Inter-Research Science Publisher

Endangered Species Research
Volume 57:253–271

Published July 3, 2025
https://doi.org/10.3354/esr01416

OPEN ACCESS

Rates of entanglement inferred from scarring prevalence of humpback whales photographed in US Oregon waters

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ABSTRACT: Entanglements in fishing gear are a significant threat to cetaceans worldwide and a concern for large whales in US waters. Yet, entanglement events are infrequently observed, and their lethal and sublethal impacts are likely underestimated. Photographic analysis of wrapping scars on whales shows promise to better assess entanglement. Here, we analyzed scars on 571 individual humpback whales photographed in Oregon, USA, waters (2005–2023). We scored 1533 photos of the tailstock and fluke regions for evidence of prior entanglement. We found that scarring prevalence varied by photo type, with perpendicular/forward tailstock photos showing the highest scarring prevalence (respectively 19.1% and 17.6% most likely caused by entanglements) compared to photos of the fluke underside that tended to miss likely entanglement events (57.4% false negatives). Depending on the scoring approach, 8.2 to 27.3% of sampled whales were likely entangled at least once in their lifetime. We found no significant spatial effect on scarring prevalence and a weak increasing (2016–2020), then decreasing (2020–2023), temporal trend. Males had a significantly higher scarring prevalence than females. Simulations of population trajectory and photographic sampling designs revealed that, even in an unrealistically optimistic scenario of new fishing regulations reducing the number of entanglements to zero, 165 ind. yr^{-1}, for 5 yr, would need to be sampled with good-quality tailstock photos to detect the decrease in scarring prevalence with 80% statistical power. Our findings enable recommendations for monitoring impacts of fishing gear interactions with humpback whales using US West Coast waters.

KEY WORDS: Fisheries bycatch · Large whales · Photographic data · Genetics · Scar analysis · Simulation · Oregon · US West Coast

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Publisher: Inter-Research · www.int-res.com

1. INTRODUCTION

Entanglements in fishing gear, or fisheries bycatch, are a major threat to marine megafauna (Lewison et al. 2014) and particularly to cetaceans (Perrin et al. 1994, Knowlton & Kraus 2001, Johnson et al. 2005, Robbins 2009, Reeves et al. 2013, van der Hoop et al. 2017, Avila et al. 2018, Nelms et al. 2021). Entanglements can lead to immediate or delayed mortality, as they can cause serious injuries, impair feeding, and disrupt behavior (van der Hoop et al. 2016, Carretta & Henry 2022). Large whales may also suffer sublethal effects as they drag fishing gear for hours to years, leading to long-term negative effects on fecundity and reproductive success (van der Hoop et al. 2017, Knowlton et al. 2022, Reed et al. 2024). Over the last 3 decades, entanglements have caused the drastic depletion of several cetacean populations (Hofman 1990), including the vaquita *Phocoena sinus* in the Gulf of California (Jaramillo-Legorreta et al. 2007, Rojas-Bracho et al. 2022) and the North Atlantic right whale *Eubalaena glacialis* along the east coast of North America (Pirotta et al. 2024, Reed et al. 2024). While direct evidence of population-level impacts of certain fisheries interactions exists, the number of individuals involved in entanglements is often underestimated due to the challenges of detecting and reporting these cryptic events (Robbins 2009, Cassoff et al. 2011, Pace et al. 2021). The difficulty in estimating entanglement rates undermines wildlife and fisheries management strategies and efficient decision making (Peltier et al. 2024).

Scarring analyses have been used to retrospectively assess the frequency of entanglements in a number of whale species: blue whales *Balaenoptera musculus* and fin whales *B. physalus* (Ramp et al. 2021), humpback whales *Megaptera novaeangliae* (Robbins & Mattila 2001, 2004, Neilson et al. 2009, Robbins 2012, Basran et al. 2019), gray whales *Eschrichtius robustus* (Bradford et al. 2009), bowhead whales *Balaena mysticetus* (George et al. 2017), and North Atlantic right whales (Kraus 1990, Knowlton et al. 2012). This approach relies on photographic documentation of the scars accumulated by whales that have experienced 1 or multiple non-lethal entanglement events. Contact between the whale's body and fishing lines may cause substantial abrasion and damage to the skin and underlying tissues, leaving noticeable persistent indentations and depigmented wrapping scars on the whale's body (Hare & Mead 1987, Kraus 1990, Philo et al. 1992, Robbins & Mattila 2001).

Since 2014, documented entanglement events involving large whales in fixed-gear fisheries (i.e. whereby whales were seen with attached gear) along the US West Coast have been above historical levels (NOAA Fisheries 2024a). When whale species and gear could be identified in these entanglements, the most common event was humpback whales entangled in commercial Dungeness crab fishing gear (Saez et al. 2021). The species is one of the most common large whales off the US West Coast, with an estimated population of 4469 individuals migrating and feeding in California, Oregon, and Washington waters (Calambokidis & Barlow 2020). This population is divided into 3 distinct population segments (DPSs) with different migratory destinations: the Hawaiian, Mexican, and Central American wintering grounds (Carretta et al. 2023). The Mexican and Central American DPSs are listed as threatened and endangered, respectively, under the US Endangered Species Act (https://www.fisheries.noaa.gov/national/endangered-species-conservation/endangered-species-act). The increased risk of entanglement to these depleted and strategic humpback whale DPSs, which appear to exhibit varying distribution and habitat use patterns across states along the coast (Becker et al. 2017, 2018, 2020, Derville et al. 2022), has prompted action at both state and federal levels. State-level managers have implemented conservation and management plans tailored to local conditions and fishery practices to mitigate these threats (CDFW 2021, ODFW 2021, WDFW 2022). For instance, in Oregon, a seasonal fishery regulation was implemented in 2021 to restrict commercial Dungeness crab fishing to waters within 40 fathoms (73.2 m) from May to August (Oregon Secretary of State 2020; see Fig. 1). This regulation was designed to limit overlap with humpback whales foraging and migrating on the continental shelf and slope (Becker et al. 2017, 2018, 2020, Derville et al. 2022), yet the effectiveness of these new measures to reduce the number of entanglements remains uncertain due to the lack of accurate estimates of true entanglement rates.

Humpback whale entanglements commonly involve the flukes (Johnson et al. 2005). Photos showing the caudal fluke and tailstock from an angle perpendicular or slightly forward of the whale before it dives are therefore considered the ideal photo type to detect entanglement scars (Robbins & Mattila 2001, 2004, Robbins 2012). However, photographs from these angles were not systematically collected on humpback whales along the US West Coast, as most research efforts were focused on capturing images of the fluke underside (i.e. ventral fluke) for photo-identification purposes (Katona et al. 1979). Hence, images of the fluke, dorsal tailstock, and ventral tailstock photographed from the rear of the whale are most common (Wall et al. 2019). Here, we explore different scarring analysis methods (Robbins & Mattila 2001, Wall et al. 2019) to allow a comparison to past studies along the US West Coast and to utilize images other than the tailstock captured from a perpendicular angle (e.g. the fluke underside, the dorsal and the ventral side of the tailstock). Inclusion of these photos in a scarring analysis may allow an improved detection of entanglements and estimation of entanglement rate in regions or time periods lacking systematically collected tailstock images (Volgenau et al. 1995). Due to the high cost and logistical challenges of collecting photographic data on whales, we highlight an approach that leverages existing photographic databases to opportunistically extract scarring data and enhance the use of available resources to improve our understanding of entanglements.

We focus this analysis on humpback whales migrating and foraging in Oregon waters, USA, as (1) this region is notably understudied in terms of whale distribution and entanglement compared to the rest of the US West Coast (Derville et al. 2022, 2023), (2) state managers tasked to address this issue are confronted with a local knowledge gap and struggle with how to effectively allocate support to monitor entanglements (Saez et al. 2021), and (3) whale site fidelity has been demonstrated along the US West Coast. Indeed, there is genetic (Buell et al. 2023) and satellite tracking (Palacios et al. 2020, Calambokidis et al. 2024) evidence of a certain distinctiveness of foraging whale herds across states, which translates into varying levels of risk and vulnerability (Martien et al. 2023). Due to the low resighting rate of individual humpback whales currently documented in Oregon, scar acquisition (i.e. appearance of new scars) could not be effectively assessed over time at the individual level to derive annual entanglement rates (e.g. Robbins & Mattila 2004, Neilson et al. 2009). Instead, we evaluated scarring prevalence (i.e. percent of the individual whale sample showing entanglement scars) at the population level — an approach that is broadly applicable to the many other whale populations where opportunistic scarring data exists but the probability of photo-identification recaptures is low due to limited survey effort and/or large population sizes. Our study aims to inform managers' efforts by (1) estimating scarring prevalence in the population of humpback whales encountered in Oregon while accounting for photo type and quality, (2) assessing the effect of space, time, and sex on scarring prevalence, and (3) simulating photographic sampling designs under specific assumptions to determine what level of effort is necessary to detect changes in the rate of entanglement events based on scarring prevalence. More specifically, the simulation aims to determine the minimum sampling effort required to detect the benefits of new fishing regulations or practices aimed at decreasing entanglement risk.

