Anthropogenic and killer whale (*Orcinus orca*) scarring on Pacific Coast Feeding Group gray whales (*Eschrichtius robustus*) in northwest Washington

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ABSTRACT

Gray whales (*Eschrichtius robustus*) face many threats to their survival which are multi-faceted and difficult to assess. In this study, we evaluate photographs of Pacific Coast Feeding Group (PCFG) gray whales taken between 2014 and 2020 off the northwest coast of Washington to document the occurrence of scarring from fishing gear entanglements, vessel strikes and killer whale (*Orcinus orca*) attacks and compare our findings with scarring prevalence in gray whales off Sakhalin Island, Russia. We found that, of the 139 PCFG whales evaluated, 11.5% had scarring from entanglements, 3.6% had scarring from vessel strikes and 25.9% had scarring from killer whale attacks. We found no differences in scarring rates between males and females. Observed rates of scarring from entanglements for PCFG whales were less than rates observed for gray whales off Sakhalin Island, Russia, while scarring rates from vessel strikes were slightly greater for PCFG whales, but the differences were not statistically significant. The frequency of scars due to killer whale attacks on PCFG whales was significantly lower than reports for whales observed at Sakhalin Island. Estimates of anthropogenic and killer whale scarring in this study are likely biased low due to limited photographic coverage of the caudal peduncle and flukes, where scarring from entanglements and killer whale attacks are most commonly observed. The methods used here were similar to studies at Sakhalin Island, suggesting the evaluations had similar biases. If we assume that observations of non-lethal scar sources on gray whales are proportional to mortality rates from those sources, findings from this study can help evaluate if current models present plausible injury and mortality estimates for PCFG and Sakhalin Island whales given the finding of no statistical difference in non-lethal scarring rates between the two groups.

KEYWORDS: GRAY WHALE; KILLER WHALE; INCIDENTAL CATCHES; SHIP STRIKES; PREDATION; FISHERIES; SURVEY-VESSEL

INTRODUCTION

Gray whales (*Eschrichtius robustus*) once spanned most of the Northern Hemisphere but were exploited to extinction in the Atlantic Ocean and near extinction in the Pacific Ocean by unsustainable commercial whaling activities (Anthony, 1921; Rice & Wolman, 1971; Mead & Mitchell, 1984; van den Hurk *et al.*, 2023). Following the cessation of commercial whaling, the gray whale population in the Eastern North Pacific (ENP) rapidly

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increased in abundance and currently fluctuates near its carrying capacity of approximately 22,062 individuals (Punt & Wade, 2012; Stewart *et al*., 2023). The abundance of gray whales that calve in the Western North Pacific (WNP) was also severely impacted by commercial whaling and was thought by some to be extinct (Nishiwaki & Kasuya, 1970; Bowen, 1974). Cooke (2018) shows that the small population of whales that feed around Sakhalin Island and the Kamchatka Peninsula is currently increasing in abundance with an estimated rate of increase of 4.1% per year.

Although the ENP gray whale population has recovered, and WNP whales are potentially showing signs of recovery, it is important to understand sources of morbidity and mortality for these populations to improve management practices (IWC, 2019; 2021). Given the overlap of gray whale foraging areas and migratory routes with coastal fishing and shipping activities (Saez *et al*., 2013; Lowry *et al*., 2018; Silber *et al*., 2021), both the ENP and WNP experience injuries and mortalities from entanglements in fishing gear and vessel collisions (Oldach *et al*., 2022). Over the past five years, a minimum annual average of 14.3 gray whale mortalities occurred throughout the North Pacific Ocean (not including Russia and China) due to non-hunting anthropogenic sources (Scordino *et al*., 2023).

Gray whales also face natural threats. The greatest threat to gray whale abundance and health in the ENP appears to be environmental factors that affect the extent of sea ice in the Arctic and the distribution and abundance of gray whale prey, leading to large-scale mortality events (Le Boeuf *et al*., 2000; Perryman *et al*., 2020; Moore *et al*., 2022; Joyce *et al*., 2023; Stewart *et al*., 2023). A lesser threat, but still important, is the role of killer whale (*Orcinus orca*) predation (Goley & Straley, 1994; Barrett-Lennard *et al*., 2011; Matkin & Durban, 2013; Weller *et al*., 2018). There are two geographic areas known to be hotspots for killer whale predation on gray whales: Monterey Bay, California (Goley & Straley, 1994) and the False Pass/Unimak Pass region of Alaska (Barrett-Lennard *et al*., 2011; Durban *et al*., 2023). Observations of killer whales attacking gray whales have also been reported outside these two hotspots (Andrews, 1914; Burrage, 1964; Morejohn, 1968; Baldridge, 1972; Fauquier *et al*., 2022; Willoughby *et al*., 2022). Killer whale predation is a natural source of gray whale injury and mortality, and understanding the magnitude of this threat is an important part of understanding gray whale population dynamics.

While observing and quantifying threats to gray whales is complex, entanglement, vessel strikes and killer whale attacks leave distinct scar patterns that can be analysed for both non-lethal and lethal interactions. Studies have been conducted at Sakhalin Island, Russia, to document the frequency and types of scars on gray whales that utilise the adjacent waters to feed (Bradford *et al*., 2009; Weller *et al*., 2018). This paper seeks to replicate the methods in those studies for documenting and evaluating scarring for a feeding group of gray whales, the Pacific Coast Feeding Group (PCFG). The PCFG is a group of ENP gray whales that show multiyear fidelity to the Pacific coast of the United States and Canada from 41°N to 52°N during the feeding season of June–November (Calambokidis *et al*., 2002; IWC, 2011). Within the PCFG range, there are well-established stranding networks that document the cause of gray whale mortalities, in addition to regulations in the United States and Canada that require mariners and fishers to report vessel strikes and fishery interactions with marine mammals (Saez *et al*., 2020; Scordino *et al*., 2023). In contrast, there is little in the way of stranding response at Sakhalin Island and the Kamchatka Peninsula, making it likely that anthropogenic mortality sources are underreported at those sites compared with PCFG whales (Lowry *et al*., 2018). This study aims to investigate non-lethal scarring for PCFG gray whales to determine prevalence rates of scarring due to anthropogenic sources and killer whale attacks and, in turn, serve as a point of comparison with Sakhalin Island whales. A comparison of this type can be used to inform modeling efforts, such as the International Whaling Commission's Rangewide Review of Gray Whale Stock Structure and Status (IWC, 2019), to help determine plausible estimates of mortalities due to anthropogenic sources for Sakhalin Island and PCFG gray whales.

