Pinger trials in Norwegian commercial fisheries confirm that pingers reduce harbour porpoise bycatch rates and demonstrate low level of pinger-associated negative impacts on day-to-day fishing operations

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Abstract
A field trial was conducted to determine the effect of acoustic deterrent devices (ADDs, or pingers) on harbour porpoise (*Phocoena phocoena*) and harbour seal (*Phoca vitulina*) bycatch in three Norwegian commercial gillnet fisheries targeting cod (*Gadus morhua*), saithe (*Pollachius virens*) and monkfish (*Lophius piscatorius*). Catch data on 2,658 net-km-days were collected by 8 fishing vessels operating gillnets in high bycatch regions over two years. A total of 19 harbour porpoises and 9 harbour seals were bycaught, with *all* harbour porpoises and 67% of harbour seals taken in control (non-pingered) nets. Bycatch was modelled using a generalized linear mixed modelling approach and fitted with penalized maximum likelihood. Modelling results indicated that using pingers on gillnets reduced the risk of bycatching a harbour porpoise by an estimated 96.9% (95% CI 95% - 98%) compared to ordinary pinger-free nets. The effect of pingers was not significantly different between different fisheries. The pingers also had no significant effect on catch rates of fish (Wilcoxon rank sum test, p = 0.61) or harbour seals (Wilcoxon rank sum test, p = 0.25). Self-reported pinger-associated extra time costs on day-to-day fishing operations were low, averaging about 2.8 minutes per operation. These results add to a growing body of scientific evidence that pingers can lead to substantial reductions in harbour porpoise bycatch rates in gillnet fisheries, and that extra time costs associated with operating nets with pingers are low.

Key words: harbour porpoise, bycatch, mitigation, acoustic alarms, pingers

Abbreviations

CPUE	Catch Per Unit Effort
PBR	Potential Biological Removal
ADD	Acoustic Deterrent Device
CRF	Coastal Reference Fleet
GLMM	Generalized Linear Mixed Model
OR	Odds Ratio
LO	Log Odds
ML	Maximum Likelihood
CI	Confidence Interval, 95% unless otherwise noted
BCa	Bias-Corrected and Accelerated (bootstrapped confidence interval)
SD	Standard Deviation

TNTRODUCTION

The unintentional entanglement of marine mammals in fishing gear, more colloquially termed *bycatch*, has recently driven one small cetacean species to extinction (Turvey et al. 2007). Additionally, 11 other species, subspecies or populations of small cetaceans listed as Critically Endangered on the IUCN Red List (Brownell Jr et al. 2019) also suffer severe risk of getting bycaught. It has been estimated that, globally, more than 650,000 marine mammals are incidentally caught in fishing gear every year (Read et al. 2006) . Most of these bycatches occur in gillnets (e.g. Dawson and Slooten 2005; Jefferson and Curry 1994; Read et al. 2006). In 2018, the total capture fisheries landed 97 million tonnes of fish with a first-sale value of USD 151 billion (FAO 2020). Small scale coastal, or artisanal, fisheries make up the vast majority of global fishers, produce about half of global annual fish catch and provide most of the fish for human consumption in the developing world (Berkes et al. 2001). Gillnets are widely used all over the world, and in particular in small-scale coastal fisheries. They can be operated from small vessels with modest fuel costs and have a low impact on the sea floor compared to towed gear (Savina et al. 2017; Suuronen et al. 2012). Gillnets in modern nylon materials are long-lasting and the costs of replacing damaged nets are low (Sinclair et al. 2002). The catchability of a gillnet depends on the size and shape of catchable animals (Carol and García-Berthou 2007; Hamley 1975), and the particular mesh size of any given gillnet therefore confers some degree of species specificity to that catchability. Even so, gillnets may still incidentally catch other species, including marine megafauna such as marine mammals.

Because gillnets are widely used in coastal small-scale fisheries and provide income and food in many coastal regions globally, reducing marine mammal bycatches is a matter of increasing urgency. As toothed whales have a well-adapted hearing system (Ketten 1994; Miller and Wahlberg 2013; Nachtigall and Supin 2008) that they use for echolocation, several methods have been explored for modifying gillnets and their properties to increase acoustic detectability for these animals. This includes increased stiffening (Bordino et al. 2013), light emitting diodes (Bielli et al. 2020), nylon barium sulphate (Koschinski et al. 2006; Mooney et al. 2004; Trippel et al. 2003), iron-oxide gillnets (Larsen et al. 2007) and passive acoustic reflectors (Kratzer et al. 2020). However, acoustic alarms, or acoustic deterrent devices, ADDs, often called pingers, have seen the widest application (FAO 2021). The ability and effectiveness of pingers in reducing small cetacean bycatch has been demonstrated in many experiments and full-scale fishery trials (e.g. Barlow and Cameron 2003; Bordino et al. 2002; Carretta et al. 2008; Kraus et al. 1997; Mangel et al. 2013; Omeyer et al. 2020; Palka et al. 2008). Several of these experiments have shown that pingers can potentially reduce bycatch of small cetaceans by 70-100%. Pinger use has been made mandatory in some US and EU gillnet fisheries.

