Received: 21 September 2021 | Accepted: 12 September 2022

DOI: 10.1111/mms.12985

ARTICLE

Marine Mammal Science

Low anthropogenic mortality of humpback (*Megaptera novaeangliae*) and killer (*Orcinus orca*) whales in Norwegian purse seine fisheries despite frequent entrapments

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Funding information
Norwegian Ministry of Trade, Industry and Fisheries

Abstract

Fishery inspector logbooks were used to estimate fishing gear interaction rates for humpback (*Megaptera novaeangliae*) and killer (*Orcinus orca*) whales in Norwegian purse seine fisheries for herring from 2011 to 2020. Estimated rates were applied to fisheries data to estimate fleet-wide totals. Estimates showed that in a 10-year period, a total of 78 humpback whales, 95% CI [41, 145] and 100 killer whales, 95% CI [63, 176] were entrapped in purse seines. Most whales were disentangled alive, with an estimated mortality of 5%, *CV* 0.69, 95% CI [0.0, 11.8] and 6%, *CV* 0.48, 95% CI [0.3, 11.9], respectively. The average yearly mortality over the study period was thus approximately 0.60 killer whales and 0.39 humpback whales corresponding to 0.008% and 0.007% of the respective abundance estimates for these whale species in Norwegian waters. Given the Potential Biological Removal sustainability limits of 98 humpbacks and 161 killer whales per year, it may be concluded that, by itself, the average yearly mortality incurred by these whale populations by Norwegian fisheries does not constitute a significant risk to either of these species, but bycatch in Norwegian purse seine fisheries may not be the only source of anthropogenic mortality.

KEYWORDS
anthropogenic mortality, fishing gear interactions, humpback whale, killer whale, purse seine

1 | INTRODUCTION

Fisheries bycatch, defined as the unintentional catch of nontargeted species, is currently the most severe threat to marine mammals globally (Read et al., 2006) and threatens several populations of cetaceans with immediate extinction (Collins et al., 2010; Jaramillo-Legorreta et al., 2019; Knowlton et al., 2012; Roberts et al., 2019; Weir et al., 2011). Most of the global marine mammal bycatches are caused by different forms of gill nets (Brownell et al., 2019; Read et al., 2006; Reeves et al., 2013), but the use of purse seines on mixed schools of small cetaceans and yellowfin tuna (*Thunnus albacares)* in the eastern tropical Pacific has demonstrated that this type of fishing gear also has the potential to kill large numbers of cetaceans (Perrin 1968, 1969). However, in other areas, and globally, purse seines are regarded as having a lower risk of catching marine mammals compared with static gear such as gill nets (Lewison et al., 2004; Wise et al., 2007).

In Norway, purse seines constitute the main fishing gear used for harvesting Norwegian Spring Spawning (NSS) herring (*Clupea harengus*) on the spawning and wintering grounds. The spawning grounds are off the Norwegian coast between 62° and 69°N. The wintering grounds are typically further north, between 69° and 71°N. When purse seine fisheries occur in these offshore waters, close interactions with cetaceans are rare, although feeding aggregations of humpback (*Megaptera novaeangliae*) and killer whales (*Orcinus orca*) at herring schools in Northern Norway have been observed (Jourdain & Vongraven 2017). However, in the period 2012–2018, the NSS herring changed wintering grounds and congregated in several sheltered fjords in northern Norway. Shifts in herring wintering grounds typically occur in years when the first time/repeat spawner ratio peaks (Huse et al., 2010). This enormous biomass of herring (the spawning stock is about four million metric tons, (Salthaug et al., 2020), concentrated in a restricted area, attracted large numbers of humpback and killer whales. During that time, and in these narrow fjords, interactions between large cetaceans and purse seine fisheries were frequent. In 2019, the NSS herring again shifted wintering grounds to more open waters, and the frequent interactions between cetaceans and purse seine fisheries became less frequent. Recently, it was discovered that a small proportion of humpback whales do not undertake their seasonal southward migration to lower latitudes, and instead spend the entire year in North Atlantic waters (Ramm, 2020). It is possible that a prolonged presence in Norwegian coastal waters throughout the year may expose them to risk of entanglements in fisheries that they previously avoided by leaving the area.

In this article, we address the incidental entrapment and entanglement or bycatch of cetaceans in Norwegian pelagic purse seine fisheries by large vessels (length overall ≥15 m) with an emphasis on humpback and killer whales bycaught in seine nets targeting herring. Following an abrupt increase in entrapments in 2016 and 2018, when the herring shifted wintering grounds, the Norwegian Directorate of Fisheries issued a new rule stating that the wellbeing of any entrapped or entangled cetaceans is to be prioritized over the catch. The rule required that a purse seine full of herring would have to be opened up again if there were cetaceans inside that could not otherwise be removed in a timely fashion, even if that meant that the catch would be lost. The postincidence response of the fishers, coast guard, and fishery inspectors, to release humpback and killer whales bycaught in seine nets is described. Bycatch rates and associated mortality rates are estimated and scaled up to total bycatch and mortality estimates using fishery data. Finally, estimates are compared against the Potential Biological Removal, PBR, (Wade, 1998) for the two bycaught species.

