WORKSHOP ON MARINE MAMMAL BYCATCH MONITORING AND MITIGATION

Ålesund, Norway,
19th -20th June 2019

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1. INTRODUCTORY REMARKS

The workshop was convened in Ålesund, Norway, 19th – 20th June 2019. The adopted Agenda is shown in Appendix 1. The list of participants is given in Appendix 2. We acknowledge all participants for their contributions to the workshop. The workshop was sponsored by the Norwegian Seafood Research Fund (FHF) and the Institute of Marine Research's Programme on the Coastal Zone Ecosystem. NOAA Fisheries NEFSC provided scientific support based on their experience with marine mammal bycatch monitoring and mitigation in US Atlantic waters.

Bjørge welcomed the participants to Ålesund and the conference venue Hotel Breisundet, which is a family run hotel in two renovated waterfront harbour warehouses that were so important to fisheries in this small coastal town. He informed the participants on the scope of the workshop, which is to give the best possible advice for future work of marine mammal bycatch monitoring and mitigation in Norway, and to provide the basis for recommendations to the Norwegian Government on implementation of bycatch mitigation measures.

2. PRESENTATION OF NORWEGIAN COASTAL WATERS AND FISHERIES ASSOCIATED WITH MARINE MAMMAL BYCATCHES

Bjørge gave a talk about Norwegian fisheries and the Norwegian coastal waters. Fish and fish products are Norway's second largest export commodity, only exceeded by export from the oil and gas industry. Most wild-fish landings are from offshore fisheries with trawl (about 1,230,000 tons); purse seine (about 830,000 tons) and longline (about 131,500 tons). These gear types are associated with modest risk of marine mammal bycatches (Bjørge *et al*. 2007; Figure 1).

Fig. 1. *Trawlers and purse seiners are associated with low risk of marine mammal bycatches.*

Another 153,000 tons of fish are taken with gillnets. Large mesh gillnets in the coastal zone and fjords, e.g. for monkfish *Lophius piscatorius* and cod *Gadus morhua,* are known to have high risk of marine mammal bycatches. In particular harbour porpoise *Phocoena phocoena*, harbour *Phoca vitulina* and grey *Halichoerus grypus* seals are vulnerable (Moan 2016; Figure 2).

Fig. 2: *The harbour porpoise, harbour and grey seals are vulnerable for incidental bycatch in large-mesh gillnets in the Norwegian coastal zone. Photographers: Florian Graner and Arne Bjørge.*

According to statistics from the Directorate of Fisheries there were 6025 registered commercial fishing vessels in Norway in 2018 (Figure 3). Of these were 5564 less than 15 m total length. Not all registered vessels were active, but most of the small vessels operate gillnets in part of the year in the coastal zone.

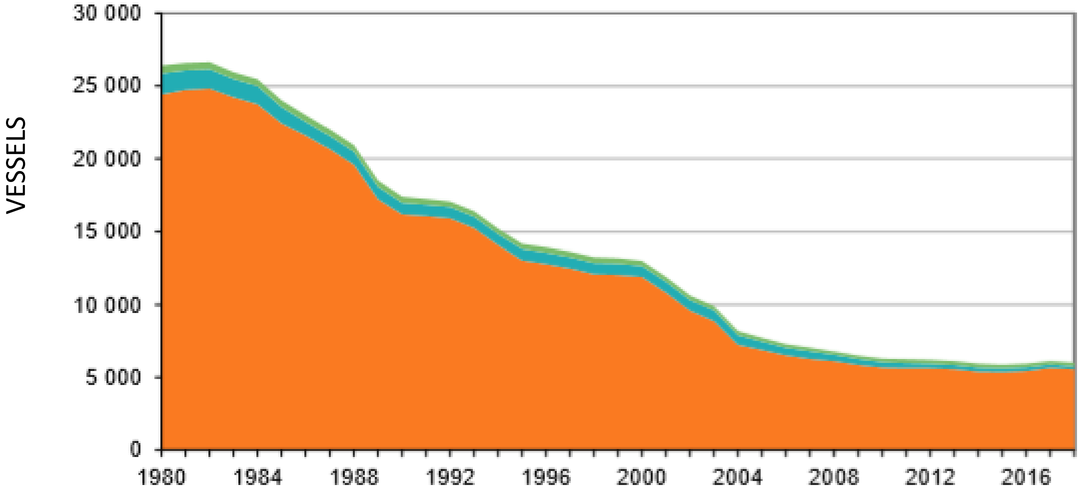

Fig. 3. *The number of registered, commercial fishing vessels have declined from more than 25000 in 1980 to about 6000 in 2018. Largest reduction in vessels less than 15 m total length. The number of vessels less than 15 have been stable since 2010.* *vessels less than 15m,* *vessels 15-27,99 m,* . *vessel 28m and above. Source: Directorate of Fisheries 2018.*

Gillnet fisheries for cod in January to April have the largest fishing effort and most of this effort is concentrated on the cod spawning grounds in Vestfjorden, Lofoten (Figure 4). Nets for cod have a half-mesh of about 10 cm and several 27.5 m long nets are set in strings. They are typically set in the early afternoon and hauled the next morning. This type of net may be used for other gadoid species, such as saithe *Pollachius virens*, outside the cod season.

Fig. 4. *Typical coastal gillnetter from Vestfjorden-Lofoten. Photographer: Eirin Egghjem*

The main fishing season for monkfish is the second half of the year. The nets used have a half-mesh of 18 cm and each net is 27.5 m long. Each vessel is allowed to use up to a maximum of 500 nets, that totals 13.75 km of nets. Several nets are set in two or more long strings. One string is typically hauled after two to three days of soak-time and set again immediately in the same operation. Monkfish nets thus have an almost continuous soak-time throughout the season.

The Norwegian coast spans from 58^{o}N to 71^{o}N and borders the North Sea, the Norwegian Sea and the Barents Sea. The very complex and convoluted coastline is 25,000 km long with alpine landscapes all the way to the outer coastline (Figure 5).

Fig. 5. *Alpine landscapes all the way to the outer coast line. The view from Reinebringen, Lofoten. Photographer: Luigi Vaccarella.*

The outer coast is often fringed by large shallow water areas with thousands of islands, islets and intertidal rocks, making up offshore archipelagos. Fjords of depths up to 1,300 m penetrate more than 200 km inland among the mountains. These fjords are often separated from the coastal waters by shallow sills at the entrance, making them unique, small 'ecosystems' (Figure 6). The Norwegian fjords are a very important habitat for the harbour porpoise.

The extent and complexity of the Norwegian coast make it difficult and expensive to monitor marine mammal populations and bycatches of marine mammals in fisheries. The complexity and variability in topography and bathymetry make it difficult to extrapolate from one area to the next.

Fig. 6. *The Geiranger fjord. Photo: Vidar Moløkken/frittfallfoto.no*

3. CURRENT MONITORING OF MARINE MAMMAL BYCATCHES IN NORWEGIAN COASTAL GILLNET FISHERIES

3.1 Introduction

Moan gave a detailed overview of the design and operation of the Norwegian fisheries sampling program (the coastal reference fleet). IMR places calls for bids from qualifying fishing vessels. Bidding vessels compete for contracts. Winners are selected pseudo-randomly with certain constraints (e.g. geography, gear use, effort and reporting reliability) and enter into a four-year engagement with IMR. Reference vessels provide IMR with detailed logs of all fishing activities (including bycatches of marine mammals) and biological samples. 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, mentors, administrators and researchers) and subject-specific workshops. Data reported are checked manually and automatically to identify errors and anomalies. The reference fleet has been collecting data since 2006, and the number of vessels in the fleet has been steadily increasing. As of June 2019, there were 25 vessels, with another three contracts planned.

Bycatch data from the reference fleet are used to estimate bycatch per unit effort in specific areas and regions per month per year using a post-stratification scheme. The per-stratum (or per-métier) estimated bycatch rates are multiplied with the whole fleet effort (obtained from fish logs) in the corresponding strata to obtain bycatch estimates for harbour porpoises and coastal seals.

Bycatch estimates are estimated using two measures of fishing effort: fish landed and number of hauls. The workshop participants recognized that fish landed is not an ideal measure of fishing effort but agreed that it is still worthwhile to use in the absence of other measures, and as a comparison to the alternative estimates obtained using number of hauls. Moan explained that the reason fish landed and number of hauls are used as measures of effort (rather than other, more representative measures such as the number of nets or nets × days) is because the commercial (non-reference vessel) fish logs do not contain information on the types or number of gillnets used, nor on net soaking duration.

3.2 Discussion and recommendations

The reference data and commercial fish logs allow IMR to produce accurate and precise estimates for harbour porpoise bycatches in the coastal gillnet fleet – about 2500 animals per year with a RME less than 0.1. Bycatch estimates for the coastal seals are more uncertain because of two reasons. First, the bycatch events are fewer as compared to the harbour porpoise by one to two orders of magnitude, and second, seal identification in the reference fleet is not reliable. The seal identification problem has persisted despite efforts by the IMR to instruct fishermen on how to tell the coastal seals apart. Moan presented a possible solution to this issue: crew on the reference vessels could take profile photos of any seals they bycatch and send them to IMR for identification. Photos can then be cross-referenced with reference vessel fish logs using automatically embedded EXIF metadata If this protocol were to be executed even for a limited period of time, it would give valuable data on 1) the reliability of the fishermen's own seal identification, and 2) the true ratio of harbour to grey seals bycaught. The proportion could then potentially be used as a correction factor in estimating whole fleet harbour and grey seal bycatch.

To obtain bycatch estimates of harbour and grey seals with a CV equal or less than 0.30 the number of monitored vessels should be increased to 60. Vølstad pointed out that IMR intends to eventually expand the fleet to 30 vessels, but that administering 30 reference vessels represents the maximum capacity of the IMR.

The workshop recommended:
That the reference fleet be expanded to 30 vessels, and an additional 30 vessels be equipped with devices for remote electronic monitoring (REM, see Chapter 9). REM can also contribute to other research objectives such as monitoring of seabird bycatch.

It was also noted that the bycatch estimates do not cover recreational fisheries. The IMR has no data on the fishing effort nor marine mammal bycatch rates in recreational fisheries.

4. PRELIMINARY EXPERIMENTS WITH PINGERS IN NORWAY

4.1 Introduction

Moan summarized the pinger trials that IMR has been running since September 2018. IMR is working with two different types of pingers: the banana pinger (manufactured by Fishtek in the UK) and the egg pinger (manufactured by Future Oceans in Australia). Trial participants were recruited preferentially from among the reference fleet (because of their established good relationship with IMR). However, to get enough participants, a few independent fishermen were also recruited. All participants operated gillnets in high bycatch areas. A total of nine vessels were originally selected for participation, but by the end of the monkfish fishery in 2018, only six had returned reports. The remaining three vessels were unable to complete their obligations due to unforeseen problems such as bad weather or mechanical issues with their boats. Pinger types were randomly assigned to participants. In the 2018 monkfish season, we collected data on a total of 60 gillnet hauls, which resulted in 0 and 6 harbour porpoise bycatches, for pingered (n=28) and control nets (n=32), respectively.

4.2. Discussion and recommendations

It was noted by the workshop that the sample size of this study would probably not yield enough statistical power to detect any difference between the effectiveness of the two pingers. Moan clarified that the purpose of using two types of pingers was not to compare the efficacy of the two types of pingers, but rather to collect hands-on experience in day to day pinger usage for different pingers. In data analyses following the conclusion of the field trials, no distinction will be made between pinger types when testing and quantifying the difference between pingered and non-pingered (control) nets.

In the pinger trials, a pinger spacing of 200 meters was used. Moan mentioned that in future iterations of the study, the intention was to increase the spacing to 250 m and eventually to 300 m.

The workshop recommended:
Given the acoustic power of the egg and banana pingers, the spacing between pingers should not be increased beyond the 200 m recommended by the manufacturers. Other trials that have reported longer distances between pingers used pingers that were much more powerful than the ones used in this study.

A power analysis should be conducted to get an informed idea of what sample size would be necessary to achieve the statistical power to detect any difference in control and pingered nets.

5. MARINE MAMMAL BYCATCH MONITORING AND MITIGATION IN USA

5.1. Overview

Lyssikatos and Palka presented experiences from marine mammal monitoring and mitigation efforts in USA. The aim of the presentation was to share techniques and lessons learned from marine mammal bycatch monitoring and mitigation programs implemented in US Northwest Atlantic fisheries (NWA). Topics included: 1) an overview of marine mammal (MM) bycatch and monitoring in US NWA gillnet fisheries, 2) approaches to monitoring and mitigating MM bycatch, 3) associated challenges and 4) tools for monitoring bycatch.

Fig. 7. *Lyssikatos (right) and Palka presented the experience from the Northwest Atlantic US waters.*

5.1.1 Background

Eleven different MM species have been documented interacting with gillnet fisheries over nearly three decades of monitoring gillnet bycatch in US waters. Five species were highlighted for demonstrative purposes, with bycatch levels ranging from the thousands of animals to less than 10 animals per year, with dramatic changes for some species over the years (Figure 8). Gulf of Maine/Bay of Fundy harbor porpoise bycatch approached 3000 animals nearly three decades ago but we're proud to say that it is now a small fraction of historical levels, less than 500 animals presently (~80 percent reduction). Mitigation techniques responsible for some of the reduction is describe below in the mitigation section. In contrast to harbor porpoise, we have seen an increase in bycatch of gray seals. The increasing US NWA gray seal population is recolonizing former habitat adjacent to popular gillnet fishing areas leading to increased interaction rates between gray seals and gillnet fishermen.

Within the last decade, observer coverage has undergone dramatic changes across the predominant gear types used in US NWA fisheries. New England gillnet observer coverage had been roughly constant, averaging ~5% historically, until 2010 when it jumped up to over 15% where it has remained on average since 2010. In contrast, Mid-Atlantic gillnet coverage has been averaging only 3.5-4% coverage. The drivers behind these regional differences mainly boil down to geographic scope, fisheries management and gillnet fleet characteristics (Figure 9).

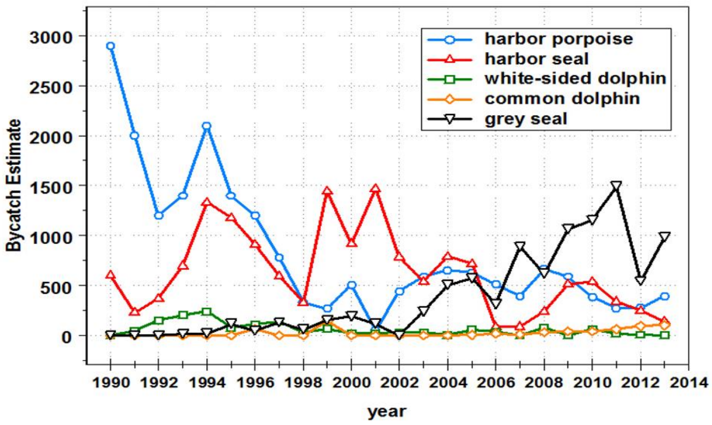

Fig. 8. The decline in harbour porpoise bycatch in gillnet fisheries since mitigation measures were introduced. These mitigation measures appear to be not effective for seals, and the increase in grey seal bycatches possibly reflect the growth of the population.

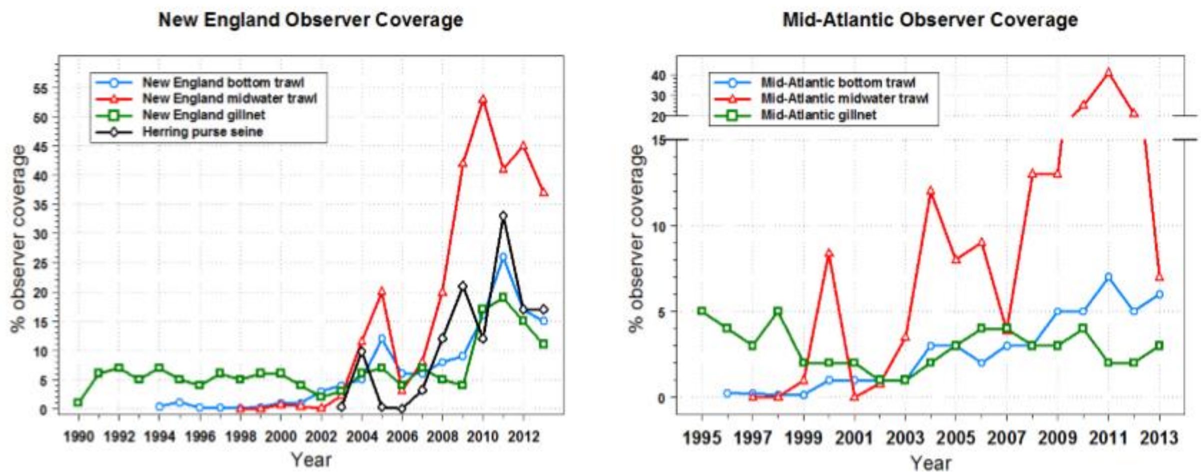

***Fig. 9.** Observer coverage in New England and Mid-Atlantic fisheries.*

We aim to achieve broad-scale coverage that is representative of all gillnet fleet characteristics designed to be proportional to total effort (Figure 10). It is important to note that even with the relatively low 3-5% broad-scale coverage in the mid-Atlantic region we have still been able to detect rare but biologically important bycatch events (<1 per year) (Figure 11).

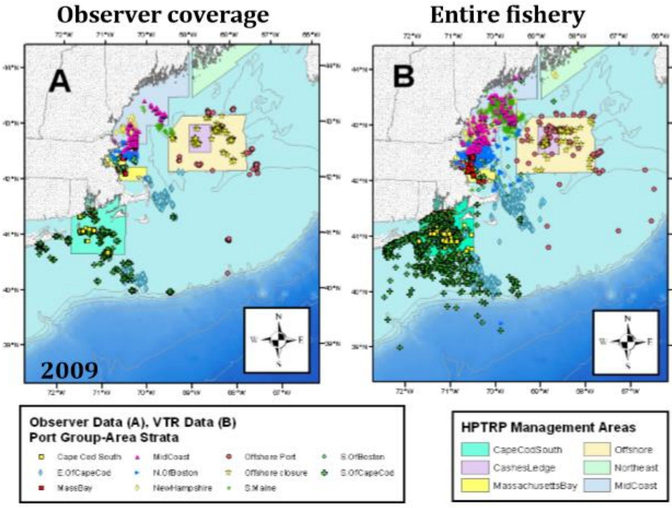

Fig. 10. *Observer coverage is deployed proportional to the total effort.*

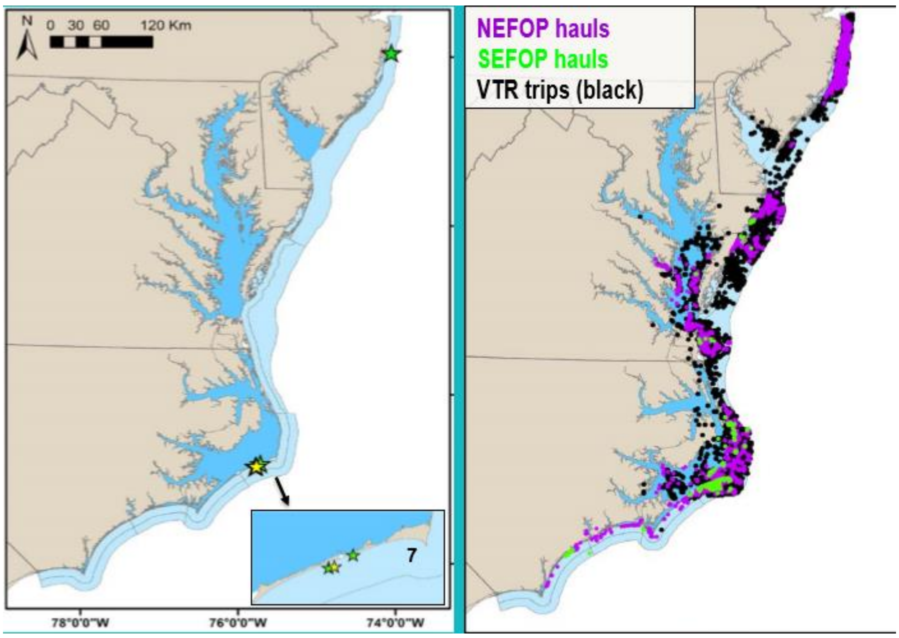

Fig. 11. *Even with the relatively low 3-5% broad-scale coverage in the mid-Atlantic region it is still possible to detect rare but biologically important bycatch events (<1 per year)*

5.1.2 Monitoring bycatch

We leverage an interdisciplinary monitoring program (https://www.nefsc.noaa.gov/fsb/), use decision criteria to prioritize species for monitoring (i.e. high risk species), and a step-wise approach to achieve target monitoring levels to achieve a target coefficient of variation (CV) = 0.30, and allocate observer sea days in space and time to achieve the target CV.

Utilizing three types of human observers, the Northeast Fisheries Science Center (NEFSC) fisheries sampling program (FSP) is designed to meet multiple objectives. Each observer type has different objectives and sampling routines when observing gillnet trips:

1. Dedicated MM observers – primary task is to monitor for MM interactions by keeping their eyes on the gear during the hauling of gear to watch for marine mammals falling or rolling out of the gear, full biological sampling of takes, full catch accounting, but biological sampling of fish kept and discard is 'limited' i.e. minimal.
2. Fisheries Observers - primary task is to sample fish kept and discards, full catch accounting but they are not tasked with watching the gear during haulback so they miss takes that 'fall-out' of the gear. However, when a take comes on board the vessel during haulback, the mandatory priority for the observer shifts to data collection and biological sampling on the MM specimen(s).
3. Fishery Monitors (since 2010) - primary task is catch accounting for monitoring quota managed species. There is no biological sampling of fish kept or discards. However, if a take comes on board, limited data collection for the animal becomes the priority. Biological sampling of takes is not required.

