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Recent Trends in the Abundance of Seasonal Gray Whales (*Eschrichtius robustus*) in the Pacific Northwest, 1996 – 2023

MAY 2025

U.S. Department of Commerce | National Oceanic and Atmospheric Administration | National Marine Fisheries Service

AFSC Processed Report

This document should be cited as follows:
Harris, J., Calambokidis, J., Perez, A., and Mahoney, P. J. 2025. Recent trends in the abundance of seasonal gray whales (*Eschrichtius robustus*) in the Pacific Northwest, 1996-2023. 2025. AFSC Processed Rep. 2025-06, 19 p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

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Recent Trends in the Abundance of Seasonal Gray Whales (*Eschrichtius robustus*) in the Pacific Northwest, 1996 – 2023

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May 2025

Abstract

The following report provides an updated estimate of abundance for Pacific Coast Feeding Group (PCFG) gray whales through 2023 using data derived from the collaborative, multi-year photographic survey of gray whales in the eastern North Pacific. The data time series spans 28 years (1996-2023) and 15 survey regions along the west coast of North America from southern California to Kodiak, Alaska. The present analysis focuses on data for animals observed between 1 June and 30 November within the PCFG range from northern California, USA, to northern British Columbia, Canada, including the western Strait of Juan de Fuca. The population models are identical to those used in recent efforts to estimate PCFG abundance through 2022. As of 2023, the PCFG abundance is estimated to be 213 individuals (se = 15.55, N_{min} = 200) within the PCFG range. Using the Potential Biological Removal (PBR) formula, with an R_{max} of 6% and a recovery factor of 0.5, the estimated PBR for the PCFG range would be 3.1. Our abundance estimates indicated that the PCFG has been stable over the last 25 years; however, the population has experienced a recent decline of 18.8 % from an observed peak in abundance in 2016.

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Introduction

The Marine Mammal Laboratory (MML) at the NOAA-NMFS Alaska Fisheries Science Center coordinates and conducts annual surveys for Eastern North Pacific (ENP) gray whales (*Eschrichtius robustus*) from northern California (USA) to British Columbia (CAN) as part of a larger research collaboration to understand ENP population abundance, movements, and stock structure. A small group of ENP whales that demonstrate strong seasonal fidelity to the Pacific Northwest was first identified by Calambokidis et al. (2004) and later recognized by the International Whaling Commission (IWC) as the Pacific Coast Feeding Group (PCFG), which includes individuals observed in two or more years between 1 June and 30 November from 41°N to 52°N latitude. Whereas transient ENP whales passing through to feed in the northern waters of the Chuckchi, Beaufort, and Bering Seas are rarely observed more than once in the Pacific Northwest, PCFG whales are frequently resighted due to their higher fidelity to the region and increased residency time through the summer and fall. Here, we update the estimates of PCFG abundance through 2023 using gray whale sighting histories since 1996 and the population modeling framework described in Calambokidis et al. (2019) and Harris et al. (2022).

Methods

Description of photographic catalog and data processing

The gray whale photographic catalog maintained by Cascadia Research Collective (CRC) provided the baseline data for generating abundance estimates for Pacific Coast Feeding Group (PCFG) gray whales. The CRC catalog is comprised of imagery associated with coastal gray whale sightings from California to Alaska between 1996 and 2023 and includes images from individuals identified as members of the PCFG and the broader Eastern North Pacific population. The underlying motivations leading to gray whale encounters varied among observers, from opportunistic sightings reported by citizen scientists to more formal surveys conducted by various research groups. Despite differences in intent, observers followed similar procedures for photographing gray whales. When possible, the left and right sides of the dorsal region proximate to the dorsal hump and the ventral fluke provided the standard for gray whale photographic identification. Photographs from each sighting were shared with CRC for matching and inclusion in the photographic catalog. Markings used to distinguish individual gray whales included variation in skin pigmentation, encrusting invertebrates, the size and spacing of knuckles along the dorsal ridge posterior to the dorsal hump, and unique scarring, which in composite have provided a reliable means of identifying individual gray whales (Darling 1984).