The first objective of this study was to characterise the frequency and types of anthropogenic injuries to PCFG gray whales and the frequency of killer whale attacks by evaluating the scarring on live whales photographed in northwest Washington, USA. Male and female gray whales have differences in migratory pathways and timing (Rice & Wolman, 1971; Herzing & Mate, 1984), which may lead to differences in exposure to anthropogenic activities. Likewise, killer whales are reported to target female-calf pairs (Ford & Reeves, 2008; Matkin & Durban, 2013), which may result in females being attacked more often than males. To better understand these threats to

PCFG whales and potential effects on population dynamics, differences in anthropogenic and killer whale scarring rates between males and females were analysed. The second objective was to compare the rates of anthropogenic and killer whale scarring of PCFG gray whales with published results of scar assessments from gray whales at Sakhalin Island (Bradford *et al.*, 2009; Weller *et al.*, 2018). We hypothesised that differences in anthropogenic scarring would be observed between Sakhalin Island and PCFG gray whales caused by differences in fishing effort and vessel activity in the two discrete feeding grounds (Saez *et al.*, 2013; Lowry *et al.*, 2018). We also hypothesised that PCFG whales would have less killer whale scarring because they intersect with fewer locations where killer whales frequently hunt gray whales than Sakhalin Island whales, which complete a much longer migration (Mate *et al.*, 2015). Addressing these two objectives will help provide a better understanding of non-lethal threats to PCFG gray whales and inform modeling efforts for both Sakhalin Island and PCFG gray whales.

METHODS

Small-vessel surveys for PCFG gray whales were conducted along the shoreline of northwest Washington, USA, a region bordered by the Strait of Juan de Fuca to the north and Pacific Ocean to the west (Fig. 1). Survey efforts for the entire region were divided into two geographic areas. One survey area occurred within the Strait of Juan de Fuca from Neah Bay (48°22.66'N, 124°35.26'W) east to Sekiu Point (48°16.10'N, 124°17.73'W). The second survey area followed the shoreline of the Strait of Juan de Fuca from Neah Bay west to Cape Flattery (48°23.25'N, 124°43.54'W) and then south along the Pacific Ocean coast to Sea Lion Rock (47°59.58'N, 124°43.45'W) (Scordino *et al.*, 2017b). Surveys were generally conducted within 1–2 km of shore during the gray whale feeding season and out to 16 km offshore during the migratory season.

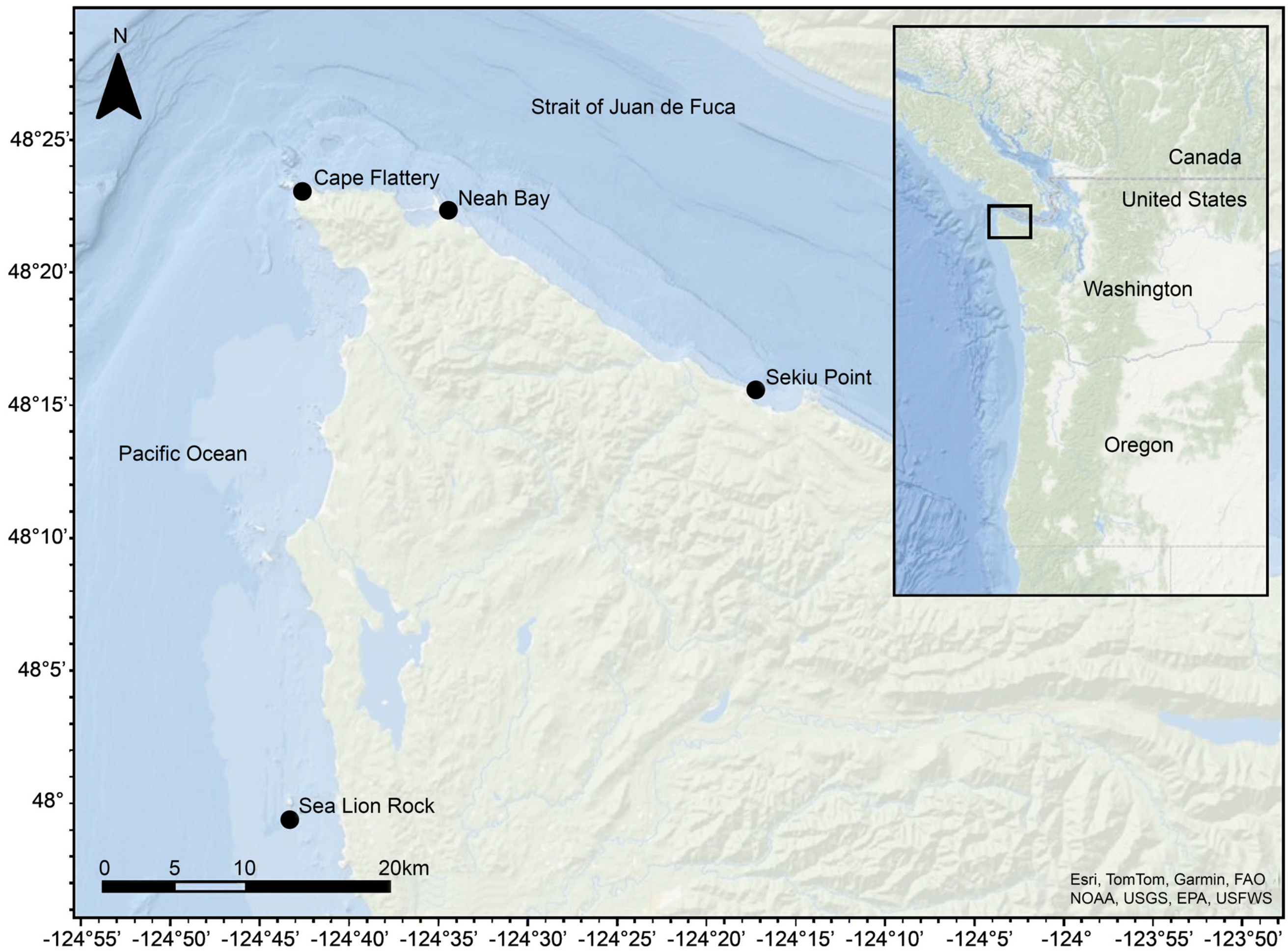

Figure 1. Gray whale survey area in northwest Washington State, USA, which encompasses an area in the Strait of Juan de Fuca from Sekiu Point in the east to Cape Flattery in the west and then south along the Pacific Ocean coast to Sea Lion Rock.