In Norway the average annual bycatch of harbour porpoise (*Phocoena phocoena*) in commercial small-vessel gillnet fisheries was 2,871 animals in the period 2006 - 2018 (Moan et al. 2020), with an unknown number also being taken in recreational fisheries and by larger commercial vessels. The Potential Biological Removal (Wade 1998) for Norwegian porpoises is 2,542 animals per year. Given that the average yearly bycatch is above the PBR, international conservation limits suggest that mitigation action is warranted. Bycatches of other small cetaceans in Norway are negligible (Moan et al. 2020), although grey (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*) are also frequently taken in gillnets. Most of incidentally caught marine mammals are taken in large-mesh, bottom-set gillnets targeting cod (*Gadus* *morhua*), stretched mesh sizes 156 – 220 mm), saithe (*Pollachius virens*), stretched mesh sizes 66 – 132 mm, and monkfish (*Lophius piscatorius*), stretched mesh size 360 mm. Our field trials aimed to 1) determine how effective pingers are as bycatch mitigation measures in these three Norwegian commercial gillnet fisheries, 2) to investigate the durability of the pingers under the physical stresses they are exposed to during setting and hauling of nets, and 3) to investigate how much extra time and effort their use involves for the fishers.

MATERIALS AN METHODS

Data collection

Study participants were recruited from among skippers on Norwegian fishing vessels that used gillnets to catch cod, saithe and monkfish in regions that had a high proportion of harbour porpoise bycatches (Figure 1). These regions were identified based on bycatch data collected by the Norwegian Coastal Reference Fleet (CRF), which is a group of about 30 vessels that is designed to be representative for the nation-wide commercial fleet of small fishing vessels (less than 15 meters length overall). Lists with names and contact information for potential participants were obtained from local divisions of the Norwegian Fishermen's Association (Norges Fiskarlag, www.fiskarlaget.no). Additionally, a few members of the CRF were also offered the chance to participate. The reason for including CRF members was that they were considered to have a proven record of reliability and long experience with scientific sampling. A simulation study was conducted before entering into any agreements with CRF fishers, to investigate to what extent CRF vessels could be included without compromising the accuracy and precision of marine mammal bycatch estimates derived from CRF reported data.

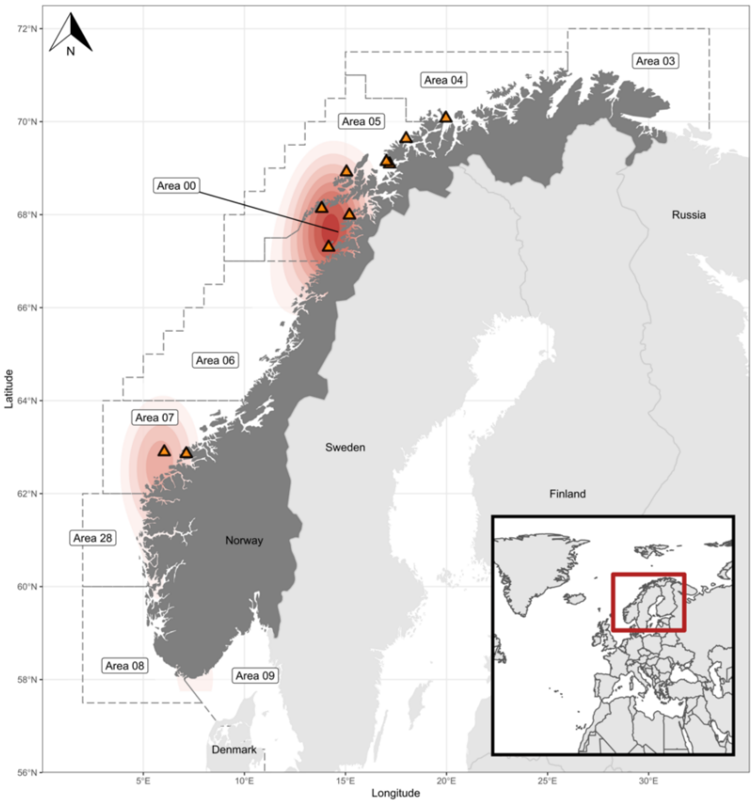

Fig. 1: Map of study region, with Norway highlighted in dark grey. White-red ellipses indicate regions of high harbour porpoise bycatch intensity. Orange triangles indicate home ports of fishing vessels that participated in the pinger trials. Dashed lines delineate coastal fishery statistical areas. The inset map shows Fenno-Scandinavia in its wider geographical context.

All participants were contacted initially by phone and interviewed to determine participation eligibility. The criteria were that the fishers used bottom-set gillnets to catch cod and monkfish, with a minimum seasonal effort that roughly corresponded to a typical small commercial fishing vessel, and that they were able and willing to do the extra work that handling the pingers and filling out detailed catch logs would involve. A total of eight participants were selected, four of whom were CRF vessels. Participants were sent a copy of a study protocol written specifically for them, that included explanations of the purpose and set up of the trial, in layman's terms, with illustrated instructions on pinger use and data reporting. After participants received the protocols, a second phone call was conducted, during which the protocol was explained verbally, and critical points emphasized. Fishers were also given the opportunity to ask any questions they may have had and encouraged to keep in touch frequently. We tried to meet all participants face to face at least once. Participants from among the CRF vessels were met with during their annual meeting, and non-CRF participants were visited on their vessels. We made an effort to establish and maintain a good relationship with all participants.