The gray whale catalog represents 15 previously defined survey regions from southern California to Alaska. For the purposes of quantifying the abundance of PCFG gray whales, we limited the assessment to nine subregions from northern California (USA) to northern British Columbia (Canada), encompassing a contiguous section of the Pacific outer coast of North America and the western portion of the Strait of Juan de Fuca (SJF; Calambokidis et al. 2019) (Fig. 1). Inland waters in Washington (other than SJF) and British Columbia are excluded from the abundance estimates because these areas are used primarily by transient whales during the northbound spring migration (Calambokidis et al. 2010, Calambokidis 2016). We temporally truncated the time series to include gray whales photographed and identified within the defined region anytime during the period between 1 June and 30 November following the IWC definition of PCFG membership (hereafter referred to as the sampling period) (Calambokidis et al. 2019).

A sighting history was constructed for each unique gray whale photographed using 28 years of data from 1996 to 2023. Multiple sightings of an individual whale within a year were treated as a single detection. However, multiple sightings over the course of a year, including observations from the spring prior to 1 June, were used to construct an observed minimum tenure (MT) for each whale. MT was defined as the number of days between the earliest and latest date the whale was photographed with a minimum of 1 day for any whale observed.

Data analysis

We followed the population modeling procedures described in Calambokidis et al. (2019) and Harris et al. (2022). To summarize, we fit open population models within RMark (an R interface for Program MARK; White et al. 1999, Laake 2013) to estimate PCFG abundance and survival using annual sighting history data from the 28-year time series. We considered the same suite of competing models as described in Calambokidis et al. (2019). We used the POPAN parameterization that included a super population size (N), probability of entry (immigration), sighting probability (p), and survival/permanent emigration ($\hat{\varphi}$) following a robust Jolly-Seber (JS) framework (Schwarz et al. 1996). We fitted all combinations of p and $\hat{\varphi}$ and used Akaike Information Criterion (AICc; Burnham and Anderson 2002) to select the most parsimonious model of the 30 fitted models (Table 1). However, multimodal inference was used to compute abundance estimates, unconditional standard errors, and confidence intervals.

The model set included parameterizations that tested for differences between "first-year" and "post-first-year" survival, as defined by the first year an individual was observed, to account for predicted differences in resighting PCFG and transient (i.e., non-PCFG) animals in consecutive years (Pradel et al. 1997). Consequently, survival as implemented here is confounded with permanent emigration, particularly within first-year survival estimates. Therefore, we expect survival estimates to be biased low relative to true survival. Survival, and the underlying emigration and transiency patterns, likely vary through time. To account for potential temporal structure in survival, we followed Calambokidis et al. (2019) and implemented two distinct sub-models representing varying degrees of complexity for first-year survival (and therefore transient proportion) by 1) including three period-specific, first-year survival estimates (1996 and 1997, 1998, and 1999 and later); and 2) permitting first-year survival to vary by year. The three periods were selected to reflect the progression in survey effort with a higher preponderance of newly identified individuals that were also members of the PCFG during the earliest years and more expansive survey coverage after 1997. The post-1998 period was intended to capture an anticipated re-distribution of animals following an unusual mortality event in 1999.

Post-first-year survival, and therefore emigration rate, was also expected to change in response to a short-term redistribution of individuals following a stranding event in 1999-2000. As in Calambokidis et al. (2019), we included a group effect in all models that represented two distinct groups and their post-first-year survival: 1) a group incorporating all non-calves newly observed prior to 1999 and all calves independent of year and 2) a group incorporating all non-calves newly observed after 1998. In order to facilitate model fitting, we assumed that all PCFG gray whales were observed in their first year (sighting probability p and probability of entry p_{ent} are fixed to 1 for each cohort year). For estimating non-fixed sighting probabilities (p), we fitted three models that varied by time (year) and/or varied by minimum tenure (MT) in the previous year (Table 1). Finally, we considered models that permit first-year survival to vary as a function of MT with the expectation that whales spending more time in the PCFG range during the sampling period are more likely to be observed in the following year. The effect of MT was either held constant through time or permitted to change across years or time periods.

