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HARNESSING THE POWER OF PHOTO-ID DATA FOR APPORTIONMENT TO MIGRATORY WHALE HERDS: U.S. WEST COAST HUMPBACK WHALE STOCK PROPORTIONS BY LATITUDE FOR THE PERIOD 2019-2024

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Executive summary

Humpback whales (*Megaptera novaeangliae*) in the North Pacific migrate between low-latitude winter reproductive areas and higher-latitude summer feeding areas, with whales from individual wintering areas migrating to multiple feeding areas and vice versa. As a result, humpback whales in feeding areas represent multiple Distinct Population Segments under the U.S. Endangered Species Act and stocks under the U.S. Marine Mammal Protection Act, complicating assessment and mitigation of anthropogenic impacts. Moreover, matrilineal population units that share the same wintering and feeding areas, known as migratory herds, form demographically independent units. This finer-scale population structure within source (wintering) areas is not accounted for by traditional 'many-to-many' mixed stock analysis, used to estimate proportions of contributing source populations, e.g., based on genetic data. The problem is further complicated by misclassification of animals from one wintering area, Central America (including southern Mexico), as belonging to another that falls along their migratory route, off central and northern Mexico.

We develop a conceptually simple approach that leverages photo-identification data to estimate proportions from different populations at the migratory herd level for spatial strata in feeding areas, while accounting for unidirectional misclassification among wintering areas. We apply this model to characterize proportions of humpback whale stocks along the U.S. West Coast, including for U.S. waters of the Salish Sea, with subregional resolution. The resulting proportions agree qualitatively and quantitatively with previous knowledge of stock abundance and patterns with latitude, while providing updated estimates with improved precision and accuracy over previously available information. To facilitate broader application, we also introduce an R package that allows users to obtain estimates of stock proportions for custom latitude ranges along the U.S. West Coast, enabling alignment with management jurisdictions and other regions of interest. Finally, we emphasize the importance of maintaining and improving spatial coverage of photo-identification efforts in both wintering and feeding areas, to ensure the availability of minimally biased information to support conservation of humpback whales into the future.

Introduction

Spatially overlapping, conspecific marine wildlife populations present a significant challenge for risk assessment and management of human impacts. This is a common problem for taxa such as marine fishes and sea turtles, where assessment and management of catch or bycatch impacts on mixed populations rely on mixed-stock analysis of genetic, chemical, or morphological data to estimate proportions belonging to each source population (e.g., Seminoff et al., 2012; Christensen et al., 2022). In cetaceans, migratory large whales, including humpback whales (*Megaptera novaeangliae*), provide prominent and well-studied examples of mixed populations.

Humpback whales, which occupy every major ocean basin, show site fidelity to both low-latitude winter reproductive areas and higher-latitude summer feeding areas. Many feeding areas host mixed populations from multiple wintering areas, necessitating estimation of mixing proportions to support risk assessment of human impacts, such as from fisheries or shipping (e.g., Schmitt et al., 2014; Steel et al., 2024).

In the North Pacific, humpback whales have a many-to-many relationship between wintering and feeding areas, with individuals from a wintering area migrating to multiple different feeding areas, and vice versa (Fig. 1; Calambokidis et al., 2001; Baker et al., 2013). Although mixed-stock analysis has been extended to handle many-to-many relationships (Bolker et al., 2007), existing approaches may not be sufficient for humpback whales, whose wintering area populations are further structured into demographically independent, matrilineal ‘migratory herds’ that correspond to different feeding areas (Martien et al., 2023). Genetic studies suggest that different migratory herds from the same wintering area may have different haplotype frequencies (Martien et al., 2020), so results of mixed stock analysis of haplotype data may not provide reliable information for management.

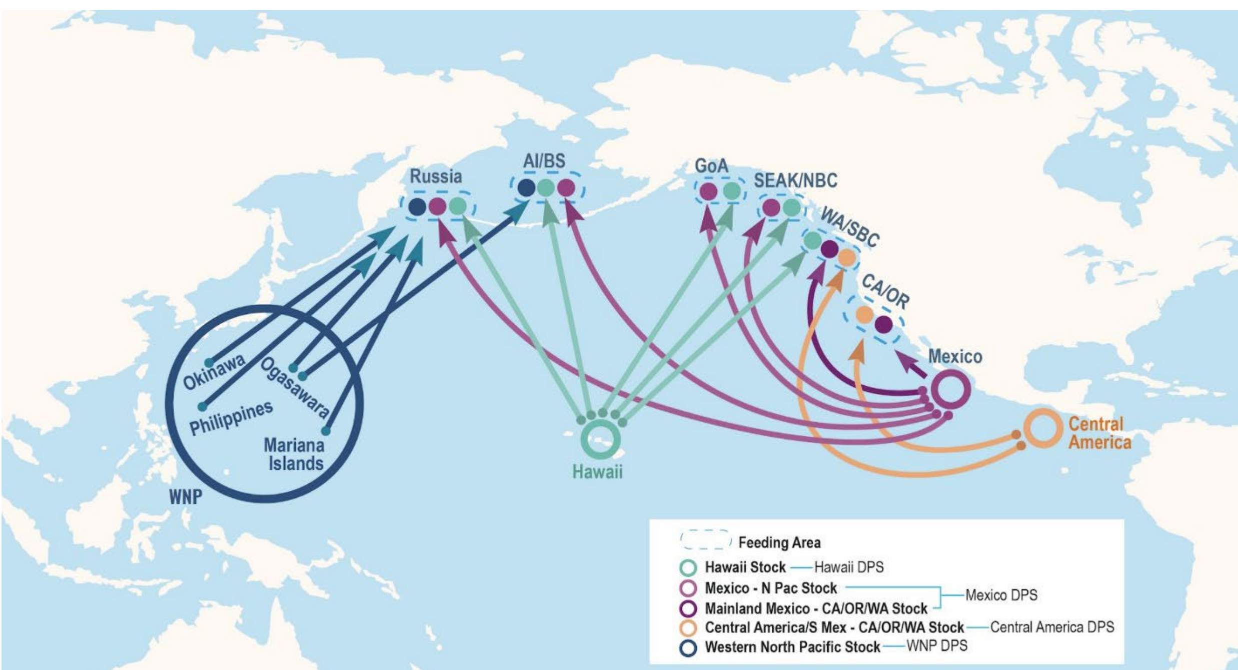

Figure 1. North Pacific basin map showing wintering and summer feeding areas of humpback whale distinct population segments (DPSs) and stocks recognized under U.S. law. Abbreviations are Aleutian Islands / Bering Sea (AI/BS), Gulf of Alaska (GoA), Southeast Alaska / Northern British Columbia (SEAK/NBC), Washington / Southern British Columbia (WA/SBC), and California / Oregon (CA/OR). Figure modified from Carretta et al. (2023).

The U.S. West Coast is an important feeding destination for humpback whales, with contributions from three wintering areas - Central America (including southern Mexico), Mexico (excluding southern Mexico), and Hawaiʻi (Fig. 1; Calambokidis et al., 2000; Rasmussen et al., 2012; Urbán et al, 2000). Each wintering area corresponds to a Distinct Population Segment (DPS) under the U.S. Endangered Species Act (ESA; Bettridge et al., 2015). Of these, the Mexico DPS has been further divided into two stocks under the Marine Mammal Protection Act (MMPA), based on an analysis of demographic independence. Whales that migrate to the U.S. West Coast have been designated as the Mainland Mexico - California-Oregon-Washington stock (henceforth MX-COW). The remaining Mexico DPS whales, currently recognized as the Mexico - North Pacific stock (MX-NP), migrate to high-latitude feeding areas across the Pacific from Russia to Southeast Alaska and Northern British Columbia (Martien et al., 2021). The Central America DPS, now understood to include whales off southern Mexico, migrates overwhelmingly to the U.S. West Coast, and has been designated as a whole as the Central America / Southern Mexico - California-Oregon-Washington stock (CASM; Rasmussen et al., 2012; Taylor et al., 2021; De Weerdt et al., 2023; Ransome et al., 2023). The Hawaiʻi DPS currently also represents a single recognized stock (HI), although it migrates to feeding areas across the North Pacific. Some MX-NP animals are presumed to migrate through U.S. West Coast waters, so in all, four stocks co-occur in this region.

The four humpback stocks that occur off the U.S. West Coast vary in population size, strategic designation under the MMPA, and listing status under the ESA, with the Central America DPS listed as Endangered, Mexico as Threatened, and Hawai'i not listed under the ESA. The proportions of these stocks shift dramatically from south to north along the U.S. West Coast (Calambokidis et al., 2000), as do anthropogenic pressures over this large geographic area, with a number of major ports and shipping channels associated with increased vessel strike risk, varying effort in fishing activities that may lead to entanglements, and other activities that may negatively affect humpback whales (e.g., Rockwood et al., 2017; Feist et al., 2021). Consequently, quantifying the proportions of humpback whales belonging to different management units, both at the stock and DPS levels, is a scientific priority for supporting effective management of human impacts.

