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Pingers reduce harbour porpoise bycatch in Norwegian gillnet fisheries, with little impact on day-to-day fishing operations

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A R T I C L E I N F O

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A B S T R A C T

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 3500 net-km-days were collected by 8 fishing vessels operating gillnets in high bycatch regions over two years. A total of 20 harbour porpoises and 9 harbour seals were bycaught, with 19 harbour porpoises and 6 harbour seals taken in control (non-pingered) nets. Bycatch was modelled using a generalized additive 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 94% (95% confidence interval CI 77–100%) 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, $p = 0.24$) or harbour seals (Wilcoxon rank sum test, $p = 0.19$). Self-reported pinger-associated extra time costs on day-to-day fishing operations were low, averaging about 2.8 min 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.

1. Introduction

Unintentional entanglement in fishing gear, or simply, *bycatch*, is a threat to marine mammals all over the world. Bycatch has recently driven one small cetacean species to extinction (Turvey et al., 2007). An additional 11 other species or populations of small cetaceans that are listed as *Critically Endangered* on the IUCN Red List (Brownell et al., 2019) also suffer a 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). Most fisheries across the globe are small scale coastal, or artisanal, fisheries. Catches from such small scale fisheries comprise about half of the global annual total fish catch, and provide most of the fish used 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 so widely used, and because they are an important means of food and income in many coastal regions, it is not likely that their use will decrease in the future. Therefore, addressing the problem of marine mammal bycatches in gillnet fisheries is a matter of growing urgency, especially as the human population and the demand for food continue to increase.

One reason why marine mammals get entangled in gillnets is that they do not always detect the nets in time to avoid them. Several methods have been developed to increase the detectability of gillnets to marine mammals. Small cetaceans, like the harbour porpoise, which is

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one of the cetaceans that is the most threatened by gillnet fisheries (Braulik et al., 2020; Bravington and Bisack, 1996; Dawson et al., 2013; IMR/NAMMCO, 2019; Jefferson and Curry, 1994; Orphanides and Palka, 2013; Tregenza et al., 1997; Trippel et al., 1999), have well-adapted hearing systems (Ketten, 1994; Miller and Wahlberg, 2013; Nachtigall and Supin, 2008), that they use for echolocation. Thus, if gillnets could be modified to increase their *acoustic* detectability for echolocating animals, then bycatches of those animals could potentially be prevented. Many methods and/or alternative gillnet twine materials have been explored for this purpose. This includes increased net 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; Dawson et al., 2013; 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%. Today, pinger use is mandatory in some US and EU gillnet fisheries. In Norway, the average harbour porpoise bycatch in commercial bottom-set gillnet fisheries between 2006 and 2018 has been estimated to 2871 porpoises per year (Moan et al., 2020), a bycatch level that exceeds a commonly used sustainability limit, the Potential Biological Removal (PBR) (Wade, 1998), which, for Norwegian porpoises, is 2542 porpoises per year (Moan et al., 2020). This highlights the importance of exploring options for bycatch mitigation in Norwegian gillnet fisheries.

The field trials reported herein aimed 1) to determine how effective pingers can be as bycatch mitigation measures in three Norwegian commercial gillnet fisheries, and 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 would involve for the fishers.

2. Materials and methods

2.1. 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 frequent harbour porpoise bycatches (Fig. 1). These regions were identified based on bycatch data collected by the Norwegian Coastal Reference Fleet (CRF), which is a group of about 25 concurrent vessels that is designed to be representative for the nation-wide commercial fleet of small fishing vessels (less than 15 m length overall) (Clegg and Williams, 2020). 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