Abundance estimation

Annual abundance was derived from a modified Jolly-Seber estimator represented by

$$\widehat{N}_j = \sum_{i=1}^{u_j} \hat{\varphi}_{ij} + \sum_{i=1}^{m_j} 1 / \hat{p}_{ij} \ ,$$

where the abundance of PCFG whales ($\widehat{N}$) in year j is comprised of newly observed individuals (u) who are expected to remain part of the PCFG ($\hat{\varphi}$) and the number of previously observed individuals (m) observed with sighting probability ($\hat{p}$). We assumed that all new PCFG whales were sighted (p = 1), and because we were only interested in estimating the abundance of whales that will remain part of the PCFG (or the portion of newly observed whales that do not permanently emigrate), we included yearly (j) and whale-specific covariates (i) (e.g., minimum tenure). To obtain an abundance estimate for 2022, we assumed that the first-year survival intercept for 2022 was the same as in 2021. For predicting the number of new whales that remained a part of the PCFG (i.e., did not permanently emigrate), a variance-covariance matrix for the abundance estimates was constructed using a Horvitz-Thompson-type variance estimator from Borchers et al. (1998) with an adaptation for the first component to predict the number of new PCFG whales.

Results

A total of 25,484 daily sightings were recorded between 1996 and 2023, including observations of 970 unique whales within the PCFG range between 1 June and 30 November (Fig. 2). The average number of whales identified in any one year was 168 throughout the PCFG range (excluding 1996-97; Table 2). Importantly, these estimates do not reflect the true numbers of whales that use the region because not all whales are observed that year and not all whales return annually to the PCFG range. The annual average number of newly observed whales (excluding 1996-1998 before the photo-id effort expanded to cover all survey regions) was 32. Of these, the annual average number of newly observed whales that were "recruited" (observed in a subsequent year, excluding 1996-1998 and 2023) into the PCFG was 13.2 (41.2%).

Abundance and recruitment

Annual PCFG gray whale abundance was derived using model-averaged estimates from the Jolly-Seber open population model sets (Table 1). Estimates for the PCFG displayed in Figure 3 are for the period between 1998 and 2023. The early years, 1996-1997, are excluded from the trend because of the reduced effort and survey coverage at the start of the study, leading to known bias in these earlier years. Our estimate of gray whale abundance for the PCFG was 213 individuals in 2023, with a N_{min} of 200. We estimated the MMPA's Potential Biological Removal (PBR) for the PCFG to be 3.1, with an R_{max} of 6.2% and a recovery factor of 0.5 (Caretta et al. 2013). New whales that are not identified as calves have appeared annually and many of these new non-calf whales have subsequently returned and been re-sighted. Within the PCFG range from 1999 to 2022, an average of 27.2 (range: 7 - 67) new non-calves were observed each year. Of these new non-calf whales, an average of 9.9 (range: 1 - 28) whales returned and were observed in subsequent years. The proportion of new non-calves that had used but were not observed as calves within the PCFG range is unknown.

Discussion

We provided an updated assessment of abundance for PCFG gray whales, extending the time series from 2022 used in Harris et al. (2022) through to 2023. Our analysis included mark-resight data collected as part of a large-scale collaborative effort to survey PCFG gray whales in coastal waters from northern California to northern Vancouver Island, British Columbia. Our abundance estimates indicated that the PCFG steadily increased before declining from a peak in abundance in 2015-2016, representing an overall decline of 18.8% during the most recent Unusual Mortality Event (+2.4% since 2022).

Importantly, mark-resight models used in estimating abundance are sensitive to survey design, most notably in this case to variation in survey effort within and across years throughout the defined PCFG range. As in Calambokidis et al. (2019), we do not explicitly account for survey effort due to inconsistencies in how effort was tracked -- if at all-- by contributors to the gray whale photographic catalog. However, given the high resightability of long-lived PCFG gray whales, the impact of excluding effort was likely limited to increased uncertainty in both sighting probabilities and survival/emigration probabilities and, therefore, reduced precision in PCFG abundance estimates. Notably, the present assessment included new contributions from Carrie Newell for data years 2016 through 2022, totaling 145 unique whales across 4,865 encounters in the area around Depoe Bay, Oregon. The inclusion of these new data did not change the abundance estimates in any substantive way (Fig. 4). In addition to effort, unaccounted for heterogeneity in behavior (e.g., individual variation in resource utilization, site fidelity, large-scale movements, and response to survey vessels) may also contribute to reduced precision in abundance estimates within a mark-resight context. Yet, as highlighted in previous assessments, the present modeling framework represents the best available for assessing PCFG abundance in light of current data limitations and knowledge gaps.