The abundance estimates for humpback and killer whales in the North-East Atlantic are 10,708 animals (*CV* 0.38, 95% CI [4,906, 23,370]), and 15,056 animals (*CV* 0.29, 95% CI [8,423, 26,914]), respectively (Leonard & Øien, 2020). These estimates are based on multiyear Norwegian shipboard surveys from 2014 to 2018. Killer whales are resident in Norwegian waters throughout the year and follow the migration of herring (Similä et al., 1996; Vogel, 2020). Humpback whales are present on their feeding grounds in Norwegian waters from late spring to early winter, when the majority depart to start their long journeys to breeding grounds in lower latitudes. Some humpbacks, on their southward migrations from the Barents Sea to lower latitudes, may stop on their way to feed on wintering herring before they resume their southward migration. The objective of this study was to address the entrapments of humpback and killer whales in purse seines set for herring and the associated mortality.

2 | METHODS

2.1 | Data collection and preparation

Data on all pelagic fishing activities conducted by large vessels (vessels with an overall length ≥15 m) were obtained from the Norwegian Directorate of Fisheries. Since the beginning of 2011, large fishing vessels operating in Norway have been required to electronically log all fishing activities. These electronic logbooks are highly detailed and include positional data as well as information on the type and number of fishing gear used, and the duration and depths at which they were used. Data on landed catch are available from before 2011 from fish tickets, but these do not include GPS coordinates or details on gear use other than a rough specification of the general type of gear used.

Bycatch data were obtained from two, partially overlapping sources:

(1) Inspector logbooks from the Sea Surveillance Unit (SSU) and the Coast Guard (CG) from 2011 to 2020. The SSU is a subdivision of the Norwegian Directorate of Fisheries. SSU inspectors stay on fishing vessels for the entire duration of a fishing trip, from disembarkation to landing the catch. The duties of the inspectors include making sure that the vessel operates in a legal manner and documenting bycatches, discards, and potential code violations. Inspectors also record sightings of marine mammals and marine mammal entanglements in fishing gear. In addition to on-board inspectors, the SSU also operates three roaming vessels that patrol the Norwegian coastline, performing unscheduled and opportunistic inspections. Together, SSU roaming vessels and CG vessels monitor nearly all purse seine operations targeting herring that are conducted within the fjords (where whale and gear interactions are most likely). This is possible because of the clumped distribution and synchronized movements of the herring biomass. For herring (and other) fisheries conducted in open waters, the coverage is substantially smaller. SSU and CG inspections are not random. The process of selecting which vessels and thereby, which fishing operations, to inspect are based on an internal risk assessment, where fisheries and vessels that are likely to have large bycatch or discard rates, a large proportion of undersized fish, or any other code violation typically are inspected more frequently. Tips and knowledge of previous offenses may factor into these risk assessments. Roaming SSU and CG vessels also respond to reports on whale activity near fishing vessels. The CG and the SSU cooperate closely, and both regularly send copies of their logbooks to the Institute of Marine Research (IMR). The selection process is likely to cause an upward bias in bycatch rates estimated using CG and SSU observer data.

(2) The central registry of whale entrapment records. In 2016 (following the aforementioned large and unexpected increase in the number of humpback and killer whale entrapments in purse seine fisheries in the northern parts of Norway), the Directorate of Fisheries established a central registry of whale entrapments and required that all Norwegian fishing vessels report marine mammal entrapments to them. These reports are collected in an informal/unstandardized manner and may make their way to the Directorate through various means. Fishers may contact the Directorate either directly or through the SSU or the CG to make their reports. Entrapments recorded in SSU and CG reports *may* therefore appear in this central registry, but not always. More importantly, the central registry may also include records of entanglements that do not appear in SSU/CG logbooks, e.g., if a fisherman contacted the Directorate directly. Furthermore, news of whale entrapments in the media may prompt the Directorate to reach out to the offending fishing vessel(s) to verify that an entrapment took place and to collect data related to that incidence.

Data from both sources were cross-referenced to identify and merge any duplicate entries by comparing date of incidence, vessel(s) involved, gear types, etc. This method was used to collate a sample of all documented interactions between cetaceans and purse seines in Norwegian fisheries. The final data set contained dates, GPS coordinates, gear types, a short description of how the animals were entrapped and later released, the species and number of animals involved, as well as the outcome for those animals. Outcome was classified as either unharmed, wounded, or lethal, and assessed by visual inspection by observers on the fishing vessel or on a nearby SSU/CG vessel. In several cases, bycatches were also documented with pictures and/or videos.

2.2 | Estimating bycatch rates and totals

All bycatch locations were initially classified either as "coastal" or "offshore." Coastal locations were defined as all locations that were <10 km from the coast (by geodesic distance). The threshold of 10 km was chosen because all locations within fjords and straits were then classified as coastal. Correspondingly, locations farther from the coast were defined as offshore locations. This classification resulted in a low number of offshore locations, so all offshore locations were grouped together in a single offshore group. Coastal bycatch locations were further divided into groups using complete linkage hierarchical clustering based on geodesic distances. Coastal bycatch hot spots were then defined by finding the smallest convex polygons that covered all points within each coastal cluster, and then expanding those polygons slightly by adding a 5 km buffer around them.

