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Original Article

Assessing the impact of fisheries-related mortality of harbour porpoise (*Phocoena phocoena*) caused by incidental bycatch in the dynamic Norwegian gillnet fisheries

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Harbour porpoise (*Phocoena phocoena*) bycatch for Norwegian commercial gillnet fisheries from 2006 to 2018 was estimated using a traditional ratio estimator and generalized additive linear mixed models, with weight of fish landed and number of gillnet hauls as proxies for fishing effort. Estimates were derived from data collected with a contracted reference fleet of small coastal vessels and scaled up to the whole fleet using data from landing statistics. Bycatch estimates exhibited large yearly variations, ranging from 1151 to 6144 porpoises per year. Bycatch estimates in 4 of the last 5 years were significantly less than in the preceding 2 years. The best ratio-based and model-based yearly bycatch estimates were 1580 porpoises [coefficient of variation, (*C.V.*) 0.10, 95% confidence interval (*CI*) 1302–1902] and 1642 porpoises (*C.V.* 0.15, 95% *CI* 1165–2142), respectively. About 75% of bycaught porpoises were taken in the cod (*Gadus morhua*) and monkfish (*Lophius piscatorius*) fisheries, while the rest were taken in a variety of different gillnet fisheries. Our results suggest that bycatch of harbour porpoise in Norwegian gillnet fisheries has been unsustainable for several of the last 13 years but are currently within international bycatch limits due to a recent reduction in monkfish fishing effort.

Keywords: bycatch, conservation, fishery interactions, GAMM, harbour porpoise, marine mammals, ratio estimator

Introduction

The harbour porpoise (*Phocoena phocoena*) is severely vulnerable to incidental entanglements in fishing gear. Entanglements occur wherever fisheries and porpoises coincide, including most, if not all, fishery nations in the Northern Hemisphere (Reeves, 2003; Northridge, 2018). Larger whales might be powerful enough to drag fishing gear to the surface and catch a breath. Time from entanglement to death in such cases may span several months (Moore *et al.*, 2006; Moore and Van der Hoop, 2012). Smaller odontocetes are not so powerful and, therefore, usually suffocate and die within minutes of entanglement (Dolman and Brakes, 2018). Harbour porpoises, being among the smallest of odontocetes (adults 1.4–1.7 m, weight 60–75 kg (Bjørge and Tolley, 2018)), most likely die shortly after entanglement. This mortality can have large population-level effects, causing negative population trajectories of harbour porpoises (IMR/NAMMCO, 2019) that may also face an increasing number of other anthropogenic threats, such as chemical pollution (Teigen *et al.*, 1993; Kleivane *et al.*, 1995; Berge *et al.*, 2004) and vessel traffic (Dyndo *et al.*, 2015; Oakley *et al.*, 2017; Wisniewska *et al.*, 2018).

In Norway, a nation with a long and rich tradition of commercial fisheries, the majority of fish is caught with bottom trawls, long lines, or purse seines. These fishing gears are not associated typically with high risk of marine mammal bycatches (Bjørge *et al.*, 2007). Instead, the single greatest threat to harbour porpoises in Norwegian waters is bottom-set large-mesh gillnets operated by the Norwegian small-vessel [<15-m length overall (LOA)] fleet (Bjørge *et al.*, 2013). Most porpoises are taken in gillnets intended to catch cod (*Gadus morhua*), monkfish (*Lophius piscatorius*), and to some extent, saithe (*Pollachius virens*). Surveys have indicated that harbour porpoises prefer coastal habitats and that they may occur in especially high densities in fjords (NAMMCO, 2019). The Norwegian small-vessel fleet operates exclusively in such coastal areas and, thus, overlaps with the spatial range and preferred habitat of harbour porpoises.

The Norwegian Institute of Marine Research (IMR) actively monitors harbour porpoise bycatch for the Norwegian coastal fleet through a coastal reference fleet that has been in operation since 2006 (described more fully in the next section). The combined harbour porpoise bycatch for cod and monkfish fisheries (not including saithe and other fisheries) has been estimated previously to be 6900 animals per year (*C.V.* 0.27) (Bjørge *et al.*, 2013). That estimate was based on data from 3 consecutive years, from 2006 to 2008. However, the landing statistics used to expand estimates of bycatch rates from the reference fleet to the coastal gillnet fishery were incorrectly coded by the Directorate of Fisheries, resulting in a substantial overestimate. In this article, we present an updated and more complete estimate (including all commercial gillnet fisheries) using improved methodology, and with corrected landing statistics, based on thirteen years of data, from 2006 to 2018.

The population size of harbour porpoises in Norwegian waters is estimated to be >180 000 animals (Table 1), which corresponds to up to 25% of the world-wide population of at least 700 000 harbour porpoises (Hammond *et al.*, 2008). The harbour porpoise bycatch estimates presented in this article make an important contribution to expanding the knowledge base on the global conservation status of this species.

Material and methods

Sampling and data collection

The Norwegian coastal fleet comprises ~5000 active fishing vessels <15-m LOA that operate mostly bottom-set fixed gillnets in the coastal zone (Årland and Bjørndal, 2002). The great majority of fishing trips undertaken by vessels is single day trips. Vessels do not report their fishing effort (e.g. number of nets and soaking duration), but the weight of each species of fish landed and associated data, such as time and date of landing, landing port, vessel name, and call sign, are available from fish tickets generated at the fish reception facilities. One fish ticket corresponds to one fishing trip, which in turn corresponds generally to 1 day at sea, except for monkfish gillnets, which can soak from 2 to 5 days. The Directorate of Fisheries provided landing statistics for the whole coastal fleet from all fish tickets generated from 2006 to 2018.

Marine mammal bycatch incidents are not usually reported to the Directorate of Fisheries by fishing vessels in the coastal small-vessel fleet, although such reporting is mandatory. Observations from the IMR Coastal Reference Fleet were used to estimate bycatch rates. The IMR has contracted a segment of the coastal fleet to participate in a monitoring programme based on self-reporting. Vessels in the reference fleet are contracted for 4–6 years via open tender, restricted to specific gears and areas of operation, and include at least two vessels in each of nine main statistical areas along the Norwegian coastline (Figure 1). Tenders are designed so that the reference fleet forms an approximately representative selection of the Norwegian high-sea fleet. Crew on reference vessels are paid to self-sample their catches after extensive training in sampling. To mitigate concerns about control and scientific data, IMR signs a confidentiality agreement with the reference fleet. The observed vessels, henceforth the "reference vessels" or the "reference fleet", provide IMR with detailed logs of all fishing activities. In addition to catch and bycatch data, these logs include information such as net type, net mesh size, number of nets shot, soak time, fishing depth, and location. Each vessel is assigned a dedicated trained research technician to serve as mentor and to facilitate communication with the IMR. The technician is responsible for following up the vessel, and for providing training, support, and data quality assurance. Technicians regularly visit the vessels. There is also an annual meeting for all participants (including fishermen, technicians, administrators, and researchers) and subject-specific workshops. Data reported are checked both manually and automatically to identify errors and anomalies by looking for missing data or extreme, unlikely or impossible values or combinations of values. In our bycatch estimation, it was assumed that the reference vessels were representative of the Norwegian gillnetter fleet. Comparing fishing effort among reference vessels in different regions, season and fisheries with the corresponding effort for the whole fleet showed an overall similar pattern for both fleets (Supplementary Figures SA7 and SA8). A study by Fangel *et al.* (2015) also provides support to this assumption. Their comparison of bycatch estimates of seabirds using data from the reference fleet and independent data from an access point survey concluded that both methods yielded approximately similar results.

