groundfish and Pacific hake, LE and OA fixed gear, and state-permitted nearshore fixed gear sectors. The WCGOP also observes several state-managed fisheries that incidentally catch groundfish, including the California halibut trawl and ocean shrimp trawl fisheries. The A-SHOP observes the IFQ fishery that delivers Pacific hake at-sea including: catcher-processor, mothership, and tribal vessels (descriptions of all of these fisheries can be found in Appendices 3 – 5). Details on how fisheries observers operate in both the IFQ (Catch Share) and Non-IFQ sectors can be found on the NWFSC website.

Humpback Whale Bycatch in West Coast Groundfish Fisheries

The primary objective of this report is to provide estimates of bycatch of humpback whales in observed U.S. West Coast federally-permitted groundfish fisheries since the last report (Hanson et al. 2019), which covered the years 2002–2017. Previous reports on marine mammal bycatch in West Coast groundfish fisheries (Jannot et al. 2018) have provided data on bycatch of humpback whales in U.S. west coast commercial fisheries.

Amount and Extent of Humpback Whale Take

The Biological Opinion Regarding the Effects of the Continued Operation of the Pacific Coast Groundfish Fishery (PCGF) (NMFS 2020) stated that:

“We anticipate that take of humpback whales would occur through entanglement with fishing gear as a result of the proposed continued operation of the PCGF, specifically with sablefish pot fishing gear…Our expectation is that information on the amount and extent of humpback whales incidentally taken in the PCGF will come primarily from the bycatch estimates produced by the NWFSC and Endangered Species Workgroup. Secondarily, opportunistic reports of humpback whale entanglements reported to the NMFS WCR Marine Mammal Stranding Program will be available to help ground truth these estimates, especially as a potential indicator of obvious discordance between estimated and known actual incidents of bycatch…Using this information, if more than 5 humpback whales are observed or estimated to have been incidentally captured in the PCGF in any one year, or if the 5-year running average of humpback whale bycatch exceeds 2.34 per year, then we would conclude that the incidental take of ESA-listed Mexico DPS and/or Central America DPS humpback whales would have been exceeded.”

This biennial report represents the fulfillment of reporting on estimated humpback whale take and associated other reporting requirements.

Methods

Data Sources

Data sources for this analysis include onboard observer data from the WCGOP landing receipt data, referred to as fish tickets, and electronic monitoring (EM) data. Fish ticket and EM data were obtained from the Pacific Fisheries Information Network (PacFIN).

NWFSC Observer Program Data

A list of fisheries, coverage priorities and data collection methods employed by WCGOP in each observed fishery can be found in the WCGOP training manual (NWFSC 2021). A-SHOP information and documentation on data collection methods can be found in the A-SHOP sampling manual (NWFSC 2020).

The sampling protocol employed by the WCGOP is primarily focused on the discarded portion of catch. To ensure that the recorded weights for the retained portion of the observed catch are accurate, haul-level retained catch weights recorded by observers are adjusted based on trip-level fish ticket records. This process is described in detail in the annual groundfish mortality report (Somers et al. 2020a). Data processing was applied prior to the analyses presented in this report. For a list of all of the groundfish species defined in the Pacific Coast Groundfish Fishery Management Plan see PFMC (2020).

Fish Ticket Data

For bycatch estimation, the landed amount of a particular fish species or species group is used as the effort metric. Thus, the retained landing information from sales receipts (known as fish tickets) is crucial for fleet-wide total bycatch estimation for all sectors of the commercial groundfish fishery on the U.S. west coast. Fish ticket landing receipts are completed by fish-buyers in each port for each delivery of fish by a vessel. Fish tickets are trip-aggregated sales receipts for market categories that may represent single or multiple species. Fish tickets are issued to fish-buyers by a state agency and must be returned to the issuing agency for processing. Fish tickets are designed by the individual states (Washington, Oregon, and California) with slightly different formats by state. In addition, each state conducts species-composition sampling at the ports for numerous market categories that are reported on fish tickets. Fish ticket and species-composition data are submitted by state agencies to the PacFIN regional database.

Annual fish ticket landings data, with state species composition sampling applied, were retrieved from the PacFIN database and subsequently divided into various sectors of the groundfish fishery. Observer and fish ticket data processing steps are described in detail in Appendix B of the annual groundfish mortality report (Somers et al. 2020a). All data processing steps specific to this report are described in the bycatch estimation methods section below.

Designation of 'take' and 'serious injury' interactions

NMFS has established guidelines for distinguishing serious from non-serious injury of marine mammals pursuant to the Marine Mammal Protection Act through a policy directive (NMFS 2012b).

Estimating Humpback Whale Bycatch

Statistical Model

We used Bayesian time-series models to estimate annual means and variability of humpback whale bycatch. Probability-based methods are particularly useful when bycatch is dominated by zeroes; there is reduced bias from rare events, the methods incorporate uncertainty and are less reliant on assumptions. The model-based Bayesian approach also reduces volatility through its formal use of all information contained in the time series, reduces arbitrary decision-making about how many years of data to combine, and it enables probabilistic inference for bycatch and mortality within years, conditional on fishing effort (Martin et al. 2015). Bayesian time-series have been used with other rare bycatch species, including cetaceans, delphinids, pinnipeds, sea turtles, sharks, and seabirds (Jannot et al. 2018, Martin et al. 2015).

We applied Bayesian time-series models to observer program data to characterize uncertainty in humpback whale bycatch estimation in the LE sablefish pot fishery (Table 1) and Open Access Fixed Gear pot fishery (Table 2). Because only one humpback whale was documented as bycatch in each fishery sector, we were restricted to using simple statistical models while estimating variances of total bycatch.

We modeled the two fisheries separately. For each of the two models, there are three parameterization choices to be made. The first is the effort metric, of which there are three possible choices: the number of gear deployments (sets), the number of gear units (pots), or the observed mass of retained catch. The second parameter is the type of bycatch rate: a constant rate or a time-varying rate. The third parameter is the type of bycatch-generating process: Poisson or negative binomial. We compared models incorporating all combinations of the above effort metrics, bycatch rates, and bycatch-generating processes.

We use methods from the `loo` package as implemented in the `bycatch` package (Vehtari et al. 2019a, Ward 2017) to compare among models with different parameter combinations within each fishery. Final estimates are presented for each of the two fisheries from the single model that best fits the data within each fishery. Estimates from the two fisheries were summed to obtain a single estimate for both fisheries combined.