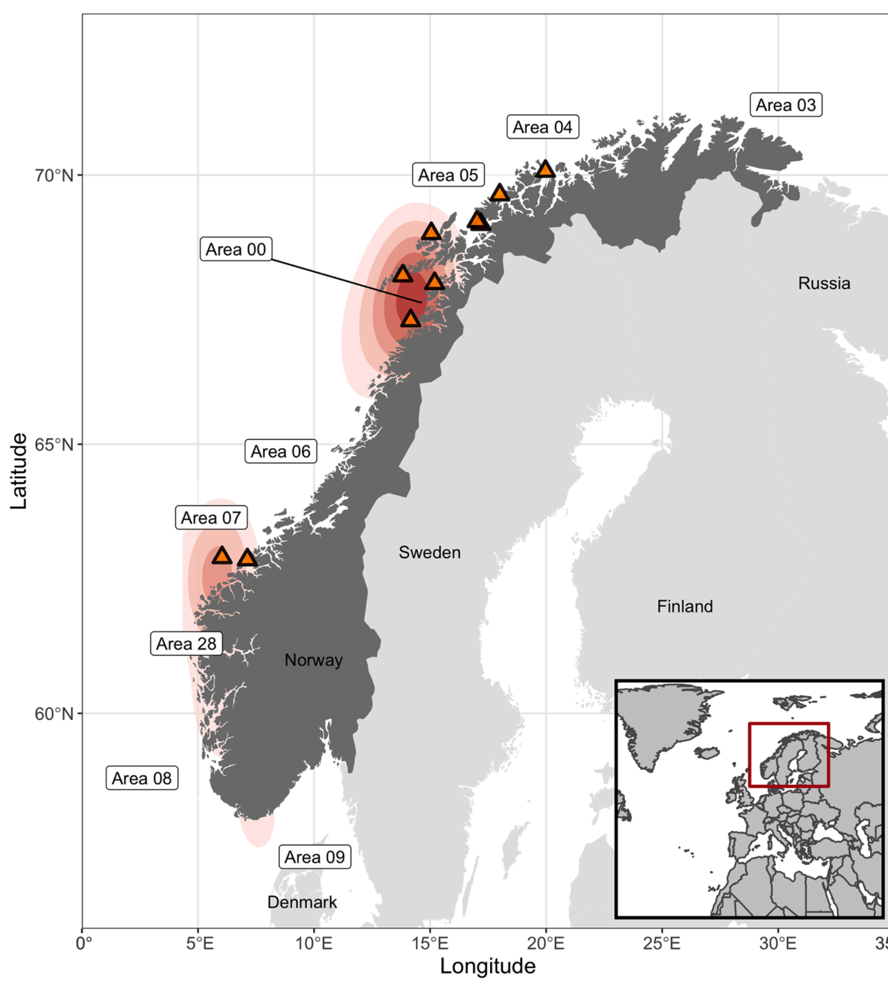

Fig. 1. Map of study region, with Norway highlighted in dark grey. White-red ellipses indicate regions of high harbour porpoise bycatch intensity. Orange triangles indicate the home ports of the fishing vessels that participated in the pinger trials. Dashed lines delineate coastal fishery statistical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

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 significantly compromising the accuracy and precision of marine mammal bycatch estimates derived from CRF reported data.

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 tried to establish and maintain a good relationship with all participants.

Two types of pingers with equivalent sound pressure levels (SPLs) 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. Most importantly, the Banana pinger had the additional feature that it randomized both the ping duration and the interval between successive pings. Unfortunately, because of the low number of bycatches, we were not able to compare the efficiency of the two types of pingers. In this manuscript, the two types of pingers are therefore assumed to be equivalent in terms of their deterrence effect.

Study participants were 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 (the pinger casings were different). These wishes were accommodated as far as possible, but with the limitation that both types of pingers must be in use by roughly the same number of vessels. Pingers were sent to fishers by mail or delivered by a researcher during an on-site visit.

The pingers were attached to the float-line either between the nets or at the end of the net fleet with approximately 200 m spacing. The pingers were attached to gillnets used in cod, saithe and monkfish fisheries. 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. Fishers were instructed to visually assess whether the pingers were working by checking the status of the LED lights. 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 any 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.).

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. SPL = sound pressure level.