Acknowledgments

This analysis would not have been possible without the collaborating organizations and individuals contributing identification photographs. Support for the photographic identification reported here, the comparison of gray whale photographs and preparation of this report came primarily from the National Marine Fisheries Service's West Coast Region with additional support from other collaborators. We thank Chris Yates, Lynne Barre, Penny Ruvelas, and Dan Lawson at the NMFS West Coast Region for providing consistent funding to MML for the field surveys and photo-identification efforts. Permission to conduct some portions of this research in U.S. waters was provided by the U.S. National Marine Fisheries Service and the Makah Tribe. Jonathan Scordino assisted with data collection and provided data off the northern Washington coast and SJF. Portions of the research in British Columbia were conducted collaboratively with Fisheries and Oceans Canada (thanks to John Ford and Graeme Ellis). Volker Deecke assisted in analysis and matching of identifications from S. Vancouver Island. William Megill coordinated providing sightings and identifications from CERF; Dawn Goley and Jeff Jacobsen coordinated effort for HSU; Christina Tombach and Dave Duffus coordinated early efforts for UVIC; Leigh Torres and her graduate students at Oregon State University (OSU) provided identification photographs from both central and southern Oregon starting in 2015 and the OSU Whale Telemetry Group provided photographs associated with their tagging efforts; Carrie Newell provided identification photographs from Depoe Bay, Oregon; Merrill Gosho, Pat Gearin, Nate Pamplin, and Jonathan Scordino provided photos from Washington. Brian Gisborne's diligence and hard work provided an immense amount of data and photographs from Vancouver Island. Mark Sawyer and Ashley Hoyland for their recent and substantive contributions to the catalog from Vancouver Island. A number of people assisted in the field effort and in the printing and matching of photographs at Cascadia Research. Jeff Laake developed the model set and associated code. Erin Falcone, Lisa Schlender, Jennifer Quan, and Amber Klimek helped compile the data from different contributors and conducted photographic matching. Randy Lumper conducted gray whale matching in the early years of this study. Sharon Melin provided many helpful comments, suggestions, and edits.

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Tables and Figures

Table 1. -- Parameter specifications for survival (φ) and sighting probability (p) in POPAN models for gray whale photographic identification data. For survival models, β_0 is the baseline intercept for non-transient survival. Fy is 1 if it is year the whale was first observed and 0 otherwise. A subscript for Fy means that it applies only for that cohort except that Fy_{99} applies to cohorts 1999 and beyond and Fy_c represents each of the cohorts from 1996 to 2023. C is 1 if identified as a calf in its first year and 0 otherwise. R is 1 for calves or any whale observed in 1998 or was already in the catalog prior to 1998 and 0 otherwise. β_r is an adjustment to post-first-year survival. MT is minimum tenure value of a whale and β_M is the estimated slope parameter for φ or p. $\beta_{M,96-97}$ applies to 1996-97, $\beta_{M,98}$ to 1998 and $\beta_{M,99}$ applies to 1999-2022. $\beta_{Fy,96-97}$, $\beta_{Fy,98}$ and $\beta_{Fy,99}$ are the first-year survival intercept adjustments for 1996-97, 1998 and cohorts 1999-2022, respectively, and $\beta_{Fy,c}$ represents 27 cohort-specific first year survival parameters for 1996-2022. β_{CF} is an adjustment for calf first year survival and β_{CM} is an adjustment for calves to the slope of MT for survival. For the sighting probability models, β_t has 26 levels for 1998-2023 and β_0 represents the 1997 value. p = 1 for 1996. The best models for the Pacific Coast Feeding Group were model 9 for φ and model 2 for p.