For each fishery, the base model assumed bycatch rate was constant and inferred annual expected mortality, given a specified level of effort, using a simple Poisson process model, where the total number of bycatch events were assumed to follow a Poisson distribution,

$$n_{take,y} \sim (\lambda_y = \theta \cdot E_y)$$

where:

$n_{take,y}$ = number of observed bycatch events (or take events) in year y
λ_y = mean expected bycatch
θ = estimated bycatch rate
E_y = effort in year y

The estimated bycatch rate θ is assumed constant through time, but the quantity $\theta \cdot E_y$ includes uncertainty, as θ is estimated. Thus, a time series of the mean bycatch can be generated for a given species, with a given metric of effort. All uncertainty in the time series originates from fluctuating levels of effort through time (percent observer coverage only affects the expansion). We used a Bayesian model (Martin et al. 2015) to generate mean and 95% CIs of the bycatch rate parameter, θ, as well as for the expected bycatch, $\theta \cdot E_y$.

We built upon the simplified model above with the goal of finding the model that most accurately estimates bycatch and variance within each fishery. To do that, we compared models to: (a) find the most suitable effort metric; (b) test the assumption that θ is constant through time; and (c) compare distributions (Poisson to negative binomial). For fishery there are a total of 12 possible models (three effort metrics, two rates, two distributions). To compare among these models, we used two model diagnostic tools (`Pareto-K` & `p-LOO`) and a model comparison method (`LOOIC`) from the `loo` package (Vehtari et al. 2019a) as implemented in the `bycatch` package (Ward 2017) and described in Jannot et al. (2021).

In this report, we present results from the single best model that uses the best effort metric, bycatch rate, and bycatch process, as judged by diagnostic statistics described in Jannot et al. (2021).

In the case of the LE Sablefish pot sector, all models failed to meet the threshold criteria for model diagnostics. Therefore, to reduce the model complexity and obtain comparable estimates of humpback bycatch in the LE Sablefish sector, we reverted to a constant bycatch rate and Poisson distribution (see above) and then compared among effort metrics to choose the single model that minimized all three model diagnostics.

Expanding Bycatch to Unobserved Portion of Fleet

Because observer coverage is less than 100% in some fleets, and variable through time, we need to expand the estimated bycatch, $\theta \cdot E_y$, to the fleet-wide level within each fishery. One approach for expansion would be to divide $\theta \cdot E_y$ by the percent observer coverage; however, this ignores uncertainty in the expansion. We accounted for uncertainty in the expansion by treating the observer coverage and estimated bycatch ($\theta \cdot E_y$) as known ('p', 'x', respectively) and sampling from the distribution of total bycatch (N) in proportion to the binomial density function. This process was repeated for each Markov Chain Monte Carlo (MCMC) draw, to propagate uncertainty in the estimates through the uncertainty in the expansion. Details on the implementation can be found in the *bycatch* package (Ward 2017). Five year means of the estimates were then calculated from the annual estimates for each fishery separately, as well as for the two fisheries combined.

Statistical Software

The statistical software `R` (R Core Team, 2020) was used to produce the analyses, tables, figures in this report. Specifically, we relied heavily on the `R` packages:

- *bycatch* (Ward, 2017) for modeling and simulation,
- *ggplot2* (Wickham, 2016) for plotting figures,
- *loo* (Vehtari et al. 2019) as implemented in *bycatch* for model comparisons,
- *knitr* (Xie, 2020) for tables and dynamic reporting, and
- *tidyverse* (Wickham et al. 2019) & *dplyr* (Wickham et al. 2020) for data wrangling.

Results and Discussion

Estimating Humpback Whale Bycatch

Using the statistical models described above, we estimated mean annual fleet-wide bycatch of humpback whales for 2002-2019 for the LE and OA pot gear sectors separately (see Appendices 1 and 2). Based on the annual estimates from the models, we also calculated a running 5-year average of bycatch for each sector of the two sectors separately (Figure 1, Table 5). Finally, to align with the incidental take statement in the 2020 Biological Opinion, we summed the annual estimates from the two sectors and also calculated a 5-year running average for the two sectors combined (Figure 1, Table 5).

The 2020 Biological Opinion incidental take limit of five humpback whales in any year or a 5-year running average of 2.34 were not exceeded in 2018-2019.

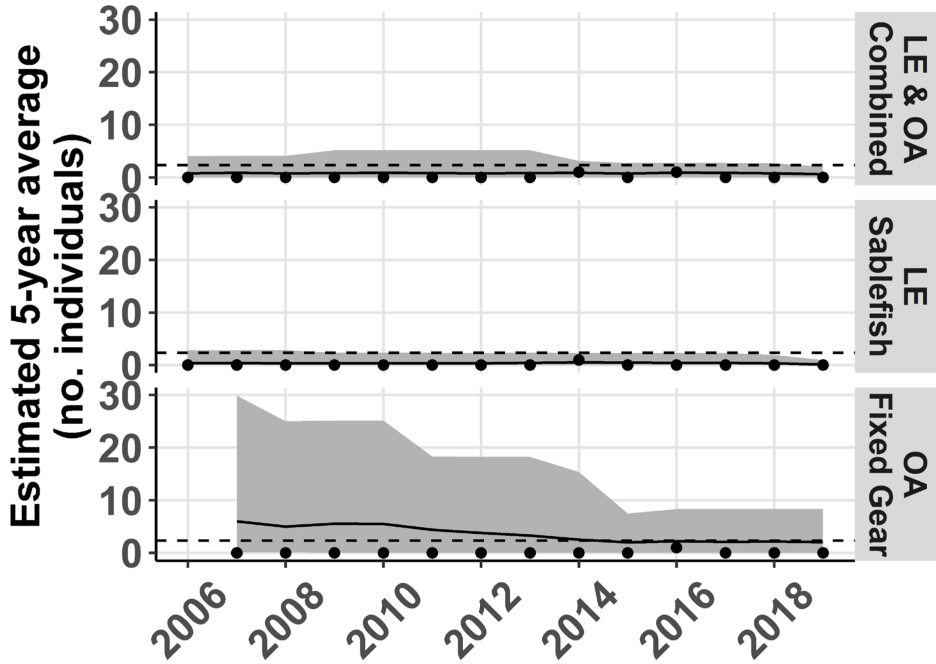

Figure 1: Estimated 5-year means for humpback whale bycatch in the Limited Entry Sablefish (LE) and Open Access (OA) Fixed Gear pot sectors combined (top), the Limited Entry (LE) Sablefish pot sector (middle), and the Open Access (OA) Fixed Gear pot sector (bottom). Black dots represent observed bycatch. Solid lines represent the estimated 5-year running mean of fleet-wide bycatch of humpback whales; gray areas represent 95% confidence limits. Dotted lines represent the 5-year incidental take limit.

