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Estimated bycatch of harbour porpoise (*Phocoena phocoena*) in two coastal gillnet fisheries in Norway, 2006–2008. Mitigation and implications for conservation

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ABSTRACT

Using data collected during 2006–2008 from a monitored segment (18 vessels) of the Norwegian coastal fleet (vessels <15 m) of gillnetters targeting monkfish and cod, we used general additive models (GAMs) to derive bycatch rates of harbour porpoise. These bycatch rates were then applied to fishery catch data on the target species to estimate the total number of porpoise taken by the coastal gillnet fisheries. The two best models estimated bycatches of 20,719 and 20,989 porpoises during 2006–2008, with CVs 36% and 27%, respectively. Thus, about 6900 harbour porpoises are taken annually in the coastal monkfish and cod gillnet fisheries. Although no abundance estimate is available for the coastal harbour porpoise population, this annual bycatch is likely not sustainable according to the management objectives defined by ASCOBANS. In the cod gillnet fishery, harbour porpoise bycatch rates decreased rapidly with increasing depth to 50 m and then levelled off. In the monkfish gillnet fishery, bycatch rates decreased linearly with increasing depth throughout the depth range fished. To reduce harbour porpoise bycatches, we recommend that large mesh nets associated with the monkfish fishery to be prohibited at depths less than 50 m. We also recommend to conduct experiments using Acoustic Deterrent Devices (ADDs or 'pingers') on nets set deeper than 50 m. If these devices prove successful in reducing porpoise bycatch, we propose that ADDs should be implemented in the Norwegian coastal gillnet fisheries for cod and monkfish.

1. Introduction

Throughout their range, harbour porpoises (*Phocoena phocoena*) are notoriously vulnerable to incidental catches in gillnets (Jefferson and Curry, 1994; Read et al., 2006; Vinther, 1999; Orphanides, 2009; IWC, 1992, 1996; ICES, 2008, 2011a). The ASCOBANS (Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas) has advised that annual bycatches should not exceed 1.7% of the best population estimate (ASCOBANS, 2000). EU has introduced a regulation for monitoring and mitigating bycatches of small cetaceans in European Union fisheries (EU Regulation 812/2004). This regulation mandates that Acoustic Deterrent Devices (ADDs or pingers) should be used in gillnet fisheries in some areas and periods for vessels larger than 12 m overall length, and obliges that observer programmes should be established for vessels larger than 15 m overall length. For small-sized fishing vessels less than 15 m overall length, the EU regulation indicates that data on incidental catches of cetaceans should be collected through scientific studies or pilot projects. According to ICES (2011b), the measures of regulation 812/2004 have not been well implemented. A shortcoming of this regulation is that it does not address bycatch monitoring and mitigation for vessels smaller than 15 m overall length, a segment of the gillnet fleet that may have substantial interactions with coastal harbour porpoises. Similar regulations to reduce bycatches of small cetaceans are not implemented in Norway, and currently no porpoise bycatch mitigation measures exist in Norway.

In the USA, an approach known as Potential Biological Removal (PBR) is used to establish limits on commercial bycatches of marine mammals (Wade, 1998). A Harbour Porpoise Take Reduction Plan (HPTRP) implements mitigation measures to reduce porpoise bycatches in US Northwest Atlantic waters; these measures include gear modifications, time area closures, and ADDs (Palka et al., 2008).

Norwegian fisheries are extensive, and fish products are Norway's second largest export commodity. Most demersal catches are taken with bottom trawls, and most pelagic catches are taken by purse seines. Onboard observer programmes have revealed that these gear types have a relatively low risk of capturing marine mammals (Bjørge et al., 2006a). Most of the effort in quantifying

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marine mammal bycatch has therefore been focused on small vessels using gillnets in the coastal zone. In a 2005 pilot study, coastal fishermen were interviewed to identify gear types associated with high incidental mortality of marine mammals. The fishermen identified three fisheries: the bottom-set gillnet fishery for monkfish (*Lophius piscatorius*), the gillnet fishery for cod (*Gadus morhua*) and the lumpsucker (*Cyclopterus lumpus*) gillnet fishery. Harbour porpoise, harbour seals (*Phoca vitulina*), and grey seals (*Halichoerus grypus*) were mentioned as the most frequently bycaught mammals. The fishery for lumpsucker has little fishing effort, a short season, and a restricted spatial distribution. In this first attempt to estimate harbour porpoise bycatch in Norwegian fisheries, we therefore restricted our efforts to the coastal gillnet fisheries for monkfish and cod.