We assumed that SSU and CG coverage was 100% in coastal bycatch hot spots in years when the herring overwintered in the fjords, and that all bycatches in those areas were registered. Bycatch rates in other/offshore areas however, were estimated for each species using a traditional ratio estimator (Cochran, 1977), and scaled up to bycatch totals in the fleet-wide purse seine fisheries using data from the electronic logbooks (Table S1).

The estimated bycatch rate $\widehat{R}_h$ in area h, is given by

$$\widehat{R}_h = \frac{\overline{y}_h}{\overline{x}_h}. \tag{1}$$

The estimated total bycatch $\widehat{Y}_h$ is similarly given as

$$\widehat{Y}_h = \widehat{R}_h X_h, \tag{2}$$

where $\overline{y}_h$ = the average number of bycaught whales in area h, $\overline{x}_h$ = average fishing effort among inspected vessels in area h, X_h = fishing effort in area h among all vessels. Fishing effort was defined as the number of purse seine fishing operations.

All analyses were done in R (R Core Team, 2020). We used the *sf* R package (Pebesma, 2018) for spatial analyses and *hclust* from the *stats* package (R Core Team, 2020) for clustering. Estimates of entrapment rates were calculated with the *survey* R package (Lumley 2004, 2020). Coefficients of variation (*CVs*) and 95% confidence intervals (CIs) and were obtained through bootstrapping using the *boot* R package (Canty & Ripley, 2020; Davison & Hinkley, 1997). In the bootstrapping procedure, we resampled with replacement from entanglement and inspection/fishing effort data, and recalculated all total estimates from the bootstrap samples in the manner described above. *CVs* and bias-corrected (BCa) CIs were obtained from the resulting distribution of 10,000 bootstrap estimates.

2.3 | Evaluating the sustainability of estimated bycatch totals

The PBR for a given marine mammal population is given by the equation

$$PBR = N_{\min} \times 0.5 \times R_{\max} \times F_r, \quad (3)$$

where $N_{\min}$ is the minimum population estimate, $R_{\max}$ is the maximum growth rate, and F_r is a recovery factor that allows one to take into account further information on the conservation status of the species in question. For cetaceans, $R_{\max} = 0.04$ is a feasible default, suggested in Wade (1998). For PBR calculations in this paper, we used $R_{\max} = 0.04$, $F_r = 1$, and $N_{\min} = 4{,}906$ (humpbacks) and 8,423 (killer whales). $F_r = 1$ was used for all species because the abundance of humpback has shown an increasing trend in recent surveys, and there is no indication of depletion in killer whale abundance (Leonard & Øien, 2020; Solvang et al., 2020).

The PBR for humpback whales in Norwegian waters, based on the most recent data, is therefore 98 animals and the corresponding value for killer whales is 168 animals. Humpback whales from the large breeding assembly in the West Indies and the smaller Cape Verde breeding assembly are mixing on the Northeast Atlantic feeding grounds (Berrow et al., 2021; Stevick et al., 2006). Because they are mixing on the feeding grounds, we anticipate that they have similar probability of entanglement, and the ratio between bycatch and PBR should be the same between the two breeding stocks. NAMMCO recognizes that killer whales in the Northeast Atlantic are grouped into three stocks after association with their main prey, and killer whales in the northern North Sea, Norwegian Sea, and Icelandic waters are all associated with herring as main prey (Foote et al., 2010), and can be regarded as one stock.

3 | RESULTS

The electronic logbooks for large fishing vessels contained 114,514 reports for purse seine fishing operations from 2011 to 2020, with an average of 11,451 ± 1,934 (yearly mean ± standard deviation) purse seine fishing operations conducted per year. The yearly number of purse seine fishing operations in the two bycatch hot spots (Figure 1a, b) coincided with the known presence of herring in each of the corresponding fjord systems. Fishing effort was shifted northwards (i.e., from hot spot 1 to hot spot 2), as the herring shifted their overwintering grounds from 2016 to 2018, seeing activity in both fjord systems in 2017.

The overall proportion of purse seine fishing operations that were observed either by the SSU or CG inspectors (total observer coverage) was on average 6.4% per year. Purse seine fishing effort and separate coverage numbers for SSU and CG inspectors per year inside and outside bycatch hot spots are shown in Figure 1. The average SSU and CG inspector coverage of purse seine fisheries in bycatch hot spots was substantially higher during the years when the herring entered the fjords (Figure 1), compared to the average for offshore and other areas. Fishing effort was concentrated in two large regions; the northern North Sea, around 60°N and 5°E and the Norwegian Sea, going into the Barents Sea along the Norwegian coast (Figure 2a). The geographical distribution of observer effort was similarly distributed.

There were 65 episodes of cetacean entrapments in purse seines from 2011 to 2020, involving a total of 40 humpback and 65 killer whales. There were no reports of entanglements in Danish seines or trawling bags, but there were three cases of entanglements of humpbacks in buoy ropes from bottom-set gill nets or fish traps. For purse seine fisheries, there were few observed entrapments in offshore locations, with several years between them (Figure 2c). Most bycatches of humpback and killer whales occurred in northern Troms County, from 65.9°–70.0°N and 18.0°–21.5°E, between 2016 and 2018, and most of them in two fjords systems, called Kaldfjord and Kvænangen (Figure 2d). Applying the clustering algorithm on the coastal bycatch locations roughly identified these two fjords, and some adjacent areas, as high bycatch regions. The encircling buffered convex hull polygon for each bycatch hot spot is shown in Figure 2d. Figure 2c also shows the coarse locations of these hot spots and other (offshore) entrapments in a larger geographical context.