Interactions with commercial fisheries likely to take humpback whales

The impact of fisheries (commercial and recreational) on the CA/OR/WA humpback whale stock is likely underestimated, since mortality or serious injury of large whales due to entanglement in gear may often go unobserved. This can occur because whales swim away with a portion of the net, line, buoys, or pots or because the entanglement may occur in a remote area of the coast or far offshore. Pot and trap fisheries in general are the most commonly documented source of serious injury and mortality of humpback whales in U.S. west coast waters (Carretta et al. 2013, 2014a,b, 2017, 2018a, 2020a), and reports have increased substantially since 2014 (Carretta et al. 2018b).

Similar to recent years, humpback whales continued to be the species with the most confirmed entanglements in 2018 (n=34; NOAA Fisheries 2019) and 2019 (n=17; NOAA Fisheries 2020). While confirmed entanglements in 2018 and 2019 were lower than the historic highs of 2015 (n=49) and 2016 (n=48), the number still represents a concerning level and continues a trend of being substantially greater than pre-2014 levels, when the average was less than 10 confirmed entanglements per year (NOAA Fisheries 2019). From 2014 to 2018, Humpback whale injuries and mortality in U.S. West Coast waters were most often reported from entanglements in pot/trap fisheries (n=87), followed by unidentified fishing gear (likely pot/trap gear; n=64), vessel strikes (n=13), and gillnet fisheries (n=8) (Appendix 4 in Carretta et al. 2020a). Documented 5-year mortality for 2013-2017, serious injury, plus prorated injury totals (i.e. entangled humpback whales with an injury score < 1) for pot/trap fisheries, in order of frequency are: California Dungeness crab pot (19.25), unidentified pot/trap fishery (7.0), Washington/Oregon/California sablefish pot fishery (2.5), California spot prawn pot fishery (2.5), Washington Dungeness crab pot fishery (1.75), Open Access Fixed Gear Pot (0.75), and Oregon Dungeness crab pot fishery (0.75)(Table 1 in Carretta et al. 2019). Three humpback whale entanglements (all released alive) were observed in the CA swordfish drift gillnet fishery from almost 9,000 sets between 1990 and 2017 (Carretta et al. 2019).

The increase in entanglements in commercial crab fisheries in recent years led the California Department of Fish and Wildlife to issue a declaration to close the California Dungeness crab fishery statewide on April 15, 2019 in all commercial fishery management zones. The closure was needed due to a greater risk of whales becoming entangled in commercial Dungeness crab pots, lines, and buoys during the spring and summer months.

The California Dungeness Crab Fishing Gear Working Group piloted the Risk Assessment and Mitigation Program (RAMP) on November 1, 2020 to assess monthly entanglement risk for humpback whales, blue whales, and Pacific leatherback sea turtles using information from confirmed entanglements and marine life density data from aerial and vessel surveys and satellite telemetry. When risk is elevated, CDFW will consult with the Working Group to implement management actions such as: fleet advisories, fishing depth constraints, vertical line reductions, fishery closures, or use of approved alternative gear.

Changes in Humpback Whale occurrence

In recent years the distribution and duration of time humpback whales stay on the feeding grounds has changed. More humpback whales have been observed in Puget Sound, the mouth of the Columbia River, San Francisco Bay, and closer to shore in general than has been observed since the end of commercial whaling (Calambokidis et al. 2017). Hydrophones and vessel surveys have also reported humpback whale detections later into the winter that has been observed in the past with some evidence that individuals may be over-wintering (Calambokidis et al. 2017). Some of the changes in whale occurrence (expansion into more peripheral habitats, greater time on feeding grounds to meet nutritional needs, and more animals overwintering or arriving early in the season) may signal reaching carrying capacity and be causing greater overlap with Dungeness crab fisheries in winter and early spring and more entanglements (Calambokidis et al. 2017). The 2014-2016 marine heat wave in the northeast Pacific Ocean changed humpback whale prey distribution and abundance, resulting in a habitat compression for the species with a coastward shift in distribution. By shifting closer to the coast, humpback whales were more likely to encounter coastal fisheries, which may have resulted in an increase in humpback whale entanglements in recent years (Santora et al. 2020). The uptick in humpback whale entanglements beginning in 2014 appears not to be due to increases in fishing activity or changes in fisheries footprints (Feist et al. 2021). However, the spatial overlap of humpbacks and crab fishery gear was intensified in 2016, when domoic acid contamination prompted an unprecedented delay in the opening of California's Dungeness crab fishery (Santora et al. 2020. Feist et al. 2021).

Status of Stock

The status of the CA/OR/WA humpback whale stock is summarized in Carretta et al. (2020b). The estimated observed annual mortality and serious injury due to commercial fishery entanglements in 2013-2017 (17.3/yr), non-fishery entanglements (0.2/yr), recreational crab pot fisheries (0.35/yr), serious injuries assigned to unidentified whale entanglements (2.1/yr), observed ship strikes (2.2/yr), represents 22.35 animals, which exceeds the PBR in U.S. waters of 16.7 animals; it is therefore not approaching zero mortality and serious injury rate. The growth rate of the CA/OR/WA stock of the North Pacific humpback whales, which consists of Hawaii, Mexico, and Central America DPS whales, has been estimated as increasing about 6-7 percent annually (Calambokidis and Barlow 2020, Carretta et al. 2020b).

Status of actions on the BiOp/RPMs and Conservation Measures

In the incidental take statement in the 2020 Biological Opinion, we included reasonable and prudent measures for management planning and take reporting that is applicable to all species considered. “Reasonable and prudent measures” are nondiscretionary measures to minimize the amount or extent of incidental take (50 CFR 402.02). “Terms and conditions” implement the reasonable and prudent measures (50 CFR 402.14). These must be carried out for the exemption in section 7(o)(2) to apply. Here we provide the reasonable and prudent measure from the 2020 Biological Opinion specific to humpback whales, followed by additional information on the status of each measure:

RPM 1: NMFS shall monitor the PCGF to ensure compliance with the regulatory and conservation measures included in the proposed action and the identified amount or extent of incidental take, including collection and evaluation of data on the capture, injury, and mortality of humpback whales.