Pinger type	Fishtek Banana pinger	Future Oceans Dolphin pinger
Frequency of ping	50 – 120 kHz (randomized)	70 kHz
Duration of ping	400 ms	300 ms
Ping loudness/SPL	145 dB	145 dB
Ping interval	4 – 12 s (randomized)	4 s
Battery time	4380 h	4380 h

2.2. 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 less than 0. Based on an earlier pilot study using pingers, and converging results from many other, independent trials reported in the literature, 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 examine any changes in harbour porpoise bycatch rates while controlling for other variables, data on the trip-level were fitted to a generalized additive mixed model (GAMM) using a Poisson distribution, and random intercepts for each set of observations grouped by fishing vessel. Counts of bycaught harbour porpoises was specified as the response variable *Y* or *hp*. *Pinger*, *fishery* and *year* (recoded from 2018 to 2020–1 - 3) were specified as parametric (fixed) effects, and log(*net km · days),* i.e. the logarithm of the product of *total length of string of nets and decimal days of soaking time*), the log of *total catch*, *longitude*, *latitude*, *month* and *lunar day* were specified as penalized smooth functions (see below). *Lunar day* was added as a proxy for the tidal cycle to evaluate whether this could have a confounding effect, given the weekly pinger cycling. *Lunar day* was calculated by dividing the lunar phase for the fishing date by a constant 0.212769. The *net km · days* variable was entered in the model as a smooth rather than a fixed offset to allow for a nonlinear relationship between catch of harbour porpoises and (logged) fishing effort. The complete model is summarized in Eqs. 1 and 2.

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

$$Y_{ij} \sim Poisson(\mu_{ij})$$

$$E[\mu_{ij}] = \lambda_{ij}$$

$$Var[\mu_{ij}] = \lambda_{ij}$$

$$\lambda = \exp(\beta_0 + \beta_1 x_{1ij} + \beta_2 x_{2ij} + \beta_3 x_{3ij} + \beta_4 x_{4ij} + f_1(x_{5ij}) + f_2(x_{6ij}) \\ f_3(x_{7ij}, x_{8ij}) + f_4(x_{9ij}) + f_5(x_{10ij}) + f_6(x_{11ij}) + \gamma_j) \quad (1)$$

where x_1 = *pinger* (0 for control nets, 1 for pingered nets), x_2 = *cod fishery* (1 for cod, 0 otherwise), x_3 = *monkfish fishery* (1 for monkfish, 0 otherwise), x_4 = *year* (1–3, representing 2018–2020), x_5 = *month* (1−12), x_6 = *lunar day* (0−29), x_7 and x_8 = *longitude* and *latitude* of fishing location, x_9 = log of *net km · days*, x_{10} = log of *catch*, x_{11} = maximum fishing depth, and $\gamma_i \sim N(0, ᒣ^2)$, representing individual vessel effects. A cyclic cubic regression spine was used for f_1 and $f2$, and thin plate splines with shrinkage for f_3 to f_6.

Correspondingly, in R-syntax:

$$porpoises \sim pinger + fishery + year + s(month, bs = \text{"cc"}, k = 11) + s(lunar\_day, bs = \text{"cc"}) + s(lon, lat, bs = \text{"ts"}) + s(\log(netkmdays), bs = \text{"ts"}) + s(\log(catch), bs = \text{"ts"}) + s(depthmax, bs = \text{"ts"}) + s(vessel, k = 8, bs = \text{"re"}) \quad (2)$$

Since our data exhibited a complete separation of porpoise counts across the two levels of *pinger* for both cod and monkfish fisheries (i.e. counts for pingered nets were all zero, see Table 2), we did not include an interaction effect between pinger and fishery. Model fit was checked using diagnostic plots. The model was also fitted against negative binomial (NB) and zero-inflated Poisson (ZIP) distributions to help evaluate whether data exhibited over-dispersion and/or zero-inflation. 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. In each bootstrap replicate, the bycatch model was refitted to the resampled data. This procedure was repeated 1000 times, and confidence intervals for each term were calculated from the bootstrap distribution of linear predictors. We used BCa (bias-corrected) confidence intervals.