Model	Parameter Logit Formula	Number of parameters
φ		
1	$\beta_0 + \beta_{Fy} Fy + \beta_r R(1 - Fy)$	3
2	$\beta_0 + \beta_{Fy} Fy + \beta_M MT\, Fy + \beta_r R(1 - Fy)$	4
3	$\beta_0 + \beta_{Fy,96-97} Fy_{96-97} + \beta_{Fy,98} Fy_{98} + \beta_{Fy,99} Fy_{99} + \beta R(1 - Fy)$	5
4	$\beta_0 + \beta_{Fy,96-97} Fy_{96-97} + \beta_{Fy,98} Fy_{98} + \beta_{Fy,99} Fy_{99} + \beta_M MT\, Fy + \beta_r R(1 - Fy)$	6
5	$\beta_0 + (\beta_{Fy,96-97} + \beta_{M,96-97} MT) Fy_{96-97} + (\beta_{Fy,98} + \beta_{M,98} MT) Fy_{98} + (\beta_{Fy,99} + \beta_{M,99} MT) Fy_{99} + \beta_r R(1 - Fy)$	8
6	$\beta_0 + \beta_{Fy,c} Fy_c + \beta_M MT\, Fy + \beta_r R(1 - Fy)$	22
7	$\beta_0 + \beta_{Fy,c} Fy_c + \beta_M MT\, Fy + \beta_{CF} C\, F_y + \beta_r R(1 - Fy)$	23
8	$\beta_0 + \beta_{Fy,c} Fy_c + \beta_M MT\, Fy + \beta_{CF} C\, F_y + \beta_{CM} C\, MT + \beta_r R(1 - Fy)$	24
9	$\beta_0 + (\beta_{Fy,96-97} + \beta_{M,96-97} MT) Fy_{96-97} + (\beta_{Fy,98} + \beta_{M,98} MT) Fy_{98} + (\beta_{Fy,99} + \beta_{M,99} MT) Fy_{99} + \beta_{CF} C\, F_y + \beta_r R(1 - Fy)$	9
10	$\beta_0 + (\beta_{Fy,96-97} + \beta_{M,96-97} MT) Fy_{96-97} + (\beta_{Fy,98} + \beta_{M,98} MT) Fy_{98} + (\beta_{Fy,99} + \beta_{M,99} MT) Fy_{99} + \beta_{CF} C\, F_y + \beta_{CM} C\, MT + \beta_r R(1 - Fy)$	10
p		
1	$\beta_0 + \beta_t$	19
2	$\beta_0 + \beta_t + \beta_M MT$	20
3	$\beta_0 + \beta_M MT$	2

Table 2. -- Classification of whales seen (calves + non-calves) within the Pacific Coast Feeding Group range (Northern California to Northern British Columbia) between 1 June and 30 November from 1996 to 2023.

Year	Total Seen	Newly Seen	Newly Seen and Seen Again
1999	150	67	12
2000	140	54	28
2001	172	61	26
2002	203	52	29
2003	157	20	15
2004	177	27	13
2005	134	17	10
2006	125	7	1
2007	120	20	9
2008	173	50	18
2009	151	20	7
2010	144	15	12
2011	163	19	5
2012	208	53	22
2013	232	58	25
2014	200	37	16
2015	210	39	19
2016	187	29	13
2017	162	16	4
2018	151	24	7
2019	183	30	12
2020	165	15	4
2021	146	32	5
2022	157	19	8
2023	192	30	
Total	4202	811	320
Average	168	32	13

Table 3. -- Model-averaged estimates of Pacific Coast Feeding Group gray whale abundance (N), standard errors (se), and minimum population estimate (N_{min}) using data from 1996 to 2023 for the area between northern California and northern British Columbia (NCA-NBC).