By analyzing photos of flukes and tailstocks of humpback whales collected between 2005 and 2023 in Oregon waters, we attempt to provide a baseline estimate of the percentage of whales that bear scars indicative of non-lethal entanglements experienced at some point in their lives, anywhere in their range. Humpback whales observed off the US West Coast migrate to different winter breeding areas (Mexico, Central America, and Hawaii; Carretta et al. 2023) and visit different foraging destinations across the North Pacific (Martien et al. 2023). Spatial fidelity to foraging areas has been demonstrated at the scale of the North Pacific (Calambokidis et al. 2001, Baker et al. 2013) and is thought to also operate at finer scale along the US West Coast (Palacios et al. 2020, Buell et al. 2023, Calambokidis et al. 2024). While we assume that fine-scale spatial fidelity to foraging areas results in differences in exposure to entanglement risk across state waters of the US West Coast, we acknowledge that the scars observed on whales using Oregon waters may result from entanglement events that have happened elsewhere. Our study therefore provides data and guidance that are relevant to scientists and managers at the state level, but also at national and international scales.

2. MATERIALS AND METHODS

Photo processing and data analysis were conducted with Adobe Bridge (2022 version) and R statistical software (R Core Team 2023).

2.1. Data collection

Photos of humpback whales *Megaptera novaeangliae* were collected during at-sea surveys conducted from various platforms and by different research, fishing, and whale-watching operators in Oregon waters of the North Pacific (41.9° N to 46.3° N) (Fig. 1). The majority came from small-boat surveys by Cascadia Research Collective (CRC; 950 photos across 403 individual whales) and Oregon State University (553 photos across 208 individual whales) aimed primarily at photographic identification. Additional photos also came from 1 whale-watching operator (Whale Research EcoExcursions: 6 photos across 2 individual whales), and by 3 fishers who were equipped with cameras, instructed about NOAA guidelines on marine mammal observation (not to approach whales within 100 yards [91 m]), and provided a small stipend for their partnership in data collection in 2023 (24 photos across 10 individual whales). For the purposes of this study, we only used photos collected with digital cameras since 2005, with the majority of photos collected since 2016. For every humpback whale group encountered, observers recorded the geographical coordinates, group size, and time. Within these groups, individual whales were photo-identified based on the unique patterns of the underside and trailing edge of their caudal fluke (Katona et al. 1979). Photo-identification was performed manually by comparison of the fluke photos to the CRC catalogue or using Happywhale, an automated photo-identification matching software (Cheeseman et al. 2021). When possible, the left and right dorsal fins and flanks of the individual whales were also photographed. Although not the primary focus of most of the field effort that contributed to this dataset, the tailstock was also sometimes photographed during the whales' dive sequence.

Small tissue samples were collected for genetic analysis from a subset of individual whales encountered on the research surveys included in this study using a biopsy dart following standard protocols (Noren & Mocklin 2012). Genomic DNA was extracted from the samples and used to identify the sex of individual whales, either through amplification of the *Sry* gene (Gilson & Syvanen 1998, Baker et al. 2013) or real-time PCR of the zinc finger genes (Morin et al. 2005, Martien et al. 2020). Genetic sex identification was either performed for the purpose of this study, or available from previous studies (e.g. Baker et al. 2013, Martien et al. 2020). In some cases, genetic sex and photographic data from the same individual whale were acquired on different occasions and reconciled *a posteriori*.

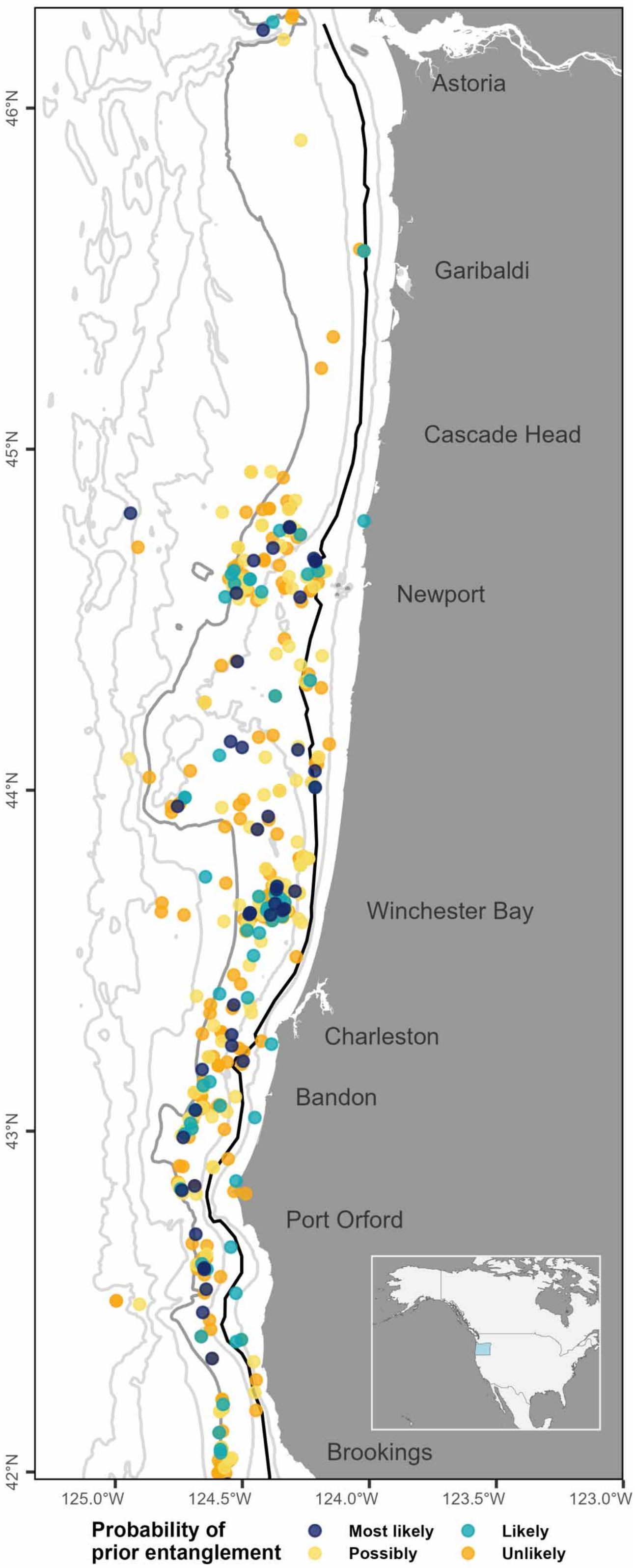

Fig. 1. Locations of humpback whale sightings and photos included in this study (inset: North America, with study area in blue). Points show the location of each of the 5 photo types selected per individual per year, colored by categorical probability of prior entanglement. Isobaths shown with light grey lines (50, 100, 500, 1000, and 1500 m). The 40 fathom (73.2 m) crab pot fishing restriction is represented with a black line. The 200 m isobath shown in dark grey delineates the continental shelf, which is a core habitat for humpback whales in Oregon waters

2.2. Photo processing of scarring

To ensure consistency, photo selection and scoring for entanglement evidence were performed by a single analyst (S. Derville). Photos were analyzed in a randomized order to avoid a shifting baseline bias that could influence temporal patterns in scarring scores (Kenkel et al. 1989, Soga & Gaston 2018). For each encounter of an individual whale, we selected up to 5 different photo types that provided the best views of each of the whale's body parts of interest: the dorsal tailstock, the left and right forward tailstock, the left and right perpendicular tailstock, the ventral tailstock, and the fluke underside, following the approach and definitions provided by Wall et al. (2019) and schematically represented in Fig. S1 in the Supplement at www.int-res.com/articles/suppl/n057p253_supp.pdf. As collecting photos of the fluke underside was generally the focus of field effort, a great number of encounters resulted in only collecting this single photo type, with no photos of the associated tailstock.

Selected photos were scored for quality based on focus, lighting, contrast, angle, obstruction by water, and overall visibility of the body part of interest. Photos were scored with the maximum score of 1 when all metrics were optimal, with a score of 2 when 1 of these criteria was not met, and a score of 3 when >1 of the criteria were not met. Photos that were of insufficient quality to detect any scarring (i.e. failing to meet 3 or more criteria, with at least 1 criterion rated as very poor) were assigned a quality score of 4 and excluded from the analysis. Quality was compared across photo types (i.e. dorsal tailstock, forward tailstock, perpendicular tailstock, ventral tailstock, and fluke underside) using an ordinal version of the χ^2 test (i.e. asymptotic generalized Pearson χ^2 test) using the *coin* R package (version 1.4-3).