For North Pacific humpback whales, photo-identification ("photo-ID") data are abundant and provide extensive spatial coverage of both wintering and feeding areas (Cheeseman et al., 2023; Cheeseman et al., 2024). Previous studies have used photo-ID data of North Pacific humpback whales to characterize proportions of whales from each wintering area in different summer feeding areas, and vice versa (e.g., Wade et al., 2022). However, these and similar studies are based on 20-year-old data, provide little spatial resolution within the broadly defined feeding areas, are subject to considerable model uncertainty, and do not necessarily align with management jurisdictions, such as state boundaries. Photo-ID data have also been applied at the sub-regional scale, as noted above, to show patterns in proportions from different wintering areas along the U.S. West Coast (Calambokidis et al., 2000). However, the results do not provide proportions at the management unit level (i.e., DPS or stock), nor do they account for varying levels of sighting effort among regions. Additionally, all such studies to date are subject to two additional sources of bias: (1) different population growth rates among contributing populations that undermine studies based partially or entirely on older data (Calambokidis and Barlow, 2020; Curtis et al., 2022; Cheeseman et al., 2024), and (2) misclassification of animals from the Central America wintering area (including southern Mexico), due to a non-negligible probability of being sighted in the Mexico wintering area (excluding southern Mexico) during migration and not in their home wintering area.

Here, we develop a simple conceptual model to estimate proportions of humpback whales belonging to each of multiple population units in one or more mesoscale spatial strata. This model is based on recent photo-ID data from both target strata and source areas, and includes a correction for population classification error. We apply it to estimate proportions of four co-occurring stocks off the U.S. West Coast by latitude, using recent humpback photo-ID data from the U.S. West Coast feeding area, and from all the contributing wintering areas, including Mexico, Central America, and Hawai‘i. Finally, we introduce a tool that allows users to obtain estimates of stock proportion for any range of latitudes off the U.S. West Coast, enabling alignment with management jurisdictions such as state boundaries or sub-state management zones. This tool supports stock apportionment of human-caused humpback whale mortality and serious injury (MSI), as required by the MMPA, and development of mitigation options that reduce human impacts on the stocks of greatest conservation concern.

Conceptual model

Within a given time frame (years), we can define the following quantities characterizing the relative contribution by each of multiple humpback whale population units (here, stocks) to overall abundance in target areas (here, discrete latitude bins along the U.S. West Coast) and to photo-ID samples in those areas (Figure 2):

- N_i: total abundance (i.e., mean number of whales present, including those migrating through) in latitude bin i
- N_x: total abundance of whales belonging to stock x and utilizing (migrating to or through) the U.S. West Coast EEZ
- $N_{i,x}$: abundance of whales in latitude bin i belonging to stock x
- $I_{i,x}$: proportion of abundance in latitude bin i belonging to stock x
- p_x: proportion of individuals in N_x that are "classified" (i.e., assigned to stock x, e.g., based on wintering area sightings) during the years included
- e_i: total number of independent sightings, including sightings of both classified and unclassified whales, in bin i (where independence is relative to temporally autocorrelated individual behavior, e.g., in response to prey patches)
- $m_{i,x}$: number of independent sightings in latitude bin i that are attributed to stock x

The above terms, either by definition or expectation, have the following relationships:

$$l_{i,x} = \frac{N_{i,x}}{N_i}$$

$\frac{m_{i,x}}{e_i} = p_x \frac{N_{i,x}}{N_i} = p_x l_{i,x}$, which can be rearranged as

$$l_{i,x} = \frac{m_{i,x}}{e_i\, p_x} \qquad (1)$$

This model assumes that any individual capture heterogeneity in wintering areas, e.g. due to sex heterogeneity or space use, is independent of space use and capture heterogeneity along the U.S. West Coast, an assumption that has been used elsewhere for North-Pacific-wide humpback abundance estimation (Barlow et al., 2011; Cheeseman et al., 2024). Furthermore, by limiting N_x to those animals that occur off the U.S. West Coast, we are inherently working at the migratory herd level, which corresponds to the finest resolution currently used to support humpback whale stock designations under the MMPA.

A substantial proportion of whales sighted in the Central America wintering area are also sighted in the Mexico wintering area, so given $p_x << 1$ for the CASM stock, a non-negligible number of CASM whales have likely only been sighted off northern Mexico and are currently misclassified as MX-COW animals. (We defined MX-NP to only include animals seen north or west of southern British Columbia, where very few CASM animals occur, so it is reasonable to ignore misclassification of CASM as MX-NP). This introduces a positive bias in tallies of MX-COW sightings ($m_{i,x}$) off the U.S. West Coast, and thus in MX-COW proportions, where substantial numbers of both MX-COW and CASM whales co-occur, so we developed a correction for misclassification. The fraction of CASM whales (stock 1) misclassified as MX-COW (stock 2) can be expressed as the product of the probability of CASM individuals being sighted in the Mexico wintering area (p_{2_1}), and the probability of not being identified in the Central America wintering area, (1-p_1). Tallies of $m_{i,2}$ are biased in proportion to $m_{i,1}$. Total CASM sightings (both individuals classified as CASM and "unknown" individuals belonging to CASM) in bin *i* can be estimated as $\frac{m_{i,1}}{p_1}$, so we can calculate a corrected statistic $m'_{i,2}$ as

$$m'_{i,2} = m_{i,2} - m_{i,1} \frac{p_{2_1}(1 - p_1)}{p_1}$$

The conceptual model could be extended to include season as well as space in the stratification scheme, if sufficient sightings are available for more than one season and if the proportions of individuals in each stock that can be classified, p_x, did not change between the seasons considered (e.g., summer and winter populations of animals off the U.S. West Coast) or could be estimated for each season.

This discrete-space model could also in theory be broadened to continuous-space generalized linear models of proportions by latitude. However, one challenge would be how to aggregate sightings (and thus position data) to longer time scales to eliminate short-term autocorrelation. More importantly, preliminary exploration showed that in practice for the U.S. West Coast, the discrete approach provided necessary flexibility to handle large variations with latitude both in sampling intensity and in the rate of change of stock proportions.

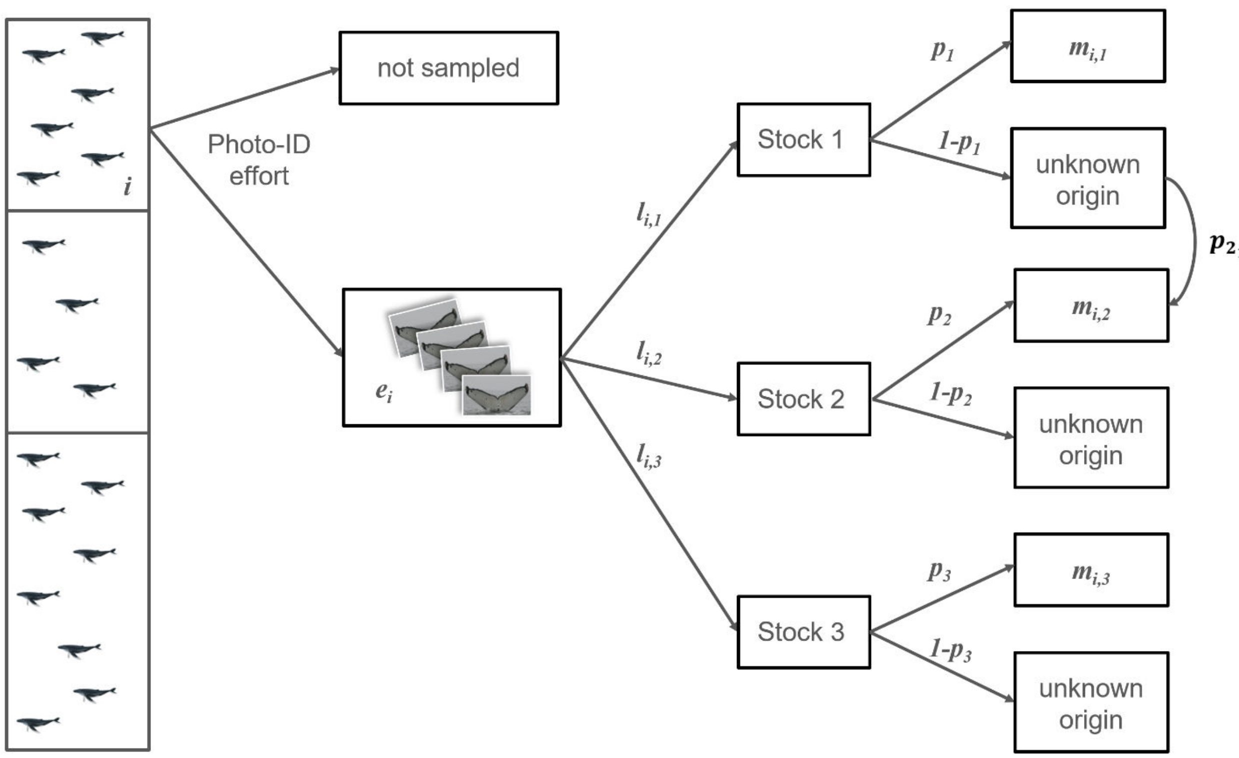

Figure 2. Diagram of conceptual model for estimating proportions of humpback whale population units in spatial bins. Here, we use latitude bins along the West Coast as the spatial bins (left side), and MMPA stocks as the population units. True proportion $l_{i,x}$ belonging to stock *x* in bin *i* is related to the observed proportion of sightings classified to that stock, $\frac{m_{i,x}}{e_i}$, by the proportion p_x of individuals that are classified for stock *x*. Individuals from stock 1 that are not classified as that stock may be misclassified as belonging to stock 2 at the rate p_{2_1}. See "Conceptual model" for further definitions of terms.

Implementation

Our implementation of the conceptual model described above to estimate humpback whale stock proportions by latitude along the U.S. West Coast was guided by the management context and the specifics of our dataset. The objective, in terms of supporting management, was to provide current, accurate estimates of stock proportions by latitude that could be used in risk assessment and conservation planning.