Two types of pingers were used; the Banana pinger by Fishtek Marine Industries and the Dolphin pinger by Future Oceans. A comparison of some of their technical specifications is given in Table 1. This study was not indented to compare the efficiency of the two types of pingers; but rather to compare nets with pingers to nets without pingers, as stated previously. The two types of pingers were considered equivalent. Study participants were therefore shown pictures and given a description of both types of pingers and asked whether they thought one would work better than the other with the hauling equipment that they used on their vessels. These wishes were accommodated as far as possible, but with the limitation that both types of pingers must be in use by multiple vessels. Pingers were sent to fishers by mail or delivered by a researcher during an on-site visit.

Table 1: Comparison of some specifications of the two types of pingers tested, the Banana pinger produced by Fishtek Marine Industries and the Dolphin pinger produced by Future Oceans.

Pinger type	**Fishtek Banana pinger**	**Future Oceans Dolphin pinger**
Frequency of ping	50 – 120 kHz (randomized)	70 kHz
Duration of ping	400 ms	400 ms
Ping loudness	154 dB	132 dB
Ping interval	4 – 12 seconds (randomized)	4 seconds
Battery time	4,380 hours	4,380 hours

Pingers were attached to the float-line of cod, saithe and monkfish nets and spaced at approximately 200 meters intervals. These three fisheries, i.e., the cod, monkfish and saithe fisheries, comprised the fishery groups referred to in the next sections.

To compare bycatch rates in nets with and without pingers under similar conditions, participants were instructed to activate the pingers during "odd weeks" (i.e., weeks with odd week numbers, e.g., week 1, week 3, etc.) and deactivate them during "even weeks", so that each vessel could serve as its own control. This was also meant to eliminate the chance of having control nets set in close proximity to pingered nets. This activation/deactivation cycle was achieved by physically removing the pinger unit from its casing during even weeks and replacing it during odd weeks. At the beginning of each week, a text message was sent to all participants to maintain contact and remind them to activate or deactivate the pingers. Other than this, the fishers fished normally. At the end of each trip, participants filled out a logbook, detailing the time and date of the fishing trip, the type and number of nets used, the GPS position and depth of the site where the nets were set, and the weight of each fish species caught, and species and counts of bycaught marine mammals. At the end of each season, participants also answered a questionnaire on how much extra time and effort they had spent on setting, hauling and clearing the nets because of the pingers, as well as how much time they had spent on pinger maintenance (replacing batteries, redoing knots, etc.).

Data analysis

The difference in counts of bycaught harbour porpoises in nets with and without pingers was tested in each fishery group using a Wilcoxon rank sum test, under a null hypothesis that the location shift between counts in pingered and control nets was equal to 0. Based on an earlier pilot study using pingers, and converging results from many other, independent trials, harbour porpoise bycatch rates were expected to be much lower in pingered nets. Thus, a one-tailed test was used to maximize power. Differences in catch of seals and fish in nets with and without pingers were tested in the same way but using two-tailed tests.

To also examine any difference in harbour porpoise bycatch rates while controlling for other variables, data on the trip-level were fitted to a generalized linear mixed model (GLMM) using a Poisson distribution, and random intercepts for each set of observations grouped by fishing vessel. Counts of bycaught harbour porpoises *hp* was specified as the response variable. The log of *net_km_days*, defined as *total length of string of nets × days of soaking time*, was specified as an offset, assuming that the probability of porpoise entanglements was correlated with fishing effort. The type of fishery (cod, saithe or monkfish) and whether pingers were used on the nets were entered as categorical variables. The complete model is summarized in equations 1 and 2.

Let *i* denote vessels, and *j* denote hauls:

$$Y_{ij} \sim Poisson(\mu_{ij})$$
$$E[\mu_{ij}] = \lambda_{ij}$$
$$Var[\mu_{ij}] = \lambda_{ij}$$
$$\lambda = \exp\left(\beta_0 + \log(w_{ij}) + \beta_1 x_{1ij} + \beta_2 x_{2ij} + \beta_3 x_{3ij} + \beta_4 x_{4ij} + \beta_5 x_{5ij} + \gamma_j\right) \quad (1)$$

where w = *net_km_days*, x_1 = *pinger* (0 for control nets, 1 for pingered nets), x_2 = *saithe fishery* (1 for saithe, 0 otherwise), x_3 = *monkfish fishery* (1 for monkfish, 0 otherwise), x_4 = *interaction term* (1 when $x_1 = x_2 = 1$), x_5 = interaction term (1 when x_1 and x_3 both = 1), and $\gamma_i \sim N(0, \tau^2)$.

Correspondingly, in R-syntax:

$$hp \sim offset(\log(net\_km\_days)) + pinger * fishery + (1|vessel) \quad (2)$$

Since our data exhibited a complete separation of porpoise counts across the two levels of *pinger* (i.e. counts for pingered nets were all zero), we used a Student's t penalty/prior with mean equal to 0, scale equal to 1 and 3 degrees of freedom for estimating all fixed effects. Model fit was checked using diagnostic plots. The model was also fitted against negative binomial (NB), zero-inflated Poisson (ZIP) and zero-inflated NB (ZINB) distributions to help evaluate whether over-dispersion and/or zero-inflation might be problematic. Confidence intervals around model coefficients were obtained through bootstrapping. We resampled a full set of observations with replacement from the original data. There were no structural conditions on the samples drawn. The bycatch model was refitted to the resampled data. This procedure was replicated 1000 times, and confidence intervals for each term were calculated from the bootstrap distribution of linear predictors. We used BCa (bias-corrected) confidence intervals.