Data collected from all three types of observers contribute to our total annual observer coverage. They all collect hierarchical data (i.e., vessel, trip, haul and gear level data).

Within the NEFSC-FSB electronic monitoring data for monitoring protected species bycatch events is still under development. As a result, video footage is not presently utilized to inform estimation of bycatch rates but that may change in the future.

To obtain broad-scale and representative coverage of our gillnet fisheries we follow a five step procedure. First, we develop criteria or decision rules to prioritize species for monitoring. The primary criteria are species that are managed under a Take Reduction Plan (TRP). If a species has a TRP, it is either presently strategic or was strategic at one time which means it was subject to a level of bycatch that exceeded its potential biological removal level. This boils down our list of candidates from 11 to 2 species: harbor porpoise in New England (NE) and coastal bottlenose dolphins in the mid-Atlantic (MA) (Table 1). Second, we determine target coverage based on a CV=0.30 for the annual estimate (not stratified estimates).

Table 1. The Strategic and Non-Strategic species/Stocks/Populations monitored for bycatches in the Northwest Atlantic. TRP = Take Reduction Plan.

Species/Stock/ Population	PBR	5. yr mean annual bycatch (CV)	Status	TRP	Priority for monitoring
GoM/BoF Harbour porpoise	851	217 (0.15)	Non-Strategic	Yes	Yes
Coastal Bottlenoise dolphin NC Estuarine stock	7.8	12:6 (0.30)	Strategic	Yes	Yes
NWA Gray Seal	1389	940 (0.09)	Non-Strategic	No	No
NWA Common dolphin	1452	419 (0.10)	Non-Strategic	No	No
NWA LF Pilot whale	306	21 (0.22)	Non-Strategic	No	No

A new Observer Coverage Simulator 2.1.1. ShinyApp (https://kacurtis.shinyapps.io/obscov/, https://github.com/kacurtis/ObsCovgTools), was developed by NOAA Fisheries Southwest Fisheries Science Center. We demonstrated how one can determine observer coverage needed to achieve a desired level of precision (CV) for estimating total bycatch. Only three parameters are required to run this application: total effort in the fishery, bycatch rate, and a dispersion parameter to reflect degree of skewness in observed bycatch frequencies (Figure 12).

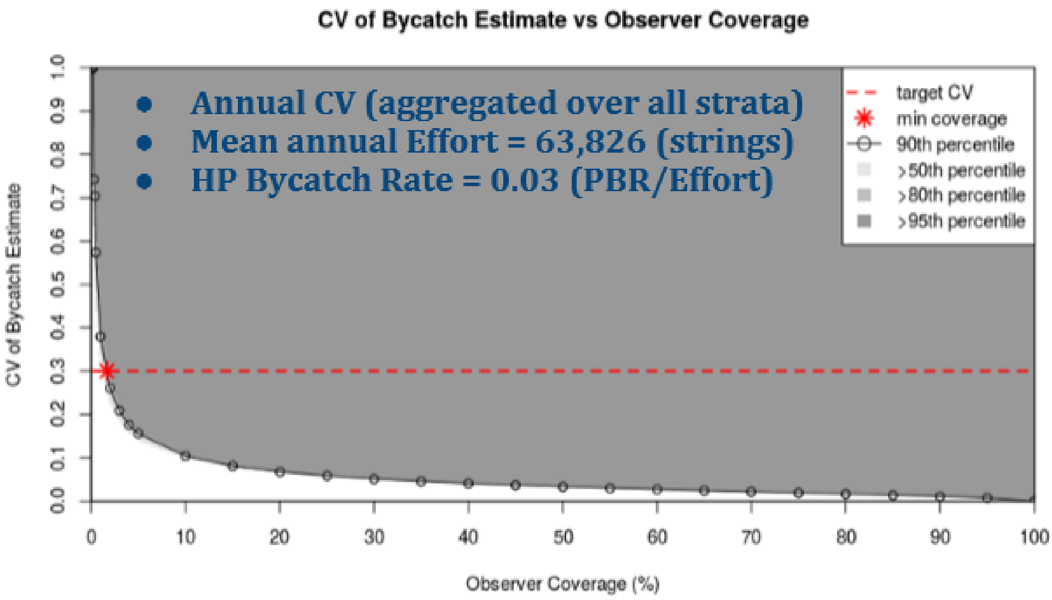

***Fig. 12**. The minimum observer coverage to achieve CV <= 0.3 with 90% probability is 1.7% based on 1100 hauls.*

Third, we prorate our target coverage (number of observer sea days) to reflect the amount of money that has been budgeted for marine mammal bycatch monitoring and additional adjustments due to other constraints. Fourth, we allocate adjusted observer sea days to times, areas, and mesh size categories - proportional to effort. The stratification scheme is an implicit way to optimally allocate observer sea days, as it accounts for inherent spatial/ temporal variability characteristic of the bycatch interactions (Figure 13).

Our fifth and final step is supplying our contractors with a vessel sampling frame – a list of all known active gillnet vessels in the NE and MA fleets to randomly select vessels to achieve assigned observer sea days. There is also a degree of opportunistic placement of observers - at ports. This is necessary when vessel lists are constrained by personal data restrictions, remote points of entry/dock locations, new ports and when fishers don't show up for a pre-assigned trip.

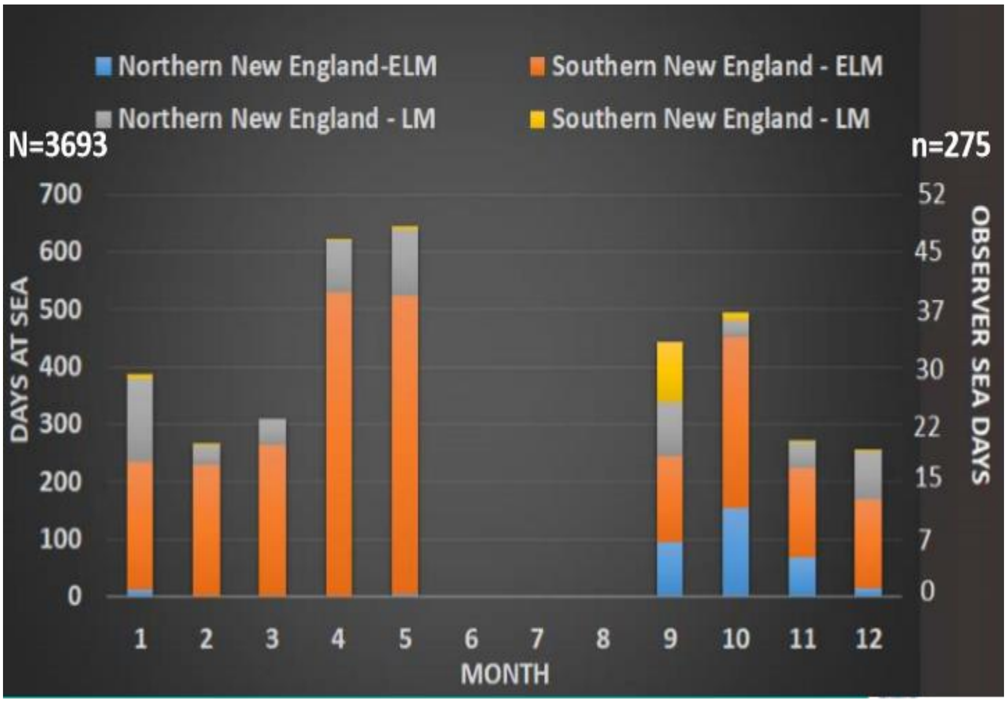

Fig. 13. *In the US we assign observers days at sea proportional to effort. This example is from the New England gillnet fleet.*

5.1.3 Data collection

When observers are deployed there are over 200 data elements they can obtain that include vessel, trip, haul, gear, detail species and biological sampling data (https://www.nefsc.noaa.gov/publications/crd/crd1807/). Among these there a selection of the most critical data elements that have informed the development of various gillnet bycatch mitigation measures in the US NWA gillnet fisheries. They are evaluated in the next section.

5.1.4 Mitigating bycatch of harbor porpoise

A combination of methods have been implemented to reduce bycatch of harbor porpoise that include 1) short term time-area closures where no gillnet fishing is allowed, 2) short-term times and areas where pingers are required on gillnets and 3) other short-term times and areas where specific gear modifications are required.

Mitigation techniques vary by region. In the NE region, time area closures of up to a month are mandated for times and areas with the highest historical bycatch. Pingers are required in times and areas surrounding the closed areas:
(https://www.greateratlantic.fisheries.noaa.gov/protected/porptrp/).
Our regulations require pingers be placed in between each net of about 300 feet within the string of nets and also at both ends of the string (Figure 14). The mitigation measures in the MA region (Figure 15) involve various gear modifications and time/area closures.

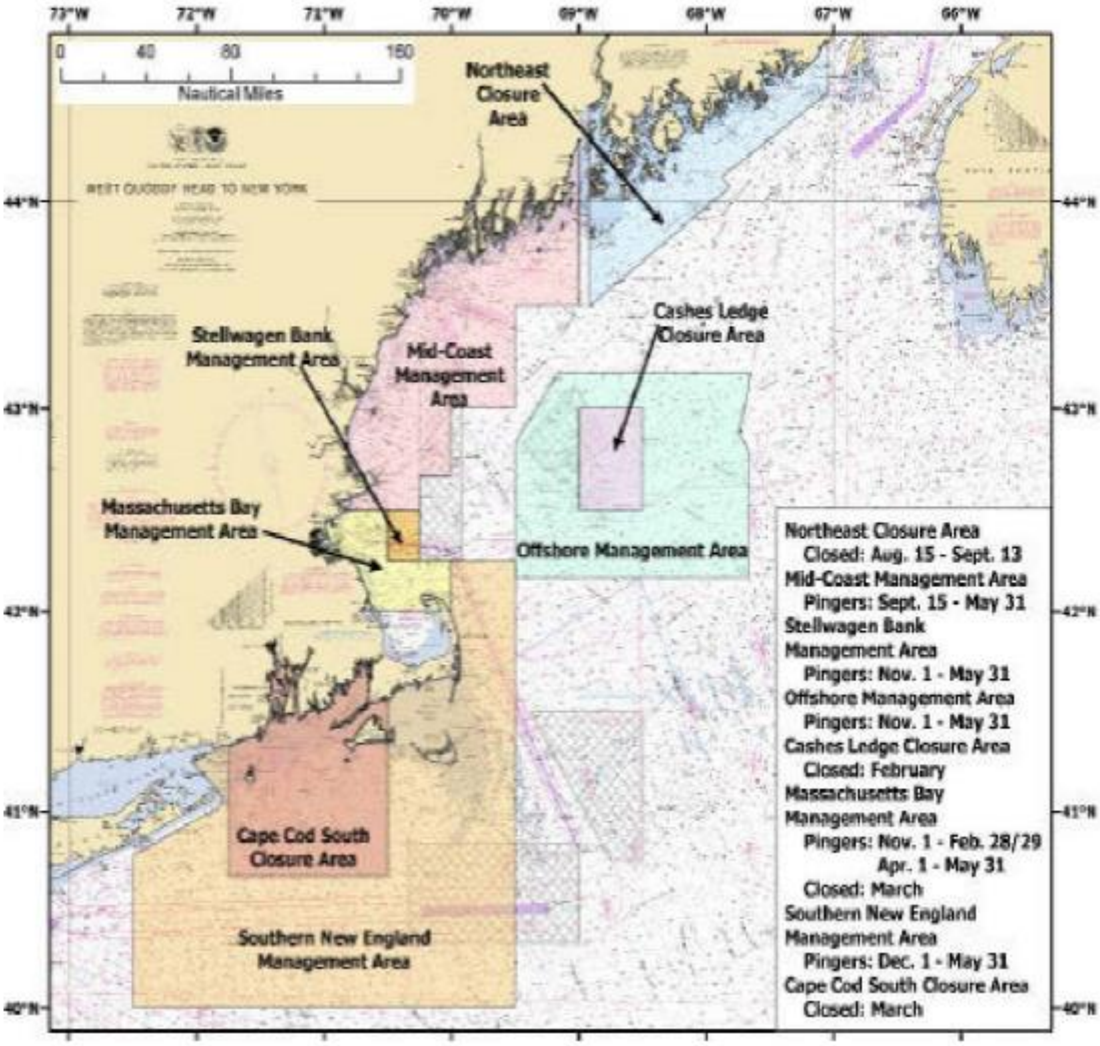

Fig. 14. *The Complete Closure Areas and the Pinger Regulation Areas for the New England gillnet fisheries. This represents the times and areas with highest bycatch rates.*

5.1.5 Developing successful mitigation measures

The process used to develop mitigation measures was basically a risk assessment of various proposed alternatives. Potential gear modification measures were developed by fishers, scientists, and other stakeholders, such as NGO's (non-governmental organizations). We relied heavily on the observer data to quantify expected reductions in bycatch under various scenarios (i.e. proposed alternatives). Observer data provided a wealth of data to explore what characteristics were associated with high and low harbor porpoise bycatch to serve as a "test" to compare present levels of bycatch against what predicted bycatch would be if potential mitigation measures were implemented. This was done by using the observer data to simulate the potential bycatch rate under various fishing characteristics. For example, if there was interest in closing a specific time and area, you can determine what the estimated bycatch rate would be if this closure was in place. To incorporate uncertainty, we defined a range of potential bycatch rates and total commercial effort (i.e. commercial landings) to predict what the landings would be under the potential mitigation measure. After multiplying the range of new predicted bycatch rates to the range of new predicted total effort resulting from the potential mitigation measure, we predicted expected bycatch under the potential mitigation measure. The results were then compared to what was actually observed in the past and what target bycatch reduction was necessary to meet our conservation goals. Applying this analytical approach that quantified expected reductions supported the implementation of mitigation measures to reduce bycatch of harbor porpoises (Palka & Orphanides 2008, (https://www.nefsc.noaa.gov/publications/crd/crd0814/).

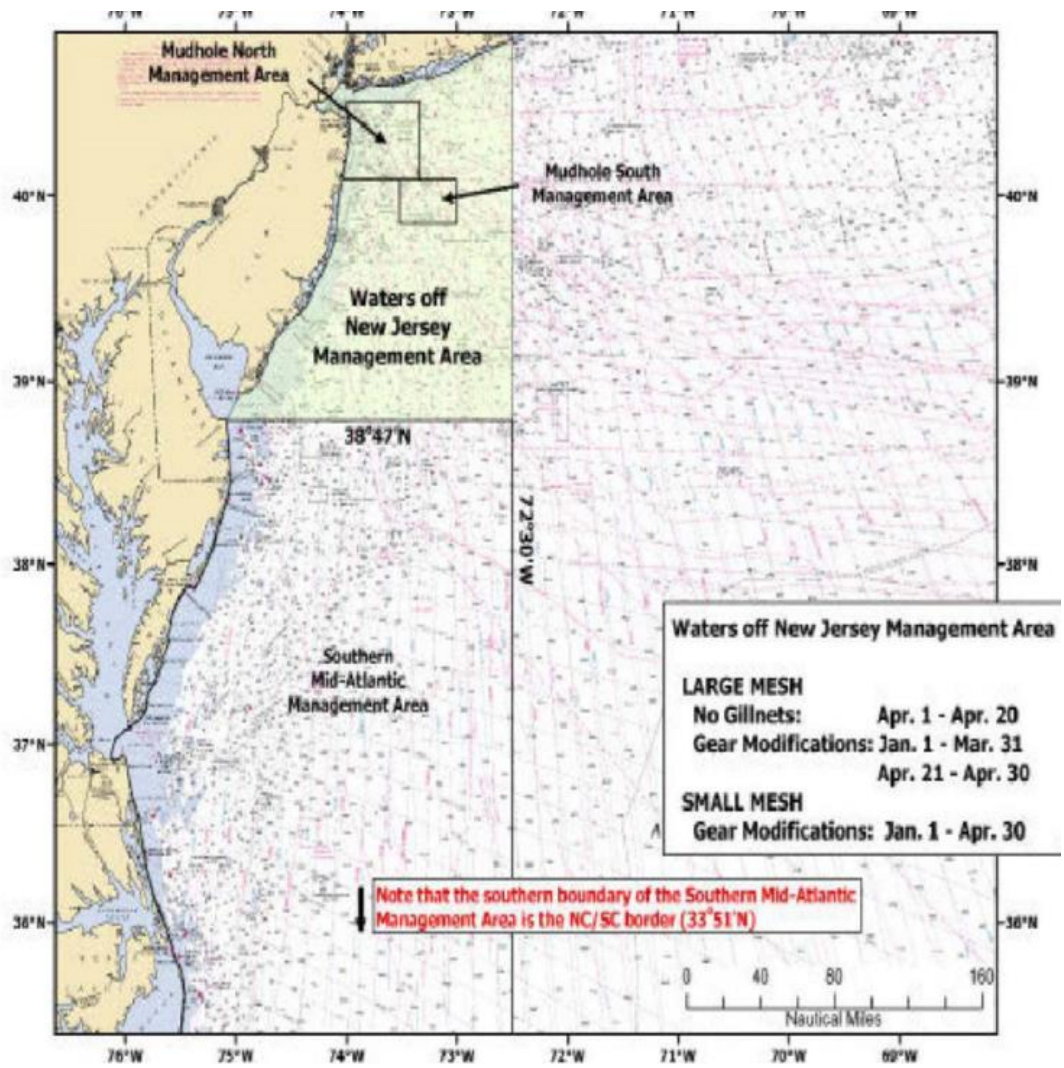

Fig. 15. *Gear modifications and time/area closures for the Mid-Atlantic gillnet fisheries. These regulations were suggested by generalized additive models (GAMs) of observer data to define time/areas and gear characteristics that were related to high bycatch.*

Bycatch of harbor porpoise in the MA region was investigated after NE measures were developed. At the time (late 1990's) there was uncertainty about the effects of using noisy pingers over large areas for long time periods. Consequently, stakeholders in the MA region preferred to use time/area closures and gear modifications to reduce bycatch. After evaluating observer data, specific fishing practices and gear characteristics were correlated with high harbor porpoise bycatch rates. There were spatial differences as well (e.g. waters off New Jersey). Over all, large mesh gillnets had higher bycatch rates that smaller mesh gillnets. Within large mesh gillnets, nets that used lighter twine size had a higher bycatch rate. Quantity of gear allowed to be fished was also limited. Consequently, a suite of gear modifications and time/area closures were adopted.

5.1.6 Evaluating effectiveness of mitigation measures

Several challenges have been encountered around evaluating the effectiveness of mitigation measures implemented to reduce bycatch of harbor porpoise in gillnet fisheries. They include:

Compliance with pinger regulations – Our pinger regulations require that all pingers are working AND all gillnet gear fished be equipped with the required number of pingers. We learned that compliance increased when fishers were reminded about the regulations through dockside outreach efforts and public take reduction meetings. Overall, when compliance increased, bycatch estimates decreased (Figure 16).

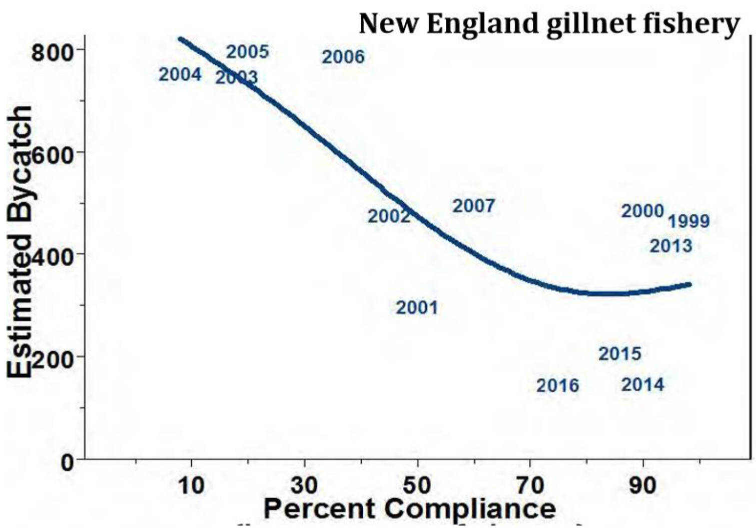

Fig. 16. *The bycatch of harbour porpoise in New England fisheries went down as the compliance to pinger usage (measured as presence of pingers) went up.*

Pinger presence and functionality - There has been inter-annual variability due to missing and/or non-functioning pingers. Palka *et al*. (2008) found that bycatch rates of nets with an incomplete number of pingers had high bycatch rates, higher than if you had no pingers (Figure 17). We don't understand the cause of this. It could include that some pingers actually on the nets were not functional. Only 36% of the tested pingers were functional during some years. Some say it could be that gaps of pingers could "look" like a space where there are no nets, and harbor porpoise try to unsuccessfully swim through what looks like a gap but ends up being caught by the net. We have since tried to get more information on the locations of 'working' pingers relative to the net with bycatch. However, we currently do not have a large enough sample to say anything other than we need to redo this analysis with more recent data to increase the sample size. We have had the additional challenge of determining if a pinger is working. In many cases it was too noisy on the fishing boat to hear if a pinger was working or not. Presently, our best estimate of functionality is 23% of the pingers were inaudible - assuming the status of the unknowns followed the same distribution of the rest of the pingers. It appears to be easier to determine functionality when pingers are equipped with LED lights to indicate if they were working (Table 2). For the brands that had a large sample size, about 25% were inaudible or did not have the LED light on.