Using SLR digital cameras with 100–400 mm lenses, photos were taken of as much of each whale as possible during each surfacing event, with an emphasis on photographing the dorsal hump region of both sides of the whale for photo-identification (photo-ID). Photos were submitted to Cascadia Research Collective for comparison to their catalogue of gray whales following methods previously described (Calambokidis *et al*., 2002). Whale catalogue numbers were provided by Cascadia Research Collective and used to create a catalogue of PCFG whales photographed in the study region during the years 2014–2020. When available, sex data from past and ongoing genetic studies (Lang *et al*., 2022) were linked with the catalogue number.

A gray whale sighting for this study was defined as at least one photograph collected with sufficient quality to identify the individual whale and assess any scarring present. Following established methods (Bradford *et al*., 2009; Weller *et al*., 2018), this study used photo analysis to determine the body region (BR) and source of anthropogenic and killer whale scars for PCFG whales. Scars were assigned to 23 pre-defined body regions (Fig. 2) following Bradford *et al.* (2009), although this study added the left and right sides of the caudal peduncle (BR10 and BR11 in Fig. 2). BR10 and BR11 were added because these regions are commonly documented as having entanglement scars (Robbins & Mattila, 2001; 2004). Visibility of each body region was classified as full visibility, partial visibility or no visibility/poor quality. To be categorised as either fully or partially visible, a body region had to be captured in one or more photographs of sufficient quality to detect and identify a potential scar. A body region was recorded as having no visibility/poor quality if the region was out of frame, obstructed from view or if the photo was too pixilated or dark to allow observation of scarring. Scars were identified and assigned to the following source categories: entanglement; vessel strike; killer whale attack; unknown (Fig. 3).

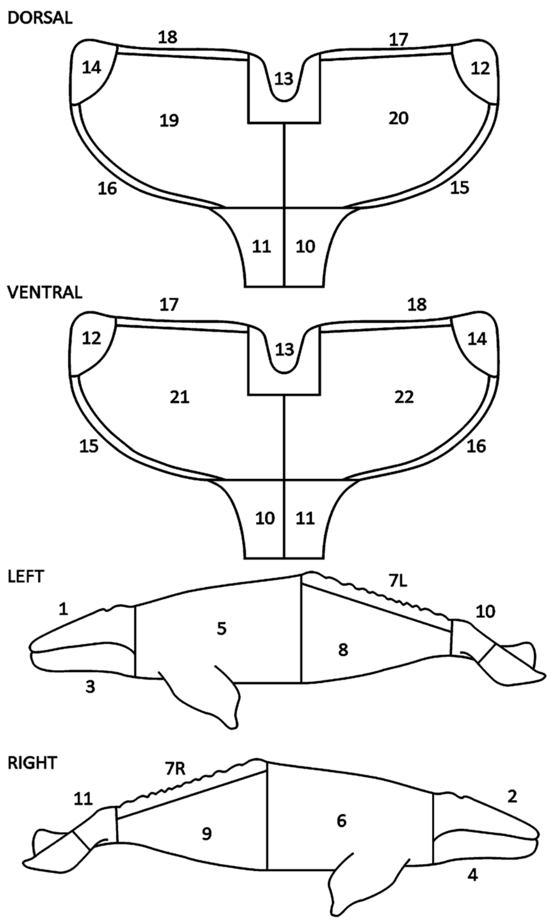

Figure 2. Body regions (BR1–22) evaluated for scarring and photographic coverage of gray whales in northwest Washington State, USA, from 2014–20, shown on the outlines of the dorsal and ventral sides of the fluke and the left and right sides of the body. Body regions adapted from Bradford *et al.* (2009), with additional regions added for the left and right caudal peduncle (BR10 and BR11).