Photos of quality 1, 2, and 3 were analyzed to detect any scars indicating that individual whales might have been entangled in fishing gear or lines of other origin in the past (e.g. wrapping, abrasion, indentations). Photos were evaluated independently, without attempting to track the appearance of new scars (potentially resulting from multiple entanglement events) by comparing images taken at different times throughout an individual's recapture history. The evaluation was performed following 2 different approaches (Table 1). First, the scoring approach designed by Wall et al. (2019) was used to assign entanglement scores to 5 different photo types that provided a good view of the fluke underside, the dorsal tailstock, the ventral tailstock, the forward tailstock (left and right when available), and the perpendicular tailstock (left and right when available). Photos were categorized based on observed scars and their likelihood of having been caused by prior entanglement: 'most likely', 'likely', 'possibly', and 'unlikely' (Fig. 2).

Second, the scoring approach designed by Robbins & Mattila (2001) and subsequently used by Robbins & Mattila (2004), Neilson et al. (2009), Robbins (2012), and Basran et al. (2019) was applied to the forward and perpendicular tailstock photos only. Scars were analyzed over as many as 6 different body regions when visible in these photos: the left and right flanks, the left and right leading edges and insertion points of the fluke, the dorsal side of the tailstock, and the ventral side of the tailstock. Scores of S0 (no scars) to S5 (scars highly indicative of prior entanglement) were assigned to each of the regions observed in a photo and then aggregated into 1 entanglement status score per sighting that ranged from E0 to E4 (Table 1). Status scores were calculated as follows: E0 (no mark present), E1 (none of the scored regions > S2), E2 (at least 1 scored region ⩾ S3), E3 (at least 2 scored regions ⩾ S3), and E4 (at least 1 scored region = S5). Even though Robbins & Mattila (2004) combined status E3 and E4 categories into one, we annotated them separately in this study so that we could explore the effect, if any, of pooling these categories for analysis. Over all photos, the occurrence of raw wounds (i.e. pink or red in color) was also noted but they were not counted as scars as they may not persist through time and to ensure comparability to previous studies using this methodology (Robbins & Mattila 2004). Similarly, the occurrence of attached gear was not counted in the scar scores (i.e. 1 occurrence across all sightings).

2.3. Entanglement scarring prevalence

Entanglement scarring prevalence in whales photographed from 2005 to 2023 was assessed with 2 different approaches, hence providing a range of estimated values, per approach and per photo type. The percent of individual whales showing 'most likely' alone or 'most likely' and 'likely' entanglement scars in any of the 5 possible photo types is presented following the Wall et al. (2019) approach. To investigate the added value of analyzing fluke photos compared to the typical perpendicular tailstock photos used by Robbins & Mattila (2001), we further report the number of individual whales whose fluke underside photos were assigned a 'most likely' or 'likely' category while their perpendicular and forward tailstock photos were either unavailable or assigned 'possible' or 'unlikely' categories. This number illustrates the number of likely entanglement cases that would have been 'missed' in this study if fluke photos had not been analyzed. In addition, the percentage of individual

Table 1. Descriptions of the entanglement scar scores used in this study, derived from Wall et al. (2019) and Robbins & Mattila (2001). In Robbins & Mattila (2001), scar codes S0 to S5 are assigned to all visible regions of the perpendicular or forward left and right tailstock photos, then aggregated into a single E0 to E4 entanglement status code

Scoring method	Photo type	Categories of entanglement likelihood	Description of scarring patterns
Wall et al. (2019)	Fluke underside	Most likely	Vertical or diagonal linear scar all the way from leading to trailing edge and associated wound (with or without indentation) on leading edge
		Likely	Vertical or diagonal linear markings all the way from leading to trailing edge and notch on trailing edge, but no confirmation on leading edge Deep groove in leading edge with no associated vertical marking nor trailing edge damage
		Possibly	Vertical linear marking all the way from leading to trailing edge with no associated notch or abrasion on leading or trailing edge A bulge/deformation of the leading edge with no other marking
		Unlikely	Flukes not showing any of the other cases but potentially showing some common natural patterns: randomly oriented marks (e.g. caused by intra-specific interactions), radiating long marks from the center notch to the insertion points (natural marking in some white flukes with black center), parallel teeth rake marks (predation), 'whisker marks' around the center notch
	Dorsal tailstock	Most likely	Deep wrapping indentation in line with insertion points Extensive wrapping scars along dorsal
		Likely	Non-wrapping indentation, scar or linear abrasion in line with insertion points or extensively along dorsal Superficial wrapping scar (there is a marking with lack of pigmentation but no clear indent or deformation) Non-wrapping, non-linear indentations or abrasions that are not in line with insertion points but damage is also visible on the dorsal side of the fluke next to the center notch
		Possibly	Non-wrapping, non-linear indentations or abrasions that are not in line with insertion points
		Unlikely	No marks Shallow indentations with no lack of pigmentation
	Ventral tailstock	Most likely	Linear scar or abrasion on ventral tailstock connected by a linear marking or aligned with a scar on at least 1 insertion point Scar at insertion point prolongated on fluke and connected to trailing edge
		Likely	Linear scar, abrasion or indentations on ventral tailstock with no associated scar on either insertion points Relatively large abrasion or indent or scar on 1 of the insertion points with no associated damage to ventral tailstock
		Possibly	Light linear scar, abrasion or indentations on ventral tailstock Light abrasion on 1 of the insertion points with no associated damage to ventral Bulge at the insertion point with no other associated marks
		Unlikely	Non-linear abrasions (e.g. black patches on white flukes) or natural lack of pigmentation all along the ventral peduncle
	Perpendicular/ forward tailstock	Most likely	Linear or wide scars wrapping around the insertion point of the fluke, paired with aligned indentation or abrasion of the dorsal or ventral peduncle
		Likely	Wrapping scars on leading edge or insertion point lacking pigmentation
		Possibly	Non-wrapping linear marks or wide areas lacking pigmentation
		Unlikely	No marks or non-linear marks or randomly oriented linear marks along leading edge or white edge due to white fluke pigmentation

(Table 1 continued on next page)

Table 1. (continued)

Scoring method	Photo type	Categories of entanglement likelihood		Description of scarring patterns
Robbins & Mattila (2001)	Perpendicular/ forward tailstock	Scar code per region	S0	No visible marks
			S1	Non-linear marks or apparently randomly oriented linear marks
			S2	Linear marks or wide areas lacking pigmentation, which did not appear to wrap around the feature
			S3	Linear or wide scars which appeared to wrap around the feature
			S4	At least 1 visible linear notch or indentation
			S5	Extensive tissue damage and deformation of the feature
		Aggregated entanglement status code	E0	No marks present
			E1	Marks were observed but did not suggest a previous entanglement. All scar codes $\leq$ S2
			E2	Entanglement-like elements were present, but there was no consistent pattern. At least 1 region was coded $\geq$ S3
			E3	Marks appeared to be entanglement-related and minor tissue damage was evident. At least 2 regions were coded $\geq$ S3
			E4	Marks appeared to be entanglement-related and major tissue damage was evident. At least 1 region was coded as S5

whales showing E4 and E3 status in either their perpendicular or forward tailstock photos is presented following the Robbins & Mattila (2001) approach.

The highest and lowest estimates of scarring prevalence (S_{high}; S_{low}) for the period 2005–2023 were highlighted among these different estimates. For this purpose, we selected 1 photo per photo type per individual, across all within- and across-year resights. The photo selected was the one that was scored with the highest categorical probability of prior entanglement and the highest quality across sightings. For the purpose of applying the Wall et al. (2019) approach, when both left and right photos of the forward and perpendicular tailstock were available, we also selected the one that was scored with the highest categorical probability of prior entanglement. This selection is different from that of Robbins & Mattila (2001), who selected the photos from the first year an individual whale entered the study. Given the variability in photo types and quality across years in our dataset, our selection is based on the assumption that our scar-based approach to entanglement detection is supposed to result in more false negatives (i.e. whale does not show scar evidence of entanglement although it was entangled) than false positives (i.e. whale shows scars that are mistakenly interpreted as having been caused by an entanglement). The 95% confidence intervals (CIs) were calculated for S_{high} and S_{low} using the formula based on the standard error described by Robbins & Mattila (2004). A Fisher's exact test was used to assess whether the difference in proportions between S_{high} and S_{low} was statistically significant.