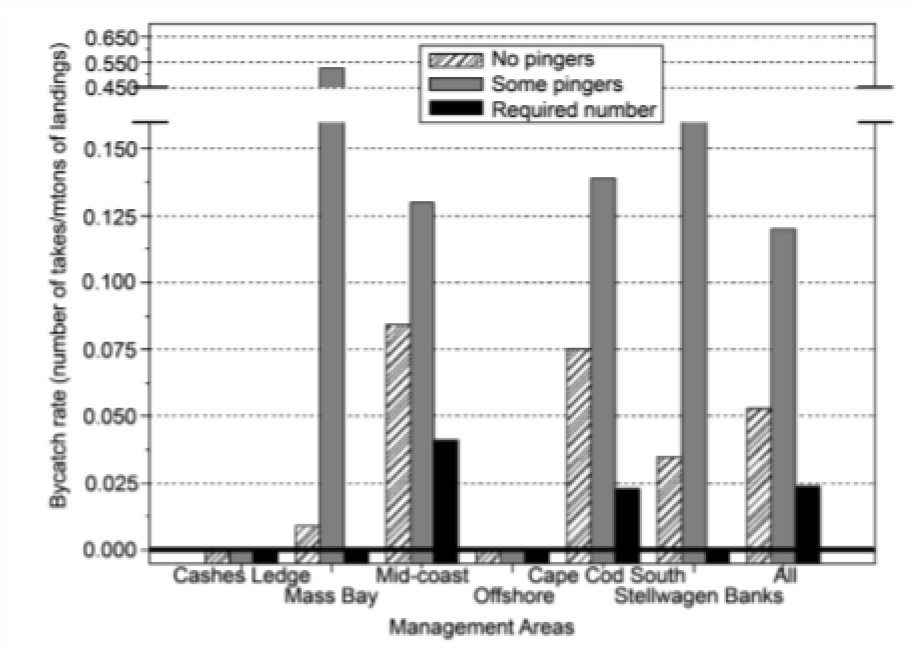

Fig. 17. *Bycatch rates (harbour porpoise permtons landed) of hauls that had no pingers (0%), some pingers (1-99%) and the required number of pingers (100%). It is not known what caused the partly pingered nets to have higher bycatch rates than nets with no pingers. This should be revisited with more recent data. From Palka* et al. *(2008)*

Table 2. *Pinger functionality by brand, sound and LED.*

Brand 2017-2018	Inaudible	Audible	Best estimate of % Inaudible	
Airmar	636	1757	27	
Dukane	28	21	57	
Fishtek	31	381	8	
Fumunda	218	992	18	
Future Oceans	870	2647	25	
Brand	LED on	LED off	Unknown	% Off
Fishtek	342	128	0	27
Fumunda	4	37	0	90
Future Oceans	1376	384	4	21

Other confounding effects – In the mid-Atlantic area off New Jersey, where pingers are not used, gear modifications are the mitigation measure. In this region harbor porpoise bycatch has undergone dramatic reductions. However, between 2010 and 2012 fishing effort in terms of landings stayed the same. Then in 2016 fishing effort increased yet the bycatch continued to stay low (Figure 18). We are unsure why, but modeling the relationship between bycatch, fishing practices and environmental variables has shown harbor porpoise bycatch was related to sea surface temperature and the winter North Atlantic Oscillation (an indicator of climatic patterns (Figure 19). Given the MA region is at the edge of harbor porpoise habitat, it appears there may be fewer porpoises to be caught no matter what kind of fishing gear was being used (Palka *et al*. 2008). Another potentially influential factor is the historical bycatch rate of small mesh gillnets have been much lower than large mesh gillnets.

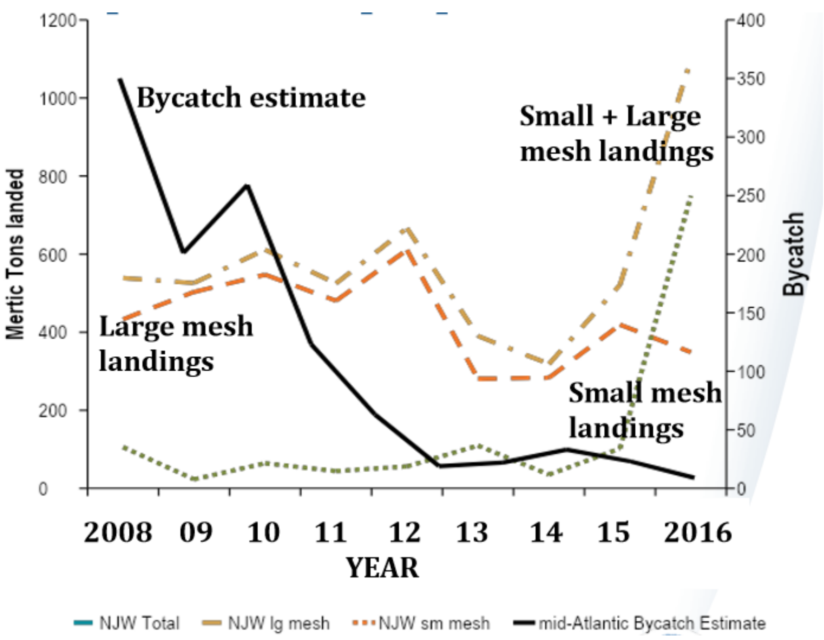

Fig 18. *Bycatch estimate (and effectiveness of mitigation measure) appear to be related to changing fishing effort, other gear characteristics, and presence of porpoises.*

Changing fishing practices has also been a challenge. For example, effort shifted into the South of New England to target monkfish. The monkfish fishery uses large mesh sizes, usually 12 inches, and has the highest harbor porpoise bycatch in this region. This was not a major fishery in New England when pinger regulations were implemented (Figure 20).

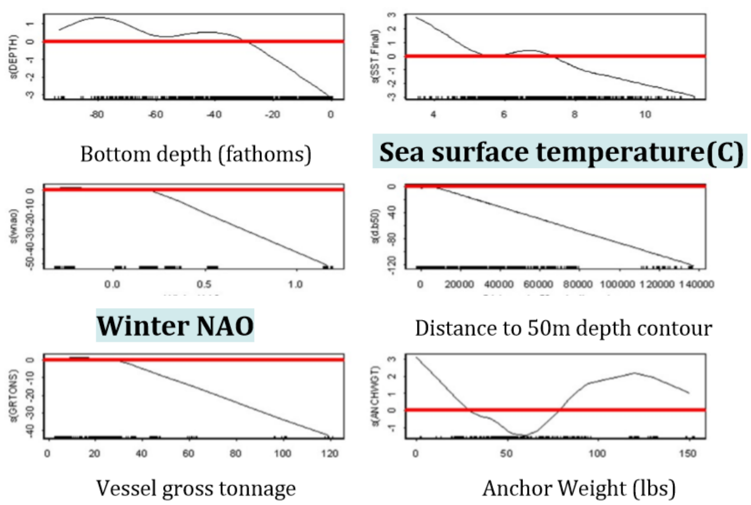

***Fig. 19**. Magnitude of harbor porpoise bycatch related to environmental factors (SST and North Atlantic Oscillation (NAO)). Given the MA region is at the edge of harbor porpoise habitat, it appears there may be fewer porpoises to be caught in periods of higher SST, no matter what kind of fishing gear was being used (Palka* et al. *2008).*

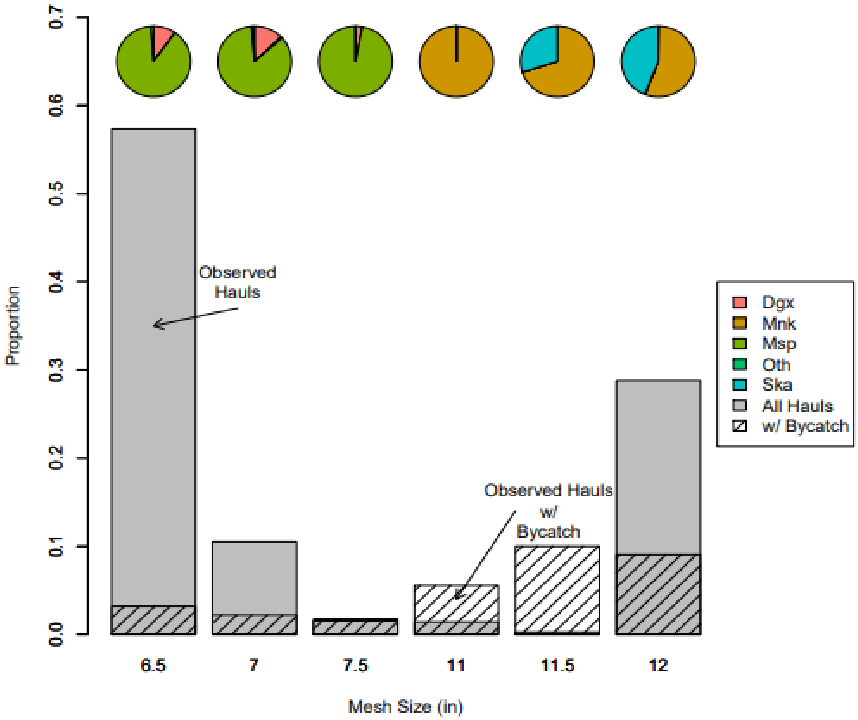

***Fig. 20.** Superimposed distributions of mesh size (in) for observed hauls and observed hauls with marine mammal bycatch in the 2013 New England sink gillnet fishery. Only those mesh sizes with observed marine mammal bycatch are shown. Pie charts above bars refer to the composition of targeted fish species for observed hauls, aggregated into five categories: Dgx = spiny dogfish (*Squalus acanthias*), Mnk = monkfish (*Lophius americanus*), Msp = multispecies groundfish, Oth = other, and Ska = skate (*Raja ocellata *or* R. eriancea*). The 'Oth' category included scup (*Stenotomus chrysops*), American lobster (*Homarus americanus*), unknown fish, smooth dogfish (*Mustelus canis*), unknown dogfish, Atlantic bonito (*Sarda sarda*), bluefish (*Pomatomus saltatrix*), and striped bass (*Morone saxatilis*). From: Hatch & Orphanides (2015).*

As a result of observer coverage in the large mesh monkfish fishery, we learned that monkfish hauls with harbor porpoise bycatch have longer soak durations than monkfish hauls without bycatch. This is a factor that appears to highly influence the bycatch, though this characteristic is not currently managed (Hatch & Orphanides, 2015; Figure 21).

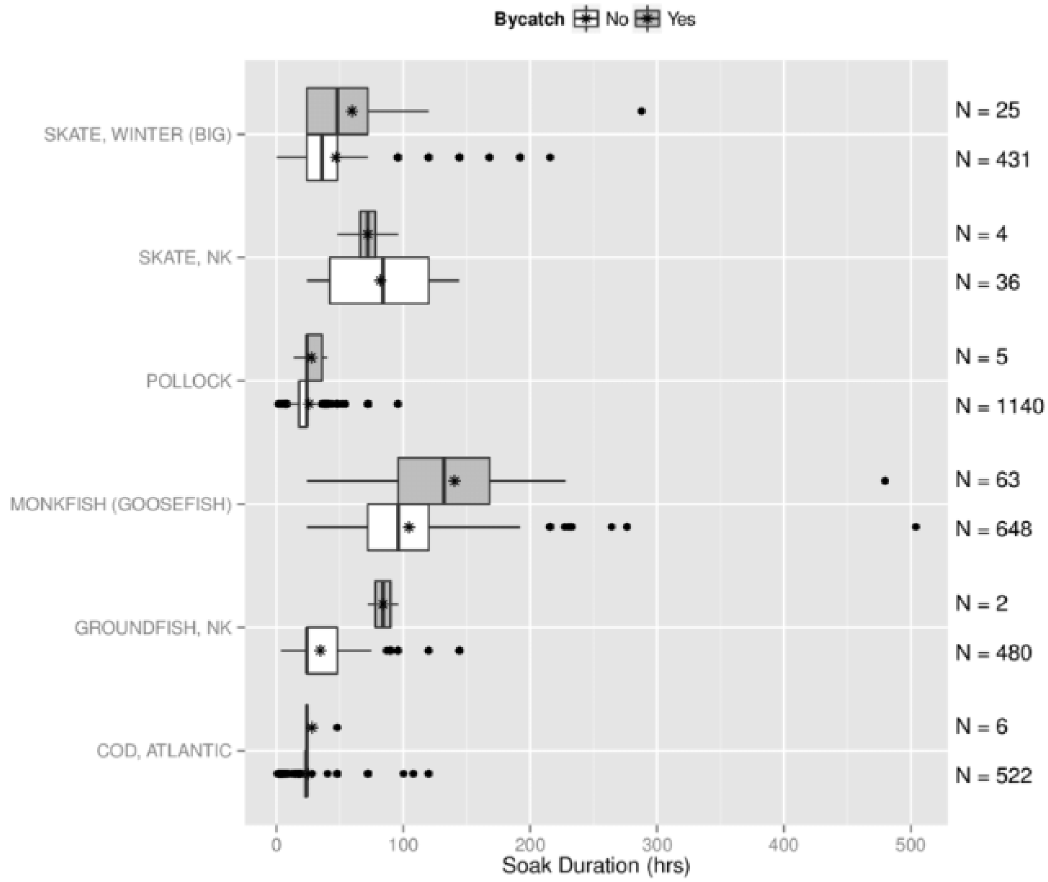

Fig. 21. *Boxplots of soak duration (hrs) by target fish species for observed hauls and observed hauls with marine mammal bycatch in the 2013 New England sink gillnet fishery. Only those target fish species with observed marine mammal bycatch are shown. Sample sizes are shown to the far right of the boxplots. Stars indicate the average, circles indicate outliers, and NK refers to an unknown species. Target fish species include winter skate (*Raja ocellata*), pollock (*Pollachius virens*), monkfish (*Lophius americanus*), and Atlantic cod (*Gadus morhua*). From: Hatch & Orphanides (2015).*

Monitoring declining bycatch – We documented that when bycatch mitigation measure work bycatch goes down! This is a good thing. But the flip side of this success is that observer coverage must increase if a high level of precision on declining bycatch estimates are still required (Figure 22). Since it is fiscally not possible for us to increase the observer coverage, practically this means the precision around bycatch estimates and statistical power of detecting bycatch are decreasing.

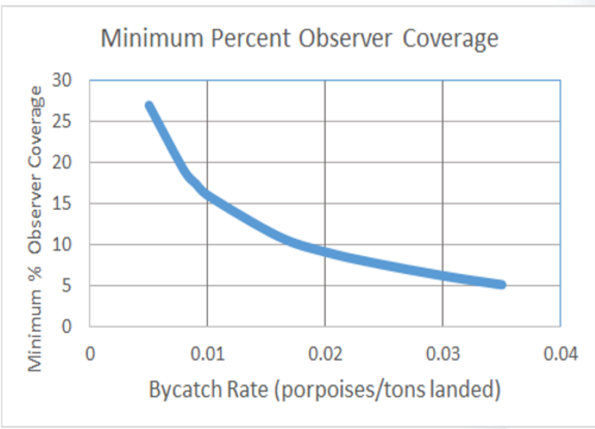

Fig. 22. *Monitoring declining bycatch rates. Since mitigation measures are working well the bycatch estimates are going down. However, the implication of this is that with the same observer overage the CV are going up and the statistical power of detecting bycatch is going down.*

5.2. Discussion and recommendations [Moderator Bjørge]

It was noted that when the Marine Mammal Protection Act was amended in 1994, Stock Assessment Reports (SAR) for all marine mammals in U.S. waters were required. Since that time, all stocks have been reviewed at least every three years or as new information becomes available. Stocks that are designated as "strategic" are reviewed annually. Each draft SAR is peer-reviewed by one of three regional Scientific Review Groups and revised and published after a public comment period.

The USA aim to get broad-scale representative observer coverage in the US Northwest Atlantic commercial fisheries and have learned that outreach to fishers improved compliance to mitigation measures that then reduced bycatch. We also monitor more than just the presence of bycatch to document changes in the fishery and bycatch, to evaluate effectiveness of mitigation measures and, as needed, to have information to develop/modify future mitigation measures.

Further it was noted that USA aimed at annual bycatch estimates with a CV equal or less that 0.30. Bycatch estimates decreased with effective mitigation measures. This is a great success story. However, the declining bycatch levels have led to statistical and logistic issues. That is, more monitoring (even to impractical levels) are required to continue to achieve precise bycatch estimates and to have enough statistical power to confidently document changes and determine if those changes were real and why they were occurring.

Compliance is a key element in successful mitigation measures. Outreach programmes directed at the fisher are essential for good compliance. This could include lectures at meetings of the Fishermen’s Association and visits onboard the vessels when they are at the harbour.

The workshop recommended:

Stock Assessment Reports be developed for harbour porpoise, harbour and grey seals in Norway and that these reports are reviewed at regular intervals.

Norway should aim at estimates of annual bycatches with a CV equal or less than 0.30, and CV and 95% Confidence Intervals be provided with the estimates.

Outreach programmes should be an integrated part of all mitigation programmes to ensure best possible compliance.

6. TOWARDS A SAMPLING DESIGN FOR ESTIMATING MARINE MAMMAL BYCATCHES IN NORWAY

6.1. Simulations of optimal sampling design and sampling effort for collecting data to estimate bycatch with sufficient precision

Moan presented a simulation study in which the reference fleet sampling fraction (effort of reference vessels compared to whole fleet effort) was manipulated in specifically targeted métiers/strata and harbour porpoise bycatch (Figure 23) estimates produced using those manipulated samples (Appendix 3). The associated estimate CVs were then compared to determine what changes (if any) to the sampling design of the reference fleet could lead to the greatest increase in the precision of the bycatch estimator. Simulations included targeting the angler fishery, the cod fishery, the angler or cod fishery in one specific season and/or region, etc. The assembly questioned the feasibility of implementing the results from the simulations because of limitations in what changes can be made to the structure, build up, activities and operation of the coastal reference fleet. It was noted that the IMR must allow the reference vessels to operate normally and without undue interference, so that statistical inferences based on fishery data are not invalidated because of lack of representability. Vølstad pointed out that the only thing that realistically can be done to improve the precision and accuracy of bycatch estimates is to recruit more fishing vessels.

***Fig. 23**. Harbour porpoises are notoriously vulnerable to entanglement in gillnets throughout the species range.*

6.2. **Discussion and recommendations** [Moderator: Vølstad]

The workshop discussed the proposed sampling design in light of the presentations of experiences with bycatch monitoring in USA, and made a number of recommendations.

> ***The workshop recommended:***
> In future simulations, use data from multiple years, e.g. the three most recent years, if they are similar, rather than just one year, as in current simulation
>
> Change the simulation so that it reports sample size rather than sampling fraction
> Aim for a CV of 0.3, and include confidence intervals for the mean and CV
>
> When sampling bycatch, consider using a lottery sampling with probability proportional to the catch in the sampled year, as is done in herring monitoring. (NB: this might be problematic because we do not know the catch until after the nets have been hauled)
>
> Focus on (re)allocation of existing effort, preferably grouping by the variance of the bycatch observations
>
> Either keep the simulation realistic in terms of what changes can actually be made to the reference fleet, or keep as is, but do not use to inform structure of reference fleet, but to explore possible future alternative bycatch sampling designs. Vølstad proposed a future scheme based on a two-way communication system that included the entire coastal fleet of small fishing vessels. In this system, every day, vessels can be picked randomly from the entire population of vessels that go fishing that day, and then asked to report bycatches for that day. Given a population of 3000 fishing vessels, then each vessel would only have to make such reports a few times a year

7. TOWARDS A DESIGN FOR DEPLOYING PINGERS WITH MAXIMUM EFFICACY TO OBTAIN REQUIRED REDUCTION OF HARBOUR PORPOISE BYCATCHES

7.1. Simulations of optimal design for deployment of pingers in Norwegian gillnet fisheries to achieve desired conservation objectives

Moan presented a simulation study of the effects of pinger use on harbour porpoise bycatch (Appendix 4). In the simulations, bycatch was simulated for one year of fisheries for the entire coastal fleet of small fishing vessels by sampling with replacement in a per-stratum manner from the observed harbour porpoise bycatches in the reference fleet. Pinger use was then simulated by randomly and reiteratively picking vessels. In each iteration, all bycatches for the picked vessel was multiplied by an assumed pinger bycatch reduction effect (e.g. 50%, 70% and 90%). The new total bycatch was then estimated. The simulations showed that equipping a relatively small number of vessels with pingers could drastically reduce harbour porpoise bycatch. Assuming a conservative pinger bycatch reduction effect of 50%, it would only take 80 pingered vessels to reduce the bycatch to 2000 animals per year. It would take 200 and 900 vessels to reduce the bycatch to 1500 and 1000 animals per year.

7.2. **Discussions and recommendations** [Moderator: Vølstad]

The workshop discussed the design for deploying pingers in Norwegian gillnet fisheries in light of the experience with mitigation measures in USA and made a number of recommendations.

The workshop recommended:

Use data from multiple years, e.g. the three most recent years, if they are similar, rather than just one year, as in current simulation

Simulate that pingers are required in one specific area (try different areas) for some number of weeks. Try different numbers. The cod spawning season would be a good starting point.

Allow some subset/some percentage of vessels that would normally fish in pinger areas to instead fish in other areas by reallocating their fishing effort to that other area (either go to adjacent areas and use existing effort, or (and this is probably a better idea), go to an adjacent area and then reassign the effort for that boat by sampling from other vessels operating in that area).

Use simulations to explore other alternative bycatch reduction measures, such as area closures, to get a comparative baseline. Choose area by looking at bycatch rates from years that you are not using (to avoid using the same data twice).

As a next step: make pingers mandatory as an experiment in a full-scale commercial fishery. The cod fishery in Vestfjorden-Lofoten (statistical area 00) from January 1st to April 30th is a good candidate. Here are very high fishing effort concentrated in time and space and the harbour porpoise bycatch rate is high. The cod stock is currently large and cod fisheries have been very profitable in recent years.