We used R packages *GLMMadaptive* (Rizopoulos 2020) for model fitting, *DHARMa* (Hartig 2019) for model checking and *boot* (Canty and Ripley 2017; Davison and Hinkley 1997) for bootstrapping confidence intervals. All analyses were run in R version 4.0.2 (R Core Team 2020).

RESULTS

Summary of data

Fishery data were collected over the course of two full cod and monkfish fishing seasons from 2018 to 2020. Eight fishing vessels participated in the pinger trials, and conducted a total of 484 hauls, distributed with 185 cod nets (mesh size 156 – 220 mm), 168 monkfish nets (mesh size 360 mm) and 109 saithe nets (66 – 132 mm) (Table 2). In the cod fishery, the average net-string length was 2,514 m and the average soak time was 24 hours. In the monkfish fishery, the average net-string length was 6,234 m and the average soak time was 60 hours. In the saithe fishery, the average net-string length was 1,500 m and the average soak time was 27 hours. There was no significant difference in fishing effort (given as *net-KM-days*) between nets with and without pingers ($F = 0.086$, $df = 1, 482$, $p = 0.77$). The effort in the monkfish fishery, however, was significantly higher than in the other two fisheries ($F = 146$, $df = 2, 481$, $p << 0.01$).

Table 2 shows the distribution of fishing effort across fisheries and nets with and without pingers, and the number of marine mammals that were bycaught in each fishery and season. A total of 19 harbour porpoises and 9 harbour seals were bycaught. All harbour porpoises and 2/3 of harbour seals were taken in unpingered control nets. All bycatches were fatalities, except one bycaught harbour seal, that was still alive when the nets were hauled.

3.2 Effect of pingers on catch and bycatch in different fisheries

Catch rates of harbour porpoises, harbour seals and fish in pinger and control nets in different fisheries are compared in Table 3. Catch rates of harbour porpoises were significantly different between nets with and without pingers, in the mixed fisheries ($p << 0.01$), the cod fishery ($p = 0.02$) and the monkfish fishery ($p < 0.01$), but not in the saithe fishery ($p = 0.10$). Catch rates of harbour seals were 44% lower in cod nets with pingers than in the corresponding control nets without pingers. In monkfish nets with pingers on the other hand, catch rates of harbour seals were 50% higher than the corresponding nets without pingers. However, none of these differences were statistically significant (Table 3). There were also no significant differences in catch rates of targeted fish species between nets with and without pingers in any fishery.

Table 2: Summary of fishing effort, total catch of fish and marine mammals for nets with and without pingers (the latter given as counts). HP = harbour porpoise and HS = harbour seal

Year	**Fishery**	**Group**	**Hauls**	**Net KM days**	**Catch (kg)**	**HP**	**HS**
2018	Monkfish	Control	21	211.2	4,739	5	0
2018		Pinger	22	215.2	3,084	0	2
2018	Saithe	Control	27	39.5	9,782	1	0
2018		Pinger	20	28.3	9,539	0	0
2019	Cod	Control	145	300.3	306,409	7	4
2019		Pinger	124	311.7	260,723	0	0
2019	Monkfish	Control	64	872.9	29,227	6	2
2019		Pinger	61	678.6	30,265	0	1
2019	Saithe	Control	33	62.7	29,812	1	0
2019		Pinger	29	49.3	24,237	0	0
2020	Cod	Control					
2020		Pinger					
Total			484	2,657.7	647,768	19	9

Model diagnostic plots indicated that the Poisson distribution was a good fit. Corresponding negative binomial (NB) and zero-inflated Poisson and zero-inflated NB models did not significantly improve the initial Poisson fit, and were therefore discarded. The estimated coefficients in the porpoise bycatch GLMM are summarized in Table 4. In this model, the effect of pingers on bycatch was significant with estimated relative rates RR = 0.01 in the monkfish fishery, RR = 0.02 in the saithe fishery and RR = 0.08 in the cod fishery, corresponding to reductions in bycatch rates of ~99%, 98% and 92%, respectively. The pinger effect did not differ significantly between fisheries and the overall (averaged) pinger effect was a reduction in bycatch rates of 96.4%. An alternative model fitted without the interaction terms (terms β_4 and β_5, equation 1/Table 3) gave an overall estimated pinger effect of RR = 0.031 (95% CI 0.02 – 0.05), corresponding to a reduction in bycatch rates of 96.9%. The reduced and the full model were not significantly different (χ^2 = 0.53, df = 2, p = 0.76) and the reduced model was also supported by a lower AIC (-14.7 vs -8.8).

Table 3: Results from hypothesis tests between catch rates of harbour porpoises, harbour seals and target species in control and pingered nets in different fisheries. Mixed fisheries represent pooled data from all fisheries. CPUE = catch per unit effort, with units ‘animals per haul’ for harbour porpoises and seals, and ‘tons per haul’ for fish. Statistic = value of two-sample Wilcoxon sum rank test.