Independent onboard observers are recommended as the best way to obtain reliable bycatch data (Northridge, 1996; IWC, 1996). The coastal gillnet fisheries in Norway, prosecuted primarily by small vessels with a total length of less than 15 m, are not suitable for carrying independent observers. Therefore, in this paper, we estimate the bycatch of harbour porpoises in the cod and monkfish coastal gillnet fisheries based on fishery-dependent data from a monitored segment of the coastal gillnetter fleet. Using the harbour porpoise bycatch rate in the monitored segment of the fleet, we derive the total porpoise bycatch in the monkfish and cod gillnet fisheries by applying the bycatch rate to the overall catches of cod and monkfish in these fisheries. The detailed information provided by the monitored segment of the fisheries also allowed for testing of potential bycatch mitigation factors, such as by evaluating the effects of soak time and water depth on harbour porpoise catch rates per net.

2. Materials and methods

2.1. The coastal reference fleet

Norwegian landing statistics for target species are comprehensive and assumed to reflect the true catches, and fishing effort

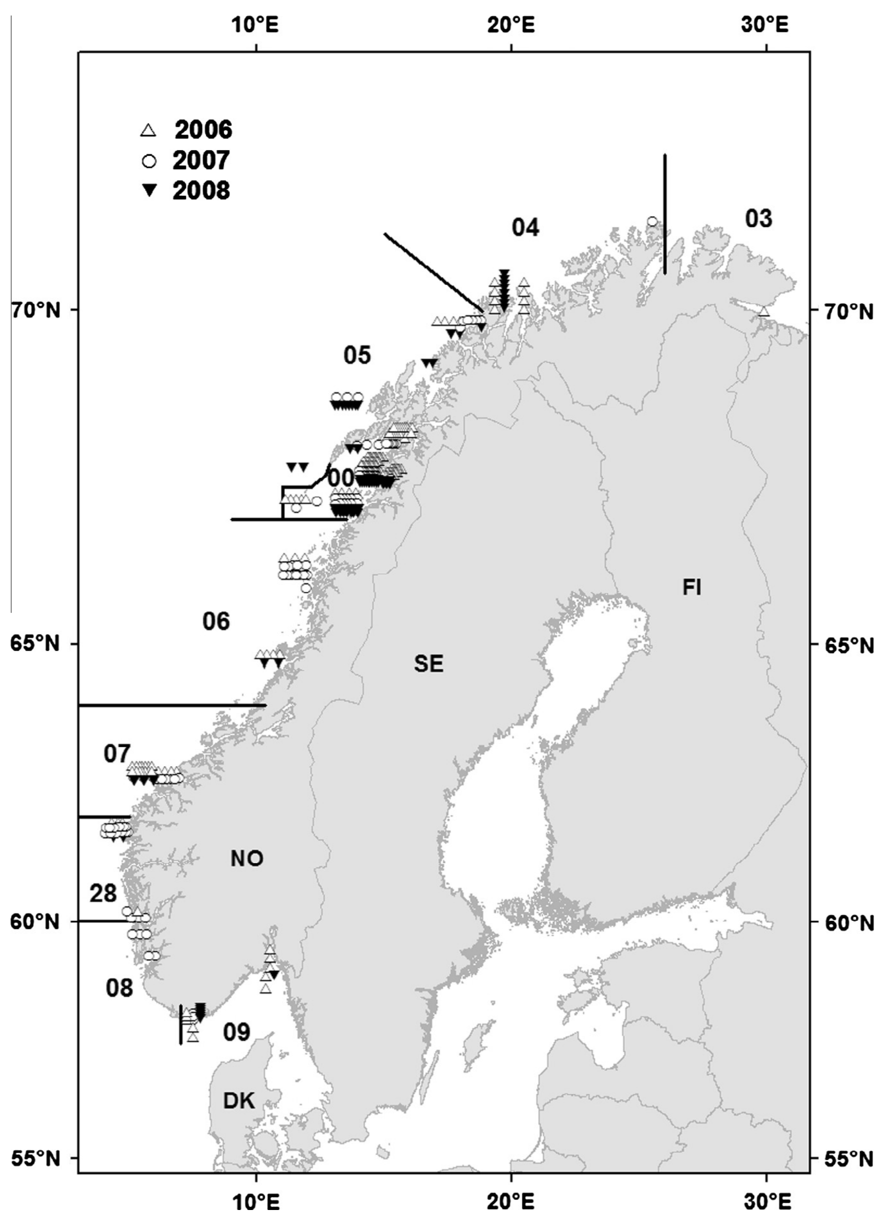

Fig. 1. Nine domestic Norwegian coastal fishery statistics areas and the distribution of porpoises caught on gillnets set for monkfish or cod by the monitored segment of the fleet (CRF) in 2006, 2007 and 2008 (see Table 3 for numbers).

statistics are available for the larger vessels via their log books. However, for the small coastal vessel fleet (where log books are not mandatory) improved information is needed on the sex, age, and size composition of all of the target species, on the relationship between fishing effort and catch of these target species, and on the species and size composition of the catches of all non-target species. Therefore, the Institute of Marine Research (IMR) contracted with two small (<15 m) fishing vessels in each of nine coastal statistical areas (Fig. 1) to provide detailed information on their fishing effort and their catches of all target and non-target species, including marine mammals and birds (Bjørge et al., 2006b). These vessels were randomly selected among commercial vessels applying for the contract. The contracted vessels are referred to as the Coastal Reference Fleet (CRF), and each CRF vessel has a contact person at IMR. The contact persons visited the vessels regularly and remained onboard on day trips at sea. Any discrepancies in statistics between days with and without IMR staff onboard may lead to termination of a vessel's contract. The main task of the IMR staff onboard was to guide the fisher in correct reporting of effort, catch and bycatch.