8. BREAKOUT GROUP ON PINGERS

8.1. Characteristics of the Fishtek Banana pinger

Dr. Enever introduced Fishtek Marine to the fishermen as a conservation engineering company proactively working to make commercial fishing more sustainable. He spoke about the value of having a team of experts with different backgrounds, from engineers to fisheries scientists with extensive sea-going experience. This ensures technology developed by Fishtek is effective, but also that it is practical for use by the fishing industry. Dr. Enever outlined Fishtek's principles for product design, stating that technology for use in the marine fishing industry must meet a very difficult set of criteria; it needs to be tough, durable, low cost, and it must have no impact on target catch or operational activity.

Dr. Enever provided details of the Fishtek Banana Pingers (Figure 24) which are currently being trialled by the fishermen in the room. He explained that, having been trialled for millions of hours in the water over eight years, the Banana Pinger is now an established design classic which is confidently used by fishmen around the world. Failure rates are less than 1%, which enables Fishtek to offer fishermen the reassurance of a two year warranty on the product. Furthermore, independent US testing (presented at the workshop) shows that the Fishtek Banana Pinger is over three times more reliable than the nearest competitor.

Fig. 24. *The Banana pinger from Fishtek Marine. The right panel shows how to attach the pinger with an extra piece of rope to the cork line.*

Dr. Enever then outlined the design features of the product, including that it is effective to over 1000 m depth, it has a durable rubber carrier designed to minimise snagging and button-holing, and that it is supremely safe for the fishermen using them. The Fishtek Banana Pinger is low cost and uses replaceable alkaline batteries which are easy to fit and readily available from supermarkets. Battery life is 4500 hours, or approximately one year of fishing. Fishermen and managers are able to view the battery indicator light to ensure each device is functioning.
The Fishtek Banana Pinger uses advanced acoustics. Each ping is randomised to prevent habituation. The frequency of the pings is set high so that seals are unable to hear the pinger on the nets, eliminating any potential interaction, which was an issue reported by fishermen using other pinger brands in the past.

Aside from the practical functionality of the Fishtek Banana Pinger, Dr. Enever showed the fishermen evidence of the efficacy of the pingers at mitigating cetacean bycatch. This included bycatch studies, behavioural tank experiments (harbour porpoise), drone studies, cliff top observational studies and underwater acoustics.

Dr. Enever was also able to demonstrate, with evidence, that the deterrent effect of the pingers was short ranged and temporary. Therefore, use of Fishtek Banana Pingers doesn’t result in habitat exclusion.

Following the presentation, feedback from the fishermen was unanimous; of all the pingers that they have tried to date, the Fishtek Banana Pinger was their preferred device.

8.2. **Characteristics of the Future Oceans 70kHz pinger**

Turner presented the Future Oceans Netguard 70 kHz Pinger (Figure 25) that operates at 145 decibels and meets European (EU 812/2004) Pinger regulations. It is the smallest and lightest Pinger available: 140 mm long x 50 mm wide and 150 grams with a battery and less than 25 grams when immersed in water. The 70 kHz Pinger has been specifically designed to work seamlessly with all setting and hauling equipment used on Norwegian gillnet vessels. The pinger uses a unique optimised sound generation that delivers consistent frequency and amplitude output. The pinger is the only Pinger that operates with either a standard C cell 1.5v Alkaline battery, with an operating life of 12 months based on 12 hours use per day, or a 3.6v Lithium Ion battery that operates for 24 months based on 12 hours use per day.

The 70kHz frequency is above the best-known hearing range of most seals; it is genuinely ”seal-safe” and will not attract seals.

Fig. 25. *The Future Oceans Netguard 70 kHz Pinger. This pinger is delivered with a line for attachment to the cork line*

The Pinger operates entirely hands free – it turns on and off automatically and instantly in and out of water due to the use of an internal capacitance switch. The Pinger is very easily and quickly attached and removed from gillnets. The ultra-bright battery level green LED is instantly visible from all angles, alerting fishermen when to change batteries.

The internal electronic housing is made from thermoplastic polymer and the external housing is made from ultra-tough, UV resistant copolymer. The Pinger is extremely durable and delivers highly reliable performance in all temperatures and conditions.

The internal electronics capsule is locked inside the external housing – there is no risk that the electronics capsule can fall out, meaning fishermen cannot lose money using this Pinger.

Future Oceans Dolphin Pingers are meant to be spaced one every 200 meters and the Dolphin Pinger conforms with EU 812/2004 Pinger regulations. Future Oceans Dolphin Pinger has been pressure tested to 1000 meters. Future Oceans offers a two-year warranty on the Dolphin Pinger. As an optional extra, Future Oceans offers a Dolphin “Data” Pinger that delivers confirmation of Pinger location, time and date, time Pinger was last used, total time pinger has been used since acquisition and remaining battery life via a mobile device application, using the GSM system. Combined with a bycatch app, fishermen can report all interactions with marine wildlife. The data Pinger and reporting app is only available from Future Oceans.

Additionally, Future Oceans can offer the Dolphin Pinger as a “Programmable” Pinger – operating from 62 kHz to 72 kHz. This provides researchers with a unique opportunity to test the pinger over a broad range of frequencies and virtually unlimited emission patterns. The program operates as a simple to use mobile device app, and any number of pingers can be easily programmed at the same time.

8.3. Practical experience with use of the pingers in Norwegian gillnet fisheries

The three fishers were unanimous, there was no problem in using the pingers, but one of the fishers argued that the pingers were getting entangled in net meshes and therefore conferred additional 'wear and tear' to the nets. The fishers reported spending some extra time initially to attach the pingers to the cork line, but once the pingers were mounted, there was little extra time associated with the pingers when setting and hauling the nets.

One fisher argued that the height of nets was an important factor for the risk of catching harbour porpoises. He suggested that reducing the height of monkfish nets would be more effective for reducing harbour porpoise bycatches than the use of pingers. He further claimed that a reduction of the height of monkfish nets would not affect the catch of monkfish since they are usually caught close to the lead-line.

8.4 Discussion and recommendations [Moderator: Bjørge]

In the breakout group, there was a good dialogue between the fishers and the pinger manufacturers. The manufacturers advised on possible improvements in attaching the pingers. It was agreed that IMR will try to explore the possibility of using net height as a parameter when bycatch rates are examined.

The workshop recommended:

To avoid pingers tearing meshes in the nets apart, it was recommended that pingers are mounted on the cork line between two nets (where two nets are joined together in a string). This may also make it easier to mount the pingers.

When the next steps were discussed the group unanimously recommended to test out the pingers in a real commercial fishery. After some considerations the group converged on a recommendation that as an experiment, pingers should be made mandatory on cod gillnets in Vestfjorden-Lofoten (statistics area 00) in the period 1st January to 30th April. This fishery has high fishing effort, is concentrated in a small area and is associated with high bycatches of harbour porpoises. The cod stock is currently very large and this fishery has been economically favourable in recent years.

The pinger manufacturers may need some time after a decision is taken to produce the sufficient number of pingers. The experiment with mandatory pinger can realistically not commence until the 1st January 2021. However, this will allow for the results on the effect on the bycatch of harbour porpoises to become available before the new US import regulations of fish and fish products enter into force January 2022.

9. REMONTE ELECTRONIC MONITORING OF MARINE MAMMAL BYCATCHES

9.1. Remote Electronic Monitoring (REM) of marine mammal bycatches in Denmark

Kindt-Larsen gave a presentation via Skype on REM in Denmark. REM systems have been used for monitoring fisheries in Denmark since 2008 and since 2010 the systems have been used to monitor by-catches of marine mammals and seabirds in the gillnet fishery.

9.1.1. The camera system and software

All vessels that participated have had a stationary camera system setup. The system consists of a computer, with associated sensors, including GPS and two cameras. The GPS indicates the position of the vessel every ten seconds and the cameras film as soon as the vessel leaves the port and until it is back in port again. The computer stores all data from GPS and cameras and the data is sent directly to DTU Aqua as soon as the vessel is within 4G networks contact. In this way, data is secured and data can be processed quickly. Also, information about the functionality of the system is sent so that errors can be corrected as quickly as possible. Two cameras film respectively the position where the net brakes the surface and when the net enters the vessel through the hauler. The camera filming where the net breaks the surface is especially important, as many marine mammals fall out of the net here because of their heavier weight in air than in water. When monitoring by-catches of marine mammals and birds, only 2 cameras are installed, as it is not necessary to film the catch sorting. This avoid filming of other work areas and the fishers can maintain almost complete privacy onboard. However monitoring of fish discard is needed, 2 cameras are not sufficient and more cameras are required depending on the arrangement onboard.

In Denmark, two different types of REM systems have been used. From 2008 to 2010, the Canadian system from Archipelago Marine Research (AMR) was used and from 2010 and onwards the Danish Black Box system from Anchor Lab is used. The Black Box system has many advantages, especially because of their software used for analyzing video and sensor data. Here it is possible to get visualized fishing routes and fishing areas. At the same time, very detailed information such as net lengths and fishing times can be extracted automatically, which are very important factors when calculating by-catch rates. In all projects from 2010 onwards, 100% of all video has been viewed, and 10% has been viewed twice to do security checks of all the people analyzing video data. The reason why all video material is viewed is because by-catches happen so relatively rarely. It is however possible to watch the videos at relatively high speed (x10), as marine mammals are large compared to fish. However, if by-catches of birds are to be detected, the speed must be reduced to (x4) due to their smaller size.

9.1.2. Incentives

All monitoring have been done on voluntary basis. However, in order to participate in the project, the participating vessels have been allocated research quotas. They have been given a supplement to their ordinary quotas of cod. The additional amount allocated to each vessel has varied between 10-20%. However, there has been a maximum quota of 10 Tons. The research quota is set high, not because it is a big job for the fisherman, but because the fisherman passes on sensitive data. It is far from all fishermen who want to pass on information about by-catches of marine mammals and sea birds, as they are nervous about how the fishery will subsequently be regulated. This is also seen in the official logbooks where there is almost nothing reported. In order to get the fishermen to record video and sensor data, they have been able to earn a significant bonus as an incentive to get them involved. However, despite the significant test quotas, there are still many fishermen who do not want to have cameras on board. The reasons are many, but most have stated that they will not be monitored and that they do not want to pass on information about accidental by-catch, as they are nervous about how it will affect their fishing in the future. This is also the reason why not all seas in Denmark have been monitored. However, are also fishermen who have been in the project because of the research quota. The reason for their participation is that they hope the data can support a more adaptive management of the gillnet fishery. They are very sure that not all fisheries have the same risk, and believe that by-catch risk in different areas and gillnet fisheries should be managed differently and REM is their only way to prove this.

8.1.3. Pros and cons of REM

Advantages:

- Close to 100% coverage of all net hauls
- Video recordings can be analyzed at 10 times normal speed
- It is possible to reviewed by several people
- Marine mammals can be easily recognized on video data
- The use of pingers (acoustic deterrent devices) can be monitored
- Control and security of system functionality is high
- Analysis software programs are well developed
- Low cost compared to onboard observers
- No observer effect, as observers often have other tasks on board and therefore do not exclusively observe by-catch of marine mammals

C*hallenges:*

- Mechanical systems can break and / or be tampered with
- Video data storage requirements
- Detailed information on catches, e.g. weight and lengths are not collected automatically
- The number of monitored vessels is limited to the number of available camera systems.
- Not all fishermen will accept having the camera system onboard
- It can be difficult to overcome fishermen's skepticism about camera surveillance
- Requires high security in relation to data confidentiality

Despite many challenges with the implementation of camera systems, the data collected has lifted the knowledge base of by-catches of marine mammals and seabirds to a very high level compared to earlier years data collected by observes, and data now allows far better bycatch estimates and support information to managers with thus can improve management measures.

9.2. The machine learning approach of Shellcatch

Bjørge presented a system that is based on machine learning to detect bycatches on video recordings. The Shellcatch REM (Remote Electronic Monitoring) system is developed for coastal fisheries with a large number of small vessels that are challenging to monitor by conventional methods. A large number of observers are required to have sufficient observer coverage and the vessels are often too small to carry an extra person. A REM system can be a solution in such fisheries (Bartholomew *et al*. 2018).

Shellcatch has successfully implemented a technological vessel catch verification system for over 500 vessels and 5 coastal sites in the Eastern Pacific (Sharma *et al.* 2019). The innovative system included the design and assembly of a small, solar-powered, waterproof video camera that can be mounted on an industrial vessel or even very small fishing vessels, and set to record sets and hauls of fishing gear (Figure 26). In addition to the design and deployment of the camera unit, Shellcatch has created a simple smart-phone app and an automatic data collection and transmission unit (Figure 27) at port that allows this video data together with GPS tracks of each fishing trip to be uploaded so that machine learning and video analysts can provide near-real time data on bycatch (or lack-thereof) as soon as the cellphone is within 3G-4G network or WiFi range. The system offers a unique opportunity to accurately monitor and collect statistics on fisheries practices, including type of gear used, locations where nets are set, and any possible seabird, turtle or marine mammal bycatch of high conservation value. The system can also be used to promote good release practices or to certify a fishing operation as bycatch free.

Fig. 26. *Shellcatch camera unit.*

Creating accurate machine learning models capable of localizing and identifying multiple objects in a single image remains a core challenge in computer vision (Huang *et al*. 2017). The beauty of machine learning lies in the fact that unlike traditional algorithms, where the computer is told exactly what to do in order to accomplish a certain task, in machine learning, the computer is not explicitly told what to do next. Instead, with machine learning, comes a set of training data that the algorithm uses to generate its own set of rules required to accomplish the task at hand (Sharma *et al.* 2019).

By default, the Shellcatch algorithm runs 4,000 training steps. Each step outputs training accuracy, validation accuracy, and the cross entropy. The training accuracy shows what percent of the images used in the current training batch were labeled with the correct class. The validation accuracy is the precision on a randomly selected group of images from a different set. The key difference is that the training accuracy is based on images that the network has been able to learn from. A true measure of the performance of the network is to measure its performance on a data set not contained in the training data; this is measured by the validation accuracy (Sharma *et al.* 2019).

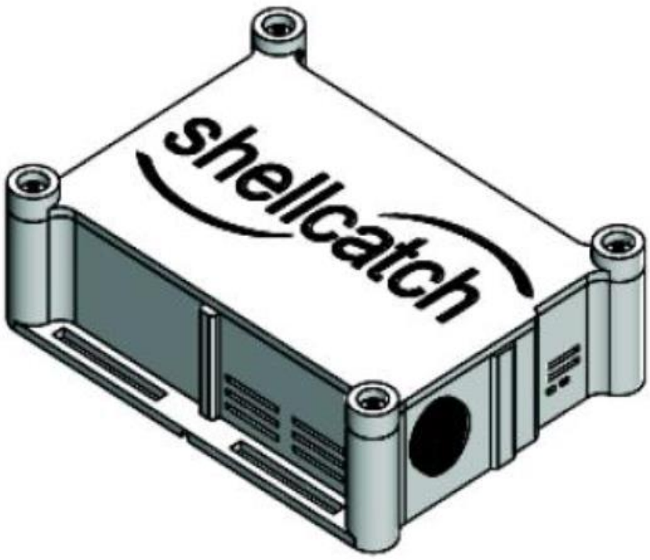

Fig. 27. *The Shellcatch transmission unit that transmits data to the 'cloud' for analyses.*

9.3 Discussion and recommendations

In the discussion it was highlighted that the human eye is a very good 'instrument' for species determination of non-target species in gillnets. However, the costs of watching hours of video recordings can be large. The success of the Shellcatch REM system depends on the ability of the machine learning approach to be able to obtain reliable species identification of bycatches. If bycaught species can be reliably identified the Shellcatch REM system has the potential to become a cost-effective method for bycatch monitoring.

The workshop recommended:

That IMR should explore whether a REM system can be used as a viable way to supplement bycatch data collected by the reference fleet. Start out with a few vessels and if successful, increase to 30 vessels in addition to 30 reference vessels. This could greatly increase the precision and accuracy of Norway's bycatch estimates and has the added advantage that it would allow the IMR to estimate bycatch dropout rates, as noted below.

Data collected using a REM system can be used to estimate dropout rates of marine mammals, which in turn can be applied as a correction factor to bycatch estimates. According to Kindt-Larsen *et al*. (2012), who compared harbour porpoise bycatch reported in fishers logbook and observed by REM, the reporting rate in fishers logbook was 63% while the detection rate in REM was 92%. Some of this discrepancy could be explained by 18% of bycaught porpoises dropping out of the nets before the nets came on board. Seven of 39 porpoises were videoed dropping out of the nets outside the vessels and therefore not seen by the fishers. Additional dropouts may occur before the porpoises are at the surface. Currently, the IMR has no data on such dropout rates, but using REM can contribute data to estimate such rates.

Additionally, a REM system installed on non-reference fleet vessels could collect data on the proportion of bycaught harbour vs. grey seals, which could be used to verify seal identifications reported by the reference fleet.

10. SPECIFIC APPROACHES TO REDUCE BYCATCH OF PINNIPEDS

The workshop discussed the current status of mitigation measures available to reduce bycatch of Pinnipeds.

Some seals may specialize in raiding fishing gear (Graham *et al*. 2011; Königson *et al*. 2006; 2011). The possibility of a 'dinner-bell effect' have been discussed (Mate & Harvey 1987; Carretta & Barlow 2011). In the first experiment with pingers in Norway with 10 kHz Future Oceans pingers, the bycatch rate of harbour seals tripled compared to nets without pingers. The frequency was then changed to 70 kHz and afterwards, there was no difference in the seal bycatch rate between pingered and control nets. It is therefore important that pinger frequencies are outside the audible range of seal hearing.

In Sweden and Finland large efforts have been invested in gear modification to prevent depredation of the fish catches by seals (Calamnius *et al*. 2018; Hemmingsson *et al*. 2008; Königson *et al*. 2015; Lehtonen & Suuronen 2004; Lundin *et al*. 2011; Lunneryd *et al*. 2003; Suuronen *et al.* 2006; Westerberg *et al*. 2007). Most of these gear modifications also reduce the bycatch of seals.

In the Northeast USA and Norway there is no mitigation measures in place to reduce bycatches of harbour and grey seals.

In USA harbour seals are not listed as threatened or endangered under the Endangered Species Act, and the western North Atlantic stock is not considered strategic under the Marine Mammal Protection Act. The 2012–2016 average annual human-caused mortality and serious injury does not exceed PBR and the population seems to be stable (NOAA 2019A). In Norway the bycatch of harbour seals most likely exceeds the PBR, but the stock has been slowly increasing over the past two decades.

In USA the grey seals are not listed as threatened or endangered under the Endangered Species Act, and the western North Atlantic stock is not considered strategic under the Marine Mammal Protection Act. The 2012–2016 average annual human-caused mortality and serious injury in U.S. waters does not exceed the portion of PBR in U.S. waters. The stock's abundance appears to be increasing in Canadian and U.S. waters (NOAA 2019B). In Norway the bycatch most likely exceeds the PBR and a recent, rapid decline in pup production has occurred in central Norway (Nilssen & Bjørge 2019). The reason for this rapid decline in pup production is not known, but high bycatch levels are believed to be an important contribution. It is therefore important to develop measures to mitigate seal bycatches.

The workshop recommended:
Norway should engage in international collaborative work to develop mitigation measures for Pinnipeds. Interactions between seals and fisheries and bycatch of seals is a global problem where efficient mitigation measures are still to be developed.

10. THE MAIN TAKE HOME MESSAGES FROM THE WORKSHOP

The main recommendations from the workshop is summarised below.

The workshop recommended:
The bycatch monitoring programme and bycatch estimation methods for the three marine mammal species at risk (harbour porpoises, harbour seals and grey seals) should allow for an estimator CV equal to or less than 0.30 for annual total estimates.

The number of vessels in the coastal reference fleet should be increased to 30 vessels. Bycatch data collected with the reference vessels should be supplemented by an additional 30 fishing vessels that collect bycatch data with a REM system such as the one described in section 9 of this report. Data from 60 vessels will allow estimation of bycatch for harbour porpoise, harbour and grey seals with a CV equal or less than 0.30. The REM fleet could operate at a small fraction of the cost of the reference fleet and could be useful for other purposes in addition to bycatch monitoring.

Bycatch mitigation measures should be designed and implemented in a manner so that they ensure that bycatches of harbour porpoises, harbour seals and coastal seals are reduced to less than the PBRs for those species. Outreach is critical to achieve high compliance, and should be an integral part of any mitigation measure.

As an experimental mitigation measure directed at reducing harbour porpoise bycatches, pingers should be made mandatory for gillnet vessels operating in Vestfjorden (fishery statistics area 00) in the cod spawning season, from January 1st through April 30th. To ensure proper pinger usage, it would be useful if the implementation included a training programme, such as travelling agents giving short lectures at fishermen association meetings, distributing training videos from pinger manufacturers, etc.)

Data quality assurance measures should be taken to ensure that harbour and coastal seals can be reliably distinguished in bycatch data collected by the coastal reference fleet, so that bycatch estimates can be developed for these species as well.

12. REFERENCES

Bartholomew D., Mangel J., Alfaro Shigueto J., Pingo Paiva S., Jimenez Heredia A. & Godley B. (2018). Remote electronic monitoring as a potential alternative to on-board observers in small-scale fisheries. *Biological Conservation* **219**. 10.1016/j.biocon.2018.01.003.

Bjørge, A., Borge, A. & Kleven, S. 2007. Observed and Reported Bycatches of Marine Mammals in Norwegian Shelf and Offshore Fisheries. NAMMCO/15/MC/BC/7. 9 pp.