Bycatch estimation method

To account for different bycatch rates in different fishing gears, each fishing trip was classified into one of the three distinct main fishery groups: *cod fishery*, *monkfish fishery* and *other fisheries*, where fishery represented the intended catch for that trip. We considered including a fourth group, *saithe fishery*, but it turned out that it was difficult to reliably distinguish saithe fisheries from other fisheries. We could not classify trips directly based on the

Table 1. Abundance estimates for harbour porpoises in Norwegian waters.

Survey region	Bycatch region	Abundance estimate	*C.V.*	95% *CI*
BS	1	73 000	0.36	36 827–144 702
ENS (SCANS X + Y+Z + W)	2 + 3	24 500	0.24	15 407–38 959
NNS + SC (SCANS V + P + P1)	4	83 013	0.21	54 481–126 486
Total	–	180 513	0.18	127 309–255 951

Bycatch region indicates the corresponding region(s) in Figure 1. Letters in parentheses indicate SCANS survey blocks.

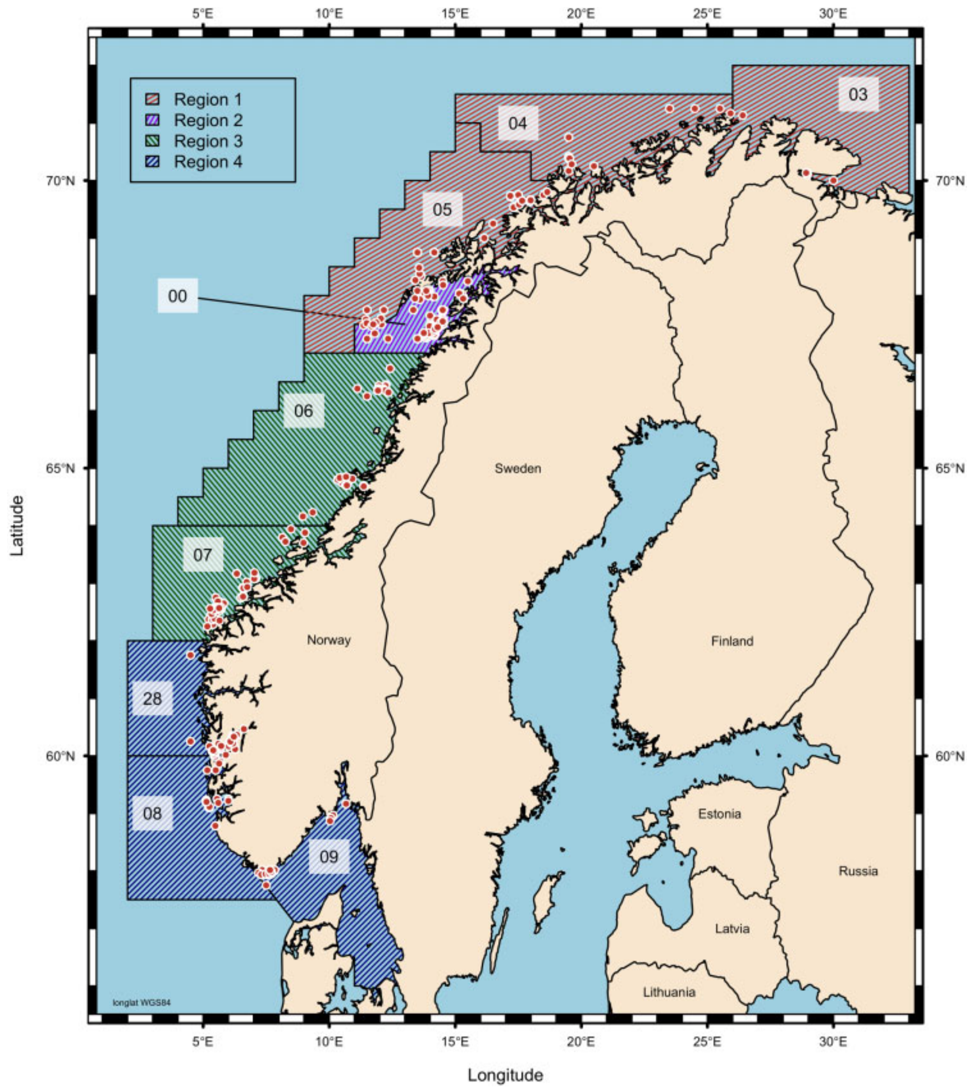

Figure 1. Main areas (numbered) and regions (colour shaded) in the study area. Red dots indicate locations of harbour porpoise bycatch incidents. Note that one incident may involve more than one harbour porpoise.

gears used, because this information did not exist for any of the non-reference vessels. Instead, the fishery group of each trip was determined from the proportions of cod and monkfish to the total catch for that trip. Exact proportions were determined by first setting baseline proportions based on observed proportions of cod and monkfish in catches from trips that we could identify as cod and monkfish trips based on mesh sizes reported in the reference fleet. We then adjusted the proportions used for classification until we achieved a high percentage of correctly classified trips. Trips with >50% cod (by weight) were classified as "cod fishery". For the remaining trips, trips with >10% monkfish (by weight) were classified as "monkfish fishery". All other trips were classified as "other fishery". To verify this approach, we compared fishery classifications of trips in the reference fleet with alternative classifications based on reported gear usage. We defined nets with mesh sizes from 150 to 210 mm as cod nets and mesh sizes from 360 mm as monkfish nets, where mesh refers to the stretched distance between two diagonal knots. Other mesh sizes were grouped as "other fisheries". We then compared the classification based on catch composition with the one based on reported gear use.