Fishery	Catch group	CPUE Control	CPUE Pinger	Statistic	p-value
	Harbour porpoise	0.074	0.000	30985.5	<< 0.01
Mixed	*Harbour seal*	0.023	0.013	29366.5	0.25
	Total catch of fish	1.311	1.363	28739.5	0.61
	Harbour porpoise	0.054	0.000	5557.5	0.02
Cod	*Harbour seal*	0.036	0.000	5462.5	0.06
	Total catch of fish	2.470	2.489	4774.0	0.90
	Harbour porpoise	0.129	0.000	3901.0	<< 0.01
Monkfish	*Harbour seal*	0.024	0.036	3484.5	0.73
	Total catch of fish	0.400	0.402	3633.5	0.37
	Harbour porpoise	0.033	0.000	1519.0	0.10
Saithe	*Harbour seal*	0.000	0.000	1470.0	1.00
	Total catch of fish	0.660	0.567	1495.0	0.44

Table 4: Penalized ML estimates of exponentiated marginalized coefficients with bootstrapped 95% BCa confidence intervals. “Mean intercept” refers to the bycatch rate in the cod fishery for the average vessel.

Term	(Relative) Rate (RR)	95% Confidence interval	
		Lower	Upper
β_0 *Mean intercept*	0.02	0.01	0.06
β_1 *Pinger*	0.08	0.01	0.57
β_2 *Saithe nets*	0.97	0.22	4.35
β_3 *Monkfish nets*	0.46	0.16	1.26
$\beta_4 = \beta_1 \times \beta_2$ *Pinger and saithe nets*	0.79	0.04	15.28
$\beta_5 = \beta_1 \times \beta_3$ *Pinger and monkfish nets*	0.44	0.03	5.75

Impacts of pingers on day-to-day fishing operations

Figure 2 shows a summary of self-reported time costs, based on end-of-season questionnaire responses. These time costs refer to the *additional* time that had to be expended by the fishers to undertake various activities related to the fishing operation. Setting and hauling pingered nets had an average time cost of 1.7 ± 4.2 minutes and 3.9 ± 3.8 minutes (mean + SD). In one case, setting nets with pingers took 15 minutes extra. Weekly maintenance (replacing batteries, redoing knots, replacing unintentionally ejected pingers into their casings, etc.) had an average time cost of 7.3 ± 7.4 minutes. The weekly activation/deactivation cycle had an average time cost of 8.7 ± 12 minutes.

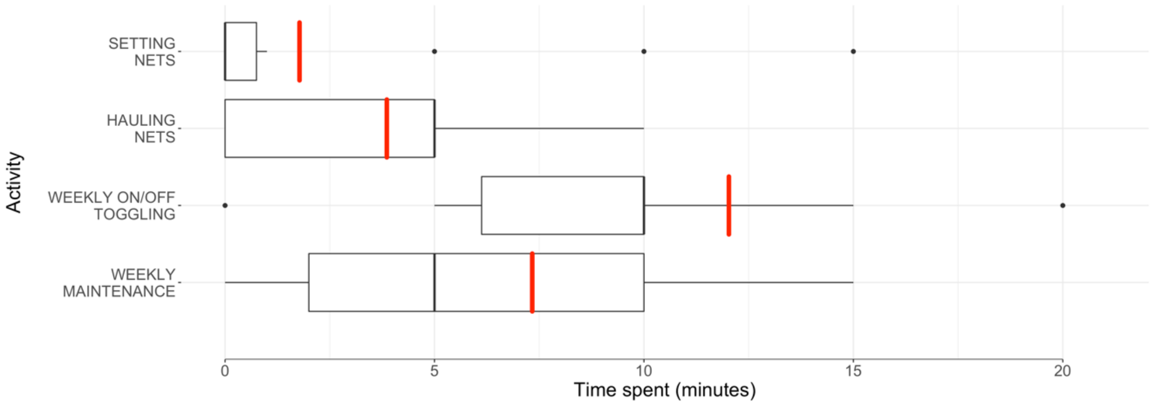

Fig. 2: Summary statistics of extra time costs of activities associated with pinger use. Black and red vertical lines represent medians and averages, respectively.

Practical challenges reported:

- Unintentional ejection of the pingers from their casings. In some cases, when the nets were hauled, the pingers would pop out of their plastic casing just as they came aboard. Popped out pinger units could be recovered from the deck of the vessel, so no pingers were lost in this way. This issue was mitigated by 1) running the hauling machinery at a slightly lower speed just as the pingers came aboard, and 2) making sure the pingers were attached in a way so that they would not be strained or under tension during hauling.
- Pingers getting entangled in nets. Loosely attached pingers would occasionally get entangled in nets, causing parts of the nets to wrap around the pingers, thus preventing the net from stretching out properly, or in some cases tearing the mesh twines apart. This issue could be mitigated by attaching the pingers between two adjacent nets in the string.
- Water intrusion. Two Dolphin pingers (out of a total of 275 Dolphin pingers in use) suffered water intrusion, when used at about 200 meters depth. None of the 195 Banana pingers in use suffered water intrusion.

DISCUSSION

A note on the reliability of data used in this study

A common objection to using self-reported data in fishery sciences is that it can be unreliable (e.g. Sampson 2011; Walsh et al. 2002). One reason for this may be that reporting bycatches could lead to restrictions on the fishery in question, thus giving fishers a strong incentive to under-report bycatches. Even if this is a common and reasonable objection in most cases, there are several reasons why the bycatch data used in this particular study can be considered reliable:

- Researchers and fishers stayed in frequent contact during the entire study, and all fishers were met face-to-face at least once.
- Relations were generally very good, and communication was frequently initiated by both sides.
- Fishers voluntarily, and sometimes by their own initiative, sent photographs of bycaught marine mammals, even thought that was not a contractual requirement.
- About half of the fishers participating in the study were also part of a national fisheries monitoring programme (the CRF; briefly described in Section 2.1) and would be subject to frequent data reviews and checks. There were no large differences in bycatch numbers reported by CRF vessels and ordinary vessels.
- Harbour porpoise bycatch rates in control nets were not significantly different from bycatch rates calculated for corresponding strata using data only reported by the CRF.