Calamnius, L., Lundin, M., Fjälling, A. & Königson, S. 2018. Pontoon trap for salmon and trout equipped with a larger seal exclusion device catches larger salmon. PLoS ONE 13(7): e0201164. https://doi.org/10.1371/journal.pone.0201164

Carretta, J. & Barlow, J. 2011. Long-term effectiveness, failure rates, and 'dinner bell' properties of acoustic pingers in a gillnet fishery. *Marine Technology Society Journal* **45**: 7-15.

Graham, M., Harris, R.N., Matejusová, I., Middlemas, S.J., 2011. Do 'rogue' sealsexist? Implications for seal conservation in the UK. *Animal Conservation* **14**: 587–598.

Hatch, J. & C.D. Orphanides 2015. Estimates of cetacean and pinniped bycatch in the 2013 New England sink and mid-Atlantic gillnet fisheries. NOAA NEFSC Technical Report. https://www.nefsc.noaa.gov/publications/

Hemmingsson, M., Fjälling, A. & Lunneryd, S.-G. 2008. The pontoon trap: Description and function of a seal-safe trap-net. *Fisheries Research* 93: 357–359. 10.1016/j.fishres.2008.06.013

Huang J., Rathod V., Sun C., Zhu M., Korattikara A., Fathis A., Fischer I., Wojna Z., Song Y., Guadarrama S. & Murphy K. 2017. Speed/accuracy trade-offs for modern convolutional object detectors. Computer Vision and Pattern Recognition. arXiv:1611.10012

IWC 1994. Report of the workshop on mortality of cetaceans in passive fishing nets and traps. *Rep Int Whal Comm* **15**: 1−71

Kindt-Larsen, L., Dalskov, J., Stage, B. & Larsen, F. 2012. Observing invidental harbour porpoise *Phocoena phocoena* bycatch by remote electronic monitoring. *Endangered Species Research* **19**: 75-83.

Königson, S., Lövgren, J., Hjelm, J., Ovegård, M., Ljunghage,r F. & Lunneryd, S.-G. 2015. Seal exclusion devices in cod pots prevent seal bycatch and affect their catchability of cod. *Fisheries Research* **167**: 114–122. 10.1016/j.fishres.2015.01.013

Königson, S., Lundström, K., Hemmingsson, M., Lunneryd S-G., and Westerberg, H. 2006. Feeding Preferences of Harbour Seals (*Phoca vitulina*) Specialised in Raiding Fishing Gear. *Aquatic Mammals* **32**:152-156

Königson, S., Fjälling, A., Berglind, M., and Lunneryd, S-G., 2013. Male grey seals specialize in raiding salmon traps. *Fisheries Research* **148**: 117-123.

Lehtonen, E. & Suuronen, P. 2004. Mitigation of seal-induced damage in salmon and whitefish trapnet fisheries by modification of the fish bag. *ICES Journal of Marine Science* **61**: 1195–1200. 10.1016/j.icesjms.2004.06.012

Lundin. M., Calamnius, L., Hillström, L. & Lunneryd, S.-G. 2011. Size selection of herring (*Clupea harengus membras*) in a pontoon trap equipped with a rigid grid. *Fisheries Research* **108**: 81–87. 10.1016/j.fishres.2010.12.001

Lunneryd S-G, Fjälling A, Westerberg H. 2003 A large-mesh salmon trap: a way of mitigating seal impact on a coastal fisher. *ICES Journal of Marine Science* **60**: 1194–1199. 10.1016/S1054e3139(03)00145-0 A

Mate, B. R. and J. T. Harvey ,1987. Acoustical deterrents in marine mammal conflicts with fisheries. Oregon Sea Grant Report ORESU-W-86-001. 116 pp.

Moan, A. 2016. Bycatch of harbour porpoise, harbour seal and grey seal in Norwegian gillnet fisheries: Master Thesis, Department of Biosciences, University of Oslo. 73 pp.

Nilssen, K.T. & Bjørge, A. 2019. Status for kystsel – anbefaling av jaktkvoter 2020. Report Institute of Marine Research. 12 pp.

NOAA 2019A: Stock Assessment Report: HARBOR SEAL (*Phoca vitulina vitulina*): Western North Atlantic Stock. https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessments. 8 pp.

NOAA 2019B: Stock Assessment Report: GRAY SEAL (*Halichoerus grypus atlantica*): Western North Atlantic Stockhttps://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessments. 10 pp.

Palka, D., Lyssikatos, M.C., VanAtten, A.S. & Orphanides, C.D. 2008**.** Effect of pingers on harbour porpoise (*Phocoena phocoena*) bycatch in the US Northeast gillnet fishery. *Journal of cetacean research and management* **10**: 217–226.

Suuronen, P., Siira, A., Kauppinen, T., Riikonen, R., Lehtonen, E. & Harjunpää, H. 2006. Reduction of seal-induced catch and gear damage by modification of trap-net design: Design principles for a seal-safe trap-net. *Fisheries Research* **79**: 129–138. 10.1016/j.fishres.2006.02.014

Westerberg H, Lunneryd S-G, Fjälling A, Wahlberg M. 2007. Reconciling fisheries activities with the conservation of seals throughout the development of new fishing gear: A case study from the Baltic fishery-gray seal conflict. Pp. 587–697 in: Nielsen J, Dodson JJ, Friedland K, Hamon TR, Musick J, Verspoor E, editors. *Reconciling Fisheries with Conservation*, Proceedings of the Fourth World Fisheries Congress, Volume I San Fransisco: American Fisheries Society.

APPENDIX 1

AGENDA

Workshop on Marine Mammal Bycatch Monitoring and Mitigation

Hotel Brosundet, Ålesund,
19-20 June 2019

Tuesday 18th June

19:30 *Dinner, Restaurant Sjøbua. Departure from Hotel Breisundet 19:00*

Wednesday 19th June, Meeting room Brosundet

09:00 Welcome

09:15 Presentation of the Norwegian coastal waters and fisheries subject to marine mammal bycatch [Bjørge]

09:30 Current monitoring of marine mammal bycatches in coastal gillnet fisheries [Moan]

10:00 Preliminary experiments with pingers [Moan]

10:30 *Morning Coffee*

11:00 Experience from mitigation efforts in Denmark [Kindt-Larsen]

11:30 Experience from mitigation efforts in USA [Palka]

12: 00 Discussion [Moderator Bjørge]

12:30 *Lunch, Restaurant Maki*

Plenary

13:30 Simulations of optimal sampling design and sampling effort for collecting data to estimate bycatch with sufficient precision [Moan]

14:00 Discussion and recommendations [Moderator: Vølstad]

15:30 *Afternoon tea*

16:00 Simulations of optimal design for deployment of pingers in Norwegian gillnet fisheries to achieve desired conservation objectives [Moan]

16:30 Discussions and recommendations [Moderator: Vølstad]

Break out group

13:30 Characteristics of the Future Oceans 70kHz pinger [Turner]

14:00 Characteristics of the Banana pinger [Enever]

14:30 Practical experience with use of the Future Ocean pinger in Norwegian gillnet fisheries

15:00 Practical experience with use of the Banana pinger in Norwegian gillnet fisheries

15:30 *Afternoon tea*

16:00 Discussion and recommendations [Moderator Bjørge]

19:00 Dinner at Restaurant Fjellstua. Buss departs from Hotel Brosundet at 18:30

Thursday 20th June

09:00 Remote Electronic Monitoring of marine mammal bycatches [Bjørge]

Discussion [Moderator Bjørge]

10:00 Continued discussions of sampling design for monitoring marine mammal bycatches [Moderator Vølstad]

10:45 *Morning coffee*

11:15 Continued discussions of design for deployment of pingers [Moderator Vølstad]

11:45 Specific approaches to reduce bycatch of pinnipeds. Open discussion. [Moderator Bjørge]

12:15 Final round of advice for continuation of the project from external advisors. [Moderator Bjørge]

13:15 Closure of the workshop

13:30 *Lunch at Restaurant Maki*

APPENDIX 2

PARTICIPANTS

Workshop on Marine Mammal Bycatch Monitoring and Mitigation

Hotel Brosundet, Ålesund,
19-20 June 2019

#	Invited participant	Affiliation	e-Address
1	Prof. Philip S Hammond	SMRU, University of St Andrews, UK.	psh2@st-andrews.ac.uk
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APPENDIX 3

Simulating alternative sampling designs to improve the precision and accuracy of bycatch estimates

André Moan
Institute of Marine Research
June 2019

ABSTRACT
In Norway, an estimated 3000 harbour porpoises (*Phocoena phocoena*) and a few hundred harbour (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) die from incidental entanglements in bottom-set gillnets every year. Bycatch is estimated from data provided by reference fishing vessels, which collectively cover about 3% of the fishing activities of the whole coastal gillnet fleet. The small sampling fraction in combination with the low frequency of bycatch events leads to potentially biased, and unprecise bycatch estimates, especially in the case of the seals, for which bycatch observations are much fewer than for harbour porpoises. In this study, I use a simulation approach to explore possible ways that the sampling design constituted by the activities of the reference vessels can be altered to improve the precision (coefficient of variation) of the stratified ratio estimator both when estimating bycatch of harbour porpoises and coastal seals. The sampling fraction was increased in specific strata according to a set of predefined targeting strategies. The results indicate that the greatest increase in the precision of the estimator can be achieved by increasing the effort in strata with the highest bycatch rates and/or strata with low fishing effort that suffer from low sampling coverage. However, it is challenging to "translate" an increased effort in one stratum into the corresponding effort in real-life fisheries, because vessels operate in multiple strata.

Abbreviations
IMR Institute of Marine Research
CRF Coastal Reference Fleet
CV Coefficient of Variation
MRE Mean relative error

Introduction
In Norway, harbour porpoises (*Phocoena phocoena*) and harbour (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) are vulnerable to incidental takes in bottom-set static gillnets in the coastal zone. The animals get entangled in the nets, and then suffocate when they are not able to return to the surface to breathe. This kind of incidental anthropogenic mortality is currently the greatest threat these animals are facing, and there is concern that bycatches can negatively impact the long-term population

trajectories of the bycaught species. Between 2000 to 3000 harbour porpoises, and a smaller number of coastal seals perish each year in Norwegian gillnet fisheries.

Among the Norwegian gillnet fisheries, the monkfish/angler (*Lophius piscatorius*) and the cod (*Gadus morhua*) fisheries have the greatest marine mammal bycatch rates. Different fisheries are distinguished by different gear use, primarily the mesh sizes (half mesh[1]) of the nets used, as the mesh size is what confers catch specificity to the fishing gear. The high bycatch rates in the aforementioned fisheries are likely caused by the large mesh size of the nets typically used. In the cod fishery, nets with mesh sizes ranging from 75 mm to 105 mm are used, and in the monkfish fishery, nets with mesh sizes of 180 mm are used. Nets with other mesh sizes (both larger and smaller) are used to target a variety of other commercial catch species, and while marine mammals are occasionally taken in these other fisheries, the fishing effort is significantly less than for the cod and monkfish fisheries, and marine mammal bycatches are rare. Smaller mesh sizes also have lower bycatch rates.

Data reported from the Directorate of Fisheries indicate that there are more than 2 000 vessels operating bottom-set gillnets in the coastal zone, setting and hauling on average 63 826 strings with an estimated total of 6 924 230 nets every year. A number of these vessels have been contracted by the Institute of Marine Research (IMR) to serve in a "coastal reference fleet" (CRF) and report detailed fishing data and metadata on the haul level, including catches and bycatches. Data collected by the CRF are used to produce estimates of bycatch rates per unit effort. These estimated rates are then applied to the whole fleet effort to obtain total bycatch estimates. To account for regional, seasonal and fishery or gear-related differences in bycatch rates, a stratified ratio estimator is used.

In this study, I explore possible ways that the sampling design constituted by the activities of the CRF can be altered to improve the precision of the stratified ratio estimator. The pooled sampling fraction per year, ignoring vessels and instead comparing the total number of hauls in the CRF and in the whole fleet across all strata, ranges from 2.1% to 4.7%, with an average of about 3%. A pooled sampling fraction of 3% corresponds to an average yearly sample size of 63 826 * 0.03 = 1 915 hauls. These hauls are distributed unevenly across many strata, and depending on the year and the stratification used, some strata may be undersampled, while others may be oversampled. Low sampling size can cause bias and imprecision in the estimator. In this analysis, I use a simulation approach to assess the potential benefit (as measured in terms of a reduction in the estimator CV) of manipulating the sample sizes in specific strata according to a set of predefined "strategies". This can inform ways in which the CRF sampling design can be optimized to obtain better bycatch estimates.

Simulation method

New bycatch data was simulated for the whole fleet by a stratified random sampling scheme, sampling at random and with replacement from the observed bycatch of harbour porpoises or coastal seals (i.e. summed number of harbour and grey seals recorded within pre-defined strata in the CRF. The two species of coastal seals were added together because of two reasons: 1) I believed the species identification in the observer data was not reliable, and 2) there were very few seal bycatch events recorded in the data. In each stratum, I took a number of samples N_i where N_i = the average yearly number of total hauls in stratum i. In this case, total hauls referred to the whole coastal gillnet fleet, and not just the reference vessels. The stratifications schemes used (ordered from fine to coarse) were *month+area*, *month+region*, *season+area* and *season+region* (Table 1). *Month* referred to the month of the year. *Season* was a factor variable with two levels, season 1 comprising the months January – June and season 2 comprising the months July – December. *Area* referred to the nine Norwegian coastal

[1] All references to «mesh size» in this document refer to half mesh, i.e the distance between two knots, rather than the stretched mesh width.

fishery statistics areas (Figure 1). *Region* referred to an alternative spatial division of the coastline obtained by combining adjacent areas into larger regions (shaded shapes in Figure 1).

***Table 1**: Overview of the different stratifications used and the number and average sampling fraction of strata under that stratification*

Resolution	Stratification	Stratification variables	Number of strata	Empty strata	Average stratum sampling fraction
Finer scale	1	Month + area + fishery	324	44	13.46%
	2	Month + region + fishery	144	4	14.11%
	3	Month + area	108	1	5.09%
	4	Season + area + fishery	54	3	6.85%
	5	Month + region	48	0	4.74%
	6	Season + region + fishery	24	0	5.55%
	7	Season + area	18	0	4.84%
	8	Season + region	8	0	4.30%
	-	None (flat structure)	1	0	3.24%

Additionally, I tried to further stratify data by fishery, where fishery was a factor variable with three levels: “cod”, “angler” and “other”. Hauls were assigned to fishery based on catch composition, rather than recorded net mesh size, because the latter was only available in the reference data, and not in the whole fleet data. Hauls where cod comprised 50% or more of the total catch were assigned to the cod fishery, and hauls where anglerfish comprised more than 10% of the total catch assigned to the angler. The third fishery level, “other”, contained all hauls that could not be classified as either “cod” or “monkfish”. To verify the fishery assignments, I compared results using this method and classifications using net mesh size instead for all hauls where mesh size was available. The catch composition method correctly identified about 80% of cod hauls, 90% of angler hauls and 86% of other hauls. I thus obtained bycatch data for one full year of fishing without making any assumptions about the underlying bycatch distribution.

The simulated data represented the “true” bycatch for one average “fishing year”. For each stratification scheme and each stratum in that stratification scheme, I sampled a fraction Z of all simulated hauls in that stratum, where Z varied according to the sampling fraction in the corresponding stratum in the original CRF bycatch data. To simulate an increased sampling effort in a stratum, the original sampling fraction was increased with k percentage points, with k going from 0.01 to 0.25. I scaled up the summed bycatch in the sample using the reciprocal of the sampling fraction (1/Z) in that stratum to obtain bycatch estimates for that stratum. Total estimates were obtained by summing up estimates for each stratum.

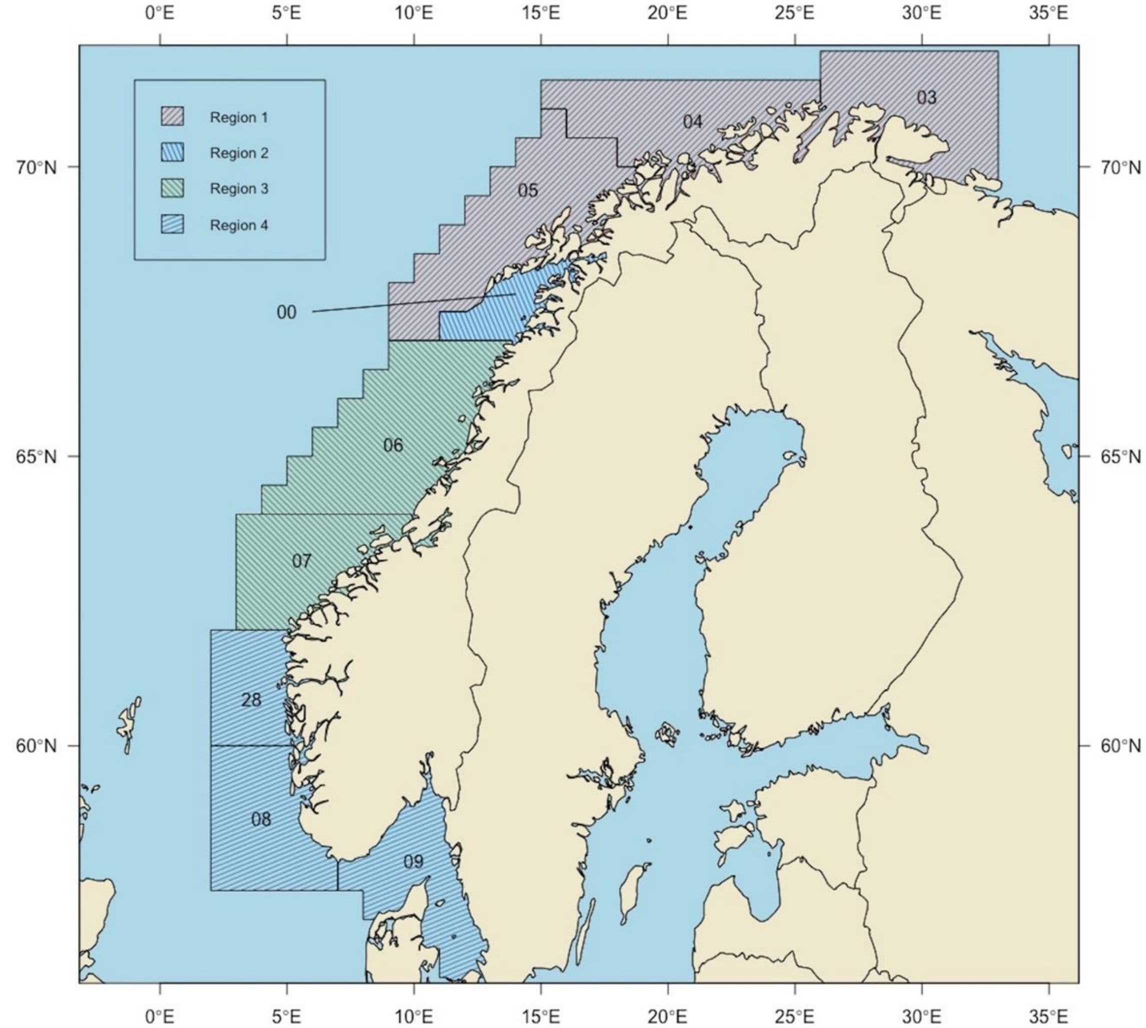

***Figure 1**: Map of the study area, showing the nine administrative / statistical areas (labelled 03, 04, 05, etc.) along the Norwegian coastline, and an alternative division of the coastline into larger regions (as designated by the different background colours; see plot legend).*

Using the procedure outlined above, I simulated changes in the sampling design according to a set of "strategies", where I selected, or "targeted", specific strata according to different criteria. Targets included strata with high or low bycatch rates, strata with high or low fishing effort, strata with high or low coverage (i.e. low sampling fractions), strata associated with particular fisheries, etc. A complete list is given in Table 2. The full set of strategies (labelled SIM1 through SIM30) were run for the season + region + fishery stratification (stratification 6, Table 1), and the subset SIM21 through SIM30 were run for all other stratifications. In strategies that targeted strata based on bycatch rates, bycatch rates were calculated per-stratum as the number of bycaught animals per haul.

Table 2: Overview of strategies used to target different strata.

Simulation	Target strata	Percentage of strata targeted
SIM1	All	100%
SIM2	Season 1	50.0%
SIM3	Season 2	50.0%
SIM4	Angler	33.3%
SIM5	Cod	33.3%
SIM6	Angler and cod	66.7%
SIM7	Angler + Season 2	16.7%
SIM8	Cod + Season 1	16.7%
SIM9	Region 1	25.0%
SIM10	Region 2	25.0%
SIM11	Region 3	25.0%
SIM12	Region 4	25.0%
SIM13	Angler + Region 1	12.5%
SIM14	Angler + Region 2	12.5%
SIM15	Angler + Region 3	12.5%
SIM16	Angler + Region 4	12.5%
SIM17	Cod + Region 1	12.5%
SIM18	Cod + Region 2	12.5%
SIM19	Cod + Region 3	12.5%
SIM20	Cod + Region 4	12.5%
SIM21	Top 10% strata with highest bycatch rates	10.0%
SIM22	Top 20% strata with highest bycatch rates	20.0%
SIM23	Top 10% strata with highest fishing effort	10.0%
SIM24	Top 20% strata with highest fishing effort	20.0%
SIM25	Top 10% strata with highest coverage	10.0%
SIM26	Top 20% strata with highest coverage	20.0%
SIM27	Top 10% strata with lowest fishing effort	10.0%
SIM28	Top 20% strata with lowest fishing effort	20.0%
SIM29	Top 10% strata with lowest coverage	10.0%
SIM30	Top 20% strata with lowest coverage	20.0%

I ran 1000 replicates of the above procedure for each stratification, each value of “k”, and for each species group (porpoises and seals), or 800 000 simulations in total. Because of limitations in computational resources, “k” took only the values [0, 5, 10, 25] percentage points. The accuracy (MRE, or mean relative error) and precision (CV, or coefficient of variation) for each run were calculated from the resulting distributions of total bycatch estimates.