In the design-based approach, we used harbour porpoise bycatch data from the reference fleet to estimate the average number of porpoises bycaught per unit effort in specific areas and regions per season and year using a post-stratification scheme and a stratified ratio estimator (Cochran, 1977). Separate estimates were calculated for each fishery group. Bycatch rates for strata that had not been observed by reference vessels in some particular year(s) were averaged from corresponding strata in other years. The resulting per-stratum estimated bycatch rates were multiplied with the whole fleet effort in the corresponding strata to obtain whole fleet bycatch estimates. We used the tonnage of fish landed and number of gillnet hauls as measures of fishing effort.

To prevent strata with few observations from disproportionately influencing the estimated bycatch rates and to minimize the number of strata for which bycatch data had to be interpolated, we combined temporal and spatial variables into new, coarser variables. Adjacent areas were combined into regions, with each region being comprised of one to three of the original areas, under the assumption that more distant areas would be more different in terms of fishing activity and harbour porpoise bycatch rates. Figure 1 shows the original main areas (numbered) and the new regions (colour-shaded). We also added a categorical variable *season*, with two levels, each corresponding to one half of the year, due to the distinct seasonality of the cod and monkfish fishing effort. Using this coarser stratification resulted in 13 years × 2 seasons × 4 regions = 104 métiers/strata for each fishery.

Harbour porpoise bycatch was also modelled using a generalized additive linear mixed model (GAMM), where the reference fishing vessels were considered primary sampling units. The original 20 645 observations on the trip level were pooled per vessel per métier, with métiers comprised of all observed combinations of the variables *season*, *region*, *fishery*, and *year*, as defined in the last paragraph. This gave a total of $n = 896$ aggregated observations. These variables and interactions between them were considered potential predictors in the bycatch model. Other potential predictors were *total weight of landed fish*, both on the original and a log-transformed scale, and as a thin plate smooth function. *Vessel* and *vessel size* were considered random effects. Initial data analyses indicated that a Poisson model would be inappropriate (Supplementary Figure SA6) due to overdispersion, so models were fit using a negative binomial (NB) error distribution and a log link. As the rate of zero bycatch in our aggregated data was ~70%, we also evaluated whether a zero-inflated NB distribution would be more appropriate.

In the starting model, counts of bycaught harbour porpoises were fit with the log of *fishing effort* (*number of hauls*) entered as an offset term. The best model, among all possible combinations of potential predictors, was determined by Akaike's information criterion (AIC) (Burnham and Anderson, 2002) using forward stepwise regression. Models were checked by inspecting residual and Q–Q plots (see Supplementary material for details). The final model was then applied to fish tickets data for all vessels in the Norwegian small-vessel coastal fleet to estimate total harbour porpoise bycatch for those vessels.

To permit bycatch predictions for the whole fleet, fish tickets data were structured like the reference data used to fit the final model, e.g. by aggregating data (i.e. number of hauls, catch) per vessel in each métier, and adding the appropriate values for the variables *season*, *region*, and *fishery*. New levels were therefore not allowed for any of the fixed effects but were allowed for the random effects, specifically the vessel term. For each new level of the vessel term, the effect for that level was sampled from a Gaussian distribution with mean 0 and the corresponding variance of the modelled vessel term. This sampling was done in a way so that each vessel had a unique value across all fish tickets.

A more detailed description of model fitting, checking, and prediction is available in the annotated R code attached to this article. For a more direct comparison with results obtained by Bjørge *et al.* (2013), we also fitted a Poisson generalized linear model (GLM), as described in their paper, to the new bycatch data. Equation (1) specifies the formula that was used:

$$\text{porpoises} \sim \exp\Big(\text{offset}\Big(\log(\text{catch}+1)\Big) + \text{fishery} + \text{season} + \text{region} + \text{fishery} : \text{season} + \text{fishery} : \text{region}\Big), \quad (1)$$

where all terms were categorical variables, except *catch*, which was numeric (Supplementary Table SA1), and with the important distinction from their analysis, that catch in this case represented all fish caught; not just cod and monkfish. The 95% confidence intervals (*CI*s) and *C.V.*s of total predicted bycatches for both design-based and model-based approaches were calculated by bootstrapping. In each bootstrap iteration, we resampled at random with replacement from the reference fleet data (with no structural conditions), re-estimated total bycatch based on the new samples, and extrapolated using the methods described above. This procedure was replicated 1000 times. *C.V.*s and bias-corrected *CI*s were calculated from the resulting distribution of bycatch estimates.

To assess whether harbour porpoise bycatch estimates presented in this article were sustainable, we compared them to two international standards for sustainability: the 1.7% limit recommended by the Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish, and North Seas (ASCOBANS) (ASCOBANS, 2000b) and the Potential Biological Removal (PBR). The ASCOBANS 1.7% limit was established using simulations performed by the IWC-ASCOBANS Working Group on Harbour Porpoises (ASCOBANS, 2000a). The working group concluded that "using a basic population model for harbour porpoises [...] and assuming no uncertainty in any parameter, the maximum annual bycatch that achieves the ASCOBANS interim objective over an infinite time horizon is 1.7% of the population size in that year", where the stated ASCOBANS objective was to "restore populations to, or maintain them at, 80% or more of the carrying capacity". The PBR on the other hand is defined as the maximum mortality that a population can sustain without depletion and is given by the equation $\text{PBR} = N_{\min} \times 0.5R_{\max} \times F_r$, where $N_{\min}$ is the minimum population estimate, $R_{\max}$ is the maximum net productivity rate, and F_r is a recovery factor that allows one to take into account further information on the conservation status of a species (Wade, 1998). The PBR may be considered a more conservative, but not necessarily biologically more appropriate, bycatch limit for two reasons. First, the ASCOBANS simulations assumed no uncertainty in the species abundance estimates, whereas the PBR uses the minimum population estimate to take uncertainty into account. PBR also uses only half the maximum net productivity rate expressly to make it more conservative.

The best abundance estimate for harbour porpoises in Norwegian waters is based on a combination of Norwegian line transect surveys in the Barents Sea (BS) (Leonard and Øien, 2020), and East Norwegian Sea (ENS) and the SCANS-III survey blocks adjacent to the Norwegian North Sea (NNS) and Skagerrak coasts (SC) (Hammond *et al.*, 2017). Table 1 shows the point estimate and associated *C.V.* and *CI* for each of these survey regions, and also indicates the corresponding "bycatch region" (Figure 1). These estimates add up to a total of 180 513 porpoises for Norwegian waters (*C.V.* 0.18, 95% *CI* 127 309–255 951). With this population estimate, the ASCOBANS 1.7% limit corresponds to 3065 porpoises and the PBR, using $R_{\max} = 0.04$ [a feasible default for cetaceans, suggested by Wade (1998)] and $F_r = 1$, assuming a stable harbour porpoise population in Norwegian waters, is 2542 porpoises.