T&C 1 for RPM 1: NMFS SFD, in cooperation with the PFMC and NMFS PRD as necessary, shall investigate the methods and feasibility associated with implementing additional pot gear marking regulations for the PCGF. The feasibility study shall consider whether additional gear marking would increase NMFS' ability to attribute humpback whale entanglements to specific fisheries and assist in identifying potential modifications to the pot gear regulations that could reduce incidental take of humpback whales. The feasibility study shall be completed by March 2023 and the findings given consideration by the PFMC for potential changes to the pot gear marking regulations by March 2024. Completion dates may be revised by mutual agreement by NMFS SFD, PFMC, and NMFS PRD. The following methods shall be evaluated, as well as any other potential methods identified by NMFS SFD, the PFMC, or NMFS PRD as part of the investigation process: a. Line marking - as an example, proposed Washington Department of Fish and Wildlife Dungeness crab regulations (October 2, 2019).* b. Additional markings on buoys/surface gear – as an example, California Department of Fish and Wildlife Commercial Trap Gear marking regulations.**	*At its April 2020 meeting, the Council made multiple recommendations regarding the humpback whale BiOp for NMFS to consider as it moves forward with satisfying the terms and conditions of the Incidental Take Statement. The Council recommended that NMFS should hold workshops with fishing industry members to develop any potential new management measures related to the humpback whales. The Council also recommended that dedicated Council meeting agenda items should be used to consider and provide input to NMFS on draft new management measures prior to finalization of any regulatory changes.* *At its April 2021 meeting, the Workgroup supported and encouraged the workshop and other efforts to get robust industry engagement.*

T&C 2 for RPM 1: NMFS SFD, in cooperation with the PFMC and NMFS PRD, shall review the Terms of Reference for the Groundfish Endangered Species Workgroup. NMFS SFD, PRD, and the PFMC will review the priority of needs associated with incidental humpback whale bycatch in the PCGF and provide any recommendations to the Workgroup. The review shall be completed by March 2021, or some other mutually agreeable date.	*The due date for this T&C was extended by mutual agreement to April 2021 to coincide with the next Groundfish Endangered Species Workgroup meeting. Prior to the Workgroup meeting, NMFS PRD, NMFS SFD, and Council Staff met to discuss if any changes to the Workgroup's terms of reference (Appendix B) were needed to comply with Term and Condition 2 from the BiOp. They concluded the terms of reference provided flexibility to address the needs of the humpback whale BiOp through development of the Workgroup agenda, and there was not an immediate/obvious need for changes to the terms of reference. The Workgroup agreed with this approach at its April 2021 meeting.*
T&C 3 for RPM 1: NMFS SFD, in coordination with the NWFSC WCGOP, shall ensure observer coverage in the PCGF's fixed gear fishery maintains the capability to provide scientifically defensible humpback whale bycatch estimates across all sectors to confirm that the take exemption for the proposed action is not exceeded. When feasible, NMFS SFD should consider observer deployment options to reduce uncertainty in humpback whale bycatch estimates and increase the understanding of the fishery dynamics in the fixed gear fishery.	*This was relayed to the WCGOP for consideration as part of their annual determination of coverage rates across various fisheries.*

T&C 4 for RPM 1: NMFS SFD, in cooperation with the PFMC and NMFS PRD as necessary, shall review and consider measures for maximizing the utility and benefit of EM with respect to gathering information from any future bycatch events of humpback whales. NMFS SFD shall complete this review and make a report of the findings available to PFMC and NMFS PRD by March 2023. Completion dates may be revised by mutual agreement by NMFS SFD, PFMC, and NMFS PRD. Factors that could be considered include, but are not limited to, the following: a. Placement of EM technology. b. Review protocols, including the amount of review and extent of analysis to be provided. c. Options for supplemental documentation and data collection.	*NMFS SFD briefed the PFMC on the Biological Opinion at the April 2021 PFMC meeting. The Council recommended NMFS consider including EM in the industry workshops noted under Term & Condition 1.*

* https://www.psmfc.org/crab/2019%20-2020%20files/letter%20to%20license%20holders_Oct%202%202019%20FINAL.pdf

** https://wildlife.ca.gov/Notices/Regulations/Marking

Section 7(a)(1) of the ESA directs Federal agencies to use their authorities to further the purposes of the ESA by carrying out conservation programs for the benefit of the threatened and endangered species. Specifically, conservation recommendations are suggestions regarding discretionary measures to minimize or avoid adverse effects of a proposed action on listed species or critical habitat or regarding the development of information (50 CFR 402.02). The following conservation recommendations replace those for humpback whales in the 2012 Opinion. Implementing these updated recommendations would provide information for future considerations of how to reduce the effects of the PCGF on Central America DPS and Mexico DPS humpback whales:

(1) Scientific tools and frameworks: To reduce real-time geographic overlap of whales and the PCGF pot fishery, which increases the entanglement risk of Central America DPS and Mexico DPS of humpback whales, NMFS should encourage the exploration and implementation of new and existing scientific tools and frameworks in coordination with the PFMC, including consideration of using: a. Near-real time environmental data streams to predict whale concentrations (e.g., Forney et al. in prep, Abrahms et al. 2019) and forage conditions (e.g., Santora et al. 2020). b. Environmental data to predict patterns of fishing effort. c. Observational/survey data and other tools to identify spatial/temporal areas of concern to avoid in a dynamic management approach.	*NMFS SFD briefed the PFMC on this conservation measure at the April 2021 PFMC meeting.* At its April 2021 meeting, the Workgroup supported potential further development of this conservation measure.
(2) Gear modifications: To reduce the severity and frequency of Central America DPS and Mexico DPS humpback whale entanglements with groundfish pot gear, NMFS should encourage the development and testing of gear modifications in coordination with the PFMC as necessary, including but not limited to: a. Weak links – as an example, see NOAA Fisheries Atlantic Large Whale Take Reduction Plan – Supplement B: Weak Links & Anchoring Techniques.11 b. Reduction of the maximum breaking strength of ropes used in the sablefish pot fishery – similar to a recent study conducted on the U.S. East Coast (Knowlton et al. 2016).12 c. Pop-up/on demand gear retrieval innovation.	*NMFS SFD briefed the PFMC on this conservation measure at the April 2021 PFMC meeting.* At its April 2021 meeting, the Workgroup supported potential further development of this conservation measure.

(3) Logbook requirements: To improve bycatch estimates for Central America DPS and Mexico DPS humpback whales and better understand the distribution of fishing effort, NMFS should complete ongoing efforts to implement a coast-wide Federal fixed gear logbook requirement for all fixed gear sectors, including pot gear. As part of this effort, NMFS should consider implementation of automated/electronic logbook reporting system that can provide comprehensive fishery effort information at fine spatial scales that could readily feed into other available data streams on whale distributions and forage conditions allowing for more rapid assessment of fishing dynamics and potential entanglement risks of the PGGF fixed gear fisheries than current approaches allow.	*In progress. NMFS is developing an electronic logbook and associated rulemaking.*
(4) To better understand fishery gear configurations and how they might contribute to the likelihood of Central America DPS and Mexico DPS humpback whale entanglements and the severity of those encounters (likelihood of mortality), NMFS should consider any needs to collect information on gear configuration and characteristics in the sablefish fishery as part of their ongoing effort to catalog and understand the characteristics of all West Coast fixed gear fisheries relative to entanglement risk and/or reported entanglements. Based on this review, NMFS should track gear configuration characteristics through the logbook and/or WCGOP. This information could result in the development of innovative gear that reduces the frequency and severity of WCGF encounters with humpback whales.	*Gear configuration is tracked by the WCGOP. NMFS is developing a logbook and associated rulemaking.*
(5) NMFS, in concert with the PFMC, should further investigate the potential for interactions between whales and trawl gear, including review of the underlying circumstances associated with the recent events documented in the Pacific whiting trawl fishery documented in this biological opinion. In addition to assessment of the risks of interactions, measures and/or data collection protocols should be developed by NMFS to help increase the capabilities to make determinations regarding the underlying circumstances of any future events where dead whales are encountered in trawl nets in the PCGF.	*NMFS SFD briefed the PFMC on this conservation measures at the April 2021 PFMC meeting.* At its April 2021 meeting, the Workgroup supported potential further development of this conservation measure.