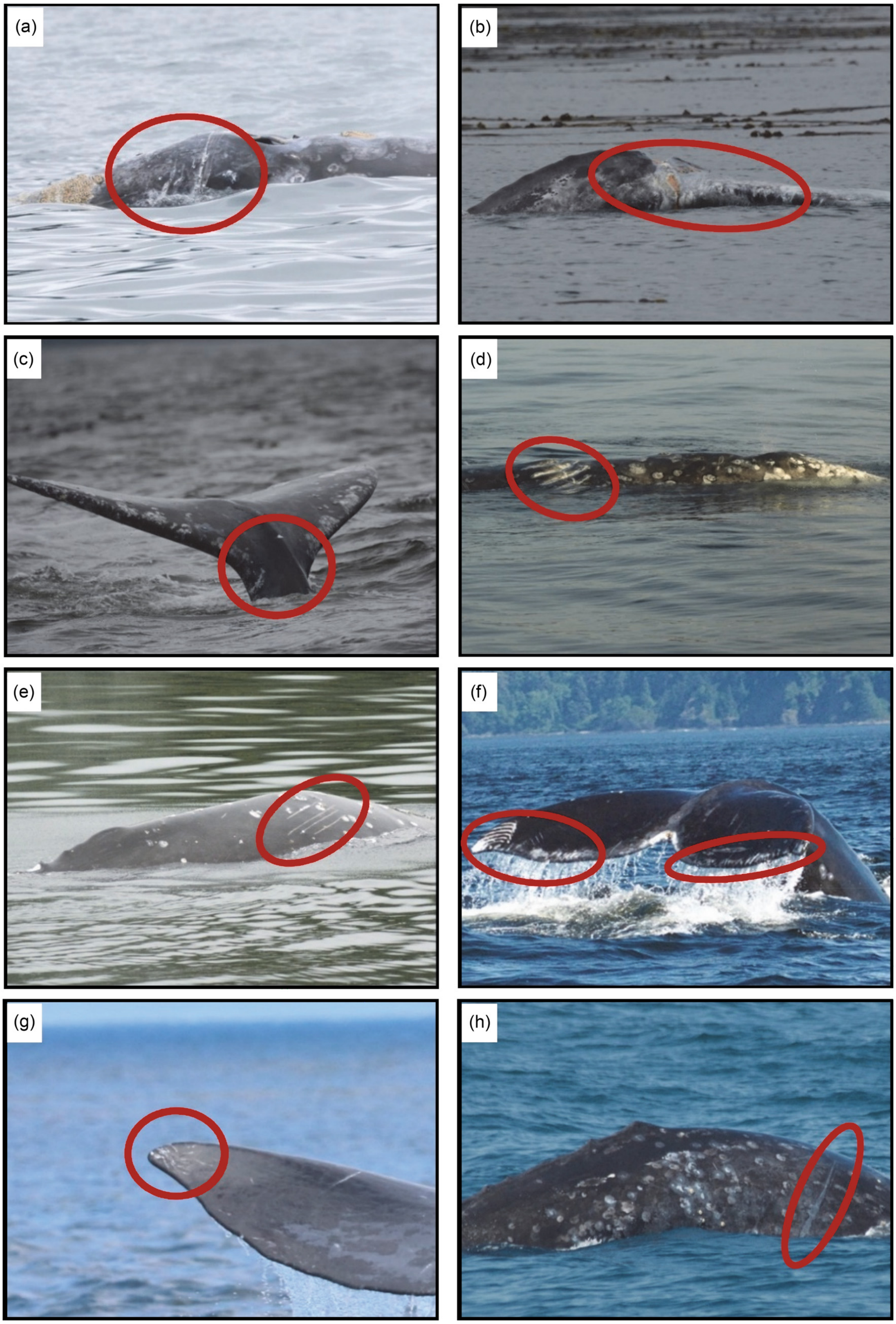

Figure 3. Example images of each scar assessment category for gray whales off northwest Washington, USA, from 2014–20, including (a) a narrow entanglement scar; (b) entanglement of the caudal peduncle; (c) potential entanglement; (d) vessel strike; (e) potential vessel strike; (f) killer whale rakes; (g) potential killer whale rakes; (h) an unknown scar.

The characteristics used to identify scar sources were based on similar studies that assessed anthropogenic and natural scar sources for other marine mammals (Robbins & Mattila, 2004; Rommel *et al*., 2007; Norman *et al*., 2017; Basran *et al*., 2019; Silber *et al*., 2021). Note that scar sources were analysed for their presence or absence rather than their frequency in each body region. Therefore, multiple scar sources could be assigned to the same body region but not multiple assignments of the same source. Unknown scars that had suggestive, but not definitive, evidence of belonging to one of the three known scar source categories were documented as 'unknown, potentially [scar source category]' (Fig. 3). These interim evaluations served to distinguish scars with varying degrees of uncertainty from those definitively assigned to one of the three scar source categories.

Scarring was analysed independently by a three-evaluator team (authors RPW, EMA and JJS). After scoring independently, the team formed consensus on scar determinations. Each scar determined to have originated from an entanglement, vessel strike or killer whale attack from the initial three-person consensus was then independently reviewed by three experts on whale injury and scarring (authors ALB, SAN and RS). The experts also reviewed scars that were classified by the three-person consensus as unknown, but potentially due to entanglement, vessel strike or killer whale attack. The expert reviewers evaluated whether the photographs showed enough evidence to assign a known source of scarring and guided the final scar evaluations. Final scar evaluations were determined by comparing the expert reviewers' independent assessments with the initial three-person consensus using a decision tree that considered both scar source and certainty (Fig. 4). For each scar of interest, four letters were used to represent the evaluation: one for the initial three-person consensus (C), and one for each independent expert reviewer that represents whether their score is the same as the three-person consensus (A), different from the three-person consensus but in agreement with other experts (D),