Photo-ID data

Our study was based on data in the Cascadia Research Collective (CRC) MN ID (humpback whale photo-ID) database, which is generally limited to sightings off the U.S. West Coast and in the Central America wintering area, as well as sightings of all whales from other regions (including Mexico and Hawaiʻi) that match to these two regions.

The MN ID database includes both directly contributed photo-IDs and sightings from Happywhale, a website and database that uses artificial intelligence to match humpback whale flukes (Cheeseman et al., 2022). In the latter case, matches for individuals are only imported once a minimum photo quality for that individual is available in either database, upon which sightings of all quality levels are imported. Quality scoring for the MN ID database and for Happywhale are described in Curtis et al. (2022) and Cheeseman et al. (2022), respectively. We imposed a standard minimum quality level across all individuals by filtering to the minimum standard quality for inclusion in the MN ID database, i.e., eliminating quality levels 3, 4 or PQ ("poor quality") based on CRC grades, and Happywhale quality levels <3 (the latter grades operate inversely to CRC quality grades).

Stock assignment

Only winter season (November-May) sightings from wintering areas during the study period (see below) were used to classify individuals to stock. Individuals were classified as HI and CASM if they were sighted in the Hawaiʻi and Central America wintering areas, respectively, with the latter defined as waters off Panama through Guerrero, Mexico (Appendix A). Individuals were classified as belonging to one of the Mexico stocks (MX-COW or MX-NP) if they were sighted in the Mexico wintering area and not in the Central America wintering area. Sightings off the Pacific coast of mainland Mexico from Michoacán through Jalisco, where Mexico and Central America DPS animals have been shown to mix (Llamas-González et al., 2023), were excluded from the analysis (Appendix A), although the results were robust to whether they were included. Mexico animals were assigned to MX-COW unless they had been sighted in a feeding area north or west of waters off southern British Columbia (north of 51°N or west of -141°W), in which case they were classified as MX-NP. Individuals sighted in both Hawaiʻi and another wintering area (Mexico or Central America) were dropped from the analysis (0.78% of all individuals classified to stock).

Estimating p_x and p_{2_1}

To ensure observation process consistency among stocks for estimating p_x, we filtered Central America, Hawaiʻi, and Mexico wintering area sightings to include only those individuals seen at least once off the U.S. West Coast (including in years previous to the study period). In the case of HI and MX-COW stocks, this also serves to limit the scope of the wintering area sightings included in this analysis to the migratory herds bound for the U.S. West Coast.

We estimated p_x, the proportion of individuals in each stock that are classified to stock, as the cumulative capture probability in the wintering area of individuals classified as belonging to that stock. Although the wintering area sightings in our dataset only include those individuals with a sighting history off the U.S. West Coast, a mark-recapture model still produces relevant estimates of capture probability, just not of abundance. For each stock, we fit a Chao M_{th} closed population model to annualized individual capture histories for the winter seasons of the included years (where the winter season is defined as November of the preceding year through May of the nominal year). We used the program CAPTURE to fit the Chao M_{th} model (White et al., 1978; Chao et al., 1992; Rexstad and Burnham, 1992), called from R with code adapted from Calambokidis and Barlow (2020; Curtis, 2025b). Cumulative probabilities of being photo-identified at least once in the wintering area were calculated by dividing the number of unique sighted individuals by the bias-adjusted "population" estimate from the model. Mark-recapture estimates restricted to humpback whale wintering areas are subject to several potential biases (Barlow et al., 2011), including sex, age, and spatial heterogeneity in capture probability. To the extent that these biases are not accounted for by the Chao M_{th} model, we assumed that their magnitude, and that of additional bias due to the violation of the population closure assumption, would be similar among wintering areas and stocks, such that they would not affect the relative estimated stock proportions off the U.S. West Coast.

The probability p_{2_1} was estimated by the fraction of individuals seen in the Central America wintering area during the study period that were also seen in the Mexico wintering area during that time. To minimize the probability that any southward straying Mexico whales off southern Mexico (Llamas-González et al., 2023) would add to the misclassification rate, we estimated p_{2_1} using only animals sighted south of latitude 14.5°N, i.e., from Guatemala southward. Attempts to estimate p_{2_1} more specifically for animals that were not seen in the Central America wintering area during the study period, and including sex heterogeneity, added complexity without appreciably changing the result, so we adhered to the above straightforward approach.

Study period and stratification

We found that at least six years of data were necessary to achieve stable estimates of p_x, particularly for HI and MX-NP, which have small sample sizes of unique individuals. We therefore defined the study period for both the wintering areas and the U.S. West Coast as the most recent six years of complete sightings data, from 2019 to 2024 (November 2018 to May 2024 for wintering areas).

U.S. West Coast sightings were selected by filtering to include only sightings inside a polygon of the U.S. West Coast Exclusive Economic Zone, including the Salish Sea (Flanders Marine Institute, 2023). Latitude bins along the U.S. West Coast were determined by aggregation from a resolution roughly reflecting distinct patches of sightings data, with aggregation of bins based on raw proportion data and expert opinion, with an eye to maximizing contrast among bins. A separate bin was designated for the Salish Sea.

As noted in the development of the conceptual model, above, the model can be extended to stratification by season as well as space, given certain assumptions are met. Most humpback whale sightings off the U.S. West Coast are collected in summer, so we defined a separate summer stratum as June through October based on monthly stock proportions in the latitude bin with the highest sample sizes for non-summer months – Monterey Bay. However, a non-summer seasonal stratum was not summarized and reported separately, for two reasons: (1) non-summer data were not available in sufficient sample sizes in more than a few locations along the U.S. West Coast, and (2) we have reservations about p_x estimates, which are calculated from sightings in wintering areas, being equally representative of humpback whales occurring off the U.S. West Coast in winter as in summer. We instead estimated stock proportions for year-round sightings off the U.S. West Coast as well as for summer alone. For the year-round data set, we considered weighting data by season, given the preponderance of sightings data from summer months, but since humpback whale densities also decline in non-summer months, we opted to weight all the sightings equally.

Calculating stock proportions

We aggregated individual sightings to monthly captures to balance the competing objectives of (1) minimizing autocorrelation due to repeated sampling of the same individuals in close spatiotemporal proximity, and (2) reflecting individual residency time, such that whales that are migrating through a latitude bin are weighted less than those showing spatial fidelity to a bin. A monthly time scale exceeds characteristic prey swarm temporal scales, which may be on the order of a week (Haury et al., 1978). Therefore, $m_{i,x}$ is the number of unique whales observed in bin i per month that are classified to stock x, summed across months and years included; and e_i is the total number of unique whales, both classified and non-classfied, observed in bin i per month, summed across months and years included.

Bin-wise totals of $l_{i,x}$ calculated from Equation (1) were all less than one (suggesting a tendency to overestimate p_x for one or more stocks), so we rescaled $l_{i,x}$ to sum to one across stocks within each bin.

For comparison to model-estimated stock proportions, we also directly calculated relative proportions of monthly sightings classified per stock (based on sighting in the wintering area at any time in the database history), and rescaled the resulting proportions to sum to one.

Uncertainty

Uncertainty in stock proportions per latitude bin was estimated through Monte Carlo simulations. Each simulation included (1) independent draws from the Chao M_{th} model distributions for estimated "abundances", used to recalculate p_x, and (2) years of photo-ID data off the U.S. West Coast resampled with replacement (six years per simulation) to characterize uncertainty due to both process and observation error off the U.S. West Coast. We also explored adding uncertainty to $m_{i,x}$ and p_{2_1} from binomial sampling process error, but given the large sample sizes, these did not influence the results and were omitted.

Application: apportioning humpback whales to stock

We anticipate that scientists and managers interested in apportioning humpback whales to stock will be interested in two additional extensions of the results from this study: (1) the ability to estimate mean proportions of each humpback whale stock across multiple or partial latitude bins, to match knowledge about an animal's movements or jurisdictional boundaries; and (2) the ability to estimate uncertainties for summed proportions across whales, for example to reflect uncertainty in stock apportionment of total annual MSI estimates. To address these needs, we developed an R package, *ApportionMnStocks*, that provides this functionality (Curtis, 2025a). The package uses humpback whale densities from species distribution models for 2018 for the U.S. West Coast and the Salish Sea (Becker et al., 2020; Wright et al., 2021), summed to abundance per 0.1° latitude and for the entire Salish Sea, respectively, to calculate weighted averages for latitude ranges that include more than one bin. Wright et al. (2021) reported densities for Canadian waters of the Salish Sea only, so we assumed equal densities in Canadian and U.S. waters of the Salish Sea within several strata (Elizabeth Becker and John Calambokidis, unpublished data; provided in the *ApportionMnStocks* package). The function also supports appropriate uncertainty estimates for across-bin weighted averages and for sums of more than one whale. This is done by calculating and standardizing to a sum of one the proportions (of sums) within each Monte Carlo simulation before averaging across simulations to return overall means and uncertainties. By the same token, any MSI proration values have to be applied at the simulation level to weight individual proportions of whales before getting mean proportions per simulation and then across-simulation averages, as above, so the function takes MSI proration values (NMFS 2023) as well. We applied the package to calculate means and uncertainties of stock proportions for a suite of latitude ranges that may be commonly used, including for each state as a whole, for the entire U.S. West Coast, and for the Risk Assessment and Mitigation Program (RAMP) Fishing

Zones used by California Department of Fish and Wildlife to assess and address entanglement risk for Dungeness crab fisheries.