2.2. Catch data from the monitored segment of the fleet, CRF

The CRF was contracted to target monkfish and cod using the same standard gillnet gear as used in the rest of the commercial coastal fleet, i.e., bottom-set gillnets with half mesh of 180 mm for monkfish, and bottom-set gillnets with half mesh of 75–105 mm for cod. The twin size was 0.7 mm in both gear types. The monkfish nets are 27.5 m long, 12.5 meshes high and 40–50 nets are typically set in a string. The cod nets are 27.5 m long and a varying numbers of nets (but far less than monkfish nets) are set in a string. The total catches of monkfish and cod harvested by the CRF in 2006, 2007, and 2008 are summarised, by coastal statistical area and overall, in Tables 1 and 2, respectively. The reported incidental catches of harbour porpoise are listed in Table 3 and the locations of the bycaught porpoises are depicted in Fig. 1.

Table 1
Catches of monkfish (kg) in 2006, 2007 and 2008 taken on monkfish nets by the monitored segment of fleet (CRF), by area listed from North to South.

Area	2006	2007	2008	Total
03	0	0	0	0
04	0	0	0	0
05	16,402	22,152	39,615	78,169
00	23,983	34,471	28,387	86,841
06	7080	0	1265	8345
07	63,322	64,978	35,828	164,128
28	6020	17,401	4870	28,291
08	646	2825	59	3530
09	5279	2187	4795	12,261
Total	122,732	144,014	114,819	381,565

Table 2
Catches of cod (kg) in 2006, 2007 and 2008 taken on cod nets and unspecified nets by the monitored segment of fleet (CRF), by area listed from North to South.

Area	2006	2007	2008	Total
03	20,651	1885	15,486	38,022
04	371,076	185,101	234,634	790,811
05	283,979	297,079	293,684	874,742
00	121,989	74,821	67,227	264,037
06	82,666	59,954	91,619	234,239
07	44,559	35,186	37,697	117,442
28	1465	563	40	2068
08	2462	1771	1846	6079
09	12,862	8595	5515	26,972
Total	941,709	664,955	747,748	2,354,412

Table 3
Incidental catches of harbour porpoise by the monitored segment of the coastal gillnetting fleet (CRF).

Area	2006	2007	2008	Total
03	1	0	0	1
04	8	1	7	16
05	4	1	16	21
00	97	54	50	201
06	7	2	2	11
07	18	5	28	51
28	4	7	4	15
08	0	5	0	5
09	10	1	4	15
Total	149	76	111	336

2.3. Landings statistics from the entire commercial fleet less than 15 m

Landings statistics for the entire commercial fleet of gillnetters less than 15 m were provided by the Directorate of Fisheries. These statistics are based on fish landed in harbours. The statistics are not specified by gillnet type, and therefore include fish taken by all types of bottom set gillnets.