Data processing and analyses were conducted in RStudio version 1.1.456 using R version 3.5.1 on OS X 10.14.6. We used glmmTMB (Brooks *et al.*, 2017) and mgcv (Wood, 2012) for GLM and GAMM modelling and mgcViz (Fasiolo *et al.*, 2020) and DHARMa (Hartig, 2019) for model checking and validation. We used boot (Davison and Hinkley, 1997; Canty and Ripley, 2014) for bootstrapping and maps (Deckmyn and Minka, 2018) and maptools (Bivand and Lewin-Koh, 2018) and rgdal (Bivand *et al.*, 2018) for map making.

Results

A total of 1024 harbour porpoises were taken by the reference fleet in 773 separate bycatch events, where an "event" refers to a gillnet where an entangled harbour porpoise was discovered and reported by the fishermen as the gillnet was hauled on board the vessel. A total of 614 of these events involved the taking of a single porpoise, 110 events involved two porpoises, and 28 events involved three porpoises. Events involving greater number of porpoises were much rarer. On one occasion, 13 porpoises were taken in a single haul. A total of 429 porpoises were taken in the cod fishery, 213 porpoises were taken in the monkfish fishery, and 282 porpoises were taken in other fisheries. Harbour porpoises were bycaught along the entire Norwegian coastline, but the greatest number of animals was taken in regions 2 and 3. Region 2 corresponds to a cod spawning hot spot that is characterized by very high levels of fishing effort targeting cod during the winter months (Figure 2). The number of bycaught harbour porpoises was weakly but significantly correlated with both total catch (Pearson's $r = 0.16$, 95% $CI = [0.044, 0.27]$, df = 279, $p < 0.01$) and number of hauls (Pearson's $r = 0.29$, 95% $CI = [0.18, 0.40]$, df = 279, $p \ll 0.01$).

The full data set spanning all 13 years contained 892 662 fish logs from a total of 5339 different fishing vessels. After classification, 446 606 logs (50%) were classified in the "cod fishery" group and 120 769 logs (14%) were classified in the "monkfish fishery" group. The fish logs from the reference vessels in the same period contained data from 20 645 fishing trips, reported by a total of 52 reference vessels. The yearly sampling fraction of the reference fleet spanned from 1.5 to 3.2%, with an average of 2.3%.

Figure 2 shows the weekly average total catch landed in the cod and monkfish fisheries. Both the cod and monkfish fisheries were distinctly seasonal, with 94% of cod catches taken in the first half of the year, and 76% of monkfish catches taken in the second half. The monthly variation in cod and monkfish fishing effort by the reference vessels followed the same pattern as the rest of the coastal fleet (Figure 2), although the relative magnitude of the peak in the monkfish fishery on average was smaller in the reference fleet. The cod fishery starts in January, reaches a top in March, and ends by the end of April. The peak of the cod fishing effort coincides with the arrival of Barents Sea cod that migrate to spawning grounds along the Norwegian coast in the winter. The monkfish fishery is spread out over a larger part of the year, starting in April, reaching intermediate levels over the summer, and peaking around September. The weight of catch landed by reference vessels and ordinary vessels in each stratum was

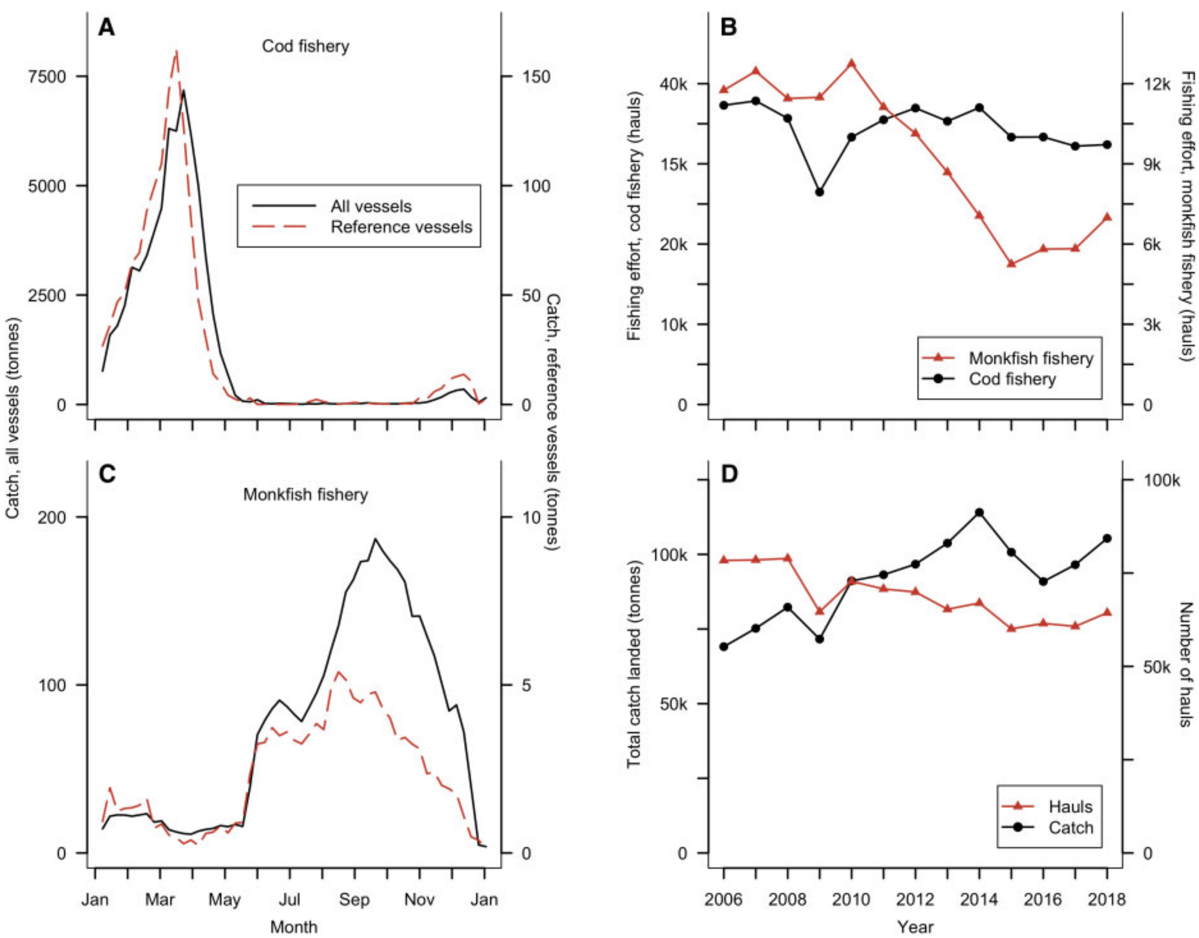

Figure 2. Left panels: comparison of landed catch in cod (a) and monkfish (c) fisheries, by all active gillnet vessels (solid black lines) and by reference vessels (dashed red lines) throughout an average fishing year. Right panels: yearly variation in fishing effort in cod and monkfish fisheries (b) and yearly variation in overall fishing effort given as total catch landed and number of hauls (d).

significantly correlated in both the cod (Pearson's $r = 0.81$, 95% $CI = [0.72, 0.88]$, df = 84, $p \ll 0.01$) and monkfish fisheries (Pearson's $r = 0.58$, 95% $CI = [0.43, 0.70]$, df = 89, $p \ll 0.01$).