With the exception of fitting of mark-recapture models with the CAPTURE program, all data manipulation and filtering, analyses, simulations, post-processing, and visualization were conducted in R 4.4.1 (R Core Team, 2024), using the CMRutils, lubridate, dplyr, tidyr, sf, ggplot2, and rnaturalearth packages (Grolemund and Wickham, 2011; Wickham, 2016; Massicotte and South, 2023; Pebesma and Bivand, 2023; Wickham et al., 2023; Wickham et al., 2024; Curtis 2025b).

Results

Humpback whale sightings along the U.S. West Coast for 2019-2024 that met our study criteria cover almost the entire U.S. West Coast (Fig. 3). The spatial stratification of the U.S. West Coast resulted in nine latitudinally defined bins along the outer coast and one bin representing U.S. waters in the Salish Sea, for a total of ten bins (Fig. 3). Monthly individual captures per bin totaled 16,213 across all bins for all seasons, including 5,776 unique individuals, and 10,983 across all bins for summer, including 4,700 unique individuals. Sample sizes per bin is shown in Figure 3 and Tables 2 and 3. The percentage of these sightings that were classified to stock based on wintering area sightings during the study period exceeded 50% for most bins. If wintering area sightings preceding the study years were used as well, that percentage increased to more than 60% in most bins.

Estimates of the percentage of each stock known from the wintering area and of the percentage of CASM individuals that are seen in the Mexico wintering area are provided in Table 1, and resulting stock proportion estimates by latitude bin and seasonal range are shown in Figure 4 and provided in Tables 2 and 3. Figure 4 also shows stock proportions directly calculated as relative proportions and rescaled to sum to one.

Results are similar among summer and all seasons, as might be expected given the predominance of summer months in the data (Figs. 3b and 4; Tables 2 and 3). In central and southern California, where the most data are available for non-summer months (Fig. 3b), CASM proportions appear to decrease and MX-COW proportions to increase in non-summer months (Fig. 4).

The greatest divergence between direct and model estimates is for CASM and MX-COW proportions in latitude bins where both stocks constitute high proportions of all animals. This result is expected, given the model correction for misclassified animals. For these two stocks, 100% of directly estimated proportions fall within the respective model confidence interval for bins to the north of California (i.e., in all bins north of 42.8°N, since the California-Oregon border lies at 42°N), whereas almost no direct estimates fall within model confidence intervals in bins off California. The similarity among estimated proportions known for different stocks (Table 1) results in smaller

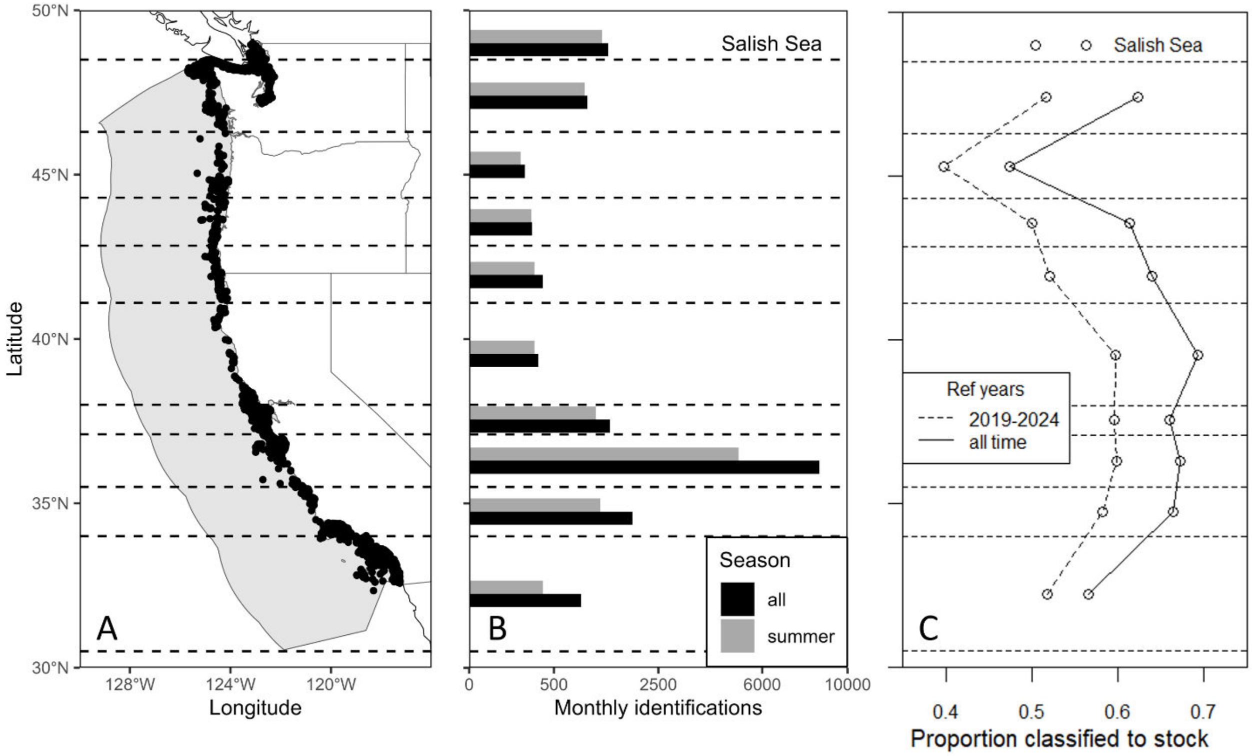

Figure 3. Distribution of data and strata used in the study. A: study area (U.S. West Coast Exclusive Economic Zone, gray shading), with distribution of all humpback whale sightings for 2019-2024 (black dots), and boundaries of latitudinally stratified bins (dashed lines). U.S. waters in the Salish Sea are included in the study area and constitute a separate spatial bin. B: distribution of monthly individual sightings, in square root space, for all seasons (January through December) and summer only (June through October) among latitude bins and for the Salish Sea (plotted at 49°N). The square root transformation best represents the relative value of additional samples in a bin. C: Percentage of monthly sightings classified to any stock based on wintering area sightings during the study period only (dashed line) or also including all available years prior to the study period (solid line; “all time”).

differences between the model expectation and direct calculations for the northern bins where MX-COW and HI dominate. To examine interannual variability in stock proportions, we calculated and plotted stock proportions by year using summer sightings (to eliminate variation in winter contributions). While these proportions are only approximate, given the much lower sample sizes, they show high consistency in the overall pattern and in approximate proportions among years (Fig. 5).

Finally, West-Coast-wide and state-wide mean proportions from abundance-weighted averages of model-based estimates calculated using the *ApportionMnStocks* package are shown in Tables 4 and 5.

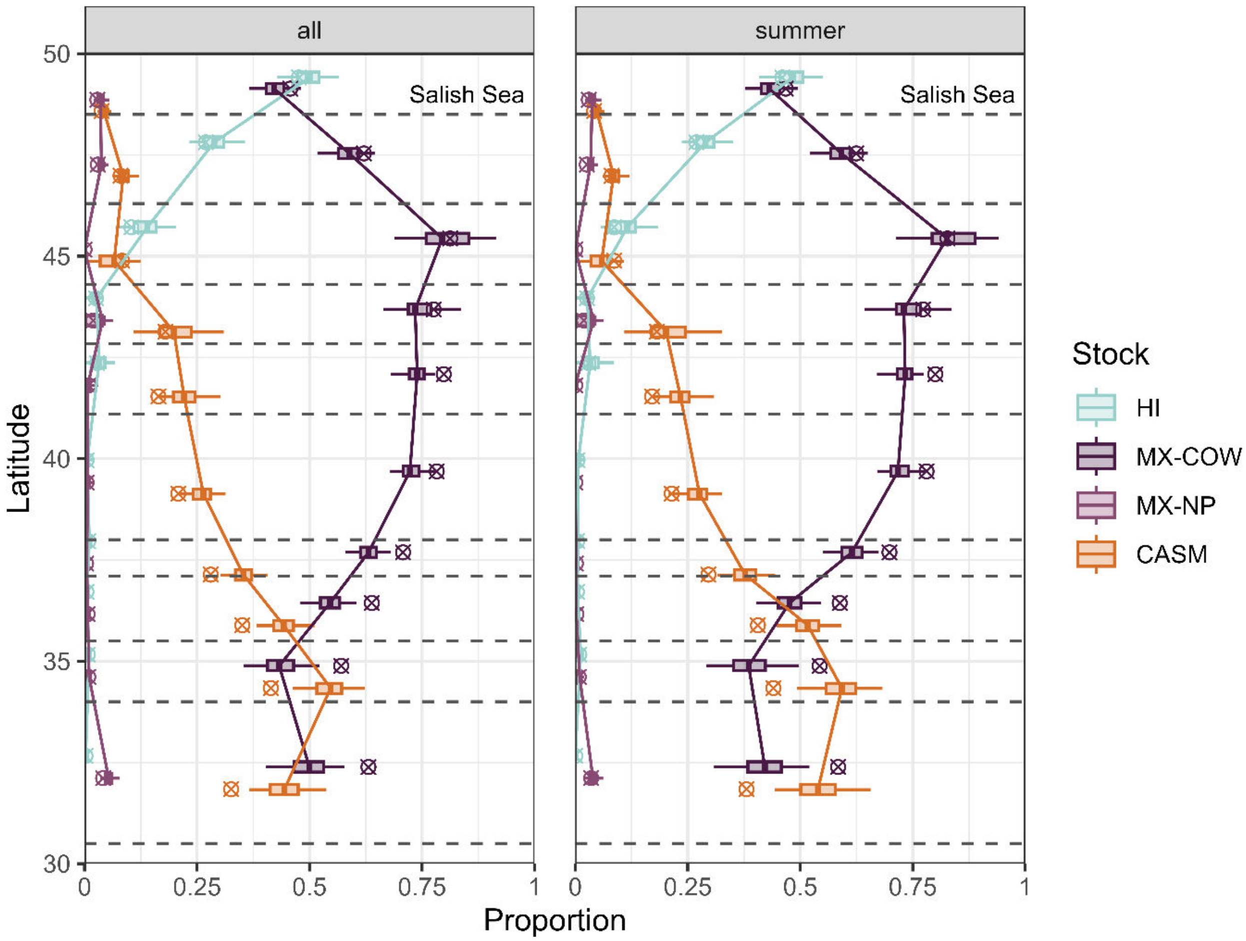

Figure 4. Stock proportions (rescaled to sum to 1 across stocks within each bin) from model-based estimates (boxplots of mean and interquartile range, with whiskers showing 95% coverage, and lines connecting means across bins) and direct calculation of relative proportions (crossed circle) for all-season sightings (January through December, left panel) and summer sightings (June through October, right panel). The proportions plotted at latitude 49°N represent sightings within the U.S. EEZ in the Salish Sea. For all other bins, dashed lines show bin boundaries and results are jittered around the midpoint of each bin. Stock abbreviations are HI = Hawai‘i, MX-COW = MMex–CA/OR/WA, MX-NP = Mexico-North Pacific, and CASM = CentAm/SMex–CA/OR/WA.