Pinger effects

Both the hypothesis testing approach and the GLMM estimates indicated that there was a strong and significant effect of pingers on the bycatch rates of harbour porpoises, with an estimated overall relative rate in pingered vs. control nets of 0.031 (95% CI 0.02 – 0.05). This corresponds to a reduction in harbour porpoise bycatch of 96.9% in pingered nets. While the *observed* relative bycatch rate of pingered vs. non-pingered nets was zero, indicating that pingers caused a 100% reduction in harbour porpoise bycatch, a larger sample size might have revealed a low, but non-zero bycatch rate in pingered nets. Other pinger trials have obtained similar, but less extreme, results, with relative bycatch rates for pingered nets between 40% and 90% (e.g. Northridge et al. 2013). Bycatch rates in non-pingered nets (Table 3) and the sample size in our study were both comparable to many of these other studies. It is also possible that the low relative rates reported here can be attributed to differences in the behavioural response to pingers of harbour porpoises inhabiting Norwegian waters compared to other regions, e.g., if the ambient background noise levels are different. More likely, improved and more mature pinger technology could have made the pingers used more efficient and less faulty compared to earlier studies.

Some studies have demonstrated that harbour porpoises may habituate to pingers over time (Carlström et al. 2002; Cox et al. 2001; Kindt-Larsen et al. 2019). As there were no changes in bycatch rates in pingered nets over the two-year span in the present trials, there was no evidence suggesting that harbour porpoises habituated to the pingers. However, it should be noted that this trial was designed to compare bycatch rates between pingered and control nets, and not to investigate habituation in particular. Cox et al. (2001) found that pingers initially displaced porpoises in the Bay of Fundy about 200 meters away, but that this displacement was decreased over the next 10-11 days. This result suggests that the weekly activation/deactivation scheme used in our trials may have inadvertently counteracted any habituation effects by removing the stimulus before "full" habituation could occur. However, data from several real-world (i.e., not experimental) fisheries also show no evidence of habituation (e.g. Northridge et al. 2013). One of the pingers used in the present trials was specifically designed to prevent habituation by randomizing both the frequency and time intervals between successive pings. The other pinger used a fixed frequency and signal interval (Table 1).

Harbour porpoise habitat exclusion have been described in areas where pingers are in use (Carlström et al. 2002; Culik et al. 2001; Kindt-Larsen et al. 2019; Kyhn et al. 2015). It is possible that using pingers on a larger scale, with many more vessels operating in the same areas, and with pingers active on all nets all the time, not just every other week (e.g., in a fishery-wide pinger use situation), both habitat exclusion and habituation may be concerns that warrant consideration.

Our results indicate that pingers had no significant effect on catch rates of neither seals nor fishes. Physiologically, there is no reason to expect that adding active pingers to the nets, should have any effect on the catch rates of fish. The pingers used in this study emit sounds with a frequency between 50 and 120 kHz. Most fish, even those with swim bladders and good hearing, are not physiologically capable of hearing sounds above 1 kHz. Cod, for example, hears frequencies between approximately 35 and 400 Hz (Hawkins and Popper 2020). Even though one might not intuitively expect any effect of pingers on fish catch rates, it is still important to verify this expectation, as it is conceivable that pingers could affect fish catch rates through some intermediary/other mechanism, e.g., by a *visual* deterring effect, or by otherwise changing the behaviour of the gillnet.

Practical aspects of pinger use in real-world fisheries

The greatest average time cost in our pinger trials was associated with the weekly activation/deactivation cycle (Figure 2). In real-world fisheries, this activation/deactivation cycle would not be necessary. Pingers could just be left on the gillnets for as long as needed. However, if a fisher wanted to change from one type of gillnet to another, and only had access to a limited number of pingers, he would have to move the pingers over to the other nets, and possibly back again later, with the time costs that both changes would necessitate. It is unclear how often such "predatory switches" might occur in Norwegian fisheries, but they are not uncommon. One solution would be to buy enough pingers to simultaneously satiate both types of nets, if the trade-off between pinger purchasing costs and pinger refitting time costs supported that.

Time costs associated with other activities, i.e., weekly maintenance and setting/hauling nets, on the other hand, are more truly representative of the actual additional time costs faced by an average gillnet fisher interested in starting to use pingers. The time costs associated with setting and hauling nets in our trials were incurred because both activities had to be slowed down slightly to ensure that that none of the issues outlined in Section 3.3 occurred. For an average gillnet fisher conducting 77 hauls in a year, assuming five trips per week (thus fishing for 16 weeks), if that fisher used pingers half the time, the total expected time cost per year would be 5.6*77 *0.5 + 15.4*77/5= 215 + 112 minutes, or roughly 5.5 hours. For an extremely prolific fisher conducting 300 hauls every year, the corresponding time cost would be 29.5 hours. Thus, the time-cost of using pingers would correspond to an extra half day of work every year for an average fisher, or roughly four days for the most active fisher. This assumes however, that pinger operating costs stay constant throughout their lifetime. It is possible that these costs would decrease as the fisher gained more experience and familiarity with using pingers, thereby learning to be more effective and streamlining activities. However, we were not able to demonstrate any such time cost reductions over the course of our pinger trials from the questionnaire results.