Year	N	se(N)	N_min
1996	38.8	2.7	36.6
1997	82.1	11.3	73.1
1998	127.4	10.6	118.8
1999	147.9	15.8	135.2
2000	148.4	15.5	135.9
2001	179.0	14.4	167.3
2002	196.0	10.3	187.6
2003	208.8	18.5	193.8
2004	215.2	16.4	201.8
2005	220.7	26.7	199.5
2006	199.1	21.9	181.5
2007	198.3	26.0	177.7
2008	212.1	19.7	196.1
2009	213.9	22.3	195.9
2010	205.6	20.7	188.9
2011	210.1	17.2	196.1
2012	223.8	15.1	211.4
2013	243.2	14.1	231.7
2014	251.7	20.9	234.7
2015	254.1	18.8	238.8
2016	262.5	25.8	241.7
2017	235.5	22.5	217.4
2018	224.5	24.9	204.5
2019	223.5	18.1	208.8
2020	216.8	18.5	201.8
2021	219.4	26.9	197.9
2022	208.0	19.0	192.6
2023	213.1	15.5	200.4

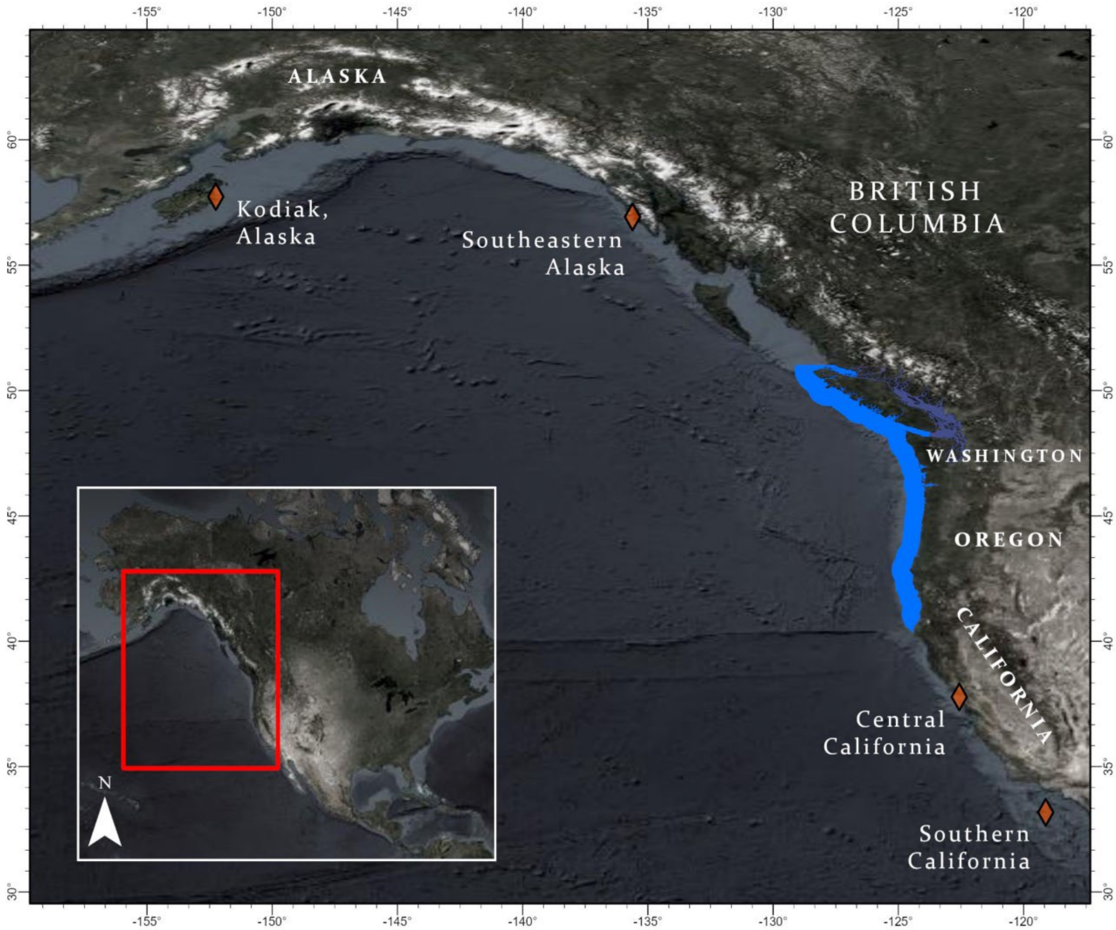

Figure 1. -- Regional areas representing field efforts for photo-identification of Eastern North Pacific gray whales (ENP). The region highlighted in light blue represents the coastal range of the Pacific Coast Feeding Group (PCFG), and encompasses all of the seasonal survey effort used in this analysis. Grey whale sightings in the inland waters of Washington and British Columbia, including Puget Sound and the greater Salish Sea (highlighted in dark blue), are most commonly members of the broader ENP as they pass through to feeding areas in the Arctic. Sightings of PCFG whales are rarer in inland waters during the June to November survey window.