2.4. Sex bias and spatio-temporal effects

The sex bias in the categorical probability of prior entanglement was investigated using a cumulative link model (CLM) with a logit link function fit with the *ordinal* R package (version 2022.11-16). A CLM is a regression model designed to handle ordered but non-continuous ordinal response data. The model was fit to the scarring categories defined by the Wall et al. (2019) approach for individual whales of known sex encountered between 2005 and 2023. The response variable was informed by selecting 1 photo per photo type per individual, across all within- and across-year resights. The photo selected was the one that was scored with the highest categorical probability of prior entanglement and the highest quality across sightings. Sex and photo type were used as explanatory variables in the CLM. Weights were used to account for the varying quality of photos included

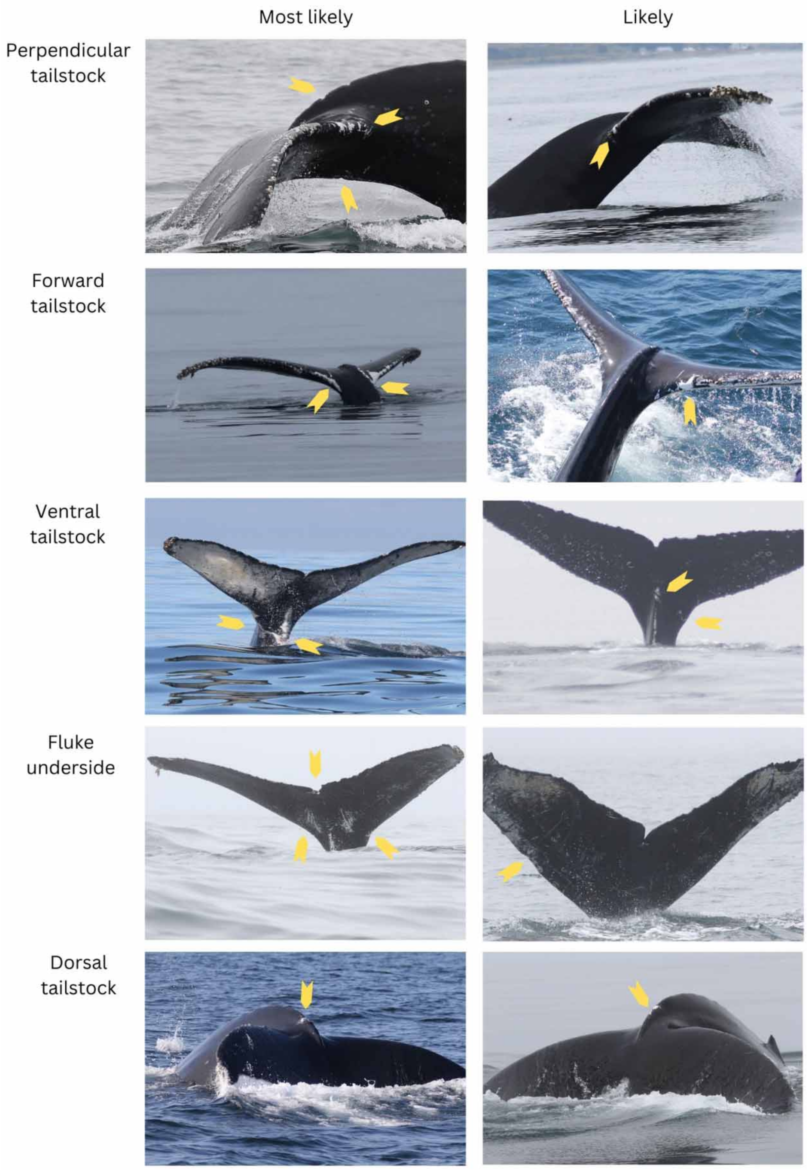

Fig. 2. Examples of 'most likely' and 'likely' entanglement scars (see Table 1 for definitions of both categories) observed in different photos of humpback whales sighted in Oregon waters. Photo types as defined by Wall et al. (2019) are listed vertically. Yellow arrows: abrasions, indentations, or depigmentation indicative of entanglements

in the model. We assumed that lower quality limits the analyst's capacity to detect scars and that our conservative approach to photo scoring would have led most low-quality photos with inconclusive results to be classified as 'unlikely' (hence likely resulting in false negatives). Following this logic, we applied a maximum weight of 3 to all of the photos assigned a 'most likely' or 'likely' score, while photos scored as 'possibly' and 'unlikely' were assigned weights varying from 3 (if quality was optimal) to 1 (if quality was equal the lowest). Integer weights were normalized by dividing them by the mean of weights before inclusion in the model, as instructed by Wood (2023), so that the overall magnitude of the log likelihood remains unchanged.

Temporal and spatial patterns of scarring prevalence were investigated using a generalized additive model (GAM; Hastie & Tibshirani 1990) fit with the *mgcv* R package (Wood 2011, version 1.9-1). The model was fit for all individual whales encountered in Oregon waters between 2016 and 2023, since very few photos were collected prior to 2016. GAMs were fitted to the categorical probability of prior entanglement following the Wall et al. (2019) approach using an ordered categorical family distribution ('ocat' family; Wood et al. 2016) and restricted maximum likelihood. The response variable was informed by selecting 1 photo per photo type per individual per year (i.e. photo with highest categorical probability of prior entanglement within year). Across-year resights of individuals were therefore included in this model. In the GAM, variable selection was conducted with a shrinkage approach implemented in the *mgcv* R package, which adds an extra penalty to each smoother and penalizes non-significant variables to zero (Marra & Wood 2011). The effect of year and latitude were modeled with penalized thin-plate regression splines with basis size limited to 3 to prevent overfitting (Wood 2017) and photo type was included as a fixed parametric covariate. Weights were used to account for photo quality with the same approach as that applied in the CLM.

2.5. Simulation for power analysis

We conducted a simulation to determine the minimum photo sampling effort that would be required to have an 80% probability of detecting a decline in entanglement rates following new fishing regulations or practices. This simulation was created to address managers' need to determine the minimum time and photo sample size required when using scarring prevalence analysis to detect an anticipated decline in entanglement following the implementation of new Dungeness crab fishing regulations in 2021 (Oregon Secretary of State 2020), assuming all other threats have remained constant. While other statistical approaches, such as those based on tracking the acquisition of new scars on the tailstock of known individual whales over time, are powerful alternatives (Robbins 2012), this simulation was designed to reflect the current configuration in Oregon. Here, whales are resighted infrequently (68 individual whales resighted at least once), and scarring prevalence is assessed in annually collected random samples of the whale population without distinguishing between new and old scars at the individual level. Within this framework, we conducted a power analysis under an unrealistic yet informative scenario in which entanglements completely ceased in a closed population (i.e. with no immigration from neighboring populations). We estimated the number of individuals photographed and years of scar monitoring needed to detect this change, hence providing managers with quantitative estimate of the reasonable time frame and minimum effort needed to evaluate the result of their new regulations. The rationale and full methods applied in this simulation are described in the supplementary methods (Text S1).

The simulation was based on a simple humpback whale population model with no age structure nor density dependence. The change in population size N between year y and $y + 1$ is modeled as a function of the number of individual whales that die and the number of individual whales that are born in the population every year. It can be expressed as a function of the population growth rate λ and the survival rate ϕ. We tested 3 population annual growth rate values of λ: 1.082 in the rapid growth scenario (Calambokidis & Barlow 2020), 1.041 in the slow growth scenario, and 1.000 in the carrying capacity scenario. Two annual survival values ϕ were tested in combination with each of the 3 population scenarios: 0.95 or 0.97 based on the range of adult survival values estimated in the North Pacific (Mizroch et al. 2004, Gabriele et al. 2022). Population trajectories simulated under these scenarios are represented in Fig. S2.

We assumed that entanglement scars were persistent (Robbins & Mattila 2001). They therefore remain detectable in the photo samples until individual whales die and are removed from the population. We assumed that entanglements of humpback whales completely ceased after Year 0 of the simulation. Lesser reductions in entanglement rates (e.g. a 5%, 10% decrease, etc.) would take greater effort to be detected. At Year 0 of the simulation, the proportion of individual whales showing scars likely caused by prior entanglement was set to 27.3%, which is the proportion observed in the 2016–2023 sample of perpendicular and forward tailstock photos analyzed in this study (see Table 3).

The simulation consisted of random photographic sampling of n_i individual whales in the population on a yearly basis, with n varying from 5 to 250. We considered an individual to be 'sampled' when good-quality perpendicular or forward tailstock photos of each side of the whale are collected. Yearly samples were added up to constitute a pool of samples: $n_y = n_0 + n_1 + n_2 + ... + n_i$ where y is the number of years after Year 0 when the change in entanglement rate was simulated. Subsampling was applied to account for a constant resighting rate of individual whales across years (for more details, see Text S1).

Yearly photographic sampling of n_i individual whales was repeated 3 times per scenario, over 1000 random runs. For every run, logistic regressions were conducted independently to determine if there was a significant change in scar prevalence over time, at 2, 5, and 10 yr after the simulated change in entanglement rates. These time frames were selected as meaningful for management and research. We recorded whether the null hypothesis (i.e. no trend in scarring prevalence over time) was rejected with a conservative significance level of 0.05. In every population scenario and for every time period (2, 5, or 10 yr), we calculated power as a function of annual sample size and estimated the number of individual whales that should be sampled to reach an 80% power level.