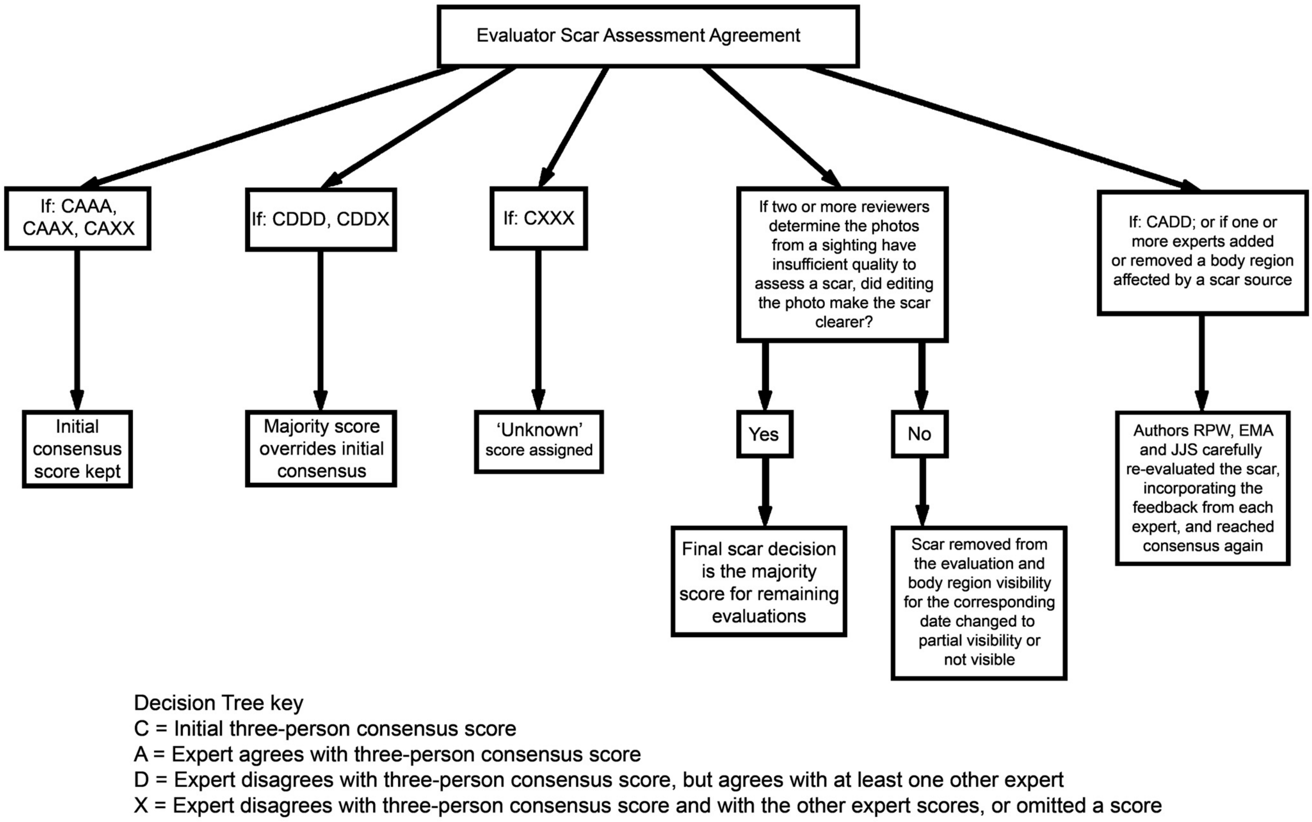

Figure 4. Decision tree used to assess the final scar determinations by comparing the initial three-person consensus (RPW, EMA and JJS) to the evaluations provided by three independent expert reviews (ALB, SAN and RS). Scar agreement scores were represented with four letters: one for the initial three-person consensus (C); one for each independent expert reviewer that represents whether their score is the same as the three-person consensus (A); as different from the three-person consensus but in agreement with other experts (D); or different from both the three-person consensus and the other expert scores (X). Scar agreement considered both scar source and certainty (i.e., 'definitive' or 'potential'). If an equal number of potential and definitive evaluations of the same scar source were present in the four independent scores (e.g., two of each), preference was given to the potential scar assignment.

or different from both the three-person consensus and the other expert scores (X). 'Definitive' and 'potential' scar assignments were considered dissimilar evaluations when determining overall agreement. If an equal number of 'definitive' and 'potential' evaluations of the same scar source category were present in the four independent scores (e.g., two of each), preference was given to the 'potential' scar assignment to be more conservative in scar assignment. Upon final decisions about the origin of a scar, any 'potential' entanglement, vessel strike or killer whale scar was considered an unknown scar source; however, a table of these 'potential' scars and their distribution across each of the 23 defined body regions assessed in this study can be found in the Mendeley Data repository for this study (Walsh *et al*., 2024). Final scar decisions were evaluated for each scarred body region provided to the experts for review for each day that a whale was sighted. The proportion of scars from the initial three-person consensus that changed or remained the same after expert review was then calculated.

Data analysis

Scar and visibility assessments for the 23 body regions from each gray whale sighting were compiled into a composite score for each individual whale. This composite recorded the presence or absence of each scar type as well as the greatest visibility assignment for each body region across all sightings of the whale during the study period. Composites for all whales were then used to analyse the proportion of whales with scars from each source, and the body regions those scars occurred in, to calculate differences in scarring by sex and body region and to compare scarring rates between PCFG and Sakhalin Island whales.

Chi-squared tests of independence and Fisher's exact tests were used to compare the frequency of scars from entanglement, vessel strike and killer whale attacks on male and female PCFG whales and to compare scarring rates observed by source between PCFG and Sakhalin Island (Bradford *et al*., 2009; Weller *et al*., 2018) whales. Fisher's exact tests were used for contingency tables with cell counts of less than or equal to five. Odds ratio tests were used to evaluate the effect size for comparisons that were found to be significantly different with Chi-squared tests. A table further detailing the use of test statistics and their results is presented in Walsh *et al*. (2024).

RESULTS

Scar assessment of PCFG whales

During 2014–2020, 197 gray whale surveys were conducted, resulting in photo-ID of 139 individual PCFG gray whales from 774 total sightings. Each gray whale was photographed during a median of three sightings (range 1–28). Of the 139 whales, 52 were female, 42 were male and 45 were of unknown sex.

Photographic coverage and visibility of each of the 23 outlined body regions (BR; Fig. 2) varied, with the areas used for photo-ID (BR5, BR6, BR7L, BR7R, BR8 and BR9) documented most frequently (Fig. 5). These body regions were most commonly assigned partial visibility because the ventral portion of BR5, BR6, BR8 and BR9 were exposed only when the whale breached, which rarely occurred. BR3 and BR4 (the underside of the head) were the least visible and were only documented as fully or partially visible for 5.0% (n = 7) of the PCFG whales photographed in this study.

A total of 252 scarred body regions were provided to three experts for evaluation. There was no change between the initial evaluation and the expert-informed final scar decisions for 201 (79.8%) scarred body regions. A change in the final scar evaluation occurred for 51 (20.2%) scarred body regions, of which 19 (37.3%) changes, across nine individual whales, were the result of a scar flagged as 'unknown, potentially [scar source category]' being elevated to the corresponding 'definitive' scar source. Only one (2.0%) final evaluation downgraded a 'definitive' killer whale scar to 'unknown, potentially killer whale.' An additional 19 (37.3%) of the changes after expert review were the result of a scarred body region being added or removed for a given whale sighting. The remaining 14 changes in evaluation were due to scar source assignments of 'unknown' being changed to either a definitive or potential scar source.

Anthropogenic scarring from either a vessel strike or entanglement was evident for 21 (15.1%; five males, nine females and seven unknown sex) of the 139 photo-identified PCFG gray whales. Scarring from entanglement