Also, some of the hauling time costs must be offset by the time it takes to handle a porpoise, once it is entangled in the nets. The most important lesson learned is the importance of attaching the pingers in a good way. Attaching the pingers incorrectly is likely to cause issues during setting and hauling. The two pingers that suffered water intrusion might have done so because they were not closed properly before being taken into use. Water intrusion might occur if the pingers that must be opened to replace batteries, are not closed tightly enough.

The pingers had no effect on catches of the targeted fish species. This was also demonstrated in the Swedish Skagerrak Sea where catches of cod, pollack (*Pollachius pollachius*), and other fish species were not affected by the sound of pingers in active strings of gillnets (Carlström et al. 2002). Similar results have been found for herring (*Clupea harengus*), cod and saithe in other field experiments using the Dukane Netmark 1000 pingers (Culik et al. 2001; Trippel et al. 1999).

The potential of pingers in Norwegian fisheries

If pingers were used in all commercial Norwegian gillnet fisheries, harbour porpoise bycatch could theoretically be almost eliminated. The average yearly bycatch in commercial Norwegian gillnet fisheries of 2,871 porpoises could be reduced to a mere 3.1%, or just 86 porpoises per year. However, the effect of pingers on bycatch rates are reported to be better in carefully designed and monitored scientific trials than in commercial fisheries. Carretta and Barlow (2011) reported 80% reduction of cetacean bycatches in trials, but only 50% after pingers became mandatory in the fishery. Palka et al. (2008) also reported a reduced effect of pingers in commercial fisheries compared to scientific trials. They considered that might be explained by an observed pinger failure rate of 13% in commercial fisheries.

Pingers are not practical to use on *all* gillnet fisheries. There is a trade-off between pinger purchasing costs and operating costs on the one hand, and the total realized bycatch reduction effect on the other. Enforcing pingers on vessels that engage in fisheries with low harbour porpoise bycatch rates, e.g., small-mesh gillnet fisheries, or deep-water gillnet fisheries, would not contribute much to reducing total harbour porpoise bycatch.

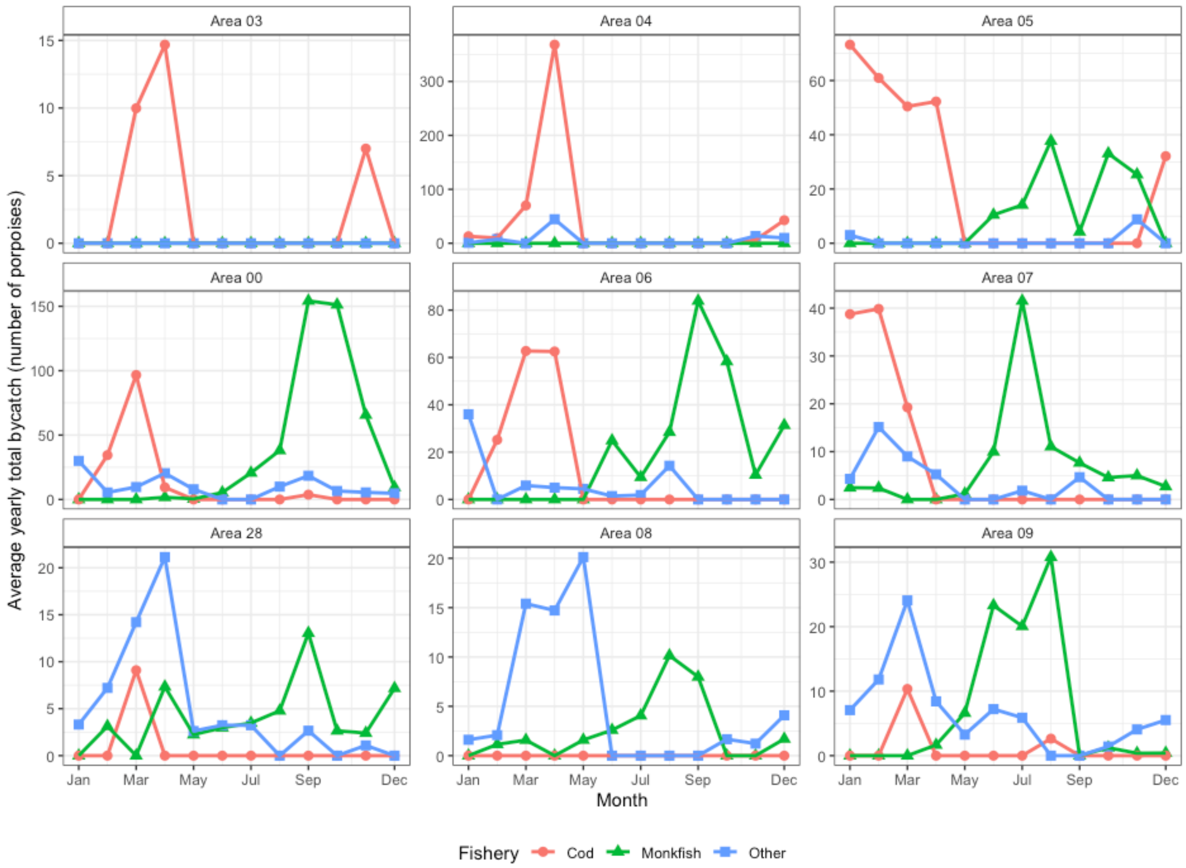

Fig. 3: Harbour porpoise average yearly total bycatch estimates by fishery, area and month, where area refers to the fishery statistics areas indicated in Figure 1. Dotted red lines indicate porpoises taken in the cod fishery. Green lines with triangles indicate porpoises taken in the monkfish fishery. Blue lines with squares indicate porpoises taken in other fisheries. Based on estimates from Moan et al. (2020).