Discussion

We have developed a simple method for estimating stock proportions of humpback whales in a case where regular mixed stock analysis approaches are not valid. This method additionally handles misclassification of Central America animals as Mexico animals.

The model-based estimates of proportions are generally similar to direct estimates based on relative proportions, but diverge substantially in southern strata where the proportion of CASM animals, and thus the correction for misclassified CASM animals, are relatively high (Fig. 4). In latitude bins south of 42.8°N, off California, direct estimates of CASM proportions are consistently about 25% lower than model estimates. The similarity in northern strata between model-based and direct estimates reflects the relatively uniform estimates of p_x among HI and both Mexico stocks for the study period (Table 1). Effort in the Central America wintering area was somewhat lower, and has historically been much lower than in the Hawaiʻi and Mexico wintering areas, so the current level of divergence between model-based and direct estimates in the southern strata is probably less than it would have been at any other time in the past decades of photo-ID data sampling of North Pacific humpback whales. This underscores the importance of accounting for both effort and misclassification in estimating stock proportions along the U.S. West Coast.

The proportions estimated here provide more recent and finer-scale information than the stock apportionments estimated from photo-ID or genetics data from 2004-2006 (Palka et al., 2024; Wade et al., 2022). Notably, both of the latter estimates place the CASM proportion for the California / Oregon feeding area at greater than half. In contrast, the density-weighted mean CASM proportion from this study for the same region, calculated using the *ApportionMnStocks* package, is 0.39, providing further support for previous work that estimated a lower population growth rate for the CASM stock compared to the U.S. West Coast trajectory as a whole (Curtis et al., 2022), and underscoring the need for stock proportion estimates based on recent data.

Corroboration of results

The general patterns shown in the results align with prior studies of wintering area destinations of U.S. West Coast humpback whales from photo-ID and genetics (Calambokidis et al., 2000; Calambokidis et al., 2017; Steel et al., 2024), with relatively high proportions of CASM animals off southern California that decrease to the north, and substantial contributions from HI limited to the northernmost strata off Washington, while MX-COW animals contribute large proportions throughout the U.S. West Coast region.

Model-predicted proportions align well with several previous studies on a more quantitative basis as well. Model results for HI vs MX-COW off Washington roughly agree with a southward extrapolation of McMillan et al.’s (2023) generalized linear model predictions of proportions of animals from Hawaiʻi versus Mexico by latitude off British Columbia. Likewise, the mean result of multiplying the model-based mean proportion of CASM for the whole U.S. West Coast in summer (Table 4) by an estimate of humpback whale abundance for the U.S. West Coast as a whole for 2019-2022 (5420, SE = 170; Calambokidis et al., 2024), which equates to 1,840, falls within the 95% credible interval of an independent abundance estimate of 1,496 (95% CrI [1087, 2085]) for the CASM stock for 2019-2021 (Curtis et al., 2022).

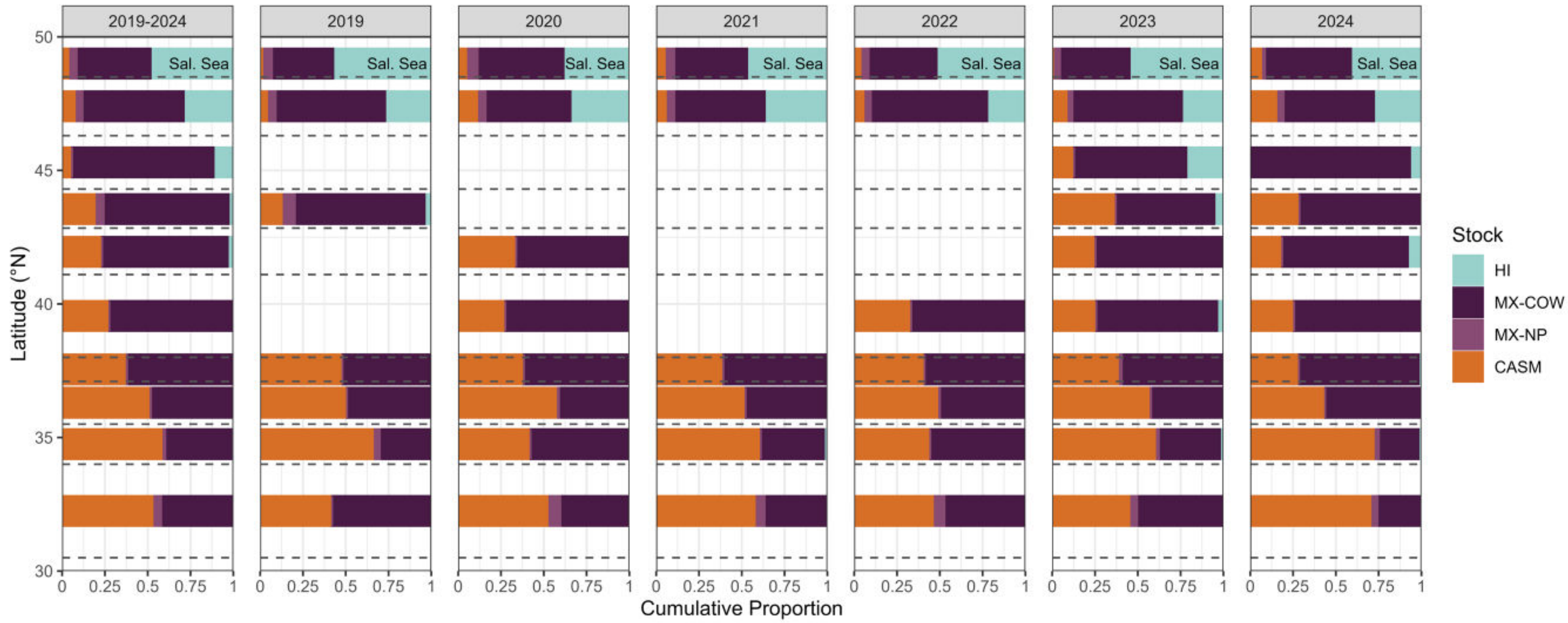

Figure 5. Stock proportions (rescaled to sum to 1 across stocks within each bin) for each individual year included in the study, from model-based estimates for summer sightings (June through October). Bins with fewer than 30 total monthly unique captures summed across months (i.e., $e_i < 30$) were omitted. Overall mean proportions for 2019-2024 are provided in the leftmost panel for comparison. The proportions plotted at latitude 49°N represent sightings within the U.S. EEZ in the Salish Sea. For all other bins, dashed lines show bin boundaries. Stock abbreviations are HI = Hawai‘i, MX-COW = MMex–CA/OR/WA, MX-NP = Mexico-North Pacific, and CASM = CentAm/SMex–CA/OR/WA.

Caveats

The approach developed here makes several key assumptions, which are also inherent to most previous studies characterizing stock proportions for humpback whales, and which should be considered when evaluating any particular application. We assumed that any bias in estimates of p_x, e.g., due to unaccounted for heterogeneity in capture probability among individuals, is similar among wintering areas, such that the relative magnitudes of p_x estimates among wintering areas remains accurate. One potential violation of this assumption could occur if juveniles have lower remigration rates (i.e., rates of migration to their wintering areas) and make up a larger fraction of one population than another. In the case study presented here, one might expect that given the suspected higher growth rate of the MX-COW stock than other stocks off the U.S. West Coast (Calambokidis and Barlow, 2020; Curtis et al., 2022; Cheeseman et al., 2024), the MX-COW stock may have a higher proportion of juveniles than do HI or CASM stocks. This could lead to relatively overestimated p_x for MX-COW and, consequently, underestimated MX-COW proportions off the U.S. West Coast.