Effects of the Proposed Action on the Proposed Critical Habitat for Humpback Whales

As (1) the bycatch of humpback whale prey species by the PCGF is limited in number, (2) humpbacks can switch to other schooling fish or euphausiids (when available) and feed in areas other than the U&As, (3) and the CA/OR/WA stock of humpbacks is increasing approximately 6-7 % per year, NMFS expects that the removal of humpback prey by the PCGF, considered in the context of the existing baseline, would be insignificant. NMFS does not anticipate that the effects of pollution through use of petroleum or minor oil spills to adversely affect the prey resources targeted by humpback whales and proposed as a physical and biological feature for critical habitat within the action area. Based on this analysis, NMFS finds that the proposed action is not likely to adversely affect critical habitat proposed for the Central America DPS and Mexico DPS of humpback whales.

References

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. RojasBracho, 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., D. Steel, J. Calambokidis, E. Falcone, U. Gonzalez-Peral, J. Barlow, A. M. Burdin, P. J. Clapham, J. K. B. Ford, C. M. Gabriele, D. Matilla, L. Rojasbracho, J. M. Straley, B. L. taylor, J. Urban, P. Wade, D. Weller, B. Witteveen, and M. Yamaguchi. 2013. Strong maternal fidelity and natal philopatry shape genetic structure in North Pacific humpback whales. Marine Ecology Progress Series. 494:291-306.

Baker, C. S., D. Steel, M. Vant, J. Barlow, A. M. Burdin, J. Calambokidis, P. J. Clapham, J. K. B. Ford, C. M. Gabriele, R. LeDuc, D. Mattila, T. J. Quinn, L. Rojas-Bracho, J. M. Straley, J. Urbán-R., P. R. Wade, D. Weller, B. H. Witteveen, K. Wynne, and M. Yamaguchi. 2008b. geneSPLASH: Genetic differentiation of eco-stocks and breedingstocks in North Pacific humpback whales. 18th Biennial Conference on the Biology of Marine Mammals, Quebec City, Quebec.

Barlow, J. 2016. Cetacean abundance in the California Current estimated from ship-based line- transect surveys in 1991-2014. Draft document PSRG-2016-06 presented to the Pacific Scientific Review Group, 25-26 February 2016, Seattle, WA.

Barlow, J., J. Calambokidis, E. A. Falcone, C. S. Baker, A. M. Burdin, P. J. Clapham, J. K. B. Ford, C. M. Gabriele, R. LeDuc, D. K. Mattila, T. J. Quinn, L. Rojas-Bracho, J. M. Straley, B. L. Taylor, R. J. Urbán, P. Wade, D. Weller, B. H. Witteveen, and M. Yamaguchi. 2011. Humpback whale abundance in the North Pacific estimated by photographic capture-recapture with bias correction from simulation studies. Marine Mammal Science 27: 793– 818.

Bettridge, S., C. S. Baker, J. Barlow, P. J. Clapham, M. Ford, D. Gouveia, D. K. Mattila, R. M. Pace, III, P. E. Rosel, G. K. Silber, and P. R. Wade. 2015. Status Review of the Humpback Whale (Megaptera novaeangliae) under the Endangered Species Act. U.S. Dept. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-540, 240 p.

Calambokidis, J., and J. Barlow. 2020. Updated abundance estimates for blue and humpback whales along the U.S. West Coast using data through 2018. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-634. 20 p.

Calambokidis J, E. A. Falcone, T. Quinn, A. Burdin, P. Clapham, J. K. B. Ford, C. Gabriele, R. LeDuc, D. Matillia, L. Rojas-Bracho, J. M. Straley, B. Taylor, J. Urban-Ramirez, D. Weller, B. Witteveen, M. Yamaguchi, A. Bendlin, D. Camacho, K. R. Flynn, A. Havron, J. Huggins, and N. Maloney. 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. Olympia, Washington: Cascadia Research.

Calambokidis, J., E. Falcone, A. Douglas, L. Schlender, and J. Huggins. 2009. Photographic identification of humpback and blue whales off the U.S. West Coast: results and updated abundance estimates from 2008 field season. Final Report for Contract AB133F08SE2786 from Southwest Fisheries Science Center. 18 p.

Calambokidis, J., J. Barlow, K. Flynn, E. Dobson, and G. H. Steiger. 2017. Update on abundance, trends, and migrations of humpback whales along the US West Coast. International Whaling Commission Paper SC/A17/NP/13. 17 p.

Carretta, J. V., K. A. Forney, M. S. Lowry, J. Barlow, J. Baker, D. Johnston, M. B. Hanson, R. L. Brownell Jr., J. Robbins, D. K. Mattila, K. Ralls, M. M. Muto, D. Lynch, and L. Carswell. 2010. U.S. Pacific Marine Mammal Stock Assessments: 2009. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-453. 336p.

Carretta, J. V., K. A. Forney, E. Oleson, K. Martien, M. M. Muto, M. S. Lowry, J. Barlow, J. Baker, B. Hanson, D. Lynch, L. Carswell, R. L. Brownell Jr., J. Robbins, D. K. Mattila, K. Ralls, and M. C. Hill. 2011. U.S. Pacific Marine Mammal Stock Assessments: 2010. NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC-476. 357 p.

Carretta, J. V., E. Oleson, D. W. Weller, A. R. Lang, K. A. Forney, J. Baker, B. Hanson, K. Martien, M. M. Muto, A. J. Orr, H. Huber, M. S. Lowry, J. Barlow, D. Lynch, L. Carswell, R. L. Brownell Jr., and D. K. Mattila. 2014a. U.S. Pacific Marine Mammal Stock Assessments, 2013. NOAA Tech. Memorandum, NOAA-TM-NMFS-SWFSC-532. 406 p.

Carretta, J. V., S. M. Wilkin, M. M. Muto, K. Wilkinson, and J. Rusin. 2014b. Sources of human-related injury and mortality for U.S. Pacific west coast marine mammal stock assessments, 2008-2012. NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC-533. 110 p.