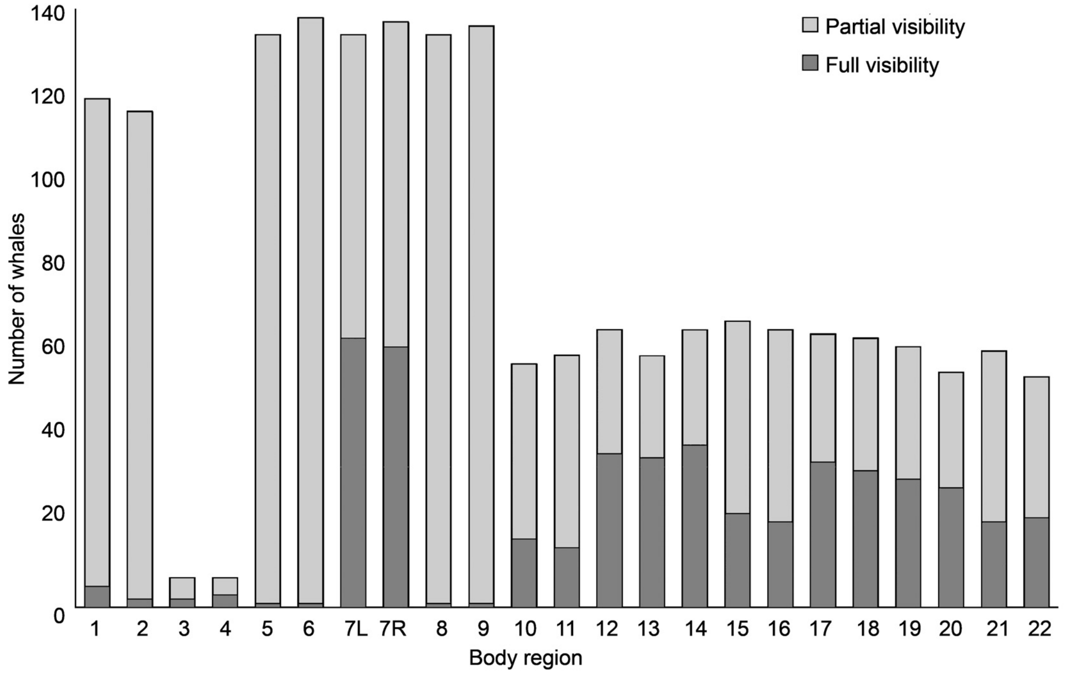

Figure 5. Number of whales photographed with full and partial visibility for each body region of the PCFG gray whales (n = 139) photographed off northwest Washington, USA, 2014–20.

injuries was evident for 16 whales (11.5%; three males, seven females and six unknown sex) and five whales (3.6%; two males, two females and one unknown sex) had evidence of a vessel strike. Scarring from killer whale attacks was observed in 36 whales (25.9%; 10 males, 14 females and 12 unknown). Six whales (4.3%; two males, three females and one unknown sex) had evidence of scars from both anthropogenic and killer whale attacks (Figs. 6 and 7). Chi-squared tests of independence and Fisher's exact tests showed no significant differences between males and females in the proportion of individuals scarred for entanglements, vessel strikes or killer whale predation. Of the 139 PCFG gray whales in this study, 100 (71.9%; 39 males, 41 females and 20 unknown sex) had scars from an unknown source. Of these 100 whales, 17 (17.0%; 10 males, four females and three unknown sex) had scars potentially due to an entanglement, vessel strike or killer whale attack.

We documented noteworthy patterns of scar sources in certain body regions, which were subsequently analysed. The visibility of certain scar types was highly dependent on being able to see specific body regions where those injury types occur most frequently. Entanglements were most commonly observed in the caudal peduncle region (BR10 and BR11; Fig. 6) but only 70 whales were photographed with at least partial visibility in either BR10 or BR11. BR10 was observed with evidence of prior entanglements on 11 (19.3%) whales. BR11 was observed with evidence of prior entanglements on nine (15.3%) whales. Vessel strikes were most often documented in the thoracic region (BR5 and BR6; Fig. 6), which was also the most frequently photographed region. BR5 was photographed for 134 whales and three (2.2%) whales were documented with scars associated with vessel strikes in this region. BR6 was photographed for 138 whales, of which five (3.6%) whales had scars associated with vessel strikes in this region. Evidence of killer whale scars was most often observed on the fluke tips in BR12 (40.0%, n = 26) and BR14 (20.0%, n = 13), which were photographed for 65 whales. In a *post hoc* analysis, we found that BR12 was 2.63 times (Odds ratio 95% Confidence Interval 1.21–5.95) more likely to have scars from killer whales than BR14 (χ^2 = 6.19, df = 1, p = 0.01). Further details on the scarring rates for each body region are presented in Walsh *et al.* (2024).

Comparison of scarring rates of PCFG and Sakhalin Island whales

Chi-squared tests of independence and Fisher's exact tests showed that there were no significant differences between PCFG and Sakhalin Island gray whales in the presence of either entanglement or vessel strike scars. While the differences were not statistically significant, less frequent entanglement and more frequent vessel

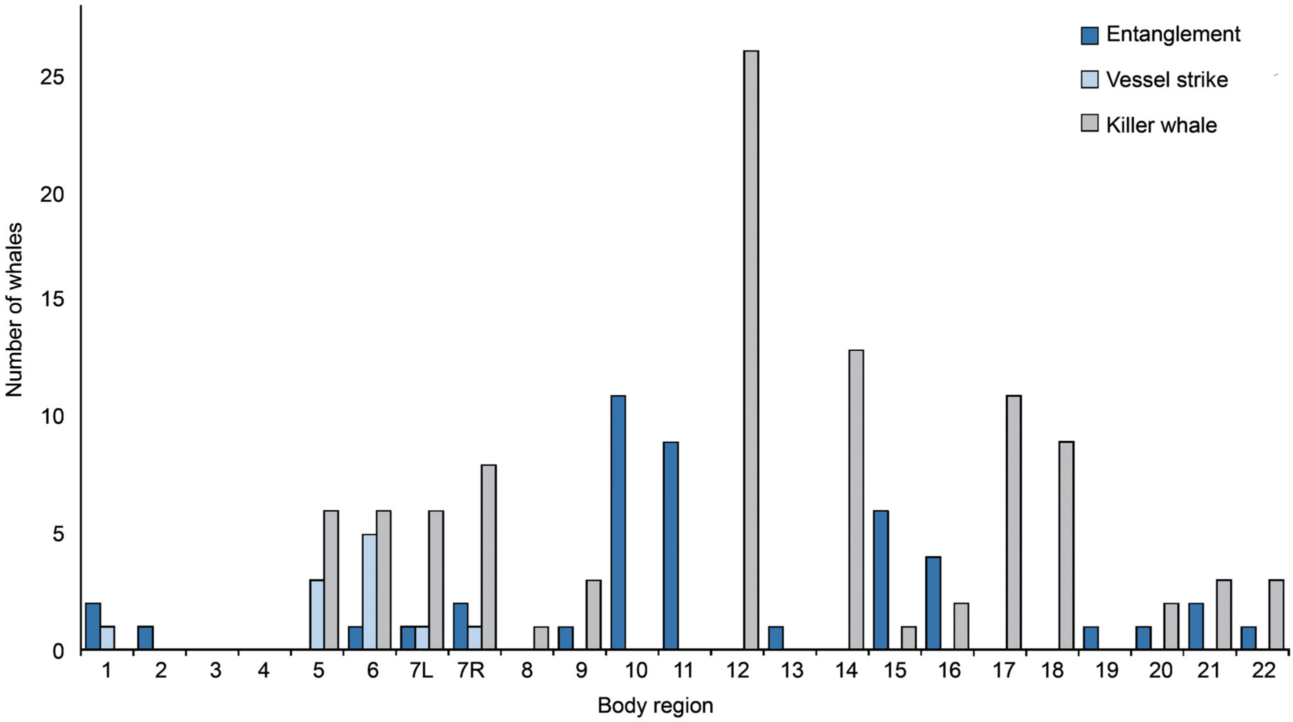

Figure 6. Number of PCFG gray whales (n = 139) photographed off northwest Washington, USA, 2014–20, with evidence of scarring from entanglement, vessel strike and killer whales for each body region.