Finally, we applied the estimated effect of pingers on harbour porpoise bycatch rates to historical bycatch rates and fishing effort to simulate the overall effect of different pinger implementation scenarios on total harbour porpoise bycatch. Mitigation schemes were defined by different combinations of sequential months and fishery (i.e. gillnet type, either cod or monkfish). Under each mitigation scheme *i*, simulated total bycatch $Bi_{,s}$ was calculated by multiplying total estimated bycatch $B_{i,e}$ by the relative bycatch rate in pingered nets vs. control nets, using bycatch estimates from (Moan et al., 2020). For each scheme, we calculated the total bycatch reduction R_i, as the difference in simulated total bycatch for the affected months/fisheries $B_{i,s}$ and estimated total bycatch in the corresponding months/fisheries $B_{i,e}$, divided by the average yearly estimated bycatch $\sum B_e$:

$$R_i = \frac{B_{i,e} - B_{i,s}}{\sum B_e} \quad (3)$$

We used R packages *mgcv* (Wood, 2015) for model fitting, *DHARMa* (Hartig, 2019) for model checking and *boot* (Canty and Ripley, 2017; Davison and Hinkley, 1997) for bootstrapping confidence intervals. The R package lunar (Lazaridis, 2014) was used for lunar phase calculations. All analyses were run in R version 4.0.2 (R Core Team, 2020).

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. Fishing effort given as net kilometer days.

Year	Fishery	Group	Trips	Net KM days	Catch (kg)	HP	HS
2018	Monkfish	Control	55	525.8	5519	5	0
2018		Pinger	34	503.8	2708	0	2
2018	Saithe	Control	6	12.7	6481	1	0
2018		Pinger	2	3.3	1287	0	0
2019	Cod	Control	70	177.0	320,737	6	4
2019		Pinger	57	156.0	246,689	0	0
2019	Monkfish	Control	67	880.9	29,236	6	2
2019		Pinger	81	699.5	30,822	0	1
2019	Saithe	Control	31	78.1	148,087	1	0
2019		Pinger	97	219.3	96,514	1	0
2020	Cod	Control	46	35.5	84,577	0	0
2020		Pinger	48	38.9	111,085	0	0
2020	Saithe	Control	73	84.9	13,544	0	0
2020		Pinger	68	84.9	14,329	0	0
Total	All	Control	343	1794.8	608,181	19	6
Total	All	Pinger	392	1705.7	503,434	1	3
Total	All	Both	735	3500.5	871,302	20	9

3. Results

3.1. Summary of data

Fishery data were collected over the course of two full cod/saithe and monkfish fishing seasons from 2018 to 2020. Eight fishing vessels participated in the trials and received a total of 200 Fishtek Banan pingers and 195 FutureOceans Dolphin pingers. Fishers did not show a clear preference for either pinger. The fishers conducted a total of 735 fishing trips, distributed with 221 cod nets (mesh size 156 – 220 mm), 237 monkfish nets (mesh size 360 mm) and 277 saithe nets (66 – 132 mm) (Table 2). In the cod fishery, the average net-string length was 1841 m and the average soak time was 24 h. In the monkfish fishery, the average net-string length was 4638 m and the average soak time was 55 h. In the saithe fishery, the average net-string length was 1626 m and the average soak time was 27 h.

There was no significant difference in fishing effort (given as *net-KM-days*) between nets with and without pingers ($F(1733) = 2.4$, $p = 0.13$). The effort in the monkfish fishery, however, was significantly higher than in the other two fisheries ($F(1733) = 327$, $p << 0.01$). 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 20 harbour porpoises and nine harbour seals were bycaught. With one exception, all harbour porpoises were taken in unpingered control nets. One harbour porpoise was caught in a saithe net in 2018. Six out of nine of harbour seals were taken in unpingered control nets. All bycatches were fatalities, except in one case, in which a bycaught harbour seal 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 pingered 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, the cod fishery, and the monkfish fishery, but not in the saithe fishery. In the cod and saithe fisheries, harbour seal catch rates were higher in control nets, with no seals taken at all in pingered nets. In the monkfish fishery, there were no consistent patterns or significant differences in the bycatch of harbour seals. Catch rates of fish in nets with and without pingers were not significantly different in the cod and monkfish fisheries. In the saithe fishery, catch rates of fish were significantly higher in control nets, on average by about 160% compared to pingered nets.