3. RESULTS

3.1. Photo identification, quality, and types

After selection for quality and photo type, the photo dataset was composed of 1533 humpback whale *Megaptera novaeangliae* tailstock and fluke photos collected between 2005 and 2023 in Oregon waters (with most photos collected after 2016, Fig. S3). These 1533 photos were collected from 571 individual whales, including 134 that were sexed genetically. The partnership with Oregon fishers in 2023 resulted in photos of 10 individual whales, 1 of which showed scars from a 'most likely' entanglement and had not been detected by research groups.

After selecting 1 photo per photo type per individual per year, flukes were the most frequent photo type (n = 619), followed by dorsal and ventral tailstock photos (n = 325 and n = 311 respectively). Perpendicular tailstock photos were far less frequent (n = 113) and forward tailstock photos were rarely collected in the field (n = 17). Per year, individual whales were represented on average by 2.2 (SD 1.0) different photo types and sides (out of 7: ventral tailstock, left and right perpendicular tailstock, left and right forward tailstock, dorsal tailstock, and fluke underside). This number dropped to 1.3 (SD 0.6) when only considering photos of quality 1. Photo quality significantly differed by photo type (ordinal χ^2 test: $\chi^2 = 91.46$, df = 4, $p < 0.001$; Table 2), with ventral tailstock photos generally having lower quality. Photos of quality 2 were the most common (47% on average across the 5 different photo types considered).

3.2. Entanglement scarring prevalence

The percentages of photos per category of likely prior entanglement (Table 3, Fig. 3) indicate important differences across photo types and dependence on the scoring approach used. Indeed, flukes were found to display the lowest scarring prevalence (2.2% scored as 'most likely' caused by entanglements) of all photo types. As a result, when selecting the highest categorical probability of prior entanglement across all photo types and sightings per individual (within and across all years), 8.2% (CI: 6.0–10.5%) (n = 47 out of 571) of individual whales were identified as 'most likely' entangled, and 19.0% (CI: 15.9–22.3%) (n = 109 out of 571) of individual whales were identified as 'most likely' or 'likely' entangled, following the Wall et al. (2019) approach. In comparison, 27.3% (CI: 19.3–35.2%) (n = 33 out of 121) of individual whales were identified as entangled from the perpendicular/forward tailstock photos following the Robbins & Mattila (2001) scoring approach and selecting the highest categorical probability of prior entanglement across all sightings per individual. Note that given that these photo types were not collected prior to 2016, this scarring prevalence applies only to the period 2016–2023. The difference between the highest and lowest estimates of scarring prevalence therefore equal to S_{high} = 27.3% (with the Robbins & Mattila

Table 2. Percentage of photo types ranked by photo quality after selection of 1 photo per photo type per individual per year (total sample size = 1510 photos) (see Section 2.2 for definitions of quality scores 1, 2, and 3). Photo selection and percentages reported separately for the 2 scoring methods by Wall et al. (2019) and Robbins & Mattila (2001). Absolute number of photos reported in parentheses

Selected for scoring method	Photo type	Quality 1	Quality 2	Quality 3
Wall et al. (2019)	Dorsal tailstock	37.8 (123)	43.4 (141)	18.8 (61)
	Fluke	24.2 (150)	47 (291)	28.8 (178)
	Forward tailstock	41.2 (7)	52.9 (9)	5.9 (1)
	Perpendicular tailstock	16.8 (19)	59.3 (67)	23.9 (27)
	Ventral tailstock	10.6 (33)	44.4 (138)	45 (140)
Robbins & Mattila (2001)	Perpendicular or forward tailstock	20.8 (26)	56.8 (71)	22.4 (28)

Table 3. Percentages of photos per category of likelihood of prior entanglement, after selection of 1 photo per photo type per individual following 2 different scoring approaches (see Table 1 for definitions of the 'most likely' to 'unlikely' scoring approach and of E0 to E4 scoring). Number of individual whales shown in parentheses (total sample size = 571 individual whales with the Wall et al. 2019 approach, and 121 with the Robbins & Mattila 2001 approach)

	Likelihood of prior entanglement				
Wall et al. (2019)	Most likely	Likely		Possibly	Unlikely
Fluke	2.2 (12)	4.2 (23)		18.4 (101)	75.2 (412)
Dorsal tailstock	5.3 (16)	7.6 (23)		15.5 (47)	71.7 (218)
Ventral tailstock	4.8 (14)	9.9 (29)		17.8 (52)	67.5 (197)
Perpendicular tailstock	19.1 (21)	19.1 (21)		26.4 (29)	35.5 (39)
Forward tailstock	17.6 (3)	5.9 (1)		35.3 (6)	41.2 (7)
Robbins & Mattila (2001)	E4	E3	E2	E1	E0
Perpendicular or forward tailstock	6.6 (8)	20.7 (26)	17.4 (21)	46.3 (56)	9.1 (11)

2001 approach) and S_{low} = 8.2% (with the Wall et al. 2019 approach) was statistically significant (Fisher exact test: odds ratio = 4.2, $p < 0.001$). This difference remained significant if S_{low} was calculated over the same time period as S_{high} ($S_{low\ 2016-2033}$ = 8.5%; Fisher exact test: odds ratio = 4.0, $p < 0.001$). Over the study period, 47 individual whales were considered to have been 'most likely' entangled based on scarring analysis. In addition, 1 individual (CRC-17743) was observed with very fresh and raw entanglement marks in August 2023 but did not show scar tissue that could qualify as a 'most likely' in the present estimate of scarring prevalence.

Analysis of photo types by individual revealed that among the 47 whales that were considered 'most likely' entangled based on analysis of the perpendicular, forward, ventral, or dorsal tailstock photos, 57.4% had only been assigned a 'possibly' or 'unlikely' score based on their fluke (e.g. Fig. S4). On the other hand, the analysis of the numerous fluke photos available in our dataset allowed the detection of a few probable cases of entanglement that would have otherwise been missed, either because other photo types were lacking, were not of good quality, or did not show scars. Indeed, 16 individual whales were scored to have 'most likely' or 'likely' been entangled based only on the photo of their fluke. Among these 16 individual whales, 7 were only represented with fluke underside photos and 9 had other photo types available