To heuristically determine the best sampling strategy “candidates”, I ranked each simulation based on the product of the resulting estimator CV and the simulated total sampling effort. The products were first sorted in descending order, and then ranks were assigned based on the index/position of the individual product in the sorted product vector, with the first index being assigned rank 1, the second index being assigned rank 2, and so on. In this way, the simulation with the greatest product was assigned the first/lowest rank, and the simulation with the smallest product was assigned the last/greatest rank.

PRELIMINARY RESULTS

The reference fleet has a low overall coverage of the commercial coastal fisheries, with the sampling fraction ranging all the way from 0 (completely unobserved strata) to 1 (strata only fished in by reference vessels). The average stratum sampling fraction after stratifying the data ranged from 4.74% to 14.11%, depending on the stratifying vdariables (Table 1). Stratifying by month, area and fishery resulted in a large number (44/324 = 13.6%) of empty strata. The boxplots in Figure 2 show the distribution of sampling fractions in individual strata under different stratification schemes. The overall sampling fraction (total observed hauls / total hauls in whole fleet) is indicated by the red bar and equalled 3.24%, or 2067 hauls. Under most stratifications, there were some strata that had a much higher coverage than others, as evidenced by the long right-hand tails in Figure 2.

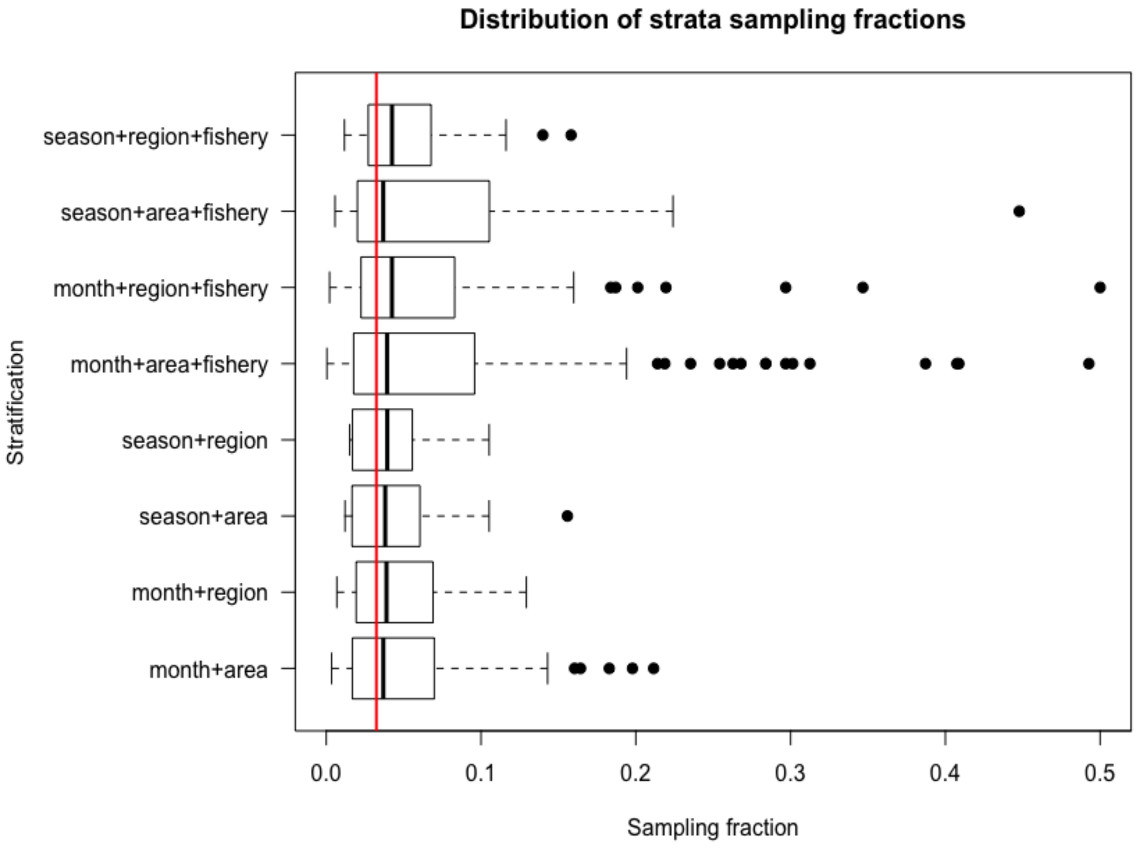

Figure 2*: Boxplot showing the distribution of the fishery sampling fractions for individual strata under each of eight stratification schemes. The vertical red bar indicates the overall sampling fraction of the unstratified data.*

Depending on the sampling strategy, an increase in the sampling fraction in targeted strata by five percentage points resulted in a simulated total sampling effort between 2 067 and 5 258 hauls, with a mean and median of 2 654 and 2 302 hauls, respectively. Correspondingly, the mean and median for 10 and 25 percentage points increases were 3 241 and 5 004 (mean) and 2 536 and 3 240 (median), respectively. Total simulated sampling efforts for individual sampling strategies under different stratifications are shown in Figure 3. The total simulated sampling effort was the same both for coastal seal and our harbour porpoise simulation. Most simulated strategies led to moderate increases in the sample size. Increasing the sampling effort in some strata, especially those with a high fishing effort resulted in very high sampling sizes, up to a maximum of 18 024 hauls, corresponding approximately to a nine-fold increase in the current sampling effort and a total sampling fraction of 0.28. However, there were a large number of strategies that yielded more moderate and more feasible increases in the total sampling effort (the crosshairs immediately adjacent to the vertical line in Figure 3).

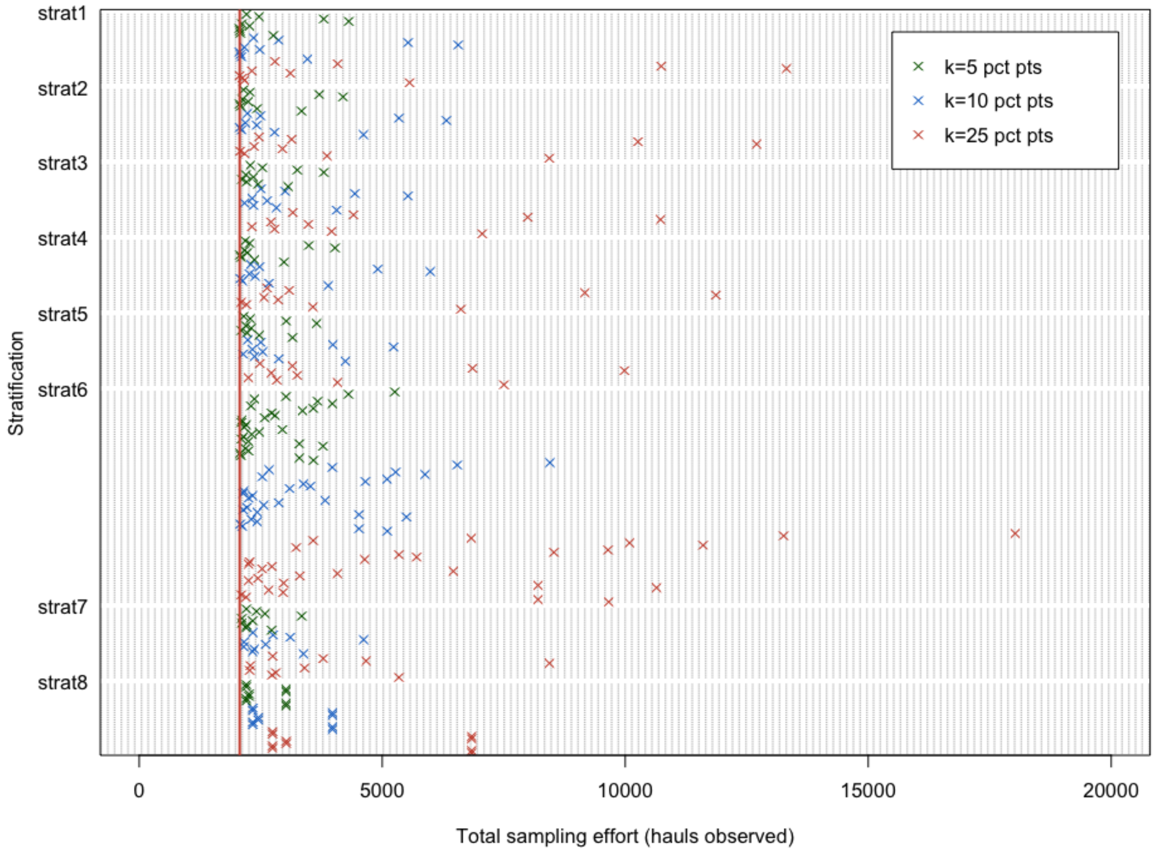

Figure 3*: Overview of the simulated total sample sizes. The crosshairs represent the total sample size in each of the simulated sampling strategies (Table 2). The colors of the crosshairs indicate the percentage points increase in the sampling fraction in the targeted strata according to the plot legend. The vertical red line represents the observed average yearly CRF sampling size.*

The reductions in the CV using stratification 6 (season x region x fishery) for sampling strategies SIM1 to SIM20 and for different values of "k" are shown in Figure 4 for the coastal seal bycatch estimator and in Figure 6 for the harbour porpoise bycatch estimator. Results for the remaining sampling strategies (SIM21 to SIM30) for all stratifications, including stratification 6, are shown in Figure 5 (seal bycatch estimator) and Figure 7 (harbour porpoise bycatch estimator). A complete list of all simulation results is given in tabulated form in APPENDIX1.

Seal bycatch simulations

In most simulations, the initial five percentage points increase in the sampling fraction produced a greater reduction in the estimator CV than did subsequent sampling fraction increases. The decrease in estimator CV typically tapered off gradually as the sampling fraction was increased further, but with some exceptions (e.g.: sim12 in Figure 4, sim30 in Figure 5A, sim25 and 27 in Figure 5B, sim27 and 28 in Figure 7B). Simulating an increase in the sampling fraction across all strata (sim1, dotdashed black line with diamonds in Figure 4) resulted in the greatest reduction in the CV of the coastal seal bycatch estimator. Increases of 5, 10, and 25 percentage points in the sampling fraction reduced the estimator CV from 0.32 to 0.18, 0.15 and 0.10, respectively. The second most efficient strategy was targeting the cod and angler fisheries (sim6, dashed black line with squares in Figure 4), which collectively constituted more than 50% of all the total gillnet fishery activity. Increasing the sampling fraction in region 1 (encompassing areas 03, 04 and 05; sim9, dashed light purple line with squares in Figure 4) reduced the estimator CV from 0.32 to 0.24, 0.23 and a more moderate 0.22, for 5, 10 and 25 percentage points increases, respectively. An increase of five percentage points in the sampling fraction of either the cod fishery (sim5), in season 1 (sim2), in the cod fishery conducted in season 1 (sim8) or in the cod fishery in region 1 (sim17) similarly reduced the estimator CV from about 0.33 to 0.27. Further increases in the sampling fraction in strata targeted by these four strategies, caused a greater reduction in the estimator CV. Increasing the sampling effort either in season 2 or only for the monkfish fishery in season 2 reduced the estimator CV only very moderately. The remaining simulation strategies led to smaller reductions in estimator CVs.

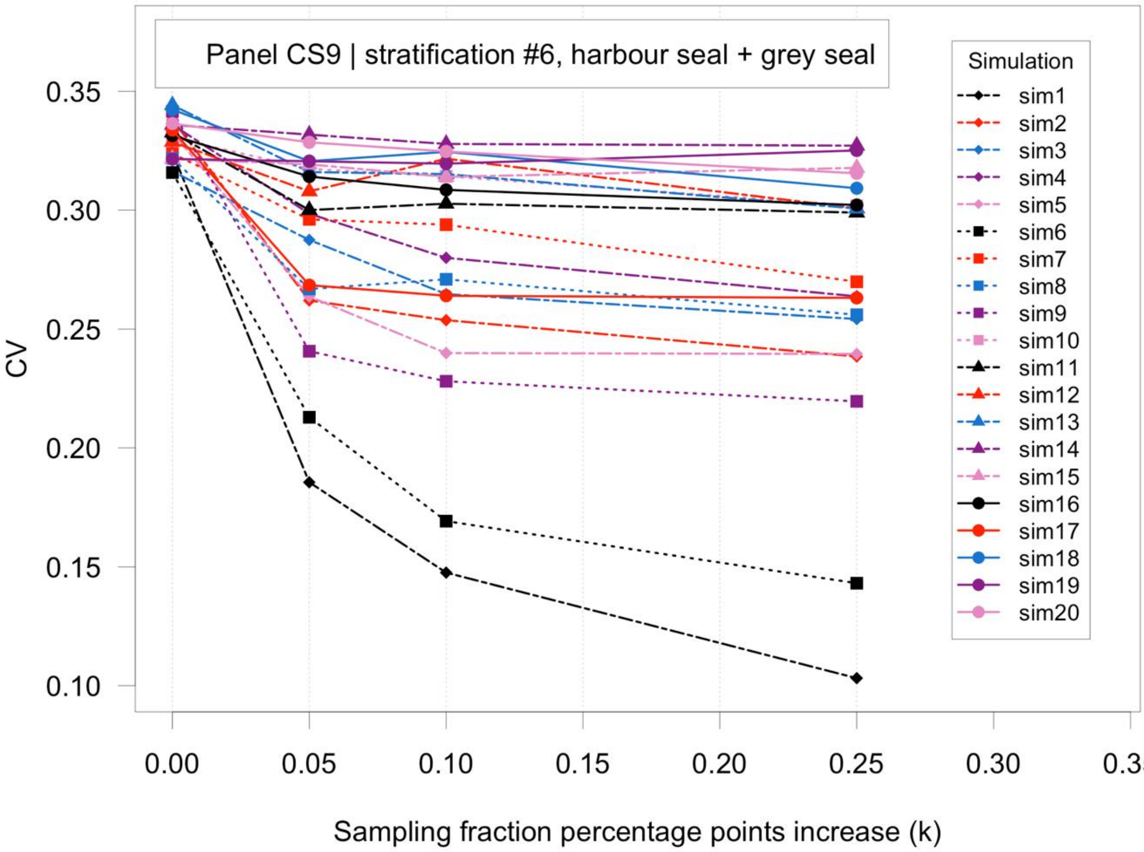

***Figure 4**: Change in seal bycatch estimator CV as the sampling fraction is increased in targeted strata using sampling strategies sim1 to sim20.*

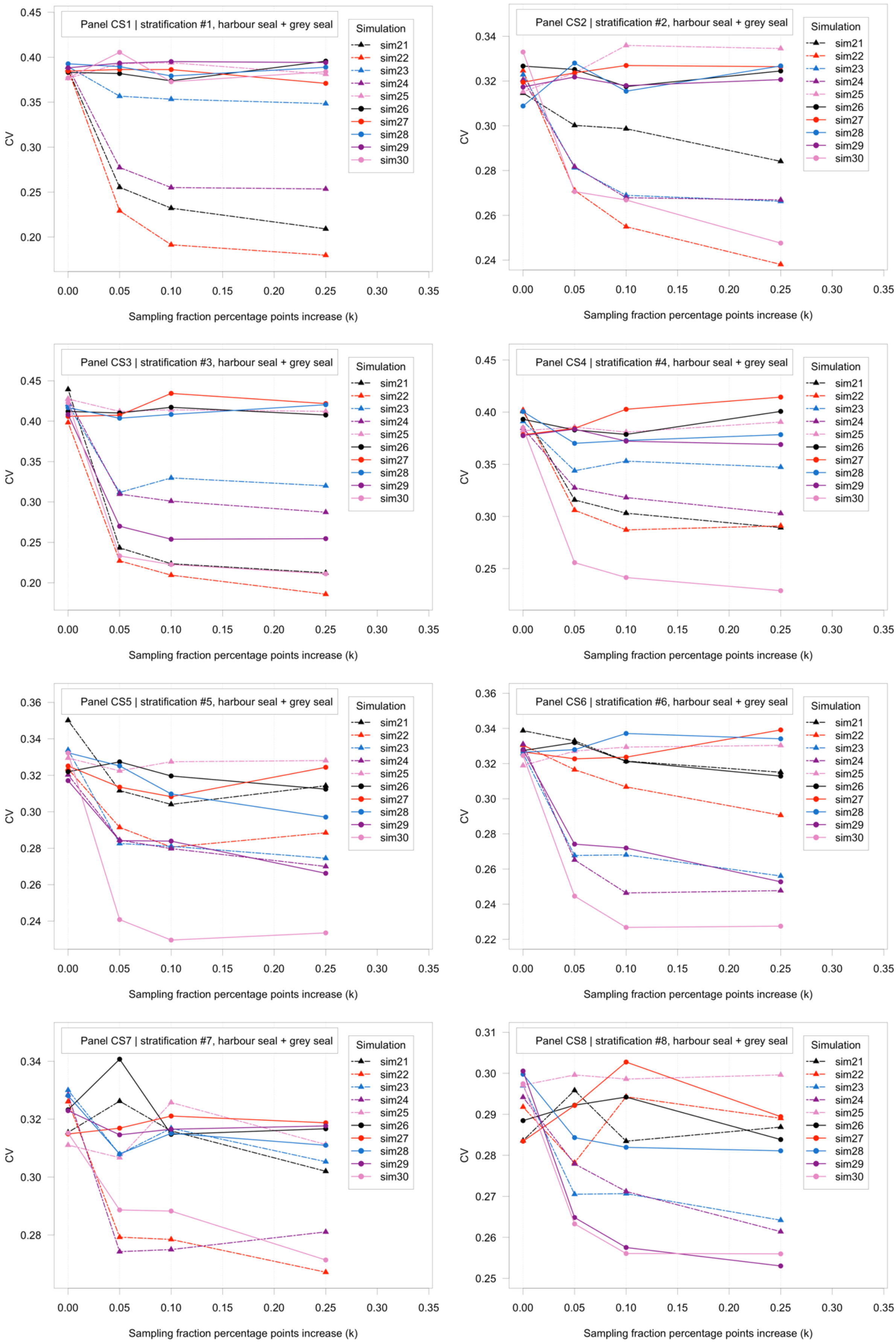

***Figure 5**: Change in seal bycatch estimator CV as the sampling fraction is increased in targeted strata using sampling strategies sim21 to sim30. Different panels show results for simulations using different stratifications. Panel A: month + area + fishery, panel B: month + region + fishery, panel C: month + area, panel D: season + area + fishery, Panel E: season + region + fishery, panel F: season + region + fishery, panel G: season + area, panel H: season + region.*

Harbour porpoise bycatch estimator

The CV of the harbour porpoise bycatch estimator was reduced the most by increasing the sampling fraction across all strata (sim1, dotdashed black line with diamonds in Figure 6). The resulting CVs were 0.09, 0.07 and 0.05 for k = 5, 10 and 25 percentage points, respectively. The second largest CV reduction was achieved by increasing the sampling fraction in the cod and angler fisheries (sim6, dashed black line with squares). Targeting the cod fishery (sim5, purple dotdash line with diamonds), season 1 (sim2, red dashed line with diamonds) or the cod fishery during season 1 (sim8, blue dotted line with squares) also caused large reductions in the estimator CV. Targeting region 1 (sim9, purple dotted line with squares) or the cod fishery in region 1 (sim17, red line with circles) caused moderate reductions in estimator CV and the remaining simulations strategies led to relatively smaller reductions in estimator CVs.

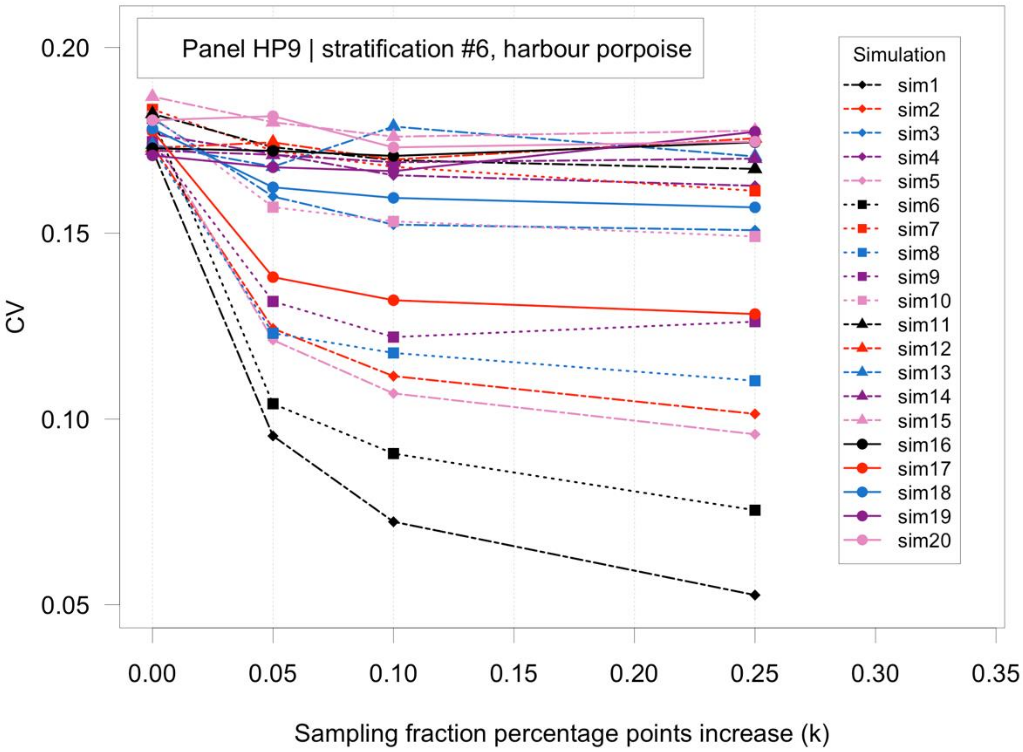

Figure 6*: Change in harbour porpoise bycatch estimator CV as the sampling fraction is increased in targeted strata using sampling strategies sim1 to sim20, using a season + region + fishery stratification (stratification 6).*

Amongst the general sampling strategies (sim21 to sim30), targeting the top 10% or 20% strata with the highest bycatch rates (sim20 and sim21) consistently achieved the lowest estimator CVs, except in the case of stratifications 7 (season + area) and 8 (season + region). Using stratifications 7 and 8 and targeting the top 20% strata with the highest fishing effort still achieved large reductions in estimator CV. Targeting the top strata with the lowest coverage also led to CV reductions of about 0.08. Targeting the top 10% strata with the highest fishing effort also led to great reduction in the estimator CV, except when stratifying by season + area.