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 'counts of animals per net km day for harbour porpoises and seals, and 'kgs of fish per net km day' for fish. W statistic = value of two-sample Wilcoxon sum rank test.

Fishery	Catch group	CPUE Control	CPUE Pinger	W statistic	p-value
	Harbour porpoise	0.011	0.001	70186	$<< 0.01$
Mixed	*Harbour seal*	0.003	0.002	29366.5	0.19
	Total catch of fish	339	295	70614	0.24
	Harbour porpoise	0.025	0.000	5557.5	0.03
Cod	*Harbour seal*	0.019	0.000	5462.5	0.10
	Total catch of fish	1908	1835	5968	0.80
	Harbour porpoise	0.028	0.000	3901.0	< 0.01
Monkfish	*Harbour seal*	0.001	0.002	3484.5	0.96
	Total catch of fish	25	28	7027	0.98
	Harbour porpoise	0.011	0.003	1519.0	0.30
Saithe	*Harbour seal*	0.000	0.000	–	–
	Total catch of fish	957	365	11559	$<< 0.01$

3.3. Bycatch modelling results

Model diagnostic plots (e.g. Q-Q plots) indicated that the Poisson distribution was an acceptable fit to our bycatch data. Corresponding negative binomial (NB) and zero-inflated Poisson (ZIP) models did not improve this initial Poisson fit, although the AIC scores of the Poisson and NB model candidates were quite similar. The AIC scores for the Poisson, NB and ZIP models were 150.1, 152.3 and 342.3, respectively. Both NB and ZIP models were therefore discarded in favour of the Poisson model. Deviance explained was 41.7% for final Poisson model. The estimated parametric coefficients in this model are summarized in Table 4 and the estimated smooth functions are shown in Fig. 2. In this model, the effect of pingers on bycatch was highly significant with an estimated relative rate of 0.06, which corresponds to an overall reduction in harbour porpoise bycatch rates in pingered nets of 94% (95% bootstrapped BCA confidence interval 77–100%). The *type* of fishery, on the other hand, did not have a significant effect on harbour porpoise bycatch rates. Similarly, the *catch* term was penalized to almost 0 effective degrees of freedom (EDF), and so was effectively removed from the model, as evidenced by the straight horizontal line in Fig. 2. The same was true for the *lunar phase* term. The term *net km · days* was reduced to a roughly straight line, with a constant slope, indicating that in the model, the probability of harbour porpoise bycatch increased with increasing fishing effort. Individual vessel effects were not found to be significant. This can be seen from the small values estimated for different vessels in Fig. 2C. The model further showed that bycatch rates decreased with increasing depths, and with increasing date numbers. The *month* smooth took on a "hump" shape, with the hump centered on August.

3.4. Impacts of pingers on day-to-day fishing operations

Fig. 3 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 min and 3.9 ± 3.8 min (mean + SD). In one case, setting nets with pingers took 15 min 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 min. The weekly activation/deactivation cycle had an average time cost of 8.7 ± 12 min.

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 m depth. None of the 195 Banana pingers in use suffered water intrusion.

Table 4
Coefficient estimates for the parametric part of the Poisson harbour porpoise bycatch GAMM with standard errors.

Term	Estimate	SE
β_0 *Intercept*	-0.42	1.36
β_1 *Pinger*	-2.86	1.03
β_2 *Cod nets*	-0.89	1.06
β_3 *Monkfish nets*	-1.06	0.86
β_4 *Year*	-1.70	0.72

4. Discussion

4.1. 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 economic incentive to under-report bycatches. Bycatches can also be missed (and under-reported) due to loosely entangled animals dropping out of the nets as they are hauled, without the fishers noticing, because they are too busy. Conversely, it is also possible (but less likely) that fishers may have an incentive to *over-report* bycatches, e.g. because they sympathize with a perceived need of the researchers to obtain convincing results. It is conceivable that such a bias could be fostered by good researcher-fisher relationships. However, it is more likely that fishers are driven by an economic rather than a relationship incentive, as the benefits in the former case are much more apparent. In this trial, we have no reason to believe our data suffered from a positive bias, especially given the extensive negative press that has harrowed the discourse on pingers in the Norwegian fishery newspapers during our trials.