The monkfish fishery primarily occurs in late summer and autumn, and is widely spread geographically (Fig. 2A and C).

Fishing effort in the coastal cod gillnet fishery is large, especially during the cod spawning season in February–April in northern statistical areas 00, 04, and 05 (Fig. 2B and D). Nets of similar mesh size are used in multispecies gadoid fisheries that occur along the entire Norwegian coast throughout the year, but with smaller effort. Gillnet landings of cod are highest during February to April and lowest during July to January. The landing statistics were aggregated by year, month, and statistical area.

2.4. Analytical approach

To estimate the total annual bycatch of harbour porpoise in the coastal cod and monkfish fisheries, we used the CRF data to derive the porpoise catch rate relative to catches of cod and monkfish, and then used this catch rate to extrapolate to the entire coastal fleet of vessels <15 m total length based on landings statistics from the commercial fisheries of the same segment of the fleet. Our approach assumes that porpoise bycatch numbers are positively related to fish catches. To extrapolate to entire fisheries, both the commercial and the CRF data were aggregated by year, month and statistical area. The CRF catches generally followed the same seasonal and geographical patterns as the commercial fisheries (Fig. 2A–D).

To develop a robust estimate of bycatch, we decided to down weight the influence of a few incidents on the predicted bycatch numbers. We therefore conducted analyses at a coarser spatial and temporal scale than month and statistical area, due to the scarce data available in some of the month $\times$ statistical area combinations (Fig. 2). To model geographic patterns, we combined neighbouring areas into a factor variable *region* with four levels (cf. Fig. 1); region 1 consisting of areas 03, 04 and 05; region 2 containing only area 00; region 3 composed of areas 06 and 07; and finally, region 4 comprising areas 28, 08, and 09. A combination of observed bycatch frequency and temporal and spatial patterns in the fisheries were used to combine areas within regions. Area 00 had elevated bycatch numbers in both the cod and monkfish fisheries relative to all other areas, and was associated with a high bycatch rate in the cod fishery while an intermediate bycatch rate