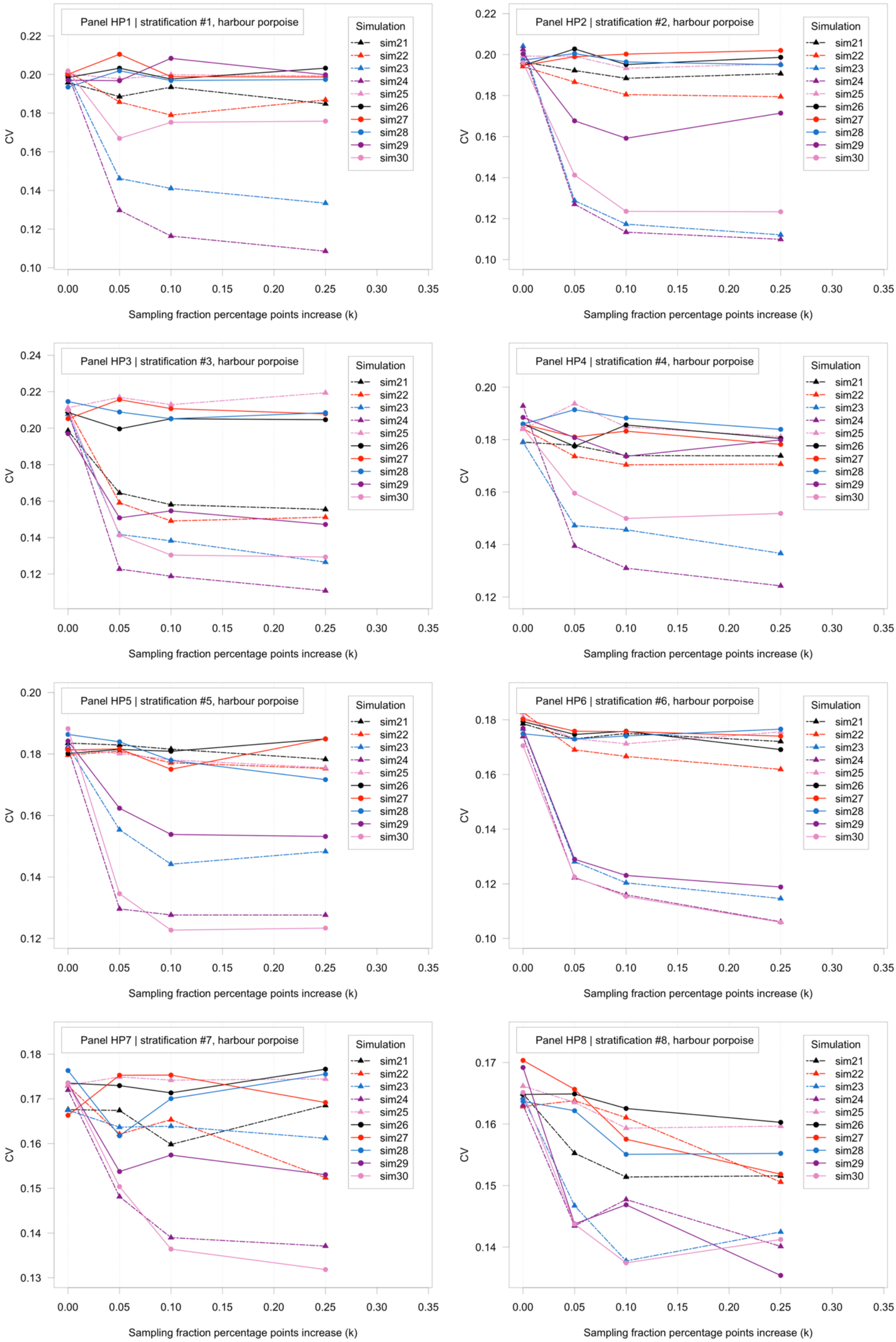

***Figure 7**: Change in harbour porpoise estimator CV as the sampling fraction is increased in targeted strata using sampling strategies sim21 to sim30. Different panels show results for simulations using different stratifications. Panel A: month + area + fishery, panel B: month + region + fishery, panel C: month + area, panel D: season + area + fishery, Panel E: season + region + fishery, panel F: season + region + fishery, panel G: season + area, panel H: season + region.*

Best strategies

The top three highest ranked sampling strategies for the two bycaught species groups and for different sample sizes (i.e. different values of k) are listed in Table 3, and a complete list of all rankings for all simulations run is available in APPENDIX2. Based on these rankings, the best strategies were to increase the sampling fraction in the top 10% and 20% strata with highest bycatch rates (sim21 and sim22) or in the top 10% and 20% strata with lowest fishing effort (sim27 and sim28). The ranking results were similar between the two species groups, but for estimating harbour porpoise bycatch, increasing the sampling fraction in the top 10% strata with the lowest coverage (sim29) ranked high, which was not the case for simulations estimating seal bycatch.

Table 3*: Overview of which sampling strategies most consistently yielded the lowest rank across all stratifications for each discrete increase in the sampling fraction.*

Species	**Sampling fraction increase (k)**	**Top ranked strategies**
Seal	5 percentage points	Sim #22, sim #27, sim #21
	10 percentage points	Sim #21, sim #22, sim #28
	25 percentage points	Sim #21, sim #27, sim #28
Porpoise	5 percentage points	Sim #21, sim #27, sim #29
	10 percentage points	Sim #21, sim #27, sim #28
	25 percentage points	Sim #27, sim #21, sim #28

DISCUSSION

Our results allow us to identify in which geographical locations and during what times and in which fisheries an increased CRF sampling effort would theoretically yield the greatest return in terms of increasing the precision of bycatch estimates derived from data collected in the CRF. Generally, increasing the sampling fraction increases the precision of the estimator, but there is a trade-off between precision and sampling size. Some of our simulations, which suggested a yearly sampling effort of observing more than 18 000 hauls, seem so high as to be unrealistic. Historical CRF data indicate that reference vessels haul on average 87 strings of nets every year. A sampling effort of 18 024 hauls would require a fleet of at least 207 reference vessels, as compared to the 24 vessels that currently serve in the reference fleet. However, other precision targets could be achieved with much smaller and more feasible sampling sizes.

Overall, our results suggest that it may be best to increase sampling effort in the strata that have the highest fishing effort and/or lowest coverage/sampling fraction, as well as in the cod fishery and/or during Season 1 (January to June). An increase in the coverage of the cod fishery would likely improve the precision of both seal and porpoise bycatch estimates. This latter finding fits well with our expectations, based on feedback received from fishermen. Even a moderate, five percentage points increase in sampling fraction in selected strata, could lead to greatly improved estimator precision. To increase the sampling fraction by five percentage points in the cod fishery in region 1, for example, would require an increased sample size of 900 extra hauls per year. However, the reference fleet currently operates with four-year contracts, so there is currently no feasible way of implementing some of the simulated scenarios. The usability of many of these simulations may therefore be greatly limited by practical, logistical, and financial concerns. It is possible that more easily applicable/realistic scenarios could be achieved by simulating the year-long activity of an increased number of vessels, and use that to determine the sampling fraction, rather than simulating increases in the sampling fraction in targeted strata, ignoring the vessel-level structure of the sampling design.

I originally wanted to distinguish between four fishery groups: angler, cod, saithe and everything else. But I was unable to reliably distinguish saithe hauls from cod and other hauls, so I had to put saithe in the "other" group. It would be nice to discuss other ways in which I can infer the correct fishery for a haul, given the information that is available to us. Perhaps a more wholistic analysis of catch composition could be used, where the presence and absence of key "mesh-size" indicator species could be used to determine the most likely fishery group. I was also unable to calculate bycatch rates based on catch/landed fish as a proxy for effort, because the simulation resampling method creates a disconnect between the hauls in the reference fleet and in the corresponding strata in the whole fleet. This means there is no way to determine the whole-fleet effort for a given stratum. However, I do not believe this is a major concern, because the number of hauls is arguable a better measure of effort than fish landed.

The reason I was unable to achieve the same CV reduction for bycatch estimates produced from simulations using stratifications 7 and 8 as with simulations using other stratifications was because of an error/bug in the program that determined which strata fulfilled the targeting criteria. The error manifested with stratifications that only had a small number of strata. Because of time constraints, I was not able to re-run the simulations before the production and write-up of this document, but the code has already been fixed, and future simulations will not have this problem.

The method used in this study constitutes a trade-off between practicality and usability. While artificially increasing the sampling fraction in a single stratum or in a specific set of strata at a time is very easy to do, it may also seem a very academic exercise with little applicability to real-life situations. In real-life, it is exceedingly unlikely that any given fishing vessel would operate only in a single stratum, for example just fishing for cod in region 2 during winter and spring (season 2) and have no activities outside of that particular stratum. Fishermen can and usually do operate in multiple regions and participate in multiple fisheries over the course of one year. Therefore, a better simulation approach might be to run the simulation on the vessel level, instead of on the stratum level, as was done in this simulation. Running the simulation on the vessel level would mean that the sampling fraction would be increased by adding more vessels to the simulated reference fleet. The sampling fraction would thus be increased not in one single stratum or in a set of strata, but in all strata in which the added vessels had operated. This would be more realistic, and the simulation results would be more easily translatable to real-life, and therefore more easily applicable. However, the simulation approach used in this study, while it has its shortcomings, would still be useful as a tool to inform in which strata the greatest return can be gained from increasing the sampling fraction.

In the future, I would like to do try more sophisticated simulations, in which I decrease the sampling fraction in one stratum and simultaneously increase it in another, thereby redistributing the effort from the former to the latter. I am also considering whether and how to simulate multiple years of data. It could also be useful do a higher-resolution analysis, increasing k in smaller increments for even finer control.

APPENDICES

Table APPENDIX1*: Tabulated results for all simulations run. Species designates either a combined harbour and grey seal bycatch estimator or a harbour porpoise bycatch estimator. Stratification refers to one of the eight stratifications listed in Table 1. Strategy refers to one of the strategies listed in Table 2. "k" is the percentage points increase in the sampling fraction in the targeted strata, bycatch is the "real" bycatch, estimate is the estimated bycatch, error is the MRE, and CV is the coefficient of variation.*

Table removed to save space and reduce file size, available from permanent Github link:
https://github.com/supermoan/bycatch_sim2019/blob/master/data/sampling_fraction.csv

Table APPENDIX2*: Calculated strategy ranks for coastal seal and harbour porpoise bycatch estimators. Ranks are based on the products of the estimator CV and the simulated total effort. Higher ranks are better. See main text for further explanation.*

Table removed to save space and reduce file size, available from permanent Github link:
https://github.com/supermoan/bycatch_sim2019/blob/master/data/ranks.csv

APPENDIX 4

Simulating pinger deployment scenarios to reduce harbour porpoise bycatch to within pre-defined sustainable limits

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June 2019

ABSTRACT
In Norway, about 3000 harbour porpoises (*Phocoena phocoena*) from a population of 168 759 animals, die from gillnet entanglements every year. This incidental bycatch is not sustainable by international standards, such as the ASCOBANS 1.7% target and PBR. The best tool for mitigating harbour porpoise bycatches is acoustic deterrent devices, which emit high-frequency pings that keep the animals away from the nets. I used a simulation approach to quantify the potential of such “pingers” to reduce the bycatch of harbour porpoises in Norwegian coastal gillnet fisheries and determine an optimal pinger implementation design. New bycatch data was generated by sampling with replacement on a per-stratum basis from observations in the Coastal Reference Fleet, and pinger effects were applied to fishing vessels using fish log data from the Directorate of Fisheries in a reiterative random selection scheme until predefined bycatch targets had been reached. The results suggest that equipping only a small fraction of the whole fleet, about 200 vessels, with pingers, could lead to a 30-50% total bycatch reduction, depending on the efficiency of the pingers. The corresponding reduction for 500 vessels was 36%-66%. Further increases in the number of vessels using pingers had diminishing returns in terms of bycatch reduction. It would take 120 - 650 fishing vessels with pingers on all nets throughout the year to reach a sustainable bycatch target of 1500 animals per year.

ABBREVIATIONS

CRF Coastal Reference Fleet
ASCOBANS Agreement on the Conservation of Small Cetaceans of The Baltic, North East Atlantic, Irish and North Seas
PBR Potential Biological Removal
ADD Acoustic Deterrent Device (pinger)

INTRODUCTION

Every day, throughout their range, harbour porpoises (*Phocoena phocoena*) unintentionally swim into bottom-set static gillnets, get stuck, and suffocate. The gillnets are intended for other commercial catch species, but marine mammal entanglement is nonetheless a frequent occurrence. Gillnet entanglement is arguably the greatest threat to marine mammals, and small cetaceans in particular, world-wide. In Norway, about 3000 animals from a population of 168 759 harbour porpoises, are killed in this way every year. There are two internationally recognized methods that can be used to evaluate whether a bycatch level of this magnitude is sustainable or not. The ASCOBANS recommends that harbour porpoise bycatch not exceed 1.7% of the best available population estimate. Based on the aforementioned population estimate, this amounts to 2869 animals per year. The USA uses an approach called Potential Biological Removal, that is based on the growth rate and the minimum expected population size. The PBR for the Norwegian harbour porpoise population (with Recovery Factor=1), is 1792 animals per year.

I therefore assert that the current level of harbour porpoise bycatch in the Norwegian coastal gillnet fisheries is too high to be acceptable given international standards for sustainable fisheries. The long-term population level effects of harbour porpoise bycatches in Norwegian fisheries are so great that it would be appropriate to take measures to mitigate this bycatch as soon as possible.

The best tool for reducing harbour porpoise bycatches is mounting acoustic deterrent devices (ADDs) on the offending gillnets. ADDs, commonly called “pingers”, emit high-frequency sounds that deter harbour porpoises from approaching the nets, thus preventing entanglement. The effectiveness of pingers in reducing bycatch in gillnet fisheries has been demonstrated in several independent studies. Results from our own experiments in Norwegian fisheries indicated a 70% harbour porpoise bycatch reduction in cod nets using pingers and a 100% harbour porpoise bycatch reduction in angler nets using pingers, but these results were not statistically conclusive. Nevertheless, under the assumption that pingers are as effective as other and my own studies have suggested, I use a simulation approach to quantify the potential of pingers to reduce the yearly bycatch of harbour porpoises in Norwegian coastal gillnet fisheries. I want to explore how pingers can be used to reduce harbour porpoise bycatch to within sustainable levels, and to answer questions such as how many pingers that are needed and how they should be distributed among fishing vessels, to maximize the per-pinger effect.

SIMULATION METHOD

To simulate the effect of pingers on harbour porpoise bycatch, I first needed to determine expected bycatch data for a full year of fishing activity. To do that, I used bycatch data from the Coastal Reference Fleet (henceforth referred to as “the CRF”), which is a monitored segment of the coastal fleet of small fishing vessels in Norway that have detailed records of their fishing operations. Each recorded haul in the CRF data was assigned to one of three fishery groups, based on catch composition. Hauls in which cod comprised 50% or more of the total catch were assigned to the cod fishery, and hauls in which anglerfish comprised more than 10% of the total catch were assigned to the angler fishery. All hauls that could not be classified as either ‘cod’ or ‘angler’ was classified as ‘other‘. To verify the fishery assignments, I used the same method to classify hauls in the CRF data, and compared the results with results from classifications using net mesh size instead. The catch composition method correctly identified about 80% of cod hauls, 90% of angler hauls and 86% of other hauls. The CRF data was then stratified by season, region and fishery, yielding a total of 24 strata per year. 'Season' was a factor variable with two levels: season 1 and season 2. '*Region'* was a factor variable with four levels: region 1, 2, 3 and 4 (Figure 1).

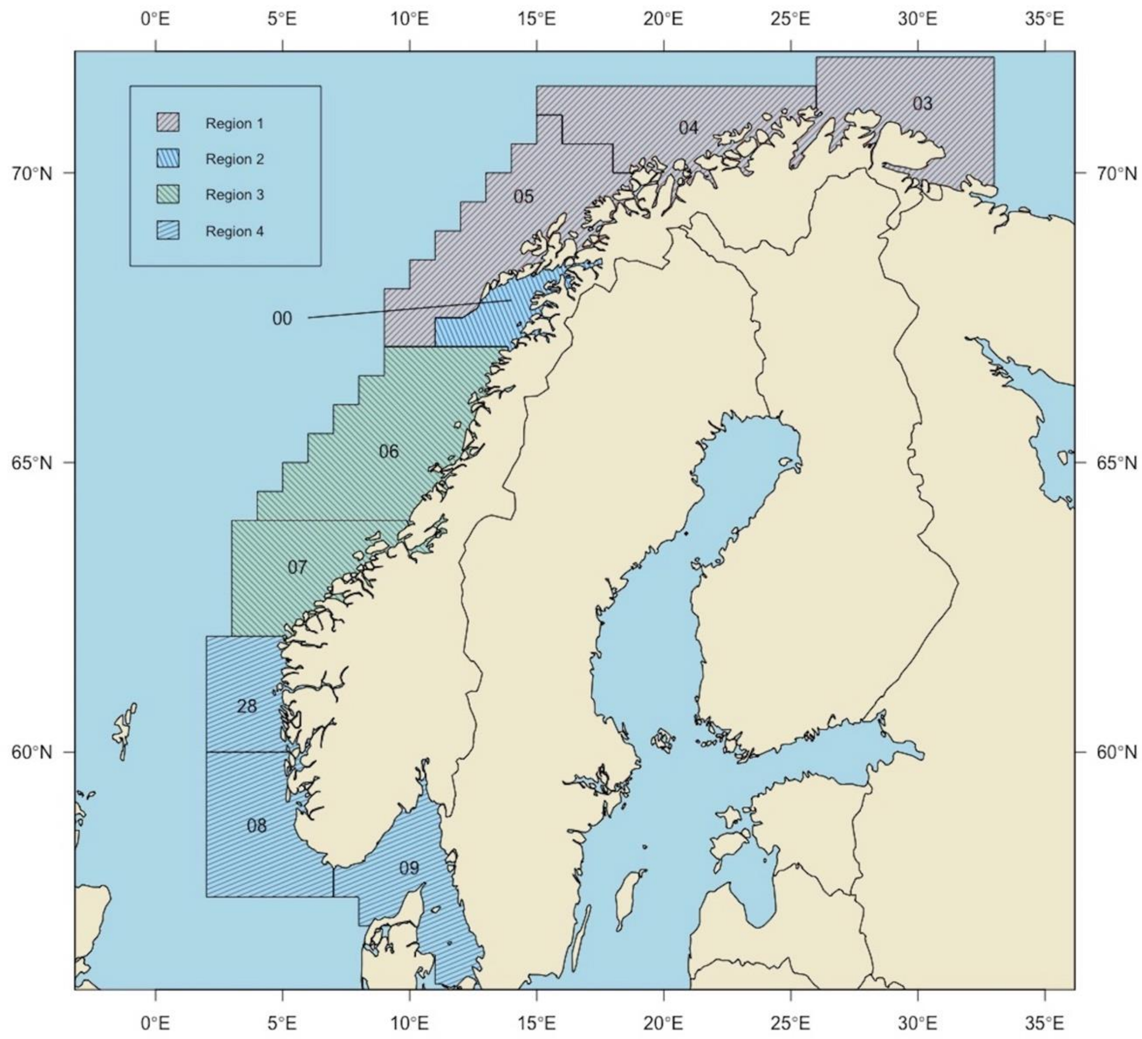

Figure 1*: Map of the study area, showing the nine administrative / statistical areas (labelled 03, 04, 05, etc.) along the Norwegian coastline, and an alternative division of the coastline into larger regions (as designated by the different background colours; see plot legend).*

Data from strata that had not been covered by the CRF in a specific year were estimated from averages in data from corresponding strata for other years. Harbour porpoise bycatch rates were estimated for each stratum using both *catch* and *number of hauls* as proxies for fishing effort. Total bycatch for each year was then estimated by multiplying bycatch rates with the corresponding effort data for the whole fleet of small coastal fishing vessels. Whole fleet data was obtained from fish logs in a national database maintained by the Directorate of Fisheries. The mean of each group (e.g. catch-based or hauls-based) of yearly bycatch estimates was considered the expected yearly bycatch. Since hauls, which in many Norwegian coastal fisheries roughly corresponds to Days-at-Sea, is an a priori more realistic estimate for fishing effort, I elected to use hauls in the denominator of the ratio estimator for our simulations.

I picked the year for which the estimated total bycatch came closest to the expected bycatch based on all years and used data from that year as a basis for the simulations. Bycatch was assigned to each haul in the whole-fleet fishery data from the selected year on a per-stratum basis by using a stratified random sampling design, sampling with replacement from CRF bycatch data from that same year. This allowed us to approximate a complete bycatch dataset on the haul-level, while also preserving structural information in the data, such as which vessels operated where, when and with what effort.