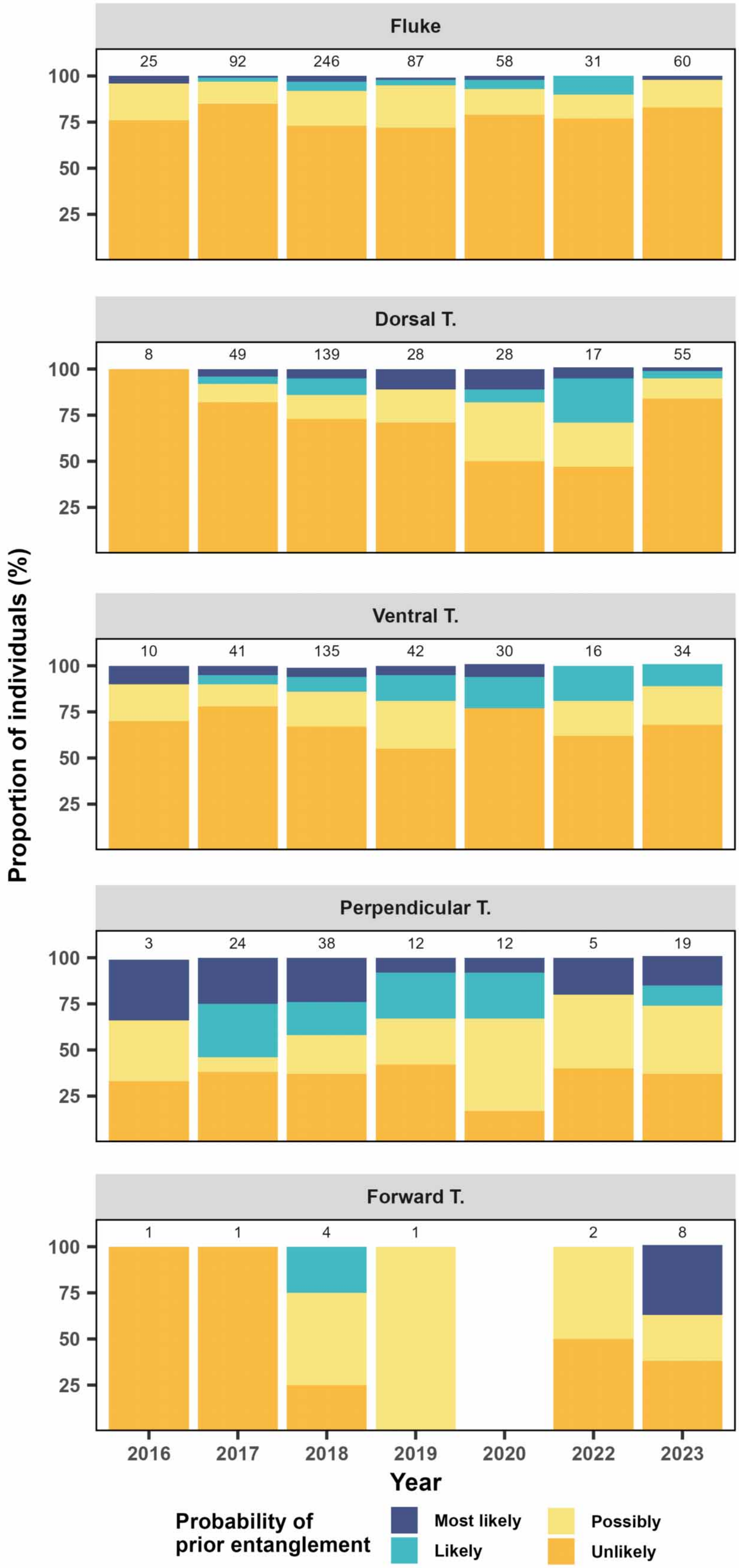

Fig. 3. Yearly proportions of individual humpback whales assigned to each categorical probability of prior entanglement following 2 scoring approaches. Sample size by year is shown at the top of each bar. Top 5 plots show scoring approaches described in Wall et al. (2019), and 6th plot shows scoring approach described in Robbins & Mattila (2001) (see Table 1 for definitions of the 'most likely' to 'unlikely' scoring approach and of E0 to E4 scoring). T.: tailstock

Fig. 3 (continued on next page)

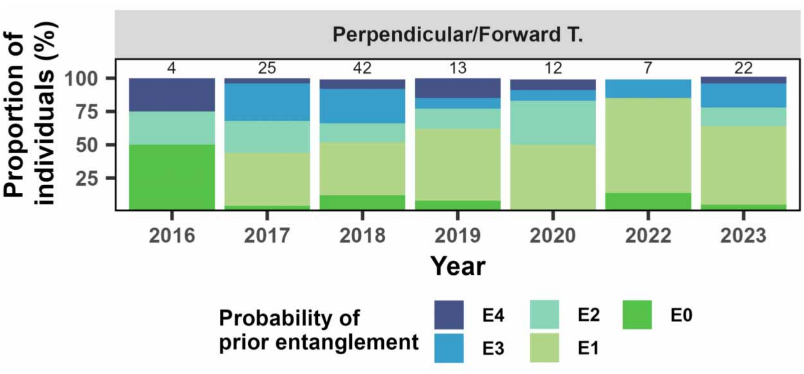

Fig. 3. (continued)

but of generally low quality (7 individuals out of 9 only had photos of quality 2 and below). These 16 individual whales represent 14.7% of all 'most likely' and 'likely' entangled individuals (n = 109).

3.3. Sex bias and spatio-temporal effects

Scarring patterns were analyzed for 54 females and 80 males photographed between 2005 and 2023 to assess the effect of sex on the categorical probability of prior entanglement (using 1 photo per photo type per individual, across all within- and across-year resights). The ordinal CLM relating categorical probability of prior entanglement to sex while accounting for photo type and photo quality found that sex was significantly correlated with the probability of entanglement (df = 1, χ^2 = 54.5, p < 0.001; Table S1). Males showed more scarring, with 16% categorized as 'most likely' (n = 13 out of 80 individual whales) and 19% as 'likely' caused by entanglements (n = 15 out of 80 individual whales; Fig. 4), compared to females with 4% as 'most likely' (n = 2 out of 54 individual whales) and 4% as 'likely' scores (n = 2 out of 54 individual whales). The same CLM run on perpendicular/forward tailstock photo scoring of 40 sexed individual whales following the Robbins & Mattila (2001) approach led to similar results, with males showing significantly more scarring likely caused by entanglements (Table S2).

Scarring patterns were analyzed for 1362 photos collected between 2016 and 2023 (Fig. 3) to assess the effect of year and latitude of the encounter on the categorical probability of prior entanglement (using 1 photo per photo type per individual per year sighted). The GAM relating the categorical probability of prior entanglement to time and space while accounting for photo type and quality had a deviance explained of 5.5%. The main contributing variable was photo type, which explained 5.0% of the deviance and followed trends similar to the percentages presented in Table 3, whereby the fluke and dorsal tailstock photos had the lowest scarring prevalence, and the forward or perpendicular tailstock photos had the highest (Fig. S5). Among the smooth terms, the latitude of the position where the photo was collected did not have a significant effect on the probability of prior entanglement (edf = 0, χ^2 = 0, p = 0.664, Fig. 1), while year had a weak effect (deviance explained = 0.4%, edf = 1.5, χ^2 = 14.2, p < 0.001). The probability of prior entanglement slightly increased between 2016 and 2020, then decreased between 2020 and 2023 (Fig. S5).

3.4. Simulating future sampling designs

The simulation suggested a minimum sample size to collect in the most realistic scenario of humpback whale population trend (i.e. 0.97 humpback whale survival and rapid growth), if entanglements completely stopped occurring, and if scarring prevalence was assessed at population level without comparing scar patterns at individual level over time. The simulation assumes a closed population and that threats remain constant outside the study area. The perpendicular tailstock of a random sample of 165 individual whales would need to be photographed every year for 5 yr to be able to detect a change in the proportion of the population with entanglement scars. If fewer individuals were photographed per year, then it would take longer to detect (e.g. 10 yr if sampling 35 ind. yr^{-1}).

The simulation was sensitive to population growth and survival rates (Fig. 5). Lower survival or higher growth rates from calf production caused more turnover in the population. Hence, these scenarios resulted in an earlier detection of the change in entanglement rate, due to older scarred individual whales being removed from the population, while scar-free young individual whales are recruited. On the other hand, scenarios simulating a slow growth or a stable population at carrying capacity resulted in low detection of a change in entanglement rates. In the scenario whereby population was at carrying capacity and adult survival was high (0.97), it appeared impossible to detect a change in the proportion of whales with entanglement scars within 10 yr and <250 samples yr^{-1} (Fig. 5). It was impossible to detect a change in any scenario with 2 yr of monitoring.

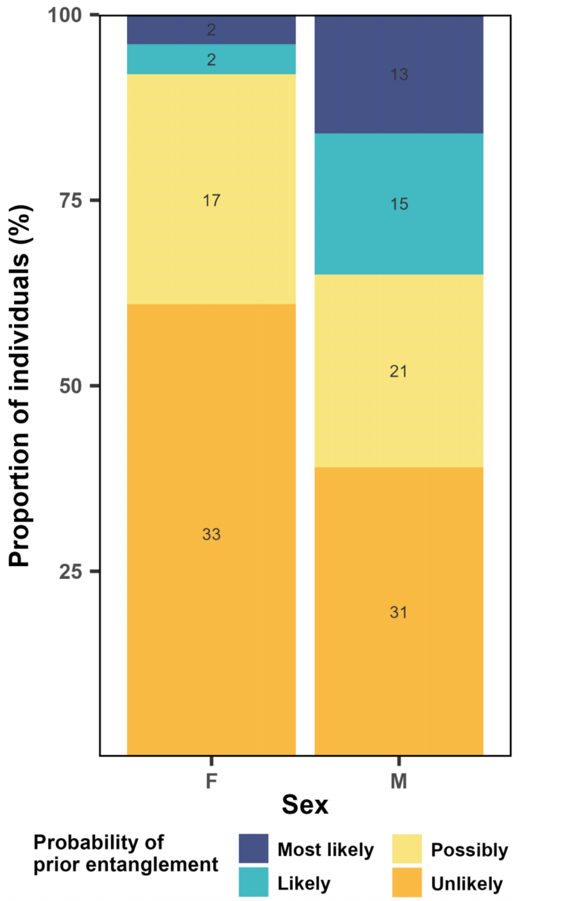

Fig. 4. Proportions of female (F) and male (M) humpback whales assigned to each categorical probability of prior entanglement following the scoring approach of Wall et al. (2019) (see Table 1 for definitions of 'most likely' through to 'unlikely'). Individual scores shown here (F: n = 54; and M: n = 80) correspond to the highest probability found across all photo types and resights of the same individual. Number of individual whales per category shown in each colored bar section

4. DISCUSSION

Entanglements in fishing gear are a notoriously under-reported and under-documented threat to cetaceans (Robbins 2012). As demonstrated in the present study, scar analysis offers a valuable opportunity to approximate entanglement rates using photographs routinely collected by research teams or contributed by citizen scientists and stakeholders (Kraus 1990, Volgenau et al. 1995, Robbins & Mattila 2001, 2004, Bradford et al. 2009, Neilson et al. 2009, Knowlton et al. 2012, Robbins 2012, George et al. 2017, Basran et al. 2019, Ramp et al. 2021). We highlight a scarring analysis approach that accommodates a photographic dataset with heterogeneous quality and photo types, gathered from different sources (research teams, fishers, and a whale-watching operator) and comparable to those curated by many whale research groups globally. With this approach, we provide an estimated range of entanglement scarring prevalence, and associated spatio-temporal and sex bias, for humpback whales *Megaptera novaeangliae* using Oregon waters. We also used this baseline knowledge to simulate a power analysis intended to inform the selection of a minimum sampling effort capable of effectively detecting a change in entanglement using scar analysis.