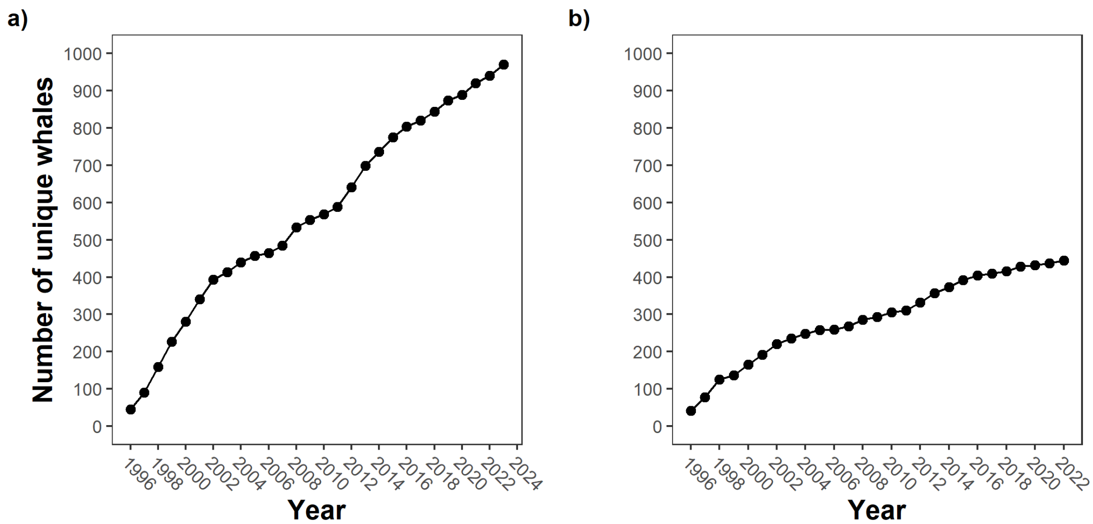

Figure 2. -- Number of unique gray whales observed within the Pacific Coast Feeding Group (PCFG) range (a) and number of unique whales recruited into the PCFG (b) between 1996 and 2023.