To apply pinger effects, I reiteratively picked a random vessel without replacement from all vessels in whichever stratum had the highest harbour porpoise bycatch rate. The number of harbour porpoises bycaught in all nets hauled by that vessel for the whole year was multiplied by the pinger "effect", where the effect was specified as a fraction $p \in [0,1)$ and not differentiated by fishery. I used $p = [0.1, 0.3, 0.5]$, which would correspond to 90%, 70% and 50% reductions in bycatch, respectively. The total bycatch for all vessels was then recalculated, now factoring in the effects of having pingers on nets set by the selected vessel, and this procedure was repeated until the total simulated bycatch reached a predefined sustainable target, or a maximum number of vessels with pingers. I defined a conservative value of 1000 harbour porpoises per year to be "sustainable" and used 1500 vessels with pingers as the maximum.

I ran 1000 replicates of the simulation. Means and standard deviations were calculated from the resulting distributions of results, with the prime statistic being the number of vessels with pingers required to achieve the set bycatch target.

PRELIMINARY RESULTS

Harbour porpoise bycatch point estimates for individual years are shown in Table 1 for the 13 years of data that have so far been recorded by the CRF vessels. Estimates calculated using hauls as a measure of effort and estimates calculated using catch as a measure of effort agree quite closely, but the former set of estimates were on average about 10% higher than the latter. The year to year variation was quite large for both sets, spanning from 1145 to 4488 animals for catch-based estimates, and from 1156 to 4613 animals for the hauls-based estimates. There were especially large deviations from the set means for the 2012 and 2013 estimates. The smallest deviation from the set means were the 2018 estimates. In our simulations, I therefore used data from 2018 as an approximation to the "expected bycatch and fishing effort" in an average year.

Allocating CRF bycatch to individual hauls in the whole-fleet fishing data from 2018 resulted in a simulated total yearly bycatch of 2506 ± 66[2] harbour porpoises (mean ± sd from 1000 replicates), which was close to the average estimated value given in Table 1.

[2] Standard deviation derived from 1000 replications (reallocations and recalculations)

Results from running the pinger simulation algorithm on simulated bycatch data are shown in Figure 2, for three different pinger effects: 50% (black line), 70% (blue line) and 90% (red line). The lines and dashed areas represent the means and standard deviations, respectively, of all replicates under each simulated pinger effect. The open circles on each line represent "stratum saturation points", which indicate when the sampling algorithm switched from sampling vessels in one stratum to sampling vessels from the next stratum. Note however that while vessels may have been sampled from one particular stratum, pinger effects for sampled vessels were applied to all hauls associated with those vessels in *all* strata in which those vessels operated. The total simulated bycatch numbers shown therefore reflect reductions across multiple strata.

Table 1*: Estimated bycatch per year. Bycatch refers to the number of harbour porpoises bycaught in a year. Difference is the difference between estimates using catch and hauls as effort variables in the denominator in the stratified ratio estimator.*

Year	**Bycatch**		**Difference**	**Percentage difference**
	Effort: catch	**Effort: hauls**		
2006	3813	3672	141	3.85%
2007	1562	1784	-221	-12.40%
2008	4488	4747	-259	-5.46%
2009	3107	2835	272	9.58%
2010	3322	3781	-460	-12.15%
2011	1668	1671	-3	-0.18%
2012	3686	4613	-927	-20.10
2013	2811	3841	-1030	-26.81
2014	1222	1643	-421	-25.63
2015	1145	1156	-11	-0.96
2016	1172	1308	-136	-10.42
2017	1507	1457	50	3.44
2018	2617	2986	-370	-12.37
Average	**2471**	**2730**	-259	-9.49%

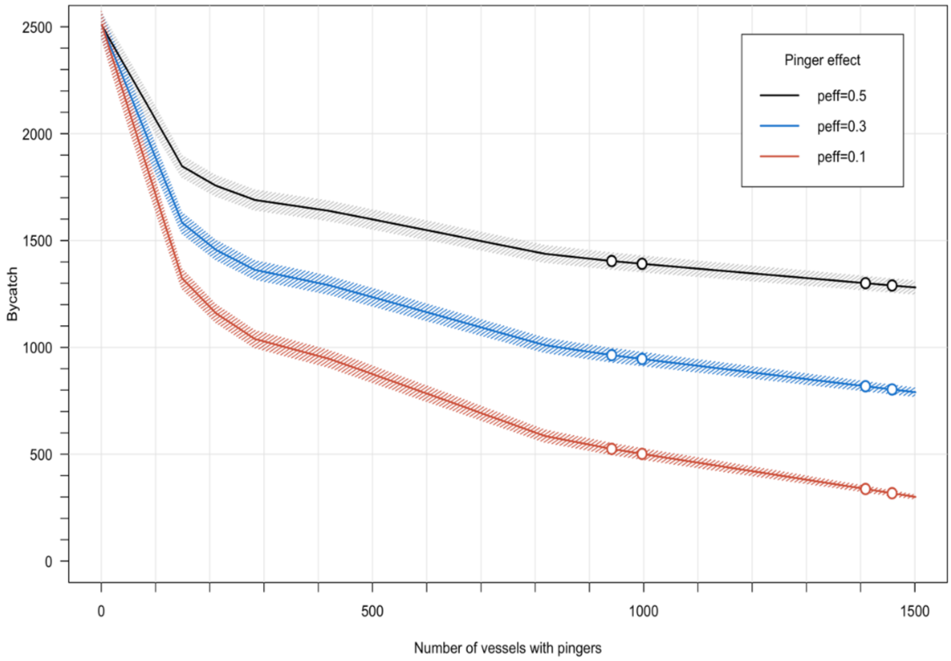

Figure 2*: Total simulated bycatch for different numbers of vessels using pingers, assuming a pinger bycatch reduction effect of 50% (black line), 70% (blue line) and 90% (red line). The shaded areas represent 1SD. Open circles indicate stratum saturation points. Number of replicates: 1000.*

The first 200 vessel selections caused a dramatic drop in bycatch, reducing the total simulated bycatch from the initial value of about 2500 to approximately 1800, 1500 and 1200 animals per year for the 50%, 70% and 90% pinger effect simulations, respectively. Subsequent vessel selections continued to reduce bycatches, but at decreasing rates, as can be seen from the gradual flattening of the curves in Figure 2. If the set bycatch target were 1500 porpoises per year, which is within the PBR, then it would take approximately 700, 300 or 120 vessels using pingers on all nets throughout the year to reach that target, assuming 50%, 70% and 90% pinger reduction effects, respectively. If on the other hand, the bycatch target were 1000 porpoises per year, then it would take 900 or 300 vessels using pingers, assuming 70% and 90% pinger reduction effects, respectively. Assuming a 50% pinger bycatch reduction effect, the simulated total bycatch was reduced to approximately 1300 porpoises per year after having selected 1500 fishing vessels. The simulations were limited to a maximum of 1500 vessel selections, and so were unable to reach a bycatch target of 1000 animals per year for 50% pinger effect simulations.

The individual contributions of each fishery group to the total simulated bycatch in the 50%, 70% and 90% scenarios are shown as stacked line charts in Figure 3, Figure 4 and Figure 5, respectively. In the 50% scenario, the contribution of the angler fishery to the total simulated bycatch was almost halved after selecting about 200 vessels, with very small reductions in the other fisheries in the beginning. Note that the maximum bycatch reduction possible is effectively limited by the pinger effect, e.g. a pinger effect of 50% allows a maximum bycatch reduction of 50%. Overall, for the 50% pinger effect scenario, most of the initial bycatch reduction came from pingers on vessels targeting anglerfish, and subsequent reductions came mostly from reducing bycatch in the cod fishery, and, to a smaller extent, in other fisheries.

The bycatch reduction in the angler fishery tapered off completely after about 280 vessel selections. The bycatch in the angler fishery was not further reduced at all with additional selections, because the maximum reduction possible, given the 50% pinger effect, had already been achieved.

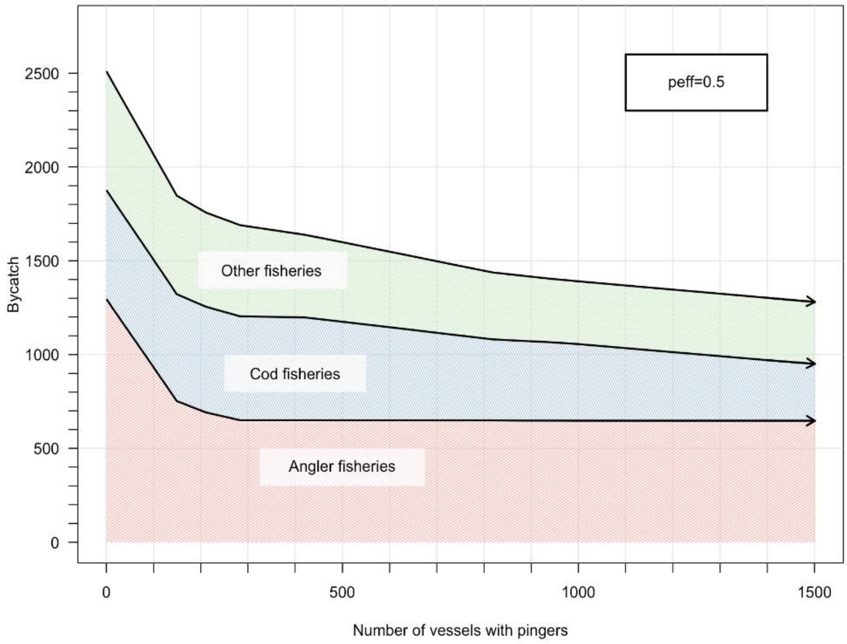

***Figure 3**: Stacked line charts showing the fishery components of the total simulated bycatch of harbour porpoises, as the number of vessels using pingers was increased in simulations with pinger effects of 50%. Number of replicates: 1000.*

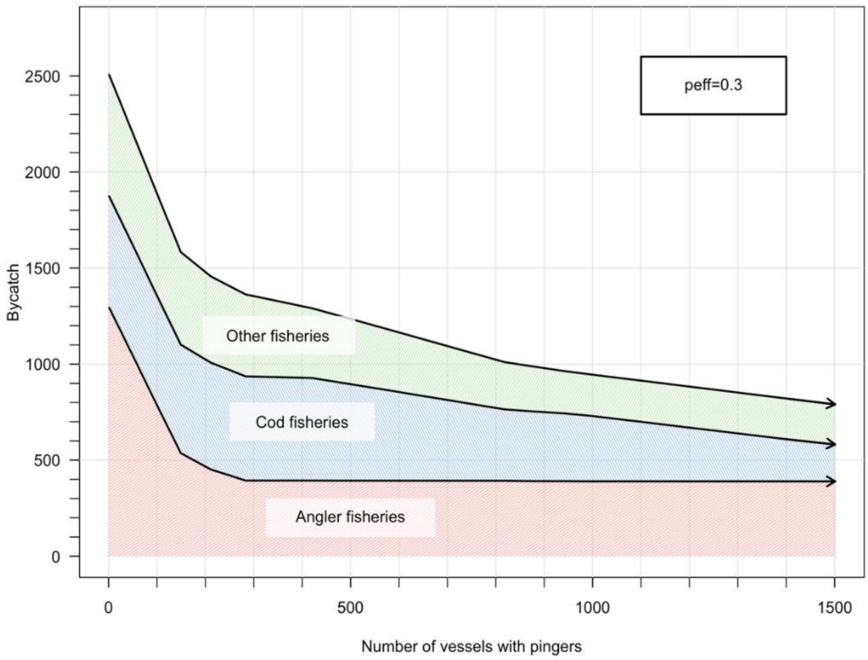

***Figure 4**: Stacked line charts showing the fishery components of the total simulated bycatch of harbour porpoises, as the number of vessels using pingers was increased in simulations with pinger effects of 70%. Number of replicates: 1000.*

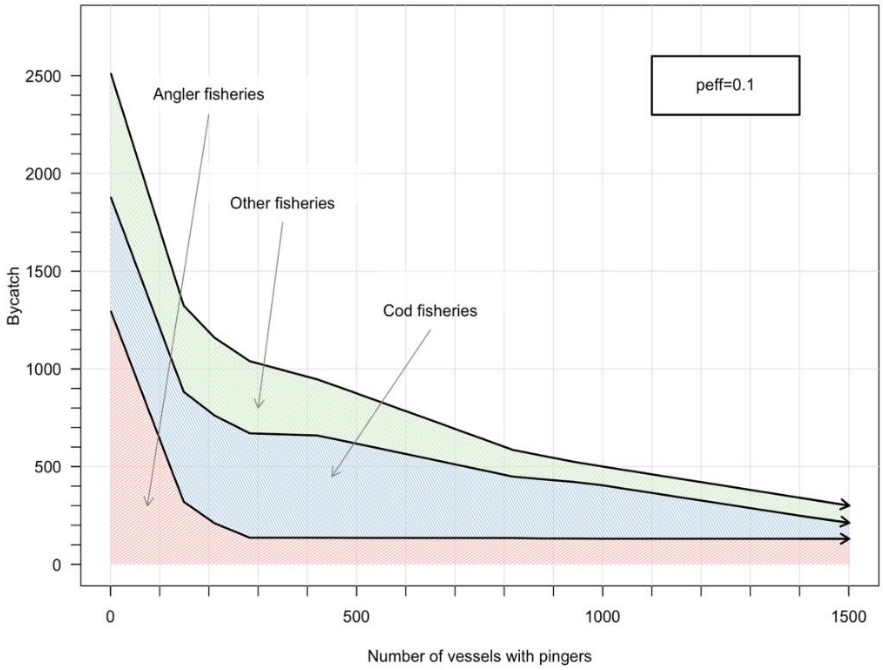

***Figure 5**: Stacked line charts showing the fishery components of the total simulated bycatch of harbour porpoises, as the number of vessels using pingers was increased in simulations with pinger effects of 90%. Number of replicates: 1000.*

In the 70% and 90% scenarios, bycatch reductions in each of the fisheries followed the same pattern as in the 50% scenario described above, with an initial large reduction mostly in the angler fishery, that quickly taper off, with further reductions coming from the cod fishery and other fisheries. The maximum reduction possible in the angler fishery was achieved after 280 vessel selections in both the 70% and 90% scenarios, but the magnitude of those reductions reflected the increased pinger effects.

Based on the detailed fish logs in the CRF, I could ascertain that the average number of nets shot at a time were 88 in the cod fishery and 218 in the angler fishery. I did not calculate the average number of nets for the last fishery group, because that group encompassed a wide range of different fisheries. Assuming a pinger spacing of 200m, the number of pingers needed per typical string of nets would be:

(79 nets * 27.5 m) / (1 pinger / 200 m*nets) = 11 pingers (cod fishery)
(173 nets * 27.5 m)/ (1 pinger / 200 m*nets) = 24 pingers (angler fishery)

Fishing vessels in the Norwegian fleet typically operate with multiple sets of nets, hauling one set, and then immediately shooting the next. To account for this, we assumed that each vessel would need at minimum 50 pingers to be able to have pingers on all their nets. This would allow for the use of two net strings of average length. An overview of the total numbers of pingers to achieve different bycatch targets under different simulation scenarios is given in Table 2.

Table 2*: Minimum estimates of the number of pingers needed to obtain different harbour porpoise bycatch targets given different pinger effects, assuming that pingers are mounted on gillnets with a spacing of 200m. All numbers approximate.*

Pinger effect	Number of vessels required to achieve target	Assumed number of pingers per vessel	Total number of pingers needed
Bycatch target: 2000 porpoises per year			
50%	120	50	6 000
70%	80	50	4 000
90%	60	50	3 000
Bycatch target: 1500 porpoises per year			
50%	700	50	35 000
70%	200	50	10 000
90%	120	50	6 000
Bycatch target: 1000 porpoises per year			
50%	>1500	50	> 75 000
70%	900	50	45 000
90%	300	50	15 000

DISCUSSION

The perhaps most important assumption that I have made in this study is that vessels that use pingers use them on all nets and throughout the year in all gillnet fishing activities. It is assumed that the pingers operate as intended, and that they are actively maintained (to whatever degree they need to be maintained, e.g. redoing mounting knots, changing batteries, or replacing lost or defective units) by the crew. To clarify, using pingers on “all nets” does not mean that each individual gillnet has one pinger. Individual gillnets used by Norwegian fishing vessels are each 27.5 meters long and arranged in long strings of multiple nets tied together. These strings can contain up to 500 nets and span up to 13.75 km. However, CRF data indicate that strings typically contain 80 nets (which would make them 2.2 km long). The actual length of the strings depends on a combination of many different factors, such as the capacity of the vessel to carry gillnets (may be limited on small vessels), the fish species being targeted and the expected catch (length goes down as expected catch goes up). Therefore, to be conservative, estimates of the number of pingers needed to fully equip the required number of vessels should use the greatest expected length of net strings. Such an estimate would further assume that pingers are moved from one type of gillnet to another when the fishermen switch from one fishery to the next, e.g. by fishing anglerfish in November and December, and then fishing cod and saithe in January and February. In reality, however, many fisheries are concurrent/simultaneous. A fisherman could set angler nets on Monday, and then set and haul multiple cod nets in the following days, before finally hauling the angler nets again on Thursday or Friday. This would further increase the number of pingers required per vessel, because in cases where both sets of nets are in use at the same time, moving pingers from one type of net to another would not be possible. However, I have assumed that pingers are mounted on nets with a spacing of 200 m. It is possibly that this spacing distance can be increased to 300 m or maybe even 400 m without significantly affecting the ability of the pingers to deter harbour porpoises from approaching the nets.

The way observed bycatch data in the CRF is “expanded” to the whole fleet by sampling with replacement from the CRF data means that no assumptions are made about the bycatch distribution, or any parameters thereof, other than that the observed bycatches are representative for all bycatches. One problem with the current implementation of the bycatch expansion algorithm is that even in the coarse stratification that has been used in this study, the CRF data does not cover all strata in all years. Because the CRF consists of only around 20 fishing vessels, the sampling scheme is vulnerable to unforeseen circumstances, such as prolonged spells of bad weather, machinery or engine-related technical problems and personal or health issues that may prevent the fishermen from fishing. If any of the above were to occur for any one reference vessel or crew, that could lead to one stratum not being fully covered, or not covered at all. Stratifying the CRF data by season, region and fishery results in one to three completely unobserved strata each year. The particular unobserved strata vary from year to year. Even though some particular strata may not have been covered by the CRF in a given year, there would still be fishing vessels operating there. This means that the bycatch generation routine is negatively biased, i.e. bycatch is underestimated. One possible way that this could be solved is to use bycatch data from another year, or averaging from several other years, as a “best guess” for those strata when assigning bycatch, but this was not implemented in this study.

I believe the simulations could be further improved if it were somehow possible to construct an "average" year of fishing and bycatch data, rather than operate based on logs from on one specific year. One way that this could be achieved is by first calculating the expected number of hauls in each stratum, and then, in a reiterative process, choose a vessel and a year at random, and construct data by including all hauls by that vessel from that year, repeating this process until the number of hauls in each stratum fits reasonably well with the expected number of hauls. This "fitting" could be done heuristically by running a large number of replicates of the reiterative process and choosing the closest match. Another, perhaps better, and more robust way to do this could be to rerun the entire simulation for each year of fish logs that are in the complete dataset, and then average the simulated bycatch for each vessel selection.

The way that strata are targeted could also be non-optimal. The targeting algorithm selectively targets the strata with the highest bycatch rates, but not the strata that altogether have the highest bycatch numbers. The bycatch rates are calculated before any pinger effects are applied, and so the order in which strata are targeted is determined initially and does not change after that. Furthermore, there is no "sanity checking" of pinger allocations, so that in the most extreme case, one stratum could theoretically be completely saturated (i.e. all vessels use pingers), while an adjacent stratum would go completely pinger-free. In reality, however, this is not likely to occur since vessels operate in multiple strata. Even so, it is still possible that the "pinger load" would be very unevenly distributed among strata. This could be fixed by implementing a maximum percentage "pinger load" in each stratum. Once some pre-defined stratum pinger load is reached (for example of 50%), the algorithm would move on to the next stratum in line. Alternative strategies could be to target the strata that have the highest bycatch numbers instead of the highest bycatch rates, and/or to recalculate per-stratum bycatch rates in each iteration of the algorithm after applying pinger effects to the selected vessel. In this way, strata can be more dynamically targeted.

Other minor concerns include the following:

- The great majority (80%) of bycatch observations in the CRF are of a single animal. Simulating the effect of pingers on a bycatch of one porpoise would reduce the bycatch down to a fraction of one porpoise. This makes no sense on the haul-level, as you cannot usually catch half an animal or a third of an animal. But for the purpose of this analysis, which only considers the per vessel, per stratum or total summed bycatch, fractional bycatch still make sense. If a vessel had bycaught one harbour porpoise on two separate trips, and allocating pingers to that vessel reduced its bycatch to 0.5 porpoises per trip, then that could be interpreted as one trip having no bycatch, and one trip having a bycatch of one porpoise. But I would still like to make a note of this so that other participants in the workshop can comment on it.
- Should bycatch be reallocated in each replication of the simulation, or should this allocation be done initially, and then used for all replicates of the simulations?

In summary, there are still technical details that need to be worked out, but I believe that the method demonstrated in this manuscript is largely appropriate for answering the question at hand: how many vessels would need to use pingers on all nets throughout the year for the Norwegian small vessel fleet as a whole to achieve different bycatch reduction goals, and in which regions and during what times should those pingers be used? More refined simulation studies, for example, where pingers are used only on either cod or monkfish gears, are also possible (and certainly realistic), but have not yet been done because of time constraints.