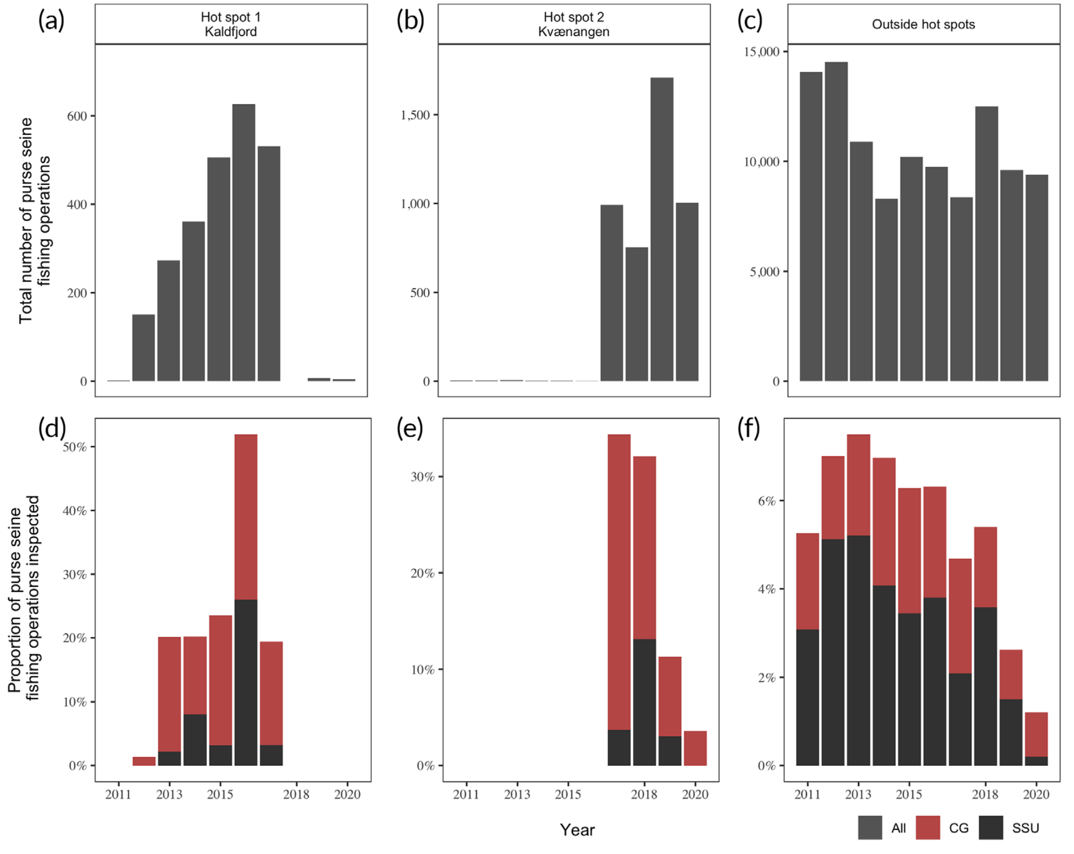

FIGURE 1 Top: Total number of purse seine fishing operations conducted per year by all large fishing vessels, in the bycatch hot spots (panels a and b) and outside those hot spots (panel c). Bottom: Stacked line chart indicating the proportions of seine fishing trips conducted by all large fishing vessels that were inspected by the CG (red columns) or the SSU (dark gray columns) per year in bycatch hot spots (panels d and e) and outside those hot spots (panel f).

Overall estimates of total bycatch (i.e., Equation 2) of cetaceans in Norwegian purse seine fisheries in offshore/other locations (i.e., not including bycatch hot spots) was 37 humpback and 37 killer whales (Table 1). Total bycatch in all areas, including bycatch hot spots was 78 humpback and 100 killer whales. The reported bycatches in the bycatch two hot spots (Figure 2d) contribute to more than 50% of the total bycatches in both species (Table 1). Bycatches of humpback and killer whales in these hot spots in the three years from 2016 to 2018 make up approximately 93% of the total bycatch for all areas in the ten years from 2011 to 2020.

The average yearly bycatch in purse seines was approximately 8 humpback and 10 killer whales, with an estimated mortality associated with purse seine bycatches of 0.05 for humpback and 0.06 for killer whales (Table 2). SSU/CG observer data indicated that most bycaught animals were successfully removed from the nets. However, reports indicate that two humpback whales and four killer wha did not survive. The estimated mortalities from bycatches in purse seine nets across all areas (i.e., including Kaldfjord and Kvænangen) were 6%, *CV* 0.48, 95% CI [0.3, 11.9] and 5%, *CV* 0.69, 95% CI [0, 11.75] for killer and humpback whales, respectively. Based on the estimated yearly average bycatch given in Table 2, the average yearly mortality rates in the study period would then be approximately 0.39 humpback whales and 0.60 killer whales, or about one humpback and one killer whale killed in purse seines every 31 and 20 months, respectively.