We compare the minimum scarring prevalence we calculated for humpback whales in Oregon waters to other studies conducted over the US West Coast, or in other humpback whale breeding and feeding areas. This comparison may provide interesting insights into the global magnitude of entanglement risk and factors such as fishing practices associated with variable scarring prevalence (Table S3). Wall et al. (2019) estimated that 10% of the individual whales observed in northern California and Oregon waters (n = 88) between 2005 and 2017 were likely entangled in their lifetime. With the same method as Wall et al. (2019), we estimated that 19.0% of the 571 individual whales observed in Oregon between 2005 and 2021 were likely entangled previously (see Table S3 for details). The comparison between these 2 values is consistent with an increase in entanglement reports since 2014–2016 (Saez et al. 2021). Indeed, Wall et al. (2019) only used photographs collected up to 2017 and were therefore less likely to detect the scars caused during the recent increased period of entanglement reports. In contrast, our estimate of the minimum scarring prevalence of 27.3% using the Robbins & Mattila (2001) approach was similar to the 24.8% estimated in Iceland in 2005–2017 (Basran et al. 2019), but considerably lower than reported for the Gulf of Maine in 2000–2002 (48–57%, Robbins & Mattila 2004) and northern Southeast Alaska in 2005–2017 (52%, Neilson et al. 2009). These differences are likely related to regional differences in fishing gear, the intensity and the timing of the fishing effort in these feeding areas, as well as along the migratory routes and in the breeding grounds of humpback whale populations. In Southeast Alaska, the majority of entanglements in the early 2000s involved crab and shrimp pots that appear to originate from Alaska and British Columbia (Neilson et al. 2009). In the northeast Atlantic, trap/pot fishing has also long been identified as a threat to large whales (Borggaard et al. 2017), with lobster pots being one of the main sources of entanglement (Johnson et al. 2005). However, scar analyses do not allow us to postulate the type or origin of the material

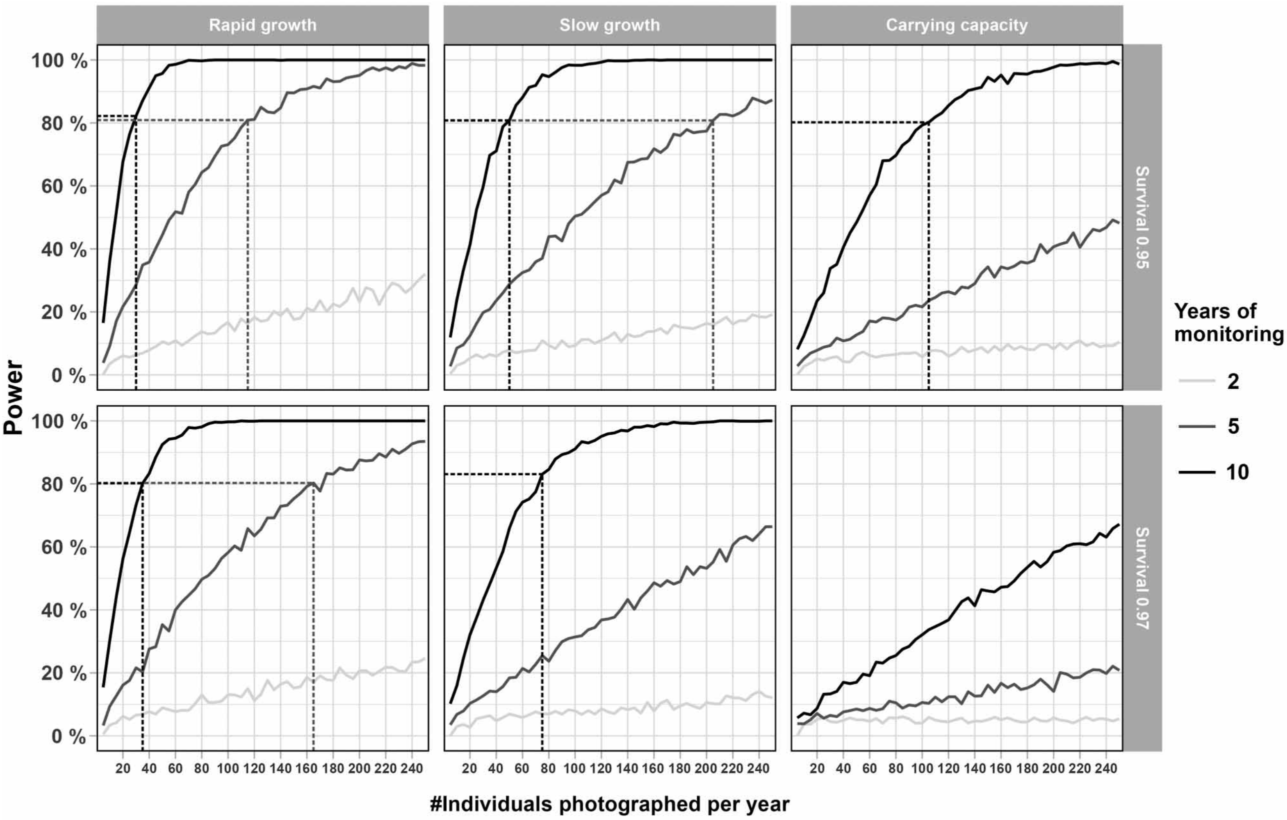

Fig. 5. Simulation of statistical power as a function of annual sample size (number of individual whales photographed) and number of years of monitoring following a drastic change in entanglement rates, whereby entanglement probability drops to zero at the start of the simulation. Dashed lines show how many good-quality perpendicular/forward tailstock photos would be necessary to collect every year to detect a significant change in scarring prevalence compared to the 2016–2023 baseline with a power of 80%. Each panel simulates statistical power under a different population scenario. Population trends vary horizontally: rapid growth (1.082 annual rate of population increase λ), slow growth (1.041), and carrying capacity (1.000). Survival varies vertically: 0.95 in the top panels and 0.97 in the bottom panels

that caused entanglements in the first place (e.g. fishing gear of various types, but also mooring chains, communication cables, oceanographic gear, etc.) and therefore need to be complemented by direct reports and documentation of entanglements, such as those carried out by the United States Large Whale Entanglement Response Network (NOAA Fisheries 2024b).

In our study, male humpback whales had significantly higher scarring prevalence, which is consistent with proportions observed in northern Southeast Alaska in 2003–2004 and the Gulf of Maine in 1997–1999 (Robbins & Mattila 2001, Neilson et al. 2009). However, this male bias appeared to be diminished in subsequent years of monitoring scar acquisition in the Gulf of Maine (Robbins & Mattila 2004, Robbins 2009, 2012). Along the US West Coast, not enough humpback whales involved in confirmed entanglements could be identified and sexed to statistically test for an effect of sex on entanglement probability (1 male and 7 females in Tackaberry et al. 2022). Scar analyses may be biased by confusing entanglement scars with marks from other origins. Males have been shown to bear generally more marks than females due to intra-specific interactions and competitive behavior during the breeding season (Chu & Nieukirk 1988). While we cannot rule out some level of misidentification between scars resulting from entanglements and intra-specific interactions, particularly in the 'possible' category, we believe that both the Wall et al. (2019) and the Robbins & Mattila (2001) methods applied here robustly distinguish entanglement scars because they rely on their distinctive wrapping shape. Therefore, 'most likely' and to a lesser extent 'likely' category proportions do seem to indicate that males more frequently bear entanglement scars. Sex bias in entanglement scarring prevalence could be due to a difference in behavior that would directly (e.g. curiosity towards fishing gear) or indirectly (e.g. foraging behavior or preferred habitat type; Robbins 2007) increase the probability of entanglement for males. It is also possible that males may survive entanglements more often than females, such that the observed difference in scarring prevalence is actually a difference in entanglement survival rate and not a sex difference in entanglement rate. Greater energetic reserves not allocated to gestation, lactation, and nursing (van der Hoop et al. 2017, Irvine et al. 2018, Bejder et al. 2019, Knowlton et al. 2022, Reed et al. 2024) might contribute to an increased entanglement survival rate for males. Males may also generally live longer, as per the higher male survival found in humpback whales feeding in the Gulf of Maine (Robbins 2007), and therefore acquire more scars over time. Finally, this bias could be due to a difference in migratory routes or timing that result in males spending more time in fishing grounds or having more overlap with fishing seasons, including fisheries occurring in breeding grounds (e.g. entanglements in Mexican waters, Frisch-Jordán & López-Arzate 2024). Although there is currently no clear evidence of a difference in migratory space use patterns in male and female humpback whales in the North Pacific, a male-biased gene flow has been demonstrated and interpreted as the result of occasional alteration to their maternal migratory path (Baker et al. 2013). More reconciliation of genetic and photographic datasets in the North Pacific, in combination with space use analyses, are needed to better understand entanglement risk across demographic classes.