The stepwise GAMM regression resulted in a final bycatch model, as described by the formula given in (2), specified in R syntax. The AICs of the best NB and ZINB models were 1786 and 1823, respectively, indicating that the NB model gave the best overall fit. Deviance explained and adjusted *R*-squared for the best NB model were 46 and 47.5%. Detailed fit statistics for this and intermediary or nested models and the corresponding ZINB models can be found in the accompanying technical document (Supplementary Tables SA2 and SA3).

$$\begin{aligned}\text{porpoises} \sim \exp\Big(&\text{offset}\big(\log(\text{das})\big) + s\big(\log(\text{catch}+1), by\\ &= \text{fishery}\big) + s(\text{vessel},\ bs = "re") + \text{year} + \text{fishery} + \text{region}\\ &+ \text{season} + \text{fishery} : \text{region} + \text{fishery} : \text{season}\\ &+ \text{region} : \text{season}\Big).\end{aligned} \tag{2}$$

Figure 3 shows average yearly estimates of harbour porpoise bycatch for the whole small-vessel fleet, calculated using design-based and model-based approaches, including in the first case estimates using total catch landed and number of hauls as proxies for fishing effort. Design-based estimates using catch as a proxy for effort were consistently lower than the corresponding design-based estimates using hauls as a proxy for effort, except in 2017, when the former type of estimate was slightly higher. There was great variation in the magnitude of the design-based yearly bycatch estimates, ranging from 1151 to 6144 porpoises per year. However, design-based yearly estimates based on catch and hauls agreed fairly well and were not significantly different from each other. The yearly variation in modelled bycatch also agreed well with the corresponding stratified ratio estimates, except for one large deviation in 2008, where the model-based estimates were much lower than the design-based ones. The range of model-based yearly bycatch estimates was much narrower, spanning from 1148 to 4720 porpoises per year. Annual harbour porpoise mortality for both design-based and model-based approaches is indicated in Figure 3 and tabulated in Tables 2 and 3, in the latter case also including regional-, seasonal-, and fishery-specific average estimates. In 4 of the last 5 years (2014–2017), design-based and GAMM bycatch estimates were significantly lower than in the preceding 2 years, indicating that total harbour porpoise bycatch has decreased. A summary of average estimated bycatch for various stratifying variables for only the last 5 years is given in Table 3.

When averaging over the full time series with all four estimation methods, the greatest numbers of porpoises (up to ~70%) were taken regions 1 and 2 and the smallest number was taken in

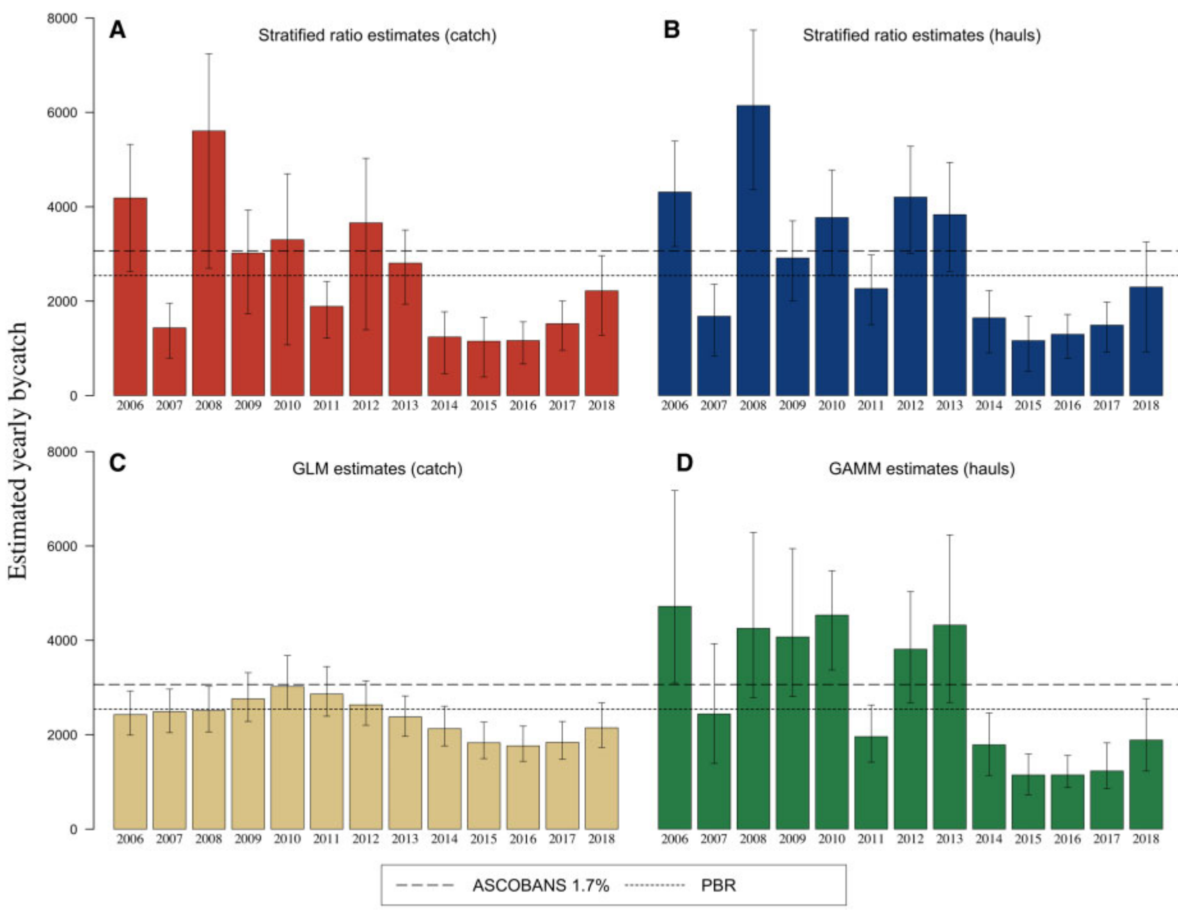

Figure 3. Total bycatch of harbour porpoises in all fishery groups per year, estimated using catch-based and hauls-based stratified ratio estimators (a and b), as well as GLM (c) and GAMM (d) approaches. Vertical lines indicate 95% *CI*s around point estimates. Dashed and dotted lines represent the ASCOBANS 1.7% limit and the PBR, respectively.