A targeted approach would be more appropriate, where pingers are used in gillnet fisheries that have a relatively large probability of catching harbour porpoises. Figure 3 shows average estimated total bycatch of harbour porpoises in different fisheries and different coastal areas along the Norwegian coast, based on bycatch estimates reported in Moan et al. (2020). Metiers (i.e., combinations of months, areas and fisheries) associated with high levels of bycatch can be identified from the line diagrams. For example, in area 04 in April, more than 350 porpoises are caught on average every year. Thus, requiring pingers on all nets set in that area in April could reduce the total yearly average bycatch by almost 12%. A few more examples of pinger-based bycatch mitigation schemes like this are given in Table 5. The column ‘ΔBycatch’ shows the percentage reduction in total yearly bycatch for each mitigation scheme. The columns ‘Vessels affected’ and ‘Hauls pingered’ indicate the average number of vessels that operate gillnets of the type specified in the areas and months given, and the number of hauls that are undertaken, respectively. ‘Nets’ give an estimate of the average number of nets used per gillnet string in the given metier. Mitigation schemes targeting metiers that are associated with fewer number of nets per string would in turn require fewer pingers *per vessel*, and therefore smaller purchasing and operating costs for each fisher.

Table 5: Examples of possible harbour porpoise bycatch mitigation schemes. See text for details. All values refer to averages ± SD for the fishery, area and month combinations given. ΔBycatch gives the theoretical expected reduction in bycatch. See Fig. 1 for an overview of coastal areas.

Scheme	Fishery	Area	Month(s)	ΔBycatch	Vessels affected	Hauls pingered	Nets
S1	Cod	03	Jan – Apr	-0.9%	227 ± 28	3592 ± 539	61
S2	Cod	04	Mar – Apr	-15.1%	402 ± 114	4574 ± 1551	73
S3	Cod	05	Jan – Apr	-8.2%	455 ± 33	7159 ± 1320	84
S4	Cod	00	Feb – Mar	-4.5%	477 ± 69	5951 ± 1558	78
S5	Cod	07	Jan – Mar	-3.4%	105 ± 34	657 ± 207	143
S6	Monkfish	00	Oct – Nov	-12.8%	92 ± 23	813 ± 322	137
S7	Monkfish	06	Oct – Nov	-5.3%	123 ± 18	1294 ± 384	336
S8	Monkfish	07	Aug	-0.4%	49 ± 25	228 ± 117	235

The bycatch reductions given in Table 5 are conditional on full compliance (gillnet strings are satiated with pingers according to manufacturer's specifications), no faulty pingers, and no habituation, i.e., that all vessels operating in the metier indicated use nets satiated with pingers, and that all of those pingers work as expected. A violation of any of these conditions under any given bycatch mitigation scheme would result in a lower realized bycatch reduction. After pingers were introduced as a bycatch mitigation measure in US north-western Atlantic in 1999, Orphanides and Palka (2013) reported that compliance and pinger effect had an inverse relationship, and that compliance was 'low even at its best', with enforcement being ineffective. This highlights the importance of taking a wholistic approach to the implementation of a pinger-based mitigation approach, by following it up with measures to increase compliance, such as outreach and education efforts.

Future work

On December 4th, 2020, the Norwegian Ministry of Trade, Industry and Fisheries introduced a new regulation stipulating that all gillnets set in Vestfjorden (Area 00, Figure 1) between January 1st and April 30th, 2021 must use pingers (https://lovdata.no/forskrift/2004-12-22-1878/§29a), and that the pingers used must satisfy the following requirements: frequency between 50 and 140 kHz, signal strength > 145dB+5dB @ 1 meter, ping duration > 300 ms, inter-ping interval 4 - 12 seconds and spacing <= 200 m. This pinger mandate, which corresponds to mitigation scheme S4 (except the pinger regulation also includes April), was intended to reduce and maintain nation-wide total harbour porpoise bycatch below the PBR limit, with area 00 chosen because the cod fishery in this region is very profitable, especially compared to other fisheries that also could make reasonable targets for mitigation efforts. Additionally, strings of cod gillnets are significantly shorter than strings of monkfish nets (Table 5), thereby minimizing pinger purchasing costs per fisher.

This new pinger regulation necessitates continued close monitoring of harbour porpoise bycatches to determine what effect that pingers have on bycatch rates in the fishery in question, which on average involves almost 500 fishing vessels. Reference vessels operating in area 00 must use pingers, like everybody else, so data reported by the Norwegian reference fleet should reflect any changes in bycatch rates in this area. However, it is critical that bycatch rate estimates can be considered in the context of data on compliance (to the regulation). If the regulation were not respected and not enforced, or if pingers were used incorrectly (e.g., by spacing them incorrectly), and the prevalence of non-compliance were unknown, then it would be very difficult to evaluate the true effect of pingers on harbour porpoise bycatch rates.

DATA AVAILABILITY

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

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