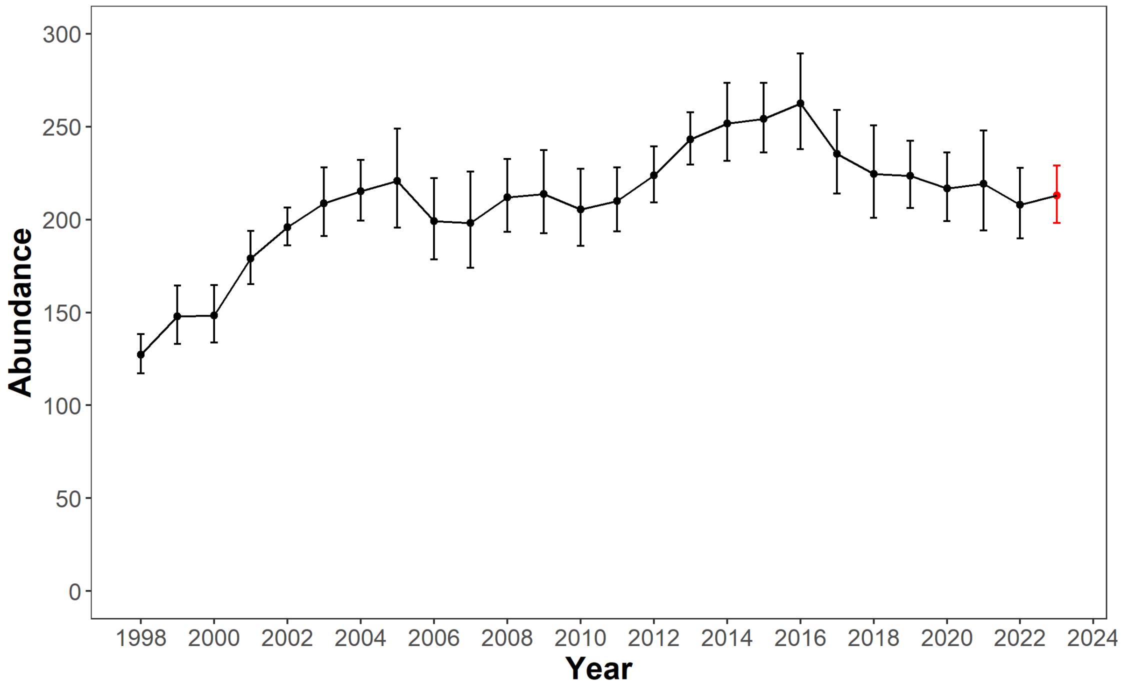

Figure 3. -- Annual Pacific Coast Feeding Group gray whale abundance estimated for 1998 through 2023 between northern California and northern British Columbia using the Jolly-Seber open population model (POPAN parametrization). Trend in red reflects updated estimates using data from 2022 through 2023.

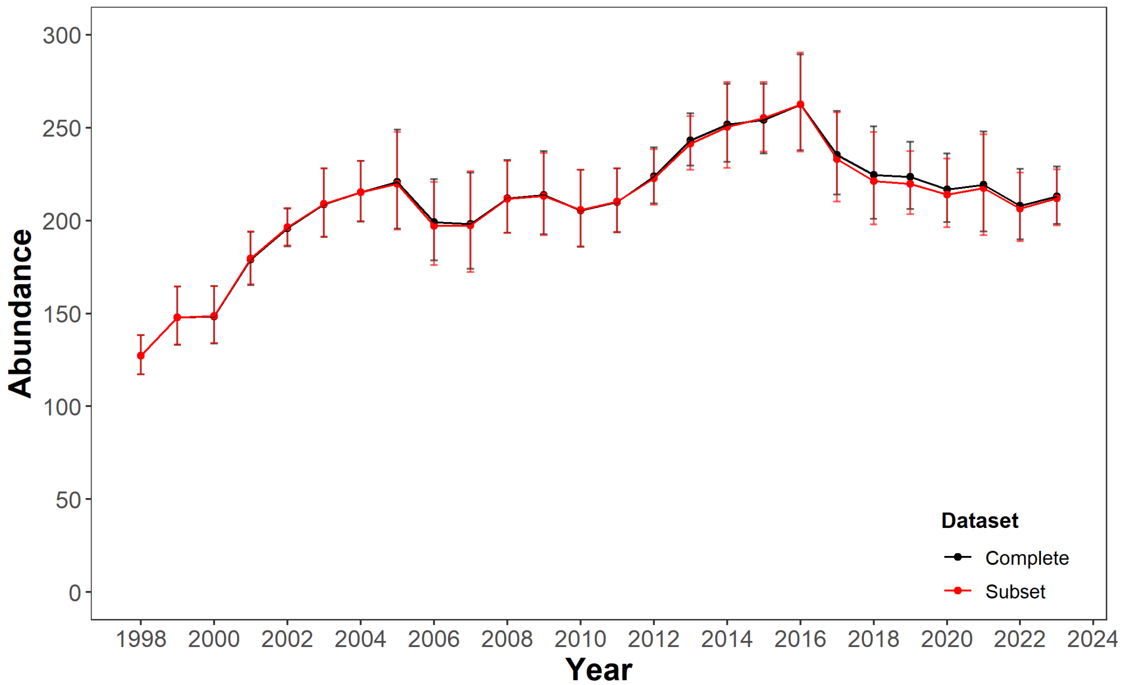

Figure 4. -- Annual Pacific Coast Feeding Group gray whale abundance estimated for 1998 through 2023 between northern California and northern British Columbia using the Jolly-Seber open population model (POPAN parametrization). The trend in red depicts estimates using a subset of the data excluding recent contributions from C. Newell (Whale Research EcoExcursions) between 2016 and 2023. The trend in black depicts estimates from the complete dataset.

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