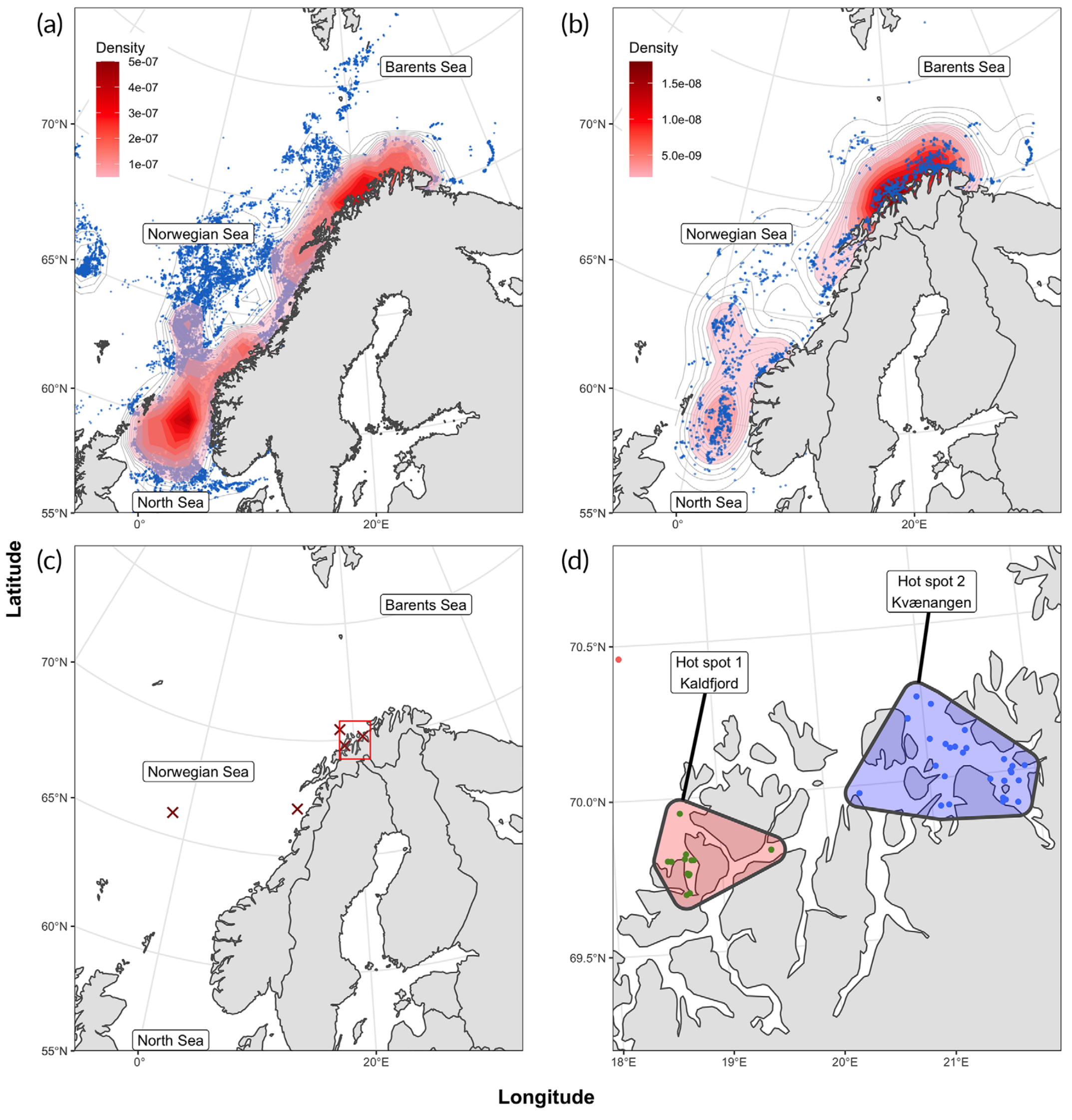

FIGURE 2 Top: Density maps showing the geographical distribution of fishing effort (a) and observer effort (b). Here, blue dots represent one fishing station, using all data from 2011 to 2020. Bottom: Map showing bycatch sites, indicted by red crosses (c). Bycatch locations and buffered convex hull polygons designating the two bycatch hot spots.

TABLE 1 Reported hot spot bycatches and bycatch estimates for other areas (with *CVs* and 95% CIs) in Norwegian pelagic fisheries. Total bycatch refers to years 2010–2020.

Species	Gear type	Region(s)	Total bycatch	*CV*	95% CI
Humpback	Seine	Hot spots	41	—	—
Humpback	Seine	All, except hot spots	37	0.93	0, 104
Killer whale	Seine	Hot spots	63	—	—
Killer whale	Seine	All, except hot spots	37	0.97	0, 113

TABLE 2 Total bycatch across all gear types as a sum of reported and estimated bycatch and bycatch associated mortality estimates for each species. The results are presented as point estimates with 95% confidence intervals in brackets.