Carretta, J. V., K. A. Forney, E. M. Oleson, D. W. Weller, A. R. Lang, J. Baker, M. M. Muto, M. B. Hanson, A. J. Orr, H. Huber, M. S. Lowry, J. Barlow, J. E. Moore, D. Lynch, L. Carswell, and R. L. Brownell Jr. 2017. U.S. Pacific Marine Mammal Stock Assessments: 2016. U.S. Department of Commerce, NOAA Technical Memorandum, NOAA-TM-NMFS-SWFSC- 577. 414 p.

Carretta, J. V., V. Helker, M. M. Muto, J. Greenman, K. Wilkinson, D. Lawson, J. Viezbicke, and J. Jannot. 2018a. Sources of Human-Related Injury and Mortality for U.S. Pacific West Coast Marine Mammal Stock Assessments, 2012-2016. U.S. Department of Commerce. NOAA Technical Memorandum NMFS-SWFSC-601.

Carretta, J. V., K. A. Forney, E. M. Oleson, D. W. Weller, A. R. Lang, J. Baker, M. M. Muto, B. Hanson, A. J. Orr, H. Huber, M. S. Lowry, J. Barlow, J. E. Moore, D. Lynch, L. Carswell, and R. L. Brownell, Jr. 2018b. U.S. Pacific Marine Mammal Stock Assessment: 2017. U.S. Department of Commerce, NOAA Technical Memorandum, NOAA-TM-NMFS- SWFSC-602.

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

Carretta, J. V., B. Delean, V. Helker, M. M. Muto, J. Greenman, K. Wilkinson, D. Lawson, J. Viezbicke, and J. Jannot. 2020a. Sources of Human-Related Injury and Mortality for U.S. Pacific West Coast Marine Mammal Stock Assessments, 2014-2018, U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-631.

Carretta, J. V., K.. A. Forney, E. M. Oleson, D. W. Weller, A. R. Lang, J. Baker, M. M. Muto, B. Hanson, A. J. Orr, H. Huber, M. S. Lowry, J. Barlow, J. E. Moore, D. Lynch, L. Carswell, and R. L. Brownell Jr. 2020b. U.S. Pacific Marine Mammal Stock Assessments: 2019. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-629.

Feist, B. E., J. F. Samhouri, K. A. Forney, and L. E. Saez. 2021. Footprints of fixed-gear fisheries in relation to rising whale entanglements on the U.S. West Coast. Fisheries Managment and Ecology 2021;1-12.

Hanson, M. B., T. P. Good, and J. E. Jannot. 2015. Humpback whale bycatch in the 2010 - 2013 U.S. West Coast Groundfish Fisheries. Report of the National Marine Fisheries Service to the Pacific Fisheries Management Council Endangered Species Workgroup. April 2015.

Hanson, M. B., T. P. Good, J. E. Jannot, and J. McVeigh. 2017. Humpback whale bycatch in 2014 – 2015 in the U.S. West Coast Groundfish Fisheries. Report of the National Marine Fisheries Service to the Pacific Fisheries Management Council Endangered Species Workgroup. April 2017.

Hanson, M. B., T. P. Good, and J. E. Jannot. 2019. Estimated humpback whale bycatch in the U.S. West Coast Groundfish Fisheries, 2002-2017. Report of the National Marine Fisheries Service to the Pacific Fisheries Management Council Endangered Species Workgroup. April 2019.

Jannot, J. E., K. A. Somers, V. Tuttle, J. McVeigh, J. V. Carretta, and V. Helker. 2018. Observed and Estimated Marine Mammal Bycatch in U.S. West Coast Groundfish Fisheries, 2002-16. U.S. Department of Commerce, NWFSC Processed Report 2018-03.

Jannot, J. E., A. Wuest, T. P. Good, K. A. Somers, V. J. Tuttle, K. E. Richerson, R. S. Shama, and J. T. McVeigh. 2021. Seabird Bycatch in U.S. West Coast Fisheries, 2002–18. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-165.

Martin, S. L., S. M. Stohs, and J. E. Moore. 2015. Bayesian infrerence and assessment for rare-even bycatch in marine fisheries: a drift gillnet fishery case study. Ecological Applications 25:416-429.

NMFS. 1991. Final Recovery Plan for the humpback whale (Megaptera novaeangliae). November 1991. U.S. Department of Commerce. National Oceanic and Atmospheric Administration. National Marine Fisheries Service. Office of Protected Resources. 105 p.

NMFS (National Marine Fisheries Service). 2012a. Continuing Operation of the Pacific Coast Groundfish Fishery - Endangered Species Act (ESA) Section 7(a)(2) Biological Opinion and Section 7(a)(2) "Not Likely to Adversely Affect" Determination. PCTS Number: NWR- 2012-876. 194 p.

NMFS (National Marine Fisheries Service). 2012b. Guidelines for Distinguishing Serious from Non-Serious Injury of Marine Mammals Pursuant to the Marine Mammal Protection Act. National Marine Fisheries Service Instruction 02-038-01 from J. Lecky. 6 Jan., 2102. 42 p.

NMFS (National Marine Fisheries Service). 2020. Continuing Operation of the Pacific Coast Groundfish Fishery (Reinitiation of consultation #NWR- 2012-876 – Humpback whale (Megaptera novaeangliae). Endangered Species Act (ESA) Section 7(a)(2) Biological Opinion and Section 7(a)(2) "Not Likely to Adversely Affect" Determination. PCTS Number: WCRO-2018-01378. 83 p.

NOAA Fisheries 2019. 2018 West Coast Entanglement Summary. Report of the West Coast Region Office. March 2017. 10 p.

NOAA Fisheries 2020. 2019 West Coast Entanglement Summary. Report of the West Coast Region Office. May 2018. 4 p.

NWFSC (Northwest Fisheries Science Center). 2020. At-Sea Hake Observer Program, 2020 Sampling Manual. Fishery Resource Analysis and Monitoring, At-Sea Hake Observer Program. NWFSC, 2725 Montlake Blvd. East, Seattle, Washington, 98112.

NWFSC (Northwest Fisheries Science Center). 2021. 2021 Training Manual. Fishery Resource Analysis and Monitoring, West Coast Groundfish Observer Program. NWFSC, 2725 Montlake Blvd. East, Seattle, Washington, 98112.

PFMC (Pacific Fishery Management Council). 2020. Pacific Groundfish Fishery Management Plan for the California, Oregon, and Washington Groundfish Fishery. Pacific Fishery Management Council, Portland, OR.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Santora, J. A., N. J. Mantua, I. D. Schroeder, J. C. Field, E. L. Hazen, S. J. Bograd, W. J. Sydeman, B. K. Wells, J. Calambokidis, L. Saez, D. Lawson and K. A. Forney. 2020. Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. Nature Communications 11, 536.