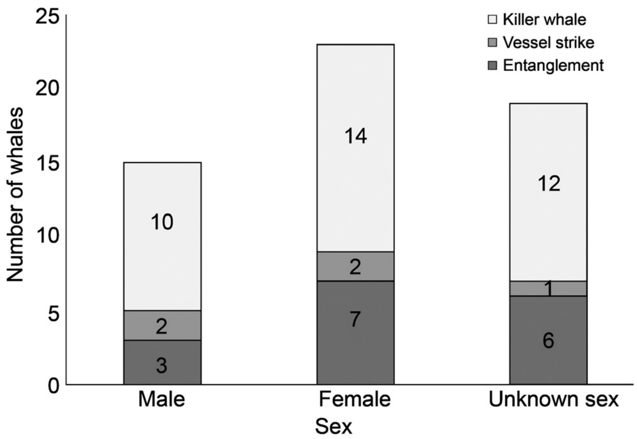

Figure 7. Number of whales exhibiting evidence of entanglement, vessel strike and killer whale scars by sex for the PCFG gray whales (n = 139) photographed off northwest Washington, USA, 2014–20.

strikes were observed on PCFG whales than Sakhalin Island whales. All test statistics for comparing scarring rates of PCFG and Sakhalin Island whales are presented in Walsh *et al*. (2024). There was, however, a significant difference in the frequency of killer whale scarring between PCFG and Sakhalin Island gray whales, with Sakhalin Island gray whales being 2.22 times (Odds ratio 95% Confidence Interval 1.37–3.64) more likely to have killer whale scars (χ^2 = 10.63, df = 1, p = 0.001).

DISCUSSION

PCFG scar source evaluations

This study found that PCFG gray whales observed off northwest Washington, USA, have evidence of interactions with anthropogenic activities that cause serious injury and mortality. Injuries due to anthropogenic sources can reduce whale survivorship and fecundity, especially if the injury is severe (Robbins *et al*., 2015; Knowlton *et al*., 2022; Henry *et al*., 2022). Entanglements of North Atlantic right whales (*Eubalaena glacialis*) have been shown to stunt growth and negatively affect their average total length at maturity (Stewart *et al*., 2021) and cause longer intervals between births for reproductively mature females (Stewart *et al*., 2022). During their migration, gray whales overlap spatially and temporally with a range of human activities, making them susceptible to anthropogenic scarring. This migration takes gray whales through coastal waters with many fixed-gear fisheries on the West Coast of Mexico, the United States and Canada, such as the Dungeness crab fishery, which are known to present risks of entanglement (Saez *et al*., 2013). In this study, most of the whales observed with anthropogenic scarring had evidence of a past entanglement, and only a small proportion had scars due to vessel strikes. Many of the entanglement scars we observed created very narrow scars (Fig. 3) that may have been due to minor gear interactions where the degree of chafing and drag from entangling gear was minimal before the whales were able to free themselves. Another possible explanation for the observation of narrow entanglement scars is that they are due to interactions with recreational fishing activity, where smaller gauge line is used compared with commercial fisheries. Gray whales in northwest Washington are typically observed nearshore, in waters between five and 15 m deep (Scordino *et al*., 2017b), which is an area commonly used by recreational anglers fishing for rockfish (*Sebastes sp.)* and lingcod (*Ophiodon elongatus*) (Beaudreau & Whitney, 2016).

No sex-based differences in scarring from anthropogenic sources and killer whale attacks were found. This finding was surprising because males have different migratory patterns compared to females with calves, with males migrating north earlier and further from shore than female-calf pairs (Herzing & Mate, 1984). These differences in migratory behavior likely change the amount of overlap of male and female gray whales with human activities, such as fisheries that are seasonally and depth restricted. In addition to differences in migratory patterns, studies have shown that killer whales often target mother-calf pairs (Matkin & Durban, 2013), making the lack of difference in scarring rates from killer whale attacks between males and females unexpected. It is possible that gray whales are most vulnerable to entanglements in times and places where both sexes coexist and exhibit similar behaviors (e.g., on their feeding grounds), or that the difference in migration route(s) between sexes does not result in a difference in their overall exposure to entanglement risk. However, the sources evaluated in this study solely arose from non-lethal events (Fig. 3). Adult females or calves of either sex might experience disproportionate incidents of lethal entanglements, vessel strikes or killer whale attacks and would therefore be unavailable in the sample of individuals used here. For management of gray whales and other cetaceans, it is important to consider rates of both lethal and non-lethal threats.

Observed rates of scarring due to entanglement, vessel strikes and killer whale attacks were likely biased lower than the true rates due to the limitations associated with photography from a small vessel. Studies have found that entanglement scars are best documented in photographs of the caudal peduncle and on the leading edge of the fluke (Robbins & Mattila, 2001; Neilson *et al*., 2009; Basran *et al*., 2019). PCFG gray whales in northwest Washington feed in shallow water (Scordino *et al*., 2017b) and do not fluke-up dive often, resulting in infrequent documentation of the caudal peduncle (BR10 and BR11; Fig. 5). Ramp *et al.* (2021) compared drone imagery to boat-based assessments of scarring and found that boat-based surveys underreport scarring, especially for species like gray whales that rarely lift their fluke above the water while diving. If we restricted our analysis of entanglements to just sightings of the caudal peduncle region, as done in other studies (Robbins & Mattila, 2001; Neilson *et al*., 2009; Basran *et al*., 2019), we would have reported a much higher rate of entanglement scarring with 18.6% of whales photographed in either BR10 or BR11 having evidence of prior entanglements. Likewise, scars from killer whale attacks are most frequently observed on the fluke and to a lesser degree on the pectoral fins (Rice & Wolman, 1971), and these regions were infrequently observed during our study (Fig. 5). Corsi *et al.* (2022) evaluated killer whale scarring of gray whale flukes and reported that 42% of gray whales had scarring from killer whale attacks. Our finding of 25.9% of PCFG whales being scarred by killer whales is also greater than the 18% Rice and Wolman (1971) reported for gray whales they examined during scientific whaling in the 1960s, despite the fact that these authors examined the full body of each whale. The greater frequency of gray whales with scarring from killer whale attacks in this study may be due to increases in the abundance of West Coast transient killer whales over the past four decades (Towers *et al.*, 2019).