Thus, we expect that any bias in our data would be negative. Despite potential biases, there are several reasons why the bycatch data used in this study can probably 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 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.

4.2. Pinger effects

Our results indicate 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 0.06 (95% CI 0.00 – 0.23). This corresponds to a reduction in harbour porpoise bycatch of 94% in pingered nets. While the *observed* relative bycatch rate of pingered vs. non-pingered nets was approximately 0.05, indicating that pingers caused a 95% reduction in harbour porpoise bycatch, a larger sample size might have revealed a slightly larger 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. Dawson 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

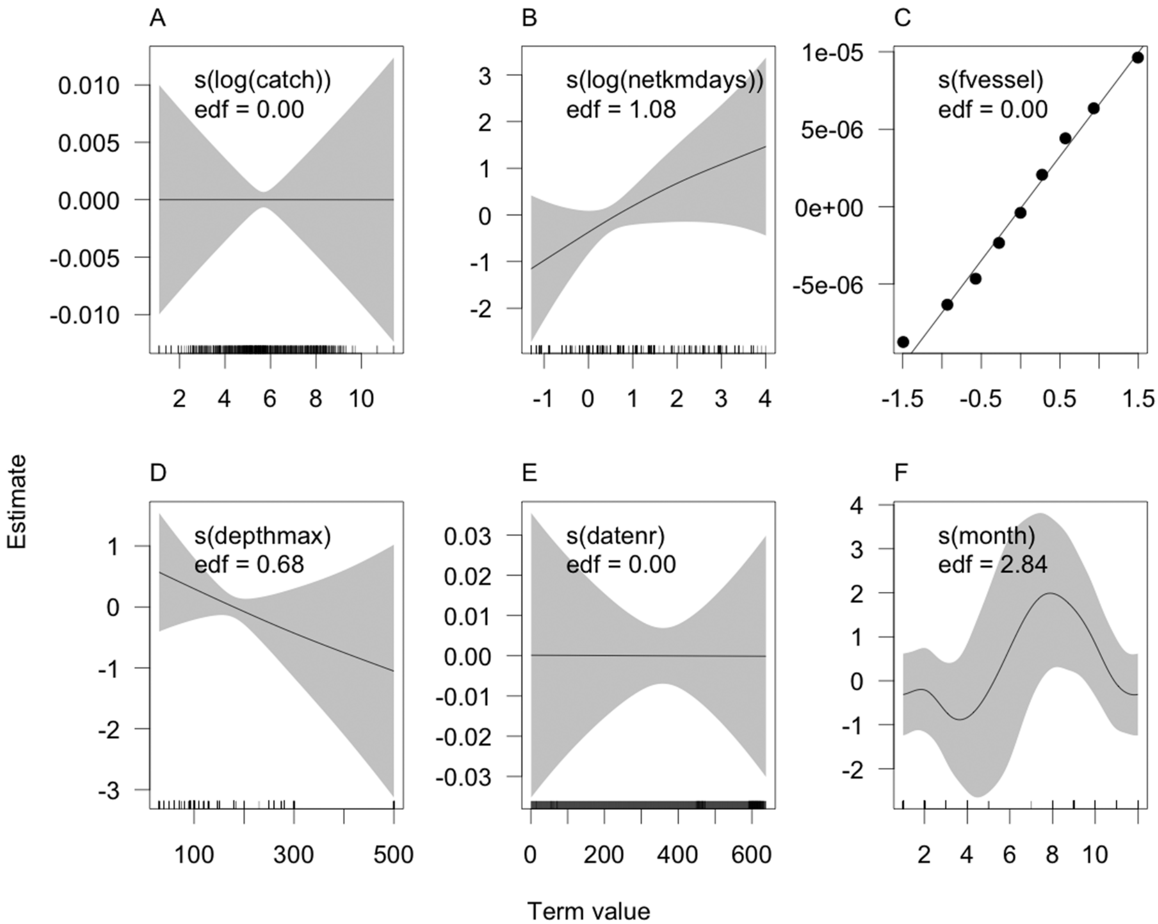

Fig. 2. Estimated smooths in the Poisson GAMM, over the range of data for each given term. "edf" refers to effective degrees of freedom. Lunar day $f_2(x_{6ij})$ and interaction between longitude and latitude $f_3(x_{7ij}, x_{8ij})$ not shown.

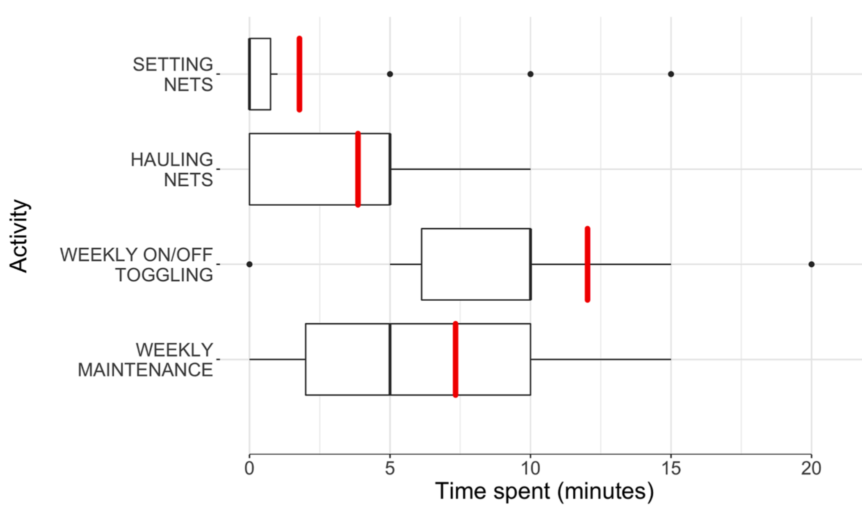

Fig. 3. Summary statistics of extra time costs of activities associated with pinger use. Black and red vertical lines represent medians and averages, respectively.

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. In Norway, cod and monkfish fisheries are responsible for about 75% of harbour porpoise bycatches (Bjørge et al., 2013; Moan et al., 2020). Based on this effect estimate, a pinger mitigation plan that specifically targets either the cod winter fishery or the monkfish fishery in area 00 (Fig. 1) can reduce bycatches by 7.8% and 6.6%, respectively (Supplementary Materials).