Somers, K. A., C. E. Whitmire, K. Richerson, J. E. Jannot, V. J. Tuttle, and J. T. McVeigh. 2019. Fishing Effort in the 2002-2017 U.S. Pacific Coast Groundfish Fisheries. West Coast Groundfish Observer Program. National Marine Fisheries Service, NWFSC, 2725 Montlake Blvd E., Seattle, WA 98112.

Somers, K. A., J. Jannot, K. Richerson, V. Tuttle, N. B. Riley, and J. T. McVeigh. 2020a. Estimated Discard and Catch of Groundfish Species in the 2018 U.S. West Coast Fisheries. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-154.

Vehtari A., Gelman A., Gabry J. 2017. Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Statistics and Computing 27, 1413-1432.

Vehtari A., Gabry J., Magnusson M., Yao Y., Gelman A. 2019a. loo: Efficient leave-one-out cross-validation and WAIC for Bayesian models. R package version 2.2.0.

Vehtari A., Simpson D., Gelman A., Yao Y., Gabry J. 2019b. Pareto Smoothed Importance Sampling. arXiv:1507.02646.

Ward, E. J. 2019. bycatch: Using Bayesian generalized linear models for estimating bycatch rates and generating fleet-level expansions. R package version 1.0.

Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wickham, H., M. Averick, J. Bryan, W. Chang, L. D. McGowan, R. François, G. Grolemund, A. Hayes, L. Henry, J. Hester, M. Kuhn, T. L. Pedersen, E. Miller, S. M. Bache, K. Müller, J. Ooms, D. Robinson, D. P. Seidel, V. Spinu, K. Takahashi, D. Vaughan, C. Wilke, K. Woo, and H. Yutani. 2019. Welcome to the tidyverse. Journal of Open Source Software, 4(43), 1686.

Wickham, H., R. Francois, L. Henry and K. Muller. 2017. dplyr: A Grammar of Data Manipulation. R package version 0.8.4.

Xie, Yihui. 2020. knitr: A General-Purpose Package for Dynamic Report Generation in R. R package version 1.28.

Yao Y., Vehtari A., Simpson D., Gelman A. 2017. Using stacking to average Bayesian predictive distributions. Bayesian Analysis doi: 10.1214/17-BA1091

Zerbini A, Clapham P, Wade P, 2010. Assessing plausible rates of population growth in humpback whales from life-history data. Marine Biology 157: 1225-1236.

Appendices

Appendix 1. Bycatch estimates of humpback whales (annual mean and lower (LCI) and upper 95% confidence interval (UCI); 5-year mean and lower (LCI) and upper (UCI) 95% confidence intervals) in the Limited Entry Sablefish pot fishery sector. The best model used soak time (time gear spent in the water) as the effort metric, the Poisson distribution for error, and the bycatch rate as constant.

Year	Sector	Mean	LCI	UCI	5-year Mean	5-year LCI_5	5-year UCI
2002	Limited Entry Sablefish	0.35	0.00	1.38	0.00	0.00	0.00
2003	Limited Entry Sablefish	0.41	0.00	1.43	0.00	0.00	0.00
2004	Limited Entry Sablefish	0.74	0.00	2.95	0.00	0.00	0.00
2005	Limited Entry Sablefish	0.16	0.00	0.65	0.00	0.00	0.00
2006	Limited Entry Sablefish	0.26	0.00	0.98	0.38	0.00	2.80
2007	Limited Entry Sablefish	0.43	0.00	1.82	0.40	0.00	2.83
2008	Limited Entry Sablefish	0.11	0.00	0.48	0.34	0.00	2.83
2009	Limited Entry Sablefish	0.65	0.00	2.42	0.32	0.00	2.36
2010	Limited Entry Sablefish	0.38	0.00	1.37	0.36	0.00	2.36
2011	Limited Entry Sablefish	0.20	0.00	0.82	0.35	0.00	2.36
2012	Limited Entry Sablefish	0.29	0.00	1.04	0.32	0.00	2.32
2013	Limited Entry Sablefish	0.55	0.00	2.32	0.41	0.00	2.41
2014	Limited Entry Sablefish	1.26	1.00	2.04	0.54	0.00	2.29
2015	Limited Entry Sablefish	0.07	0.00	0.31	0.47	0.00	2.29
2016	Limited Entry Sablefish	0.07	0.00	0.26	0.45	0.00	2.29
2017	Limited Entry Sablefish	0.25	0.00	1.04	0.44	0.00	2.29
2018	Limited Entry Sablefish	0.06	0.00	0.26	0.34	0.00	1.94
2019	Limited Entry Sablefish	0.17	0.00	0.65	0.13	0.00	1.00

Appendix 2. Bycatch estimates of humpback whales (annual mean and lower (LCI) and upper 95% confidence interval (UCI); 5-year mean and lower (LCI) and upper (UCI) 95% confidence intervals) in the Open Access Fixed Gear (pot) fishery sector. The best model used the number of sets (number of gear deployments) as the effort metric, the Poisson distribution for error, and the bycatch rate as constant.

Year	Sector	Mean	LCI	UCI	5-year Mean	5-year LCI_5	5-year UCI
2003	OA Fixed Gear	9.00	0.10	30.34	0.00	0.00	0.00
2004	OA Fixed Gear	2.99	0.09	8.91	0.00	0.00	0.00
2005	OA Fixed Gear	5.12	0.10	17.30	0.00	0.00	0.00
2006	OA Fixed Gear	7.63	0.10	25.85	0.00	0.00	0.00
2007	OA Fixed Gear	5.12	0.10	17.10	5.97	0.09	29.89
2008	OA Fixed Gear	3.98	0.19	13.70	4.97	0.09	25.00
2009	OA Fixed Gear	5.73	0.00	18.45	5.51	0.01	25.11
2010	OA Fixed Gear	4.92	0.09	16.24	5.47	0.01	25.11
2011	OA Fixed Gear	2.27	0.00	7.50	4.40	0.00	18.32
2012	OA Fixed Gear	2.14	0.00	7.14	3.81	0.00	18.23
2013	OA Fixed Gear	1.42	0.00	4.75	3.29	0.00	18.23
2014	OA Fixed Gear	1.90	0.00	6.26	2.53	0.00	15.36
2015	OA Fixed Gear	2.23	0.00	7.39	1.99	0.00	7.49
2016	OA Fixed Gear	3.19	1.00	8.41	2.17	0.00	8.31
2017	OA Fixed Gear	1.73	0.00	5.12	2.09	0.00	8.31
2018	OA Fixed Gear	1.72	0.00	5.41	2.15	0.00	8.31
2019	OA Fixed Gear	1.43	0.00	4.73	2.06	0.00	8.31

Appendix 3: A description of permits, gears used, target groups, vessel length range, fishing depth range, and management of catch share fishery sectors and subsectors in federally managed and monitored West Coast groundfish fisheries. Catch share sectors use individual fishing quotas (IFQ) to manage certain species. Observer coverage in these is 100%, except for vessels using electronic monitoring (EM). The IFQ program began in 2011; regulations prior to 2011 are excluded. For brevity, management descriptors are generalized and are not meant to be complete or comprehensive. Vessel lengths and fishing depths are based on observed vessels and might not represent the fleet as a whole.