Species	Total bycatch	Average yearly bycatch	Estimated bycatch mortality
Humpback	78 [41, 145]	7.8 [4.1, 14.5]	0.05 [0.00, 0.12]
Killer whale	100 [63, 176]	10 [6.3, 17.6]	0.06 [0.03, 0.12]

4 | DISCUSSION

4.1 | Choice of stratification, and bias and reliability of estimates

Unstratified, overall ratio and total estimates do not take into account that entanglement rates may differ between different fisheries, regions, seasons, or other relevant variables. Generally, single or multivariable stratifications allow more refined estimates that are more truly representative of the real world. Unfortunately, the low number of cetacean entanglement observations reported in our bycatch did not allow for fine stratifications since most strata in any stratification would have a rate of zero entanglements.

The ratio estimator that was used to produce our entanglement estimates assumes that data originate from a random sample. To satisfy this assumption, every single fishing operation undertaken in each of the Norwegian pelagic fisheries examined must have an equal probability of being inspected within its gear group. For the SSU and CG observer data, this was not the case. As explained in Section 2.1, SSU and CG inspections were *not* random. This means that the ratio estimator would produce biased estimates when applied to SSU and CG inspector data. However, given the mode of operation of the SSU and CG, it can be expected, by design, that the discovery rate of marine mammal entanglements is much higher than what the relatively low yearly inspection coverage of approximately 1%–8% (Figure 1f) might suggest. The geography of the two bycatch hot spots, for the most part featuring narrow fjords and straits (Figure 2d), would also make it easier for a roaming SSU/CG vessel stationed in the area to simultaneously monitor cetacean bycatches for most, if not all, purse seine vessels operating in that area.

For these reasons, bycatch estimates derived from opportunistic inspector data using a ratio estimator must be *positively* biased, and it is likely that this bias is very large, i.e., that a large proportion of bycatches are discovered and logged. Thus, bycatch estimates for humpback and killer whales reported here should be considered maximum estimates, and with this important caveat of a potentially large upward bias in mind. The actual numbers of humpback and killer whale entanglements are most likely considerably lower than what our estimates may indicate. It should also be noted that all point estimates given in this paper have a very high CV due to the extremely low observed bycatch rates. Caution must be exercised in the use and interpretation of these estimates. However, the results indicate that the total bycatch risk to large cetaceans in Norwegian pelagic fisheries is very low, even when taking estimation uncertainty into account.

4.2 | Causes of entanglements

The entanglement rates of humpbacks and killer whales in purse seines must be seen in the context of the seasonal movements of the very dynamic NSS herring stock. When the herring stock moved into the narrow fjords, a substantial spatial and temporal overlap occurred between whales feeding on herring and fishermen operating fishing gear at the same time. This was particularly evident between 2016 and 2018. In this period, there were frequently several vessels operating purse seines in close proximity to each other, with groups of whales interspersed around the area. Killer whales may have even learned to associate the sound of active purse seiners with the idea of increased prey availability. Mul et al. (2020) recently demonstrated through simulations that killer whale movements were biased towards fishing activities, especially if they were within 20 km of a fishing vessel (which would be very likely in a fjord, especially a narrow one like Kaldfjord). Additionally, the geography and the small area of the fjords may have limited the effective ability of the whales to disperse away from fishing vessels, e.g., after they were done feeding. All these factors may have contributed to the large peak in entanglements that occurred between 2016 and 2018, particularly in 2017. The strong relationship between cetacean entanglement rates and herring amassing in fjords is further supported by the abrupt absence of any such entanglements after the herring moved further north along the coast. It is difficult if not impossible to predict the erratic seasonal migrations of the herring stock from year to year, but if the herring stock were to return to fjords such as Kaldfjord, it is likely that cetaceans would follow suit, potentially causing an increase in entanglements.

4.3 | Mortality and sustainability of entanglements

Before 2016, there were not many reported cases of cetacean entanglements in purse seines, and such incidents most likely only occurred very rarely. At that time, there were still no government directives or official rules in place governing how to handle cetacean entrapments or entanglements, and it was up to the fishermen to deal with such situations themselves. It is possible, but not documented, that this would lead to securing the catch being prioritized over releasing the cetaceans from the seine net. It is therefore possible that the mortality associated with entanglements before 2016 was higher than our estimates of 5% and 6%. However, in the few purse seine entrapment cases that have been reported before 2016, the entangled whales were successfully released in all cases. We do not know the health status or long-term survival of released whales. This new regulation to prioritize disentanglement of cetaceans over harvesting the fish, fell under the purview of the SSU and the CG. SSU inspectors and CG personnel were then given training in response to large whale entanglement. This training was tutored by David Mattila, IWC, and in line with IWC's best practice guidelines for entanglement responders. However, with the limited data set presented here, it was not possible to evaluate whether there was any change in the mortality resulting from an entanglement before and after this training.

Average mortality estimates of 0.39 humpback and 0.60 killer whales per year correspond to 0.008% and 0.007% of the respective abundance estimates for these whale species. Both mortality estimates are well within the PBR limits of 98 humpback and 161 killer whales per year. Even in the peak year of 2017, the yearly total mortality for both species would be within the PBR.