Furthermore, this study found that the tips of the fluke (BR12 and BR14) had the greatest occurrence of killer whale rakes as compared to other fluke regions (Fig. 6). Despite BR12 and BR14 being photographed for the same number of whales (n = 65), killer whale rakes were 2.63 times as likely to occur in BR12 (the left fluke tip) than BR14 (the right fluke tip), suggesting lateralisation of either killer whale attack strategies or gray whale defense behaviour.

Identifying the source of scars on large whales can be challenging and there is uncertainty in determining how some scars originated. Gray whales acquire scars from barnacles, foraging activities and other sources within their environment that are not always easy to distinguish from scars originating from entanglements, vessel strikes or killer whale predation. Added to that challenge are the many factors associated with scarring on a living whale, including its age, overall health and the healing process of a scar-producing injury, all of which likely impacted the characteristics and clarity of the scar through time. Specific characteristics of each scar source also likely impacted their appearance, including the size and type of entangling fishing gear, the type and speed of a vessel and the size and behavior of the killer whale(s), in addition to the body region impacted and both the angle and duration of impact. In this study, 71.2% (n = 100) of whales had scarring of an unknown source, of which 17.0% had scars determined to have a 'potential' scarring source. The 'potential' entanglement, vessel strike and killer whale scar assignments reflect the uncertainty and challenge of determining the source of scars. In this study, scars assigned to a 'potential' source were considered an unknown source upon final scar decisions. However, if we were to utilize these 'potential' source assignments, a maximum magnitude of scarring could be determined by combining 'definitive' scar sources to their respective 'potential' scar sources. In this case, with a degree of uncertainty, we would have reported a maximum of 23 (16.6%) whales with evidence of entanglement, nine (6.5%;) whales with evidence of a vessel strike and 42 (30.2%) whales with evidence of killer whale predation. The frequency for each of these three scar sources would have been inflated from the 16 whales (11.5%) we reported to have entanglement scars, five whales (3.6%) documented with evidence of a vessel strike and 36 whales (25.9%) observed with killer whale rakes. Additional information about the 'definitive' and 'potential' scar assignments for each observed body region is provided in the Mendeley Data repository for this study (Walsh *et al.*, 2024).

There was a high proportion of agreement (79.8%) between the evaluations of the experts and the initial assessments of the three-person consensus, despite the challenges of evaluating scars on large whales from vessel-based photographs. In all cases in which the experts disagreed with the initial three-person consensus, the disagreement was in the confidence of assigning a scar to a source and not in determining the source of the scarring. Conducting the scar assessment in phases and with expert involvement facilitated thorough discussions of scar sources and assisted in the evaluation of more ambiguous scars.

Comparison of scarring rates of PCFG and Sakhalin Island whales

An objective of this study was to compare scarring rates of PCFG whales with whales observed at Sakhalin Island. Sakhalin Island gray whales had a significantly higher rate of scarring from killer whales than did PCFG whales. Some of the whales feeding at Sakhalin Island migrate to and from wintering grounds in Baja California, Mexico, passing known hot spots for killer whales hunting gray whales at Monterey Bay, California (Goley & Straley, 1994) and around Unimak Island, Alaska (Barrett-Lennard *et al.*, 2011; Durban *et al.*, 2023). In contrast, most PCFG whales are likely to only migrate past the Monterey Bay hotspot. Andrews (1914) documented many occurrences of killer whales attacking gray whales along the southern coast of the Korean Peninsula, suggesting that gray whales migrating south from Sakhalin Island to wintering grounds in Asia may also frequently encounter killer whale predation.

The model used to conduct the Rangewide Review of Stock Structure and Status of Gray Whales (IWC, 2019) and the 2020 Implementation Review of aboriginal subsistence whaling on gray whales (IWC, 2021) incorporated all known sources of anthropogenic mortality in the North Pacific Ocean based on stranding records and self-reports of fishers and mariners available at the time (Scordino *et al*., 2017a; 2020). The model was affected by the collection of data on anthropogenic mortality by area, with the best reporting along the west coasts of Canada and the contiguous United States where stranding networks are well funded and coastlines are more accessible. If we assume that mortalities of gray whales due to entanglements and vessel strikes are proportional to the frequency that whales receive visible scars from anthropogenic sources, then we can make important inferences about mortality rates from anthropogenic sources for Sakhalin Island whales. We found no statistical difference between the proportion of PCFG and Sakhalin gray whales with anthropogenic scarring after implementing similar scar assessment methods between the two study regions. Given the lack of stranding network coverage at Sakhalin Island (Lowry *et al*., 2018), results from this study suggest that the observed rates of mortalities of PCFG whales caused by entanglements and vessel strikes can be used, to some degree, as an informed estimate for anthropogenic mortality rates of Sakhalin Island whales.

ACKNOWLEDGEMENTS

All field work was conducted under MMPA permit numbers 16111-00, 19430 and 23970. Funding for fieldwork was provided by the Species Recovery Grant to Tribes through NOAA Fisheries and by the Climate Resilience Program through the Bureau of Indian Affairs. Funding for this analysis was provided by a grant from the Bureau of Indian Affairs Tribal Climate Resilience Program. We thank Adrianne Akmajian, Maria Gonzales, Ray Colby, Seraphina Gagnon, Quinton Thompson, Joshua Monette, Patrick Gearin, Merrill Gosho and Jeff Harris for help with fieldwork. We thank John Calambokidis, Alie Perez, Amber Klimek and others at Cascadia Research Collective for matching our photographs to their catalogue of PCFG gray whales. We thank Leigh Torres and the Geospatial Ecology of Marine Megafauna Laboratory (GEMM Lab) at Oregon State University for their assistance and collaboration. We would lastly like to express our gratitude for the feedback from two anonymous reviewers which helped to improve the manuscript.

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