Investigating the spatial patterns of entanglement risk in a region where several humpback whale DPSs transit and forage is challenging. The lack of latitudinal effect on scarring prevalence in Oregon was not unexpected. Indeed, a whale observed with entanglement scars at a specific location may have acquired these scars years before and in a very different place (e.g. on migration). In conducting this analysis, we assumed that humpback whales exhibit spatial fidelity to specific foraging areas along the Oregon coast, as suggested by genetic differentiation analyses (Calambokidis et al. 1996, 2001, Buell et al. 2023) and satellite tracking studies (Palacios et al. 2020, Calambokidis et al. 2024). Therefore, it is plausible that whales observed within a particular zone share similar migratory patterns (Martien et al. 2023) and consequently entanglement risks, but this pattern may be more detectable at a larger spatial scale than that tested in this study. Further investigation into the spatial fidelity of humpback whales on their foraging grounds in the North Pacific would enhance our understanding of entanglement risks and inform both state-level and coast-wide management strategies.

This study offers valuable insights into the challenges and opportunities of using scar analysis to detect whales that have experienced entanglements. While the scoring approach developed by Wall et al. (2019) enabled us to make better use of opportunistic scarring data and detect a few more entanglement cases (e.g. when fluke underside photos were the only ones available or when other perpendicular tailstock photos were of poor quality), it is clear that the assessment of scars in fluke photos or dorsal/ventral tailstock photos is challenging. First, entanglement scars could be mistaken with scars of other origin such as propeller hits when only one of these photo types was available and could be analyzed for an individual. Second, fluke photos rarely showed entanglement scars with certainty and often did not show any scarring, when it was clear from the tailstock that the individual had in fact been entangled (see Fig. S5 for examples). The comparison of scarring prevalence across photo types suggested that about half of entanglement cases detectable through scar analysis may have been missed if relying solely on photos of the fluke underside. As a result, the Wall et al. (2019) approach provided a significantly lower scarring prevalence estimate than the Robbins & Mattila (2001) approach. The natural pigmentation patterns, predation marks (e.g. killer whale teeth rake marks), and scars of undetermined origin that often occur on the flukes and the ventral side of the tailstock may easily mask, or be confused with, entanglement scars. Finally, the insertion points and leading edge of the fluke, where entanglement scars would be more likely to appear, were often masked by water (the full length of the leading edge was only visible in 39% of the fluke photos). For now, a thorough documented and validated analysis of fluke underside and ventral tailstock injuries and scarring following actual entanglements is needed to refine the categories designed by Wall et al. (2019) to decipher the origin of scars on ventral fluke photos. Future studies should also explore scars on other body parts, such as the mouth and flippers, where fishing gear can typically be anchored (Johnson et al. 2005). Alternative field approaches, such as underwater or airborne imagery (e.g. Ramp et al. 2021), may complement and enhance this effort.

Investigating the temporal trend in scarring prevalence between 2016 and 2023 in Oregon, we found an increase up to 2020 followed by a decrease in more recent years. While weak, this pattern corresponds with the higher levels of entanglements reported between 2014 and 2019 over the US West Coast (Saez et al. 2021, NOAA Fisheries 2024b). Yet, the slight decrease observed since 2022 cannot be considered conclusive, due to large variations in data collection efforts. In fact, our simulations suggested a greater sample size would be needed to accurately detect even a drastic decline in entanglements (i.e. collecting good-quality tailstock photos from 165 ind. yr^{-1} for 5 yr). We recognize that the basic population model and sampling scenarios tested here only offer a rough estimate of the minimum sampling effort needed for scar analysis to be an effective tool in the early detection of the impacts of new management strategies. The uncertainty around population parameters (such as survival and calf production), the use of a constant resighting rate, the assumption of a closed population, and the mismatch between local scar observations and regional entanglement risk, all entail significant limitations to generating robust predictions. Yet, several lessons can be drawn from our simulation. Short-term monitoring of scarring prevalence (i.e. 2 yr) is not sufficient to detect changes in entanglement rates, and relatively high annual sample sizes are needed. Scar analysis can be a powerful tool for documenting and estimating the impact of entanglements at both individual and population levels, yet it requires dedicated and sustained effort to collect sufficient suitable photos over multiple years and at a relevant spatial scale.

This study provides a useful estimate of 27.3% of the humpback whale population visiting Oregon waters since 2016 that were non-lethally entangled at least once in their lifetime. While these numbers are not directly comparable, the contrast between this value and the number of confirmed humpback whale entanglements over a similar time period is thought-provoking. One hundred and twenty-five observed entanglement events were recorded along the US West Coast between 2016 and 2021 (data provided by National Marine Fisheries Service West Coast Region [NMFS WCR], April 2021), which represents 2.8% of the California, Oregon, and Washington population as estimated by Calambokidis & Barlow (2020). While this rough comparison supports the assumption that the vast majority of entanglement events go undetected, it also highlights the biases that are inherent to these estimates of the proportion of the population potentially affected by entanglements. On one hand, under-reporting of entangled whales may be most extreme in areas with low levels of whale-watching activity and poorer weather (like Oregon) compared to areas like Monterey Bay, California (where many entanglements are reported) that have many year-round whale-watch operators and better weather conditions. On the other hand, scarring prevalence only reflects non-lethal events where whales were able to free themselves (with or without the help of a response team) and is biased for body parts that may get entangled but are rarely photographed from boats (e.g. mouth, flippers). Additionally, scarring prevalence is not an instantaneous indicator, as scars can remain forever detectable on an individual that was once severely entangled. An avenue for future research on the US West Coast (as conducted for other regions, e.g. Robbins & Mattila 2004, Neilson et al. 2009, Robbins 2012) is to collate longitudinal photographic documentation of individuals' scar acquisition throughout their migratory range to determine inter-annual changes, resulting in a quicker method to inform changes in scar-based estimates of entanglement rates. This approach would also better estimate (1) where and when entanglements likely occurred while accounting for spatio-temporal sampling bias (e.g. Robbins 2012), and (2) how entanglements affect individual fitness and survival (e.g. Reed et al. 2024).

The simulation conducted in this study provides valuable insights into the photographic sampling effort required to detect changes in entanglement rates in a whale population that has been subject to relatively low survey effort, such as the Oregon humpback whales. Indeed, in this study, individual whales were too rarely resighted within Oregon waters to allow a longitudinal analysis of annual scar acquisition along individual resighting histories. In this context, our results suggest that no less than 165 ind. yr^{-1} should be photographically sampled through good-quality perpendicular or forward tailstock photos, to detect changes in scarring prevalence at the population level in a timely manner. In addition to enhanced data collection throughout the season (May–October) and along the coast, sharing of existing photographic data throughout the North Pacific migratory range of humpback whales will be key to track the appearance of new entanglement scars on known individual whales over time. Finally, partnerships with fishers, who spend the most time on the water, can be a useful way to obtain more photographs of whales. In general, contribution of all ocean users to photographic data collection should be encouraged to extend data coverage and foster a shared conservation goal among stakeholders.

Data and code availability. R codes and data files to reproduce this work are available on a GitHub repository (https://github.com/SoleneDerville/HW_scarring_analysis). Whale photos are available on Figshare (https://figshare.com/projects/SLATE_Scar-based_Long-term_Assessment_of_Trends_in_whale_Entanglements/244745).

Acknowledgements. This study was funded by NOAA Fisheries (federal award number #NA22NMF4690373) through the Oregon Department of Fisheries and Wildlife (ODFW sponsor award #421-22). We thank Cristy Milliken for her contribution to data processing and preliminary photo analysis. We thank Dawn Barlow, Todd Chandler, Allison Dawn, Alejandro Apolo Fernandez Ajo, Lisa Hildebrand, and Greg Krutzikowski who participated in small-boat work with the GEMM Lab. We thank Alexandra Vanderzee for her help with data processing at CRC. We also thank Troy Buell and Kelly Corbett (ODFW) for their partnership over the OPAL and SLATE projects. We thank Justin Yager, Cyle Barnhart, Aaron Ashdown, and Josh Allman for their contribution in data collection. We thank Jim Carretta for helpful feedback on an earlier version of our manuscript. Finally, we thank the 3 anonymous reviewers who reviewed this study.

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Editorial responsibility: Brendan Godley,
University of Exeter, Cornwall Campus, UK
Reviewed by: C. J. Basran, S. Kraus and 1 anonymous referee
Submitted: November 9, 2024; Accepted: April 14, 2025
Proofs received from author(s): June 23, 2025