Another important assumption common among this and previous studies is that there is no spatial bias in sampling in source areas that would translate to spatial bias among target strata. For example, effort off southern Mexico is consistently higher than elsewhere off Central America, and animals from southern Mexico may migrate on average somewhat further north off the U.S. West Coast. The dataset used here includes two years of well-distributed effort in the Central America wintering area during the SPLASH 2 project in 2021-2022, minimizing any potential spatial bias for that area. In contrast, in the Mexico wintering area, a major aggregation of whales off Sinaloa was recently documented that has scarcely been sampled (Ransome 2022), which may contribute to variation in total proportion known among strata that otherwise appear similar, with high proportions belonging to MX-COW, particularly off Northern California and Oregon (Figs. 3c, 4). During exploratory data analysis, this inter-stratum variation in total proportion known was mitigated by including animals sighted off Baja California, which serves partially as a migratory corridor (Martínez-Aguilar et al., 2017), as known members of one of the Mexico stocks. Inclusion of Baja California sightings also greatly increased the overall proportion known and the mean sum of proportion estimates per bin prior to rescaling to sum to one. Nonetheless, the resulting stratum-wise proportions proved remarkably robust to whether either Baja California or Jalisco/Nayarit sightings were omitted from the Mexico dataset. Lastly, off the U.S. West Coast, animals occurring further offshore are less well sampled, so we assume that proportions of animals closer to the coast are representative of the population in an area. Since human activities for which these results might inform management are typically most concentrated near the coast, and offshore densities of humpbacks are also orders of magnitude lower (Becker et al., 2020), this is likely relatively inconsequential.

Finally, seasonal resolution for this study is limited by both reduced sightings data availability outside summer months and the inability to assume that proportions of whales classified per stock, p_x, are the same among summer and non-summer populations of humpback whales off the U.S. West Coast. Thus, seasonal variation in proportions due to migration, including any differences in migration timing among stocks, is not well captured.

Application

The primary motivation for this work is to support assessment of impacts and risk at the levels of relevant population units to support management under the MMPA and the ESA. The current results focus on humpback whale stocks as designated under the MMPA, but point estimates of proportions for stocks from the same wintering area can simply be added to obtain DPS-specific proportions. Uncertainty for DPS-level information for Mexico stocks, while largely captured by the uncertainty for the MX-COW proportions, would theoretically need to be recalculated at the simulation level, which could easily be implemented as an additional option in the *ApportionMnStocks* package.

Application of the estimated proportions provided here and through the *ApportionMnStocks* package is straightforward where the question is simply what proportions of whales from different population units occur in a specific location or range of latitudes for a given time of year. However, decisions about what location or range of latitudes to use in estimating stock membership probabilities for a given whale, most commonly in the case of apportioning MSI of humpback whales to stock, are subject to some leeway in interpretation of how best to use available information for an individual whale. Many scenarios exist and the user should consider all the available information. One suggestion for a standardized approach to using information for a given whale from sightings and from information about the source of injury is provided in Appendix B.

If a photo-ID of a whale is obtained and the wintering area for that individual is known, the proportions estimated here and implemented in the *ApportionMnStocks* package are not needed. Specifically, if fluke photos for an entangled whale are available and match to either the Central America or Hawaiʻi wintering area, the wintering area may be considered known. If the whale matches to Mexico only, the substantial potential for misclassification of Central America animals means assignment remains uncertain, and occurrence information for the whale from the U.S. West Coast may inform stock apportionment (Appendix B).

Future work

We provide a framework for characterizing humpback stock proportions that can be applied to other feeding areas where data and interest are sufficient. Further work will also be needed to extend and update the results provided here. As noted above, a simple extension is to provide DPS as well as stock-level apportionment information. It also seems plausible that combining proportion estimates with concurrent spatial density estimates may offer an approach to estimating migratory herd abundances. Future updates to this information will be needed; given that the study period covers six years, it may be sufficient to update estimates every three or more years. Longer lags in updating results would lead to more conservative risk assessment with respect to apportioning MSI to stocks, because estimated proportions of populations with the lowest growth rates would be increasingly positively biased as time goes on. In the event of major reductions in sampling intensity in one or more wintering areas over several years, it may also be advisable to use “operational strategy evaluation” to assess how robust model-based versus direct estimates of proportions are to such shifts. Lastly, as additional information becomes available on variation in and location of the geographic boundary between the Central America and Mexico wintering areas, data selection for each wintering area may need to be revised, and simulation used to quantify the effect of such variations on stock proportion estimates.

The consideration of available information on entangled whales highlights the need for further work on movement probabilities among areas along the U.S. West Coast and for different stocks, which would provide a better basis for inferring how best to use sighting information for a single whale from multiple locations along the coast. Elaboration of the above simple model in a Bayesian framework might enable direct integration of such movement information, as well as the ability to explore interannual and seasonal variation in proportions as a function of oceanographic regime and respective population sizes. Integrated models may also aid in quantifying potential sources of bias among seasons and stocks in estimated proportions classified.

Finally, the ongoing maintenance of spatially distributed sightings effort throughout the North Pacific, and the extension of such effort to cover under-sampled areas such as off Sinaloa, Mexico and in winter off the U.S. West Coast, are paramount to maintaining and improving the accuracy of scientific information available to support management of human impacts at the stock and DPS levels.

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Supplementary Information

Appendix A. Geographic boundaries used to filter wintering area sightings

Appendix B. Guidelines for stock apportionment of humpback whale injury cases off the U.S. West Coast

Additional information available online:

The R package *ApportionMnStocks* (Curtis, 2025a) is available at: https://github.com/kacurtis/ApportionMnStocks

R code and results (Curtis, 2025c) are available at: https://github.com/kacurtis/Mn-StockProportions-USWC-2025

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Tables

Table 1. Estimates of the proportions of each stock that could be classified based on wintering area sightings (p_x), and the probability that a CASM individual will be sighted in the Mexico wintering area (p_{2_1}). Standard errors of estimates (S.E.) are from Monte Carlo simulations.

Parameter	Stock	Estimate (S.E.)
p_x	CASM	0.490 (0.032)
p_x	HI	0.580 (0.052)
p_x	MX-COW	0.618 (0.018)
p_x	MX-NP	0.512 (0.107)
p_{2_1}	CASM	0.527

Table 2. Model-based humpback stock proportion estimates for each bin, for all seasons combined (January through December), with uncertainty (SE=standard error, LCL=lower confidence limit, UCL=upper confidence limit), as well as total individual monthly sightings (e_i), and sightings classified to stock ($m_{i,x}$, before application of any correction).

Geographic Bin	e_i	Stock	$m_{i,x}$	Proportion (SE)	LCL (95%)	UCL (95%)
(47,49] Salish	1351	CASM	23	0.0428 (0.0078)	0.0278	0.0589
(47,49] Salish	1351	HI	318	0.5002 (0.0343)	0.4283	0.5649
(47,49] Salish	1351	MX-COW	298	0.4213 (0.0287)	0.3661	0.4807
(47,49] Salish	1351	MX-NP	20	0.0356 (0.0092)	0.0197	0.0557
(46.3,48.5]	974	CASM	33	0.0859 (0.015)	0.0625	0.1209
(46.3,48.5]	974	HI	131	0.2883 (0.0316)	0.2331	0.3567
(46.3,48.5]	974	MX-COW	303	0.5884 (0.0324)	0.5171	0.6455
(46.3,48.5]	974	MX-NP	15	0.0374 (0.0074)	0.0246	0.0532
(44.3,46.3]	216	CASM	4	0.0659 (0.0338)	0	0.1244
(44.3,46.3]	216	HI	10	0.1393 (0.0353)	0.0688	0.2038
(44.3,46.3]	216	MX-COW	63	0.7948 (0.0614)	0.6892	0.9147
(44.3,46.3]	216	MX-NP	0	0 (0)	0	0
(42.8,44.3]	275	CASM	19	0.1986 (0.0527)	0.109	0.3093
(42.8,44.3]	275	HI	3	0.0265 (0.0108)	0	0.0419
(42.8,44.3]	275	MX-COW	99	0.7348 (0.0458)	0.6636	0.8369
(42.8,44.3]	275	MX-NP	4	0.04 (0.0202)	0	0.0634
(41.1,42.8]	379	CASM	29	0.2213 (0.0407)	0.1613	0.3028
(41.1,42.8]	379	HI	5	0.0322 (0.0195)	0	0.0678
(41.1,42.8]	379	MX-COW	138	0.7392 (0.0309)	0.6804	0.779
(41.1,42.8]	379	MX-NP	1	0.0073 (0.0087)	0	0.0301
(38,41.1]	334	CASM	37	0.264 (0.0276)	0.2058	0.3134
(38,41.1]	334	HI	1	0.006 (0.0057)	0	0.0192
(38,41.1]	334	MX-COW	148	0.7231 (0.0257)	0.6791	0.7785
(38,41.1]	334	MX-NP	1	0.0068 (0.0066)	0	0.0225
(37.1,38]	1384	CASM	196	0.353 (0.0263)	0.3027	0.4065
(37.1,38]	1384	HI	7	0.0107 (0.0033)	0.004	0.0169
(37.1,38]	1384	MX-COW	549	0.6312 (0.0257)	0.5799	0.6802
(37.1,38]	1384	MX-NP	3	0.0052 (0.0033)	0	0.0124
(35.5,37.1]	8564	CASM	1543	0.4425 (0.0326)	0.3816	0.5109
(35.5,37.1]	8564	HI	21	0.0051 (0.0019)	0.0019	0.009
(35.5,37.1]	8564	MX-COW	3242	0.5455 (0.0315)	0.4798	0.6038
(35.5,37.1]	8564	MX-NP	25	0.0069 (0.0018)	0.0039	0.0107
(34,35.5]	1862	CASM	408	0.5469 (0.0411)	0.4623	0.6233
(34,35.5]	1862	HI	9	0.0102 (0.0029)	0.0034	0.015
(34,35.5]	1862	MX-COW	630	0.4326 (0.0431)	0.3539	0.5224
(34,35.5]	1862	MX-NP	8	0.0103 (0.0032)	0.0044	0.017
(30.5,34]	874	CASM	143	0.4442 (0.0447)	0.3666	0.5374
(30.5,34]	874	HI	1	0.0026 (0.0025)	0	0.0085
(30.5,34]	874	MX-COW	281	0.4997 (0.0455)	0.4032	0.5771
(30.5,34]	874	MX-NP	18	0.0535 (0.0113)	0.0343	0.0782

Table 3. Model-based humpback stock proportion estimates for each bin, for summer (June through October), with uncertainty (SE=standard error, LCL=lower confidence limit, UCL=upper confidence limit), as well as total individual monthly sightings (e_i), and sightings classified to stock ($m_{i,x}$, before application of any correction).