Table 2. Estimated average yearly harbour porpoise bycatch by different grouping variables, using four estimation approaches.

	Stratified ratio estimates (w/catch as fishing effort)			Stratified ratio estimates (w/hauls as fishing effort)			GLM estimates			GAMM estimates		
Grouping variable	**Bycatch**	***C.V.***	**95% *CI***	**Bycatch**	***C.V.***	**95% *CI***	**Bycatch**	***C.V.***	**95% *CI***	**Bycatch**	***C.V.***	**95% *CI***
By region												
Region 1	592	0.16	355–717	957	0.11	744–1 151	550	0.15	408–748	893	0.23	552–1 260
Region 2	909	0.15	587–1 109	773	0.09	621–916	836	0.18	634–1 276	1 161	0.35	539–1 772
Region 3	610	0.09	492–715	722	0.09	595–848	538	0.19	369–795	421	0.34	219–732
Region 4	460	0.10	366–544	434	0.09	351–507	445	0.17	324–613	396	0.25	242–605
By season												
January–June	1 176	0.11	817–1 356	1 523	0.08	1 279–1 742	1 075	0.13	859–1 432	1 394	0.15	890–1 690
July–December	1 395	0.08	1 141–1 568	1 363	0.06	1 184–1 527	1 294	0.12	1 030–1 665	1 477	0.26	792–1 983
By fishery												
Cod	1 300	0.08	1 050–1 489	1 126	0.06	975–1 258	708	0.16	525–987	1 127	0.24	650–1 456
Monkfish	647	0.10	497–767	1 134	0.10	904–1 334	1 131	0.11	920–1 442	1 234	0.23	770–1 739
Others	624	0.21	331–806	626	0.10	493–738	530	0.24	375–965	510	0.23	259–626
Total	2 571	0.07	2 131–2 831	2 886	0.05	2 576–3 142	2 369	0.09	1 969–2 843	2 871	0.17	1 910–3 324

Estimates are yearly averages from 2006 to 2018.

Table 3. Estimated average yearly harbour porpoise bycatch in the years 2014 to 2018, by different grouping variables, using four estimation approaches.

	Stratified ratio estimates (w/catch as fishing effort)			Stratified ratio estimates (w/hauls as fishing effort)			GLM estimates			GAMM estimates		
Grouping variable	**Bycatch**	***C.V.***	**95% *CI***	**Bycatch**	***C.V.***	**95% *CI***	**Bycatch**	***C.V.***	**95% *CI***	**Bycatch**	***C.V.***	**95% *CI***
By region												
Region 1	297	0.29	151–487	428	0.30	216–757	540	0.16	374–716	578	0.22	385–889
Region 2	292	0.16	206–404	219	0.20	141–307	628	0.24	431–1 028	554	0.28	299–903
Region 3	228	0.18	153–317	347	0.17	236–460	368	0.19	244–505	219	0.30	106–366
Region 4	644	0.14	486–837	586	0.13	448–752	407	0.17	286–569	291	0.25	185–504
By season												
January–June	829	0.13	635–1 050	1 026	0.14	780–1 330	1 080	0.14	850–1 453	960	0.16	709–1 321
July–December	632	0.15	475–844	554	0.13	429–727	863	0.13	669–1 137	682	0.23	412–1 003
By fishery												
Cod	370	0.23	215–559	625	0.25	318–857	770	0.16	560–1 053	443	0.22	254–607
Monkfish	746	0.13	579–965	532	0.12	494–799	664	0.13	517–858	843	0.19	604–1 268
Others	345	0.16	240–468	423	0.15	303–554	509	0.27	339–881	356	0.20	245–509
Total	1 460	0.10	1 216–1 788	1 580	0.10	1 302–1 902	1 943	0.11	1 630–2 495	1 642	0.15	1 165–2 142

region 4 (Table 2). This reflects the geographical distribution of fleet-wide fishing effort, with most gillnet fishing taking place in the northern regions. Seasonally, bycatch was quite evenly divided, and season-specific average estimates were not significantly different. The number of porpoises taken in different fisheries varied greatly from one estimation method to the next. For the estimates that were derived using number of hauls as a measure of fishing effort, porpoise bycatches were quite evenly divided among cod and monkfish fisheries. The catch-based ratio estimator, on the other hand, partitioned about twice as many bycatches to the cod fishery. Conversely, GLM estimates suggested that 60% more porpoises were taken in monkfish fisheries than in cod fisheries. The number of porpoises taken in the *other* fishery group did not change significantly from one approach to the next. Regardless of which approach was used, the great majority (∼75%) of the estimated bycatch was taken in the combined cod and monkfish fisheries. By comparison, when only averaging over the last 5 years (Table 3), a larger proportion of bycatch was apportioned to region 4 and to the cod season/fishery.

These estimates indicate that harbour porpoise bycatch has been on a consistent high level in years 2008–2013, possibly peaking early in this period. More recent estimates, from 2014 to 2017, on the other hand, were particularly low. In 2018, however, the bycatch was again higher than in the preceding 4 years. Averaging the yearly bycatch estimates over the whole 13 gave an annual mortality of 2571 porpoises, using catch as effort (*C.V.* 0.07, 95% *CI* 2131–2831), and 2886 porpoises, using number of hauls as effort (*C.V.* 0.05, 95% *CI* 2576–3142) for the design-based approach. Predicted yearly bycatch using the fitted GLM and GAMM were on average 2369 (*C.V.* 0.09, 95% *CI* 1969–2843) and 2871 porpoises per year (*C.V.* 0.17, 95% *CI* 1910–3324).

Correspondingly, if averaging only over the last 5 years (i.e. 2014–2018, Table 3), the yearly average estimates were 1460 porpoises, using catch as effort (*C.V.* 0.10, 95% *CI* 1216–1788), and 1580 porpoises, using number of hauls as effort (*C.V.* 0.10, 95% *CI* 1302–1902) for the design-based approach. Predicted yearly bycatch using the fitted GLM and GAMM were on average 1943

(*C.V.* 0.11, 95% *CI* 1302–1902) and 1642 porpoises per year (*C.V.* 0.15, 95% *CI* 1164–2142).