Some studies have demonstrated that harbour porpoises may habituate to some types of 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, we found no evidence suggesting that harbour porpoises habituated to the pingers. This conclusion was also supported by our modelling results, which indicated that sequential date numbers were not a significant predictor of harbour porpoise bycatch rates. However, it should be noted that this trial was designed to compare bycatch rates between pingered and control nets, and not to investigate habituation. Cox et al. (2001) found that pingers initially displaced porpoises in the Bay of Fundy about 200 m 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. Dawson 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.

Our results indicate that in our trials, pingers had no significant effect on catch rates of seals or fishes in cod and monkfish nets. The latter finding 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). However, we did find a large and significant difference in fish catch per unit effort in saithe nets with and without pingers (Table 3). From a physiological point of view, 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). However, 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 possible 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.

4.3. 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 (Fig. 3). In real-world fisheries, this activation/deactivation cycle would not be necessary. Time costs associated with other activities, i.e., weekly maintenance and setting/hauling nets, on the other hand, are more representative of the additional time costs faced by an average gillnet fisher using 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 3.4 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 $5.6 * 77 * 0.5 + 15.4 * 77/5 = 215 + 112$ min, or roughly 5.5 h. For an extremely prolific fisher, conducting 300 hauls every year, the corresponding time cost would be 29.5 h. 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.

CRediT authorship contribution statement

André Moan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft. **Arne Bjørge**: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106564.

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