Geographic Bin	e_i	Stock	$m_{i,x}$	Proportion (SE)	LCL (95%)	UCL (95%)
(47,49] Salish	1232	CASM	23	0.0477 (0.0087)	0.0312	0.0656
(47,49] Salish	1232	HI	276	0.4834 (0.036)	0.4086	0.5509
(47,49] Salish	1232	MX-COW	275	0.4313 (0.0297)	0.378	0.4942
(47,49] Salish	1232	MX-NP	19	0.0377 (0.0094)	0.0212	0.058
(46.3,48.5]	931	CASM	31	0.085 (0.0151)	0.0614	0.1204
(46.3,48.5]	931	HI	125	0.2896 (0.0287)	0.2367	0.3507
(46.3,48.5]	931	MX-COW	289	0.5914 (0.0327)	0.5218	0.65
(46.3,48.5]	931	MX-NP	13	0.0341 (0.0073)	0.0219	0.0503
(44.3,46.3]	185	CASM	3	0.0585 (0.0291)	0	0.1085
(44.3,46.3]	185	HI	7	0.1155 (0.0356)	0.0559	0.1843
(44.3,46.3]	185	MX-COW	55	0.826 (0.0609)	0.7135	0.9404
(44.3,46.3]	185	MX-NP	0	0 (0)	0	0
(42.8,44.3]	271	CASM	19	0.202 (0.0566)	0.109	0.3258
(42.8,44.3]	271	HI	3	0.027 (0.0112)	0	0.0435
(42.8,44.3]	271	MX-COW	97	0.7304 (0.0501)	0.6433	0.8369
(42.8,44.3]	271	MX-NP	4	0.0407 (0.0204)	0	0.0636
(41.1,42.8]	298	CASM	24	0.2338 (0.0395)	0.1699	0.3085
(41.1,42.8]	298	HI	4	0.0329 (0.0233)	0	0.0864
(41.1,42.8]	298	MX-COW	108	0.7332 (0.0315)	0.6704	0.7739
(41.1,42.8]	298	MX-NP	0	0 (0)	0	0
(38,41.1]	298	CASM	34	0.2759 (0.0303)	0.2076	0.3257
(38,41.1]	298	HI	1	0.0069 (0.0065)	0	0.0225
(38,41.1]	298	MX-COW	130	0.7172 (0.0295)	0.6708	0.7846
(38,41.1]	298	MX-NP	0	0 (0)	0	0
(37.1,38]	1120	CASM	170	0.3775 (0.0338)	0.315	0.4442
(37.1,38]	1120	HI	3	0.0056 (0.0031)	0	0.0114
(37.1,38]	1120	MX-COW	442	0.6148 (0.0323)	0.5503	0.6745
(37.1,38]	1120	MX-NP	1	0.0021 (0.0019)	0	0.0065
(35.5,37.1]	5069	CASM	1067	0.5167 (0.0371)	0.4475	0.5911
(35.5,37.1]	5069	HI	12	0.0049 (0.0013)	0.0026	0.0077
(35.5,37.1]	5069	MX-COW	1823	0.4761 (0.0371)	0.4027	0.5458
(35.5,37.1]	5069	MX-NP	5	0.0023 (0.0011)	0.0004	0.0047
(34,35.5]	1198	CASM	286	0.5924 (0.0491)	0.4923	0.6828
(34,35.5]	1198	HI	7	0.0123 (0.0043)	0.0023	0.0192
(34,35.5]	1198	MX-COW	391	0.3854 (0.0526)	0.2911	0.4971
(34,35.5]	1198	MX-NP	5	0.0099 (0.0044)	0.0022	0.0198
(30.5,34]	381	CASM	79	0.5395 (0.0558)	0.4436	0.6563
(30.5,34]	381	HI	0	0 (0)	0	0
(30.5,34]	381	MX-COW	121	0.4213 (0.0553)	0.3084	0.5204
(30.5,34]	381	MX-NP	6	0.0392 (0.0105)	0.0207	0.062

Table 4. Abundance-weighted mean proportions across bins for several common broad-scale management regions for the U.S. West Coast, calculated using the *ApportionMnStocks* R package. Seasons are defined as “all” = January through December, and “summer” = June through October. Humpback whale stock abbreviations are CASM = CentAm/SMex–CA/OR/WA, HI = Hawai‘i, MX-COW = MMex–CA/OR/WA, and MX-NP = Mexico-North Pacific.

		Mean proportion (S.E.)			
Geographic Range	**Season**	**CASM**	**HI**	**MX-COW**	**MX-NP**
U.S. West Coast incl. Salish Sea	all	0.3082 (0.0215)	0.0698 (0.0053)	0.607 (0.0228)	0.015 (0.0035)
Washington incl. Salish Sea	all	0.076 (0.0126)	0.3326 (0.0251)	0.5551 (0.0244)	0.0363 (0.0073)
Oregon	all	0.1562 (0.0309)	0.0682 (0.0148)	0.7573 (0.0374)	0.0183 (0.009)
California	all	0.4044 (0.026)	0.0089 (0.002)	0.5778 (0.0264)	0.0089 (0.0023)
Northern California (38.769°N to 42°N)	all	0.2461 (0.025)	0.017 (0.0073)	0.7299 (0.0207)	0.007 (0.0048)
Central California (34.45°N to 38.769°N)	all	0.4272 (0.0278)	0.0076 (0.0015)	0.5581 (0.0282)	0.0071 (0.002)
Southern California (30.5°N to 34.45°N)	all	0.4959 (0.0396)	0.0064 (0.0025)	0.4659 (0.04)	0.0318 (0.0063)
U.S. West Coast incl. Salish Sea	summer	0.3394 (0.023)	0.0675 (0.0052)	0.5815 (0.024)	0.0116 (0.0028)
Washington incl. Salish Sea	summer	0.0762 (0.0129)	0.3294 (0.0234)	0.5601 (0.0246)	0.0343 (0.0074)
Oregon	summer	0.1578 (0.03)	0.06 (0.0129)	0.7653 (0.0373)	0.017 (0.0085)
California	summer	0.4511 (0.0289)	0.0084 (0.002)	0.536 (0.0287)	0.0046 (0.0011)
Northern California (38.769°N to 42°N)	summer	0.2583 (0.0274)	0.0178 (0.0084)	0.7239 (0.0226)	0 (0)
Central California (34.45°N to 38.769°N)	summer	0.4782 (0.0312)	0.0068 (0.0014)	0.5114 (0.0313)	0.0036 (0.0012)
Southern California (30.5°N to 34.45°N)	summer	0.5661 (0.048)	0.0062 (0.0022)	0.4033 (0.0479)	0.0245 (0.0051)

Table 5. Abundance-weighted mean proportions for Risk Assessment and Mitigation Program (RAMP) Fishing Zones used by California Department of Fish and Wildlife in risk assessment and management actions addressing entanglement risk for the commercial and recreational Dungeness crab fisheries, calculated using the *ApportionMnStocks* R package. Geographic information on RAMP Fishing Zones obtained from the California State Geoportal (https://gis.data.ca.gov/datasets/CDFW::risk-assessment-and-mitigation-program-ramp-fishing-zones-r7-cdfw-ds3120/about). Seasons are defined as "all" = January through December, and "summer" = June through October. Humpback whale stock abbreviations are CASM = CentAm/SMex–CA/OR/WA, HI = Hawai'i, MX-COW = MMex–CA/OR/WA, and MX-NP = Mexico-North Pacific.

		Mean proportion (S.E.)			
Fishing Zone (latitude range, °N)	**Season**	**CASM**	**HI**	**MX-COW**	**MX-NP**
Zone 1 (40.167, 42)	all	0.2387 (0.0279)	0.0215 (0.0107)	0.7326 (0.022)	0.0071 (0.0054)
Zone 2 (38.769, 40.167)	all	0.264 (0.0276)	0.006 (0.0057)	0.7231 (0.0257)	0.0068 (0.0066)
Zone 3 (37.183, 38.769)	all	0.3306 (0.0245)	0.0095 (0.0028)	0.6543 (0.0239)	0.0056 (0.0039)
Zone 4 (36, 37.183)	all	0.4355 (0.0315)	0.0055 (0.0017)	0.5523 (0.0307)	0.0067 (0.0017)
Zone 5 (34.45, 36)	all	0.5072 (0.0361)	0.0083 (0.0019)	0.4755 (0.0367)	0.009 (0.0021)
Zone 6 (30.5, 34.45)	all	0.4959 (0.0396)	0.0064 (0.0025)	0.4659 (0.04)	0.0318 (0.0063)
Zone 7 (36.639, 38.958)	all	0.373 (0.0247)	0.0077 (0.0016)	0.6131 (0.0251)	0.0061 (0.0026)
Zone 1 (40.167, 42)	summer	0.251 (0.0294)	0.0223 (0.0126)	0.7267 (0.0231)	0 (0)
Zone 2 (38.769, 40.167)	summer	0.2759 (0.0303)	0.0069 (0.0065)	0.7172 (0.0295)	0 (0)
Zone 3 (37.183, 38.769)	summer	0.352 (0.0297)	0.0059 (0.0023)	0.6405 (0.0289)	0.0016 (0.0014)
Zone 4 (36, 37.183)	summer	0.5057 (0.0364)	0.005 (0.0013)	0.487 (0.0364)	0.0023 (0.0011)
Zone 5 (34.45, 36)	summer	0.5636 (0.0389)	0.0095 (0.0026)	0.4199 (0.0403)	0.007 (0.0027)
Zone 6 (30.5, 34.45)	summer	0.5661 (0.048)	0.0062 (0.0022)	0.4033 (0.0479)	0.0245 (0.0051)
Zone 7 (36.639, 38.958)	summer	0.4147 (0.0309)	0.0056 (0.0014)	0.5779 (0.0308)	0.0019 (0.001)

Appendix A. Geographic boundaries used to filter wintering area sightings

Central America (including southern Mexico) is delimited by latitudes from 5 N to 18 N and longitudes -102.2 W to -75 W.