The ASCOBANS 1.7% limit applied to harbour porpoises in Norwegian waters was 3064 animals per year and the PBR was 2542 animals per year. Both the haul-based stratified ratio average bycatch estimate of 2886 animals per year and the corresponding GAMM-derived estimate of 2871 animals per year were slightly within the ASCOBANS limit but greater than the PBR. The corresponding average yearly estimates for the last 5 years, on the other hand (1580 and 1642 porpoises), were far below either bycatch limit, regardless of which estimation method was used. It must therefore be concluded that our results suggest that bycatch of harbour porpoise in Norwegian gillnet fisheries have been unsustainable for several of the last 13 years (Figure 2) but is currently within international bycatch limits.

Discussion

Since cod fishing effort has been relatively stable throughout the study period (with one important exception; see below), the yearly variation in harbour porpoise bycatches roughly followed the yearly variation in monkfish fishing effort, which has been more varied. Pooling monkfish fishing effort with effort data from cod and other, much larger fisheries completely masked the variation of the former. In particular, the gradual decline and subsequent consistently low monkfish fishing effort that started in 2010 likely explain the decrease in harbour porpoise bycatches from 2014 through 2017. As monkfish fishing effort increased in 2018, so did harbour porpoise bycatches. The large and significant dip in estimated harbour porpoise bycatches in 2007, on the other hand, may be explained by a significant reduction in cod fishing effort among reference vessels that year, which did not take place among non-reference vessels. Because of this, harbour porpoise bycatch in 2007 may have been underestimated, possibly by a factor of 2, assuming that actual bycatch that year was not significantly different from 2006 and 2008. In 2011, the number of harbour porpoise bycatches reported by the reference fleet was fewer than in 2010 and in 2012, resulting in lower CPUE and total bycatch estimates. It is possible that this reduction in observed bycatches can be explained by an incomplete reference fleet coverage that year. Two reference vessels, which in previous and later years reported harbour porpoise bycatches, and who were supposed to, but ultimately could not fish 2011, did not report any data that year. The absence of that data may have negatively biased the harbour porpoise bycatch estimates for 2011.

While both design- and model-based approaches showed a reduction in bycatch in 2007, the modelling approach should be less sensitive to such data issues, since model predictions are based on a combination of many different of covariates fitted in the context of the specified model, while the ratio estimates would be directly and proportionately reduced by the reduced fishing effort. The more extreme values (i.e. larger range) of the ratio estimates reflect this. Overall, however, estimates produced using the design- and model-based approaches agreed well and estimates for the same year calculated with different methods were not significantly different (Figure 3). One of the advantages of the GAMM approach is that a random effect term can be used to account for individual vessel effects. This is necessary because bycatch data collected by the coastal reference fleet are nonrandomly clustered among vessels, and so the independency assumptions of both the GLM and the stratified ratio estimators are inherently violated. The mixed effects GAMM should therefore *a priori* most accurately reflect the sampling design of the Norwegian marine mammal bycatch monitoring programme. Ignoring this violation would lead to negatively biased estimates of standard errors. For these reasons, the GAMM estimates should be preferred over the other estimates, even though associated *C.V.*s and *CI*s are considerably larger for the GAMM approach.

Bycatch estimates reported in this article represent the incidental mortality imposed to harbour porpoises by the Norwegian commercial coastal gillnet fisheries. Our estimates account for the majority of harbour porpoise bycatches that occur in Norwegian waters, but taken as comprehensive national estimates, our estimates may be negatively biased for two important reasons. First, when gillnets emerge from the water and are hauled aboard the fishing vessel, entangled animals may spontaneously drop out of the nets and would most likely not be detected by the fishermen. Tregenza *et al.* (1997) reported a harbour porpoise dropout rate of ∼50% in hake (*Merluccius merluccius*) fisheries using 100–150 mm mesh nets. Kindt-Larsen *et al.* (2012) reported an undetected harbour porpoise dropout rate of 18% across a variety of mesh sizes. We have no data on dropout rates in any of the Norwegian fisheries. However, it is reasonable to expect that dropouts occur on Norwegian reference vessels too. Assuming that the dropout rate is the same in Norwegian and Danish fisheries, i.e. only 82% of bycaught harbour porpoises are registered by the reference fishermen across all gillnet types, and then the dropout corrected average yearly GAMM bycatch estimate for the last 5 years would be 2003 porpoises (or 3502 porpoises if averaging over all 13 years of data). Another source of bias is the use of gillnets in recreational fisheries. There is no systematic collection of data on fishing effort or bycatch rates in recreational fisheries in Norway, but we speculate that the number of harbour porpoises caught this way is fewer than those taken in commercial fisheries and that even if they could be included in our estimates, the conclusion of sustainability would not change. However, it should still be emphasized that our bycatch estimates must be considered minimum estimates for the *commercial* Norwegian gillnet fisheries.

Comparison of results with previous studies

The annual bycatch of harbour porpoises in the cod and monkfish fisheries in Norway in 2006–2008 was previously estimated to be 6900 animals (Bjørge *et al.* 2013), also using data collected by the reference fleet; however, in that study, statistics provided by the Norwegian Directorate of Fisheries, which were used to extrapolate estimated bycatch rates, erroneously contained landings of cod and monkfish taken with *all* gear types. In addition to bottom-set gill nets, this included hand jigs, long lines, purse seines, Danish seines, and demersal trawls, none of which are typically associated with high bycatch rates of harbour porpoises. Thus, the landed tonnage of fish was highly exaggerated. For the month of January 2006, for example cod landings totalled 4079 tonnes, but cod caught in gillnets was only 2447 tonnes. This corresponds to an overestimation of ∼66% for that month. Specific catch numbers for the other months varied, but the trend was consistent. The estimated bycatch of 6900 animals must therefore be considered a substantial overestimate. The GLM estimates included in this article represent a reapplication of their bycatch model on corrected data and can be considered an update of those estimates. However, it must be noted that our estimates may not be comparable directly to those of Bjørge *et al.* (2013), because all Norwegian commercial gillnet fisheries were included

Table 4. Abundance and bycatch estimates of harbour porpoises in Norwegian waters and seven North-Atlantic AUs, as defined in IMR/NAMMCO (2019).

Area (AU)	Abundance estimate	Sustainable bycatch (1.7%)	Bycatch estimate	% of abundance
Norwegian waters (last 13 years)	180 266	3 065	2 871	1.59
Norwegian waters (last 5 years)	180 266	3 065	1 642	0.91
Belt Seas, Denmark	42 324	720	758	1.79
North Sea	345 306	5 870	4 500	1.30
Celtic and Irish Sea	35 232	599	852	2.42
West Scotland and Ireland	42 920	730	720	1.68
Gulf of St Lawrence	185 258	3 149	2 305	1.24
Newfoundland and Labrador	48 723	828	1 428	2.93
Gulf of Maine—Bay of Fundy	72 573	1 234	292	0.40

Sustainable bycatch refers to the 1.7% limit set by ASCOBANS (2000b).

in our estimation, whereas Bjørge *et al.* (2013) only included the cod and monkfish fisheries. In addition, Bjørge *et al.* (2013) only used the cod and monkfish portion of landed catch to represent fishing effort, thus excluding any other fish taken in the same gillnets. We have used all catch data across all species and catch-based estimators.