Sector	Sub-sector	Permits[a]	Gears	Targets	Vessel length (m)	Depth (m)	Management
Limited Entry (LE) Trawl	LE Trawl	LE permit with trawl endorsement	Bottom Trawl, Hook & Line, Pot	Groundfish[b]	15-40	10-1600	IFQ; some vessels use EM in lieu of 100% observer coverage
Limited Entry (LE) Trawl	Midwater Rockfish	LE permit with trawl endorsement	Midwater Trawl	Midwater rockfish[c]	15-33	>70	IFQ; some vessels use EM in lieu of 100% observer coverage
Limited Entry (LE) Trawl	Midwater Hake	LE permit with trawl endorsement	Midwater Trawl	Pacific hake[d]	17-40	>70	IFQ; some vessels use EM in lieu of 100% observer coverage
At-Sea Hake	Mothership-catcher vessels (MSCV)	LE permit with MSCV endorsement	Midwater Trawl	Pacific hake[d]	8-138[e]	53-460[e]	IFQ; some vessels use EM in lieu of 100% observer coverage
At-Sea Hake	Catcher-processors (CP)	LE permit with CP endorsement	Midwater Trawl	Pacific hake[d]	82-115	60-570	IFQ
At-Sea Hake	Tribal	None	Midwater Trawl	Pacific hake[d]	<38	53-460	IFQ

[a] A.k.a. LE permit. All LE permits are issued by NOAA.

[b] Vessels with a California halibut permit, issued by the state of California, can land CA halibut under California's CA halibut fishery regulations.

[c] *Sebastes* spp.

[d] *Merluccius productus*

[e] Average values for catcher vessels

Appendix 4. A description of permits, gears used, target groups, vessel length range, fishing depth range, and management of non-catch share fishery sectors and subsectors in federally managed and observed U.S. West Coast groundfish fisheries. Observer coverage on these vessels is less than 100%. For brevity, management descriptors are generalized and are not meant to be complete or comprehensive. Vessel lengths and fishing depths are based on observed vessels and might not represent the fleet as a whole.

Sector	Sub-sector	Permits	Gears	Targets	Vessel Length (m)	Depth (m)	Management
Non-Nearshore Fixed Gear	Sablefish endorsed	LE permit with fixed gear endorsement and sablefish quota[a]	Longlines, Pots	Sablefish[c]	7-32	20-1300	Sablefish tier quotas; Seven-month season
Non-Nearshore Fixed Gear	Sablefish non-endorsed (a.k.a. Zero Tier)	LE permit with fixed gear endorsement w/o sablefish quota	Longlines, Pots	Sablefish, rockfish, flatfish[d, e]	7-32	20-1300	Trip limits
Non-Nearshore Fixed Gear	Open Access	None	Longlines, Pots	Sablefish, other groundfish	3-30	20-1300	Trip limits
Pacific Halibut Commercial		IPHC Pacific Halibut permit[b]	Longlines	Pacific halibut[f]	3-32	40-400	10-hr. fishing periods s. of Pt. Chehalis, WA; Legal size >82 cm; Trip limits

[a] A.k.a. LE permit. All LE permits are issued by NOAA.

[b] Issued by the International Pacific Halibut Commission (IPHC)

[c] *Anoploma fimbria*

[d] *Sebastes* spp.

[e] Pleuronectiformes

[f] *Hippoglossus stenolepis*

Appendix 5. A description of permits, gears used, target groups, vessel length range, fishing depth range, and management of fishery sectors and subsectors in state-managed, observed fisheries. Observer coverage on these vessels is less than 100%. For brevity, management descriptors are generalized for the given time period and are not meant to be complete or comprehensive. Vessel lengths and fishing depths are based on observed vessels and might not represent the fleet as a whole.

Sector	Permits	Gears	Targets	Vessel Length (m)	Depth (m)	Management
Open Access (OA) California Halibut	CA Halibut permit[b]	Bottom trawl	California Halibut[c]	9-22	10-200	Fishing mainly within the CA halibut trawl grounds; Minimum mesh sizes; Seven month season
Nearshore Fixed Gear[a]	CA or OR state nearshore permits and endorsements	Variety of hand lines, pot gear, stick gear, rod and reel	Rockfish, Cabezon, Greenlings[d,e,,f]	3-15	<100	Federal and state regulations; Area closures; 2-month trip limits; Minimum mesh size
Pink Shrimp	WA, OR, or CA state pink shrimp permit	Shrimp trawl	Pink shrimp[g]	11-13	60-800	State regulations; Bycatch reduction devices; Trip limits (groundfish)
CA Ridgeback Prawn	Prawn permit[b]	Shrimp or Bottom trawl	Golden, Spot, Ridgeback or other prawn[h]	9-19	45-700	Oct-May season; Trip limits; Area restrictions; Landing requirements
CA Sea Cucumber	Sea cucumber trawl permit[b]	Bottom trawl	California sea cucumbers[i]	9-12	<100	Logbook requirement; Area and seasonal closures

[a] The state of Washington does not conduct a nearshore fishery.

[b] Issued by the state of California

[c] *Paralichthys californicus*

[d] *Sebastes* spp.

[e] *Scorpaenichthys marmoratus*

[f] Hexagrammidae

[g] *Pandalus jordani*

[h] *Crangon* spp., *Lysmata californica, Pandalus clanae, P. jordani, P. platyceros, Sicyonia ingentis*

[i] *Parastichopus californicus*

Appendix 6. Fishing effort (observed vessels, trips, hauls, pots), observed catch (in metric tons) proportion of the fleet-wide catch observed, and observed humpback whale takes in the Catch Shares fixed gear pot sector, 2011-2019 (data from the West Coast Groundfish Observer Program).

Year	Observed Vessels (#)	Observed Trips (#)	Observed Hauls (#)	Observed Pots (#)	Observed Catch (MT)	Observed fleet-wide catch (%)	Observed Humpback takes (#)
2011	17	233	1,536	41,310	814	99	0
2012	19	278	1,709	52,248	741	100	0
2013	10	100	1,086	30,097	471	100	0
2014	14	118	1,288	31,876	681	100	0
2015	8	62	584	18,808	405	100	0
2016	8	61	584	15,785	387	100	0
2017	6	44	574	16,288	366	100	0
2018	6	24	310	11,510	293	100	0
2019	6	35	491	16,733	369	98	0