Hawaiʻi is delimited by latitudes 15 N to 30 N and longitudes -180 W to -150 W.

Mexico is delimited by latitudes 18 N to the maritime boundary with the U.S. West Coast EEZ, excluding sightings that have both latitude greater than 20 N and longitude greater than -106 (i.e., the Pacific coast of Mainland Mexico).

Appendix B. Guidelines for stock apportionment of humpback whale injury cases off the U.S. West Coast

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The R package *ApportionMnStocks* (Curtis, 2025) includes two latitude arguments, *minlat* and *maxlat*, used to return humpback whale stock proportions corresponding to that latitude range off the U.S. West Coast. We propose preliminary guidelines for setting these latitude limits when applying the package to apportion mortality and serious injury (MSI) of humpback whales to stock, based on a range of potential information (Table B1). Examples (below) apply to entanglements or vessel strikes where a U.S. source of human-caused MSI is known or inferred to have occurred within the U.S. West Coast Exclusive Economic Zone. Humpback whale MSI detected only in Canada or Mexico, for example, without a U.S. source injury attribution are generally omitted from U.S. West Coast MSI databases and do not count against the potential biological removal (PBR) in stock assessments that specify a prorated U.S.-only PBR. However, in the case of the Hawaiʻi stock, PBR is calculated range-wide, thus, MSI attributed to this stock from any region would count towards PBR thresholds. MSI in Canadian waters that does not involve U.S. gear is not apportioned to stock using *ApportionMnStocks*, which has a maximum input latitude equal to 48.5 degrees corresponding to the northernmost latitude of U.S. West Coast outer coast waters. MSI in non-U.S. waters for the Hawaiʻi stock is accounted for in Alaska marine mammal stock assessments (Young et al. 2023)

Stock names from stock assessment reports (SARs) and abbreviations used in *ApportionMnStocks*:

Central America / Southern Mexico - California-Oregon-Washington (CASM)

Mainland Mexico - California-Oregon-Washington (MX-COW)

Hawaiʻi (HI)

Mexico-North Pacific (MX-NP)

Table B1. Approach for stock apportionment of U.S. West Coast humpback whale entanglement and vessel strike cases, where a U.S. source of injury is known or inferred.

<table>
<tr><th colspan="3">1. Information on stock from wintering area sighting(s)</th></tr>
<tr>
<td>1A. Stock ID is considered ‘known’ from a photo-ID on the HI or CASM wintering area.

Assign a 100% probability to the known stock based on the CASM or HI wintering area sighting, regardless of where the MSI was detected.

In Alaska region SARs, where possible, HI stock injuries are assigned to either the Hawaiʻi - SE Alaska / N British Columbia DIP or the Hawaiʻi - North Pacific unit. Current data and analyses do not provide a clear understanding of unit membership for Hawaiʻi whales seen off the U.S. West coast, but the SAR currently assigns M/SI off Washington to the Hawaiʻi - Southeast Alaska / Northern British Columbia DIP.</td>
<td>1B. Stock ID is partially known from a photo-ID in the Mexico wintering area (north of 18 N). Because CASM whales also migrate through the Mexico wintering area, there is some misclassification of CASM whales as either (primarily) MX-COW or MX-NP animals.

Use latitude range based on available information from entanglement or vessel strike and any sighting history off the U.S. West Coast to inform stock proportions (see 2). Because whales are rarely seen in both Hawaiʻi and Mexico wintering areas and the origin of these individuals is not truly known, set the HI proportion to zero and rescale the remaining MX-NP, MX-COW, and CASM proportions to sum to one[1].</td>
<td>1C. No information on stock ID from wintering area sightings.

Use proportions for latitude range based on available information from entanglement or vessel strike and any sighting history off the U.S. West Coast to inform stock proportions (see 2).</td>
</tr>
<tr><th colspan="3">2. Information on U.S. West Coast occurrence of individual</th></tr>
<tr>
<td>2A. Multiple point locations or information constraining the range of potential locations (e.g., identified state fishery or known ferry route)

Use the range of latitudes provided from combined information, as applicable, from sightings locations for the individual and geographic range of the potential interaction location (e.g., ferry route or identified state fishery) to inform stock proportions.</td>
<td>2B. Single point location

Examples include unidentified fishery entanglements, self-reports, stranded or at-sea carcasses with evidence of a vessel strike and eye witnessed vessel strikes. No further sightings are available for the individual.

Whale is seen once. Use the reported latitude to inform stock proportions.</td>
<td>2C. None

Entanglement or vessel strike location is unknown, but assumed to have occurred in U.S. waters, and no sightings of the whale occurred in U.S. waters.

If the whale is only seen outside the U.S. West Coast EEZ, stock is only partially known or unknown, and the interaction is inferred to have occurred off the U.S. West Coast but no further information on interaction location is available, use the full range of the U.S. West Coast EEZ (30.5 to 49).</td>
</tr>
</table>

[1] This approach effectively assigns slight additional risk to the endangered CASM and threatened MX-COW and MX-NP stocks. See examples below for an implementation of this approach.

Examples

All examples use proportions for “all” seasons.

1A. Whale previously documented from only a Hawaiʻi or Central America wintering area. Assign a 100% probability of the whale belonging to one of these stocks, no matter where in the summering area it was detected.

1B. Whale is entangled in Washington state Dungeness (outer coast) gear and is not sighted in U.S. waters, but is later sighted in the Mexico wintering area. Use the latitude range of the Washington state fishery (*minlat* = 46.3, *maxlat* = 48.5) to inform initial stock proportions: Set the Hawaiʻi stock proportion to zero and rescale the remaining stock proportions (MX-NP, MX-COW, CASM) to sum to one (Table B2). Use the same strategy for whales entangled in Oregon or California gear, using latitude ranges that reflect the area where the fishery operates.

Table B2. Example calculation for zeroing out HI stock proportion and rescaling remaining ‘Initial proportions’ to sum to one. Rescaling factor = 1 / (CASM + MX-COW + MX-NP), based on input latitudes *minlat* = 46.3 and *maxlat* = 48.5.

	CASM	**HI**	**MX-COW**	**MX-NP**
Initial proportions	0.0854	0.2849	0.5932	0.0365
Rescaled proportions	0.1194	0	0.8295	0.0510

2A. Example 1: Whale of unknown stock ID is detected once in Monterey Bay, with CA Dungeness crab gear. Use the known range of the fishery (Point Conception to CA-OR border; *minlat* = 34.45 and *maxlat* = 42) to inform stock proportions:

CASM = 0.3983, HI = 0.0091, MX-COW = 0.5854, MX-NP = 0.0071

Example 2: Whale of unknown stock ID is detected once in Monterey Bay at 36.8 N, with WA Dungeness crab gear (outer coast fishery). Use the range between the sighting location in Monterey Bay (*minlat* = 36.8) and the northern extent of the WA state fishery (*maxlat* = 48.5) to inform stock proportions:

CASM = 0.2382, HI = 0.0771, MX-COW = 0.6693, MX-NP = 0.0154

In the case of a vessel strike, use any known location information, such as the location of the strike if witnessed, or the range of latitudes representing the vessel's route. If the vessel route is unknown and a whale carcass is found wrapped around the bow of the ship in the port of Long Beach, CA, use that latitude to inform stock proportions.

2B. Whale of unknown stock ID is detected once in Monterey Bay with an entanglement or vessel strike injury that cannot be attributed to a specific fishery or vessel. Use the detection latitude (*minlat* = 36.8 and *maxlat* = 36.8) to inform stock proportions:

CASM = 0.4425, HI = 0.0051, MX-COW = 0.5455 MX-NP = 0.0069

2C. Whale seen once off Cabo San Lucas, Mexico, with a pot-trap fishery entanglement that is attributed to U.S. gear styles, but the specific fishery is unknown. Since U.S. pot-trap fisheries span the length of the U.S. West Coast, including the Salish Sea, use the broadest range of latitude values available in the R-package (*minlat* = 30.5 and *maxlat* = 49) to inform initial stock proportions.

CASM = 0.3082, HI = 0.0698, MX-COW = 0.6070, MX-NP = 0.0150

Setting the HI proportion to zero (see 1B) and rescaling the remaining proportions to sum to one yields:

CASM = 0.3313, HI = 0, MX-COW = 0.6525, MX-NP = 0.0161

References

Curtis, K.A. 2025a. *ApportionMnStocks*. Version 1.0.0. NOAA Fisheries, Southwest Fisheries Science Center, 8901 La Jolla Shores Dr., La Jolla, CA 92037, DOI: 10.5281/zenodo.15540189

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