How do Norwegian bycatches compare to bycatch levels in some other North-Atlantic areas?

Using information from an international workshop convened in Tromsø to assess the status of harbour porpoises in the North-Atlantic (IMR/NAMMCO, 2019), the bycatch in Norwegian waters could be compared to other regions. The workshop assessment used eight Assessment Units (AUs), collectively covering most of the North-Atlantic (Table 4). One of these AUs was Norwegian waters bounded in the south by the 62°N parallel. By this definition, the Norwegian coastal areas further south (areas 28, 08, and 09, Figure 1) were included in the North Sea AU. Genetic analyses of samples from harbour porpoises bycaught in the Barents and the North Sea have not demonstrated distinct populations but suggest that all porpoises in Norwegian waters belong to one population where subtle genetic differences are due to separation by distance (Andersen *et al.*, 2001; Tolley *et al.*, 2001; Quintela *et al.*, 2020). In our comparison and in Table 4, we have therefore instead included these areas as Norwegian waters.

Table 4 shows how the harbour porpoise bycatch in Norwegian waters relate to the 1.7% ASCOBANS limit and to the levels in the seven other AUs. The Norwegian bycatches are close to the 1.7% ASCOBANS limit and comparable to bycatch levels in most other European waters. The Celtic and Irish Seas have a higher bycatch level, with bycatches constituting 2.42% of the abundance. However, the International Council for the Exploration of the Sea, ICES, Working Group on Bycatch of Protected Species used the latest definition of a Celtic Sea subpopulation suggesting that levels of mortality in 2017 due to bycatch may be between 2.12 and 5.57% of that subpopulation (ICES, 2019). This clearly exceeds the level of unacceptable bycatch advised by ASCOBANS. In the Gulf of Maine—Bay of Fundy area, where effective mitigation measures are in place and enforced (e.g. time-area closures and pingers), formerly high bycatches have been reduced strongly (Palka *et al.*, 2008) and now constitute only 0.4% of the estimated abundance.

Although Norwegian bycatch levels are comparable to levels in most European waters, bycatch of harbour porpoise in commercial Norwegian gillnet fisheries in recent years is within international standards for sustainable fisheries, even when accounting for unobserved dropouts. However, the recent reduction in harbour porpoise bycatch is most likely associated with a reduced monkfish fishing effort in recent years, and any future increase in monkfish fishing effort has the potential to again raise harbour porpoise bycatch over the PBR and/or the ASCOBANS limits. We therefore assert that the harbour porpoise bycatch situation in Norway continues to warrant concern and necessitate continued close monitoring. Furthermore, as per the precautionary principle, which serves ideally as a guiding principle in the management of natural resources, bycatch mitigation measures should be explored and implemented for the Norwegian gillnet fisheries, and the cod and monkfish fisheries in particular.

Time-area closures represent the single most reliable way of reducing or eliminating harbour porpoise bycatches. Banning certain gillnet fisheries in high bycatch areas has the potential to reduce harbour porpoise bycatches to within sustainable limits. For example, if monkfish gillnets were banned in region 2 in September and October, the yearly harbour porpoise bycatch could be reduced by up to 30%. If such a ban was extended to include August as well, that could potentially bring the bycatch down as much as 46%; however, this would dramatically curtail profitability of the monkfish fishery in the region, possibly to the extent to be uneconomical for fishermen to cover overhead costs of maintaining equipment and gear. The gillnet fisheries have very long traditions in Norway, and they are the economic basis for many of the small communities and the main reason for settlements in many rural regions. Closing down gillnet fisheries could therefore have severe socioeconomic local impacts.

The use of acoustic deterrent devices (or "pingers") on gillnets is another, less intrusive way that bycatches of harbour porpoises can be reduced (Kraus *et al.*, 1997; Palka *et al.*, 2008; Larsen *et al.*, 2013; Larsen and Eigaard, 2014). Assuming conservatively that pingers have a bycatch reduction effect of 50%, use of mandatory pingers in the cod fishery from January to April could reduce harbour porpoise bycatch by up to 14%, while still allowing fisheries to be conducted. Preliminary results from experiments in Norwegian fisheries indicated a >70% harbour porpoise bycatch reduction in cod nets and a 100% reduction in monkfish nets, but these results were not statistically conclusive (A. Bjørge and A. Moan, unpublished data). The IMR is currently conducting a large-scale multi-year experiment on the use of pingers on cod, saithe, and monkfish gillnets. If the results of these new experiments are positive, then mandatory use of pingers in selected fisheries and/or areas during specific times of the year has the potential to maintain the nation-wide bycatch of harbour porpoises in commercial fisheries on a sustainable level, even if monkfish fishing activity increases in the coming years.

Future work

Based on reports from ongoing harbour porpoise bycatch monitoring in Norway, the Norwegian Directorate of Fisheries has recently submitted a proposal for mandatory use of pingers in Vestfjorden (area 00, Figure 1), which is on congressional hearing until September 2020. The objective of this proposal is to bring (or maintain) harbour porpoise bycatch in all statistical areas well below the PBR level. The Norwegian coastal reference fleet continues to operate and collect data on bycatches of marine mammals in gillnet fisheries along the Norwegian coastline, in addition to its many other important tasks. The IMR intends to increase the number of vessels in the fleet to a total of 30 vessels in the near future. While the main task of the reference fleet is fishery monitoring for stock assessment and management, increasing the number of reference vessels also increases the gillnet fleet sampling fraction of the observer program, which in turn also improves coverage, representability, and the precision of bycatch estimates derived from data collected by the reference fleet. To further improve the quality of marine mammal bycatch estimates, the IMR and a commercial partner are exploring the possibility of supplementing the observer programme with an additional remote electronic monitoring (REM) programme. In this REM programme, video-surveillance equipment would be installed on fishing vessels. Gillnets would then be recorded as they are hauled on board, and the recorded videos would be analysed to identify and report marine mammal bycatches. In addition to increasing the proportion of sampled hauls from the gillnet fleet, we hope that this would allow us to estimate dropout rates, as an REM system might spot animals that would otherwise be missed by human observers.

Supplementary data

Supplementary material is available at the ICESJMS online version of the manuscript.

Data availability

The data underlying this article were provided by the Norwegian Directorate of Fisheries and cannot be shared publicly due to the protection of the privacy of the fishermen involved in its collection. Data will be shared on reasonable request to the corresponding author.

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