Based on these results, we conclude that the mortality incurred by these whale populations by Norwegian pelagic fisheries does not alone constitute a significant risk to either of these populations, but they must be considered in context of other anthropogenic threats such as ship collisions and bycatch in other areas. It is possible that entrapments in purse seines may have welfare implications/other adverse effects on individual whales, e.g., from stress induced or physical wounds incurred by being entrapped and subsequently released from a purse seine.

ACKNOWLEDGMENTS

We acknowledge the Directorate of Fisheries, the Sea Surveillance Unit, and the Norwegian Coast Guard for data used in these analyses. It was the efforts of the inspectors and the data curators at the Directorate that made this manuscript possible. We also thank Christian Roll Valen (Directorate of Fisheries), Hans Hagen Stockhausen and Kjell Nedreaas (IMR) for taking time out of their busy schedules to assist us in obtaining and understanding the data that we needed. This research was funded by the Ministry of Trade, Industry and Fisheries.

AUTHOR CONTRIBUTIONS

Arne Bjørge: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing – original draft; writing – review and editing. **André Moan:** Data curation; formal analysis; investigation;

methodology; visualization; writing – original draft; writing – review and editing. **Kathrine A. Ryeng:** Writing – review and editing. **Jørgen R. Wiig:** Investigation; resources; writing – review and editing.

DATA ACCESSIBILITY

Data will be shared on reasonable request to the corresponding author.

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REFERENCES

Berrow, S. D., Massett, N., Whooley, P., Jann, B. V. M., Lopez-Suarez, P., Stevick, P. T., & Wenzel, F. W. (2021). Resighting of humpback whales (*Megaptera novaeangliae*) from Ireland to a known breeding ground: Cabo Verde, West Africa. *Aquatic Mammals*, *47*(1), 63–70. https://doi.org/10.1578/AM.47.1.2021.63

Brownell, R. L., Jr., Reeves, R. R., Read, A. J., Smith, B. D., Thomas, P. O., Ralls, K., Amano, M., Berggren, P., Chit, A. M., & Collins, T. (2019). Bycatch in gillnet fisheries threatens Critically Endangered small cetaceans and other aquatic megafauna. *Endangered Species Research*, *40*, 285–296. https://doi.org/10.3354/esr00994

Canty, A., & Ripley, B. (2020). *Boot: Bootstrap R (S-Plus) functions* (R Package Version 1.3-25) [Computer software]. https://cran.r-project.org/web/packages/boot/boot.pdf

Cochran, W. G. (1977). *Sampling techniques*. John Wiley & Sons.

Collins, T., Boumba, R., Thonio, J., Parnell, R., Vanleeuwe, H., Ngouessono, S., & Rosenbaum, H. (2010). *The Atlantic humpback dolphin* (Sousa teuszii) *in Gabon and Congo: cause for optimism or concern*. Paper SC/62/SM9 presented to the Scientific Committee of the International Whaling Commission.

Davison, A. C., & Hinkley, D. V. (1997). *Bootstrap methods and their application*. Cambridge University Press.

Foote, A. D., Vilstrup, J. T., de Stephanis, R., Verborgh, P., Abel Nielsen, S. C., Deaville, R., Kleivane, L., Martin, V., Miller, P. J. O., Øien, N., Perez-Gil, M., Rasmussen, M., Reid, R. J., Robertson, K. M., Rogan, E., Similä, T., Tejedor, M. L., Vester, H., Vikingsson, G. A., … Pierney. S. B. (2010). Genetic differentiation among North Atlantic killer whale populations. *Molecular Ecology*, *20*(3), 629–641. https://doi.org/10.1111/j.1365-294X.2010.04957.x

Huse, G., Fernö, A., & Holst, J. C. (2010). Establishment of new wintering areas in herring co-occurs with peaks in the 'first time/repeat spawner' ratio. *Marine Ecology Progress Series*, *409*, 189–198. https://doi.org/10.3354/meps08620

Jaramillo-Legorreta, A. M., Cardenas-Hinojosa, G., Nieto-Garcia, E., Rojas-Bracho, L., Thomas, L., Ver Hoef, J. M., Moore, J., Taylor, B., Barlow, J., & Tregenza, N. (2019). Decline towards extinction of Mexico's vaquita porpoise (*Phocoena sinus*). *Royal Society Open Science*, *6*, Article 190598. https://doi.org/10.1098/rsos.190598, 6

Jourdain, E., & Vongraven, D. (2017). Humpback whale (*Megaptera novaeangliae*) and killer whale (*Orcinus orca*) feeding aggregations for foraging on herring (*Clupea harengus*) in Northern Norway. *Mammalian Biology*, *86*, 27–32. https://doi.org/10.1016/j.mambio.2017.03.006

Knowlton, A. R., Hamilton, P. K., Marx, M. K., Pettis, H. M., & Kraus, S. D. (2012). Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. *Marine Ecology Progress Series*, *466*, 293–302. https://doi.org/10.3354/meps09923

Leonard, D., & Øien, N. (2020). Estimated abundances of cetacean species in the Northeast Atlantic from two multiyear surveys conducted by Norwegian vessels between 2002–2013. *NAMMCO Scientific Publications*, *11*. https://doi.org/10.7557/3.4695

Lewison, R. L., Crowder, L. B., Read, A. J., & Freeman, S. A. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends in Ecology & Evolution*, *19*(11), 598–604. https://doi.org/10.1016/j.tree.2004.09.004

Lumley, T. (2004). Analysis of complex survey samples. *Journal of Statistical Software*, *9*(8), 1–19. https://doi.org/10.18637/jss.v009.i08

Lumley, T. (2020). *Survey: analysis of complex survey samples* (R package version 4.0) [Computer software]. https://cran.r-project.org/web/packages/survey/survey.pdf

Mul, E., Blanchet, M.-A., Mcclintock, B. T., Grecian, W. J., Biuw, M., & Rikardsen, A. (2020). Killer whales are attracted to herring fishing vessels. *Marine Ecology Progress Series*, *652*, 1–13. https://doi.org/10.3354/meps13481

Pebesma, E. J. (2018). Simple features for R: Standardized support for spatial vector data. *The R Journal*, *10*, 439–446. https://doi.org/10.32614/RJ-2018-009

Perrin, W. F. (1968). The porpoise and the tuna. *Sea Frontiers*, *14*, 166–174.

Perrin, W. F. (1969, October 17–18). *The problem of porpoise mortality in the US tropical tuna fishery*. Proceedings of the Sixth Annual Conference on Biological Sonar & Diving Mammals, Stanford Research Institute, Palo Alto, CA.

R Core Team. (2020). *R: A language and environment for statistical computing* [Computer software]. R Foundation for Statistical Computing.
Ramm, T. (2020). *Hungry during migration? Humpback whale movement from the Barents Sea to a feeding stopover in northern Norway revealed by photo-ID analysis* [Master's thesis]. UiT The Arctic University of Norway.
Read, A. J., Drinker, P., & Northridge, S. (2006). Bycatch of marine mammals in US and global fisheries. *Conservation Biology*, *20*(1), 163–169. https://doi.org/10.1111/j.1523-1739.2006.00338.x
Reeves, R. R., McClellan, K., & Werner, T. B. (2013). Marine mammal bycatch in gillnet and other entangling net fisheries, 1990 to 2011. *Endangered Species Research*, *20*(1), 71–97. https://doi.org/10.3354/esr00481
Roberts, J., Webber, D., Roe, W., Edwards, C., & Doonan, I. (2019). *Spatial risk assessment of threats to Hector's and Māui dolphins* (Cephalorhynchus hectori) (New Zealand Aquatic Environment and Biodiversity Report No. 214). Ministry of Fisheries, Wellington, New Zealand.
Salthaug, A., Stenevik, E. K., Vatnehol, S., Anthonypillai, V., Ona, E., & Slotte, A. (2020). Distribution and abundance of Norwegian spring-spawning herring during the spawning season in 2020.
Similä, T., Holst, J. C., & Christensen, I. (1996). Occurrence and diet of killer whales in northern Norway: seasonal patterns relative to the distribution and abundance of Norwegian spring-spawning herring. *Canadian Journal of Fisheries and Aquatic Sciences*, *53*(4), 769–779. https://doi.org/10.1139/f95-253
Solvang, H. K., Skaug, H. J., & Øien, N. (2020). Abundance of common minke whales in the Northeast Atlantic based on survey data collected over the period 2014–2019. *Scientific Committee Document SC/68c*, International Whaling Commission.
Stevick, P. T., Allen, J., Clapham, P. J., Katona, S. K., Larsen, F., Lien, J., Mattila, D. K., Palsbøll, P. J., Sears, R., Sigurjonsson, J., Smith, T. D., Vikingsson, G., Øien, N., & Hammond, P. S. (2006). Population spatial structuring on the feeding grounds in North Atlantic humpback whales (*Megaptera novaeangliae*). *Journal of Zoology*, *270*(2), 244–255. https://doi.org/10.1111/j.1469-7998.2006.00128.x
Vogel, E. F. (2020). *The influence of herring* (Clupea harengus) *biomass and distribution on killer whale* (Orcinus orca) *movements on the Norwegian shelf* [Master's thesis]. UiT The Arctic University of Norway.
Wade, P. R. (1998). Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*, *14*(1), 1–37. https://doi.org/10.1111/j.1748-7692.1998.tb00688.x
Weir, C. R., Van Waerebeek, K., Jefferson, T. A., & Collins, T. (2011). West Africa's Atlantic humpback dolphin (*Sousa teuszii*): endemic, enigmatic and soon Endangered? *African Zoology*, *46*(1), 1–17. https://doi.org/10.3377/004.046.0101
Wise, L., Silva, A., Ferreira, M., Silva, M. A., & Sequeira, M. (2007). Interactions between small cetaceans and the purse-seine fishery in western Portuguese waters. *Scientia Marina*, *71*(2), 405–412.

SUPPORTING INFORMATION

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How to cite this article: Bjørge, A., Moan, A., Ryeng, K. A., & Wiig, J. R. (2022). Low anthropogenic mortality of humpback (*Megaptera novaeangliae*) and killer (*Orcinus orca*) whales in Norwegian purse seine fisheries despite frequent entrapments. *Marine Mammal Science*, 1–11. https://doi.org/10.1111/mms.12985