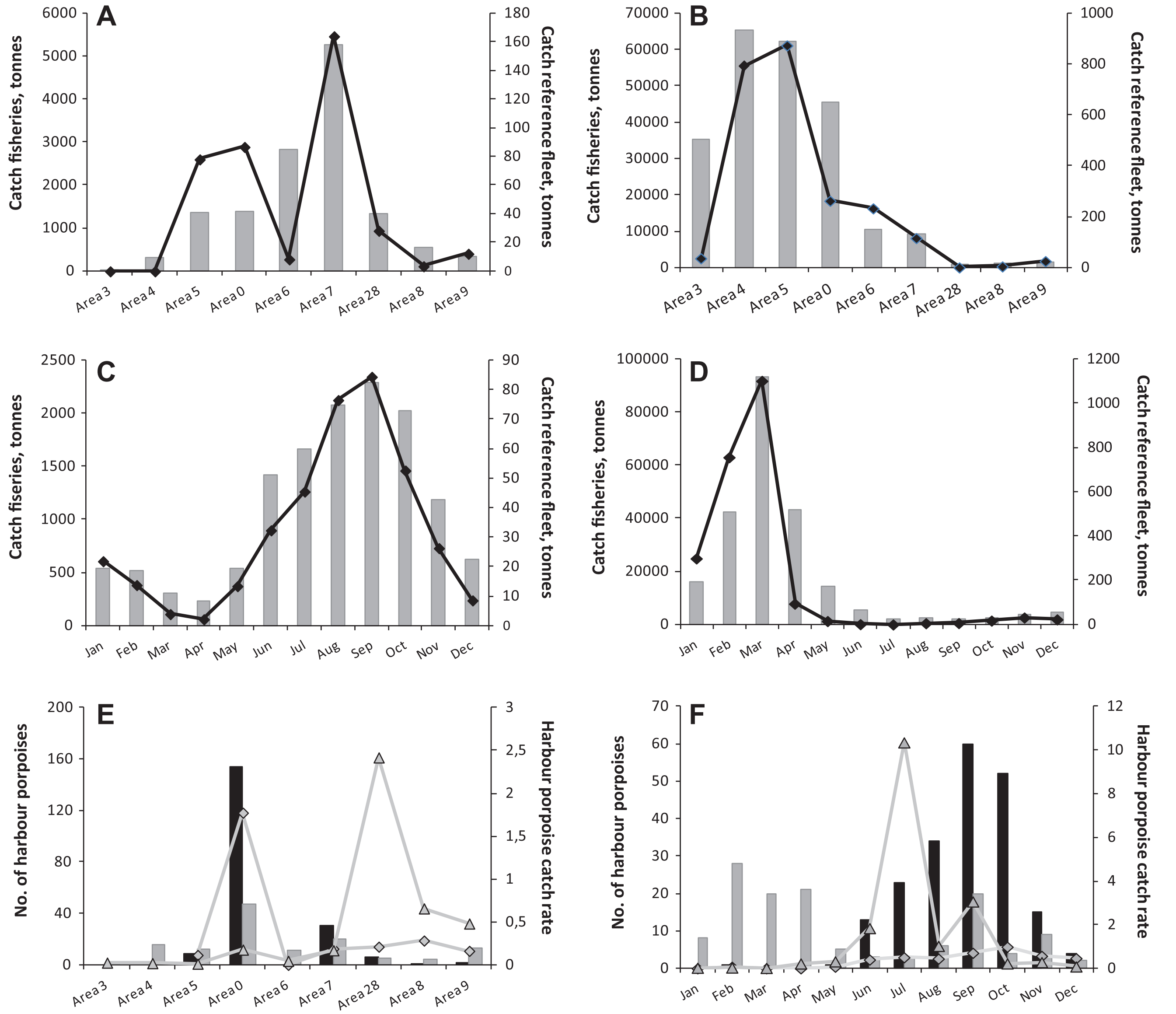

Fig. 2. Landings by commercial fisheries (bars) and the coastal reference fleet (dots). Of monkfish (A and C) and cod (B and D) by area and month. Catch of harbour porpoises by monkfish fisheries (black bars) and associated catch rates (diamonds, *N* porpoises × tons landed fish^{-1}) and for cod fisheries (grey bars and triangles) by area (E) and month (F).

in the monkfish fishery (Fig. 2E and F). Therefore, area 00 was included in its own region (i.e., region 2).

We also tested a smoothed function of area, by using the relative position of each area along the coast (numbered from 1 to 9) as a continuous variable. In this way, the estimated bycatch rate in one area would be related to the bycatch rates in neighbouring areas. However, this approach would also smooth bycatch rates between neighbouring areas having potentially very different cod and monkfish catch rates, such as between areas 05 and 00. To model seasonal effects, we selected half year (January–June; July–December) as a factor variable. A pronounced seasonal shift in catches occurs in both the cod and monkfish fisheries, but porpoise bycatch rates are higher in each fishery during the second half of the year than in the first (Fig. 2F).

The analytical approach was similar to the approach presented by Orphanides (2009). We used general additive models (GAMs) to model bycatch rates from the CRF, where number of harbour porpoises was entered as the response variable and assumed to follow a Poisson distribution, and catch by the fisheries was entered as an offset. We combined the data for both fisheries in the statistical analyses, and included type of fisheries (monkfish or cod) as a factor variable. We did not attempt to include season × area interactions due to the low effort in several season × area combinations. However, we found the sampling sufficient to include the interactions season × fisheries and area × fisheries, in addition to main effects of fishery, season and area. Thus, the full model combining the two fisheries included the following terms:

$$\text{No. of harbour porpoises} \sim \text{offset}(\text{log.catch}) + \text{fishery} + \text{season} + \text{region} + \text{fishery} * \text{season} + \text{fishery} * \text{region} \quad (1)$$

where season was included as half year, and area as a factor variable of region with four levels, or as a smooth function of areas, s(region). For each of the two approaches, all possible models nested within the model in Eq. (1) were run, and the best models selected based on Akaike's Information Criterion adjusted for small samples, AICc (Akaike, 1974). Model fit was further assessed by plotting predicted versus observed values and evaluating dispersion. Year was included as a random factor in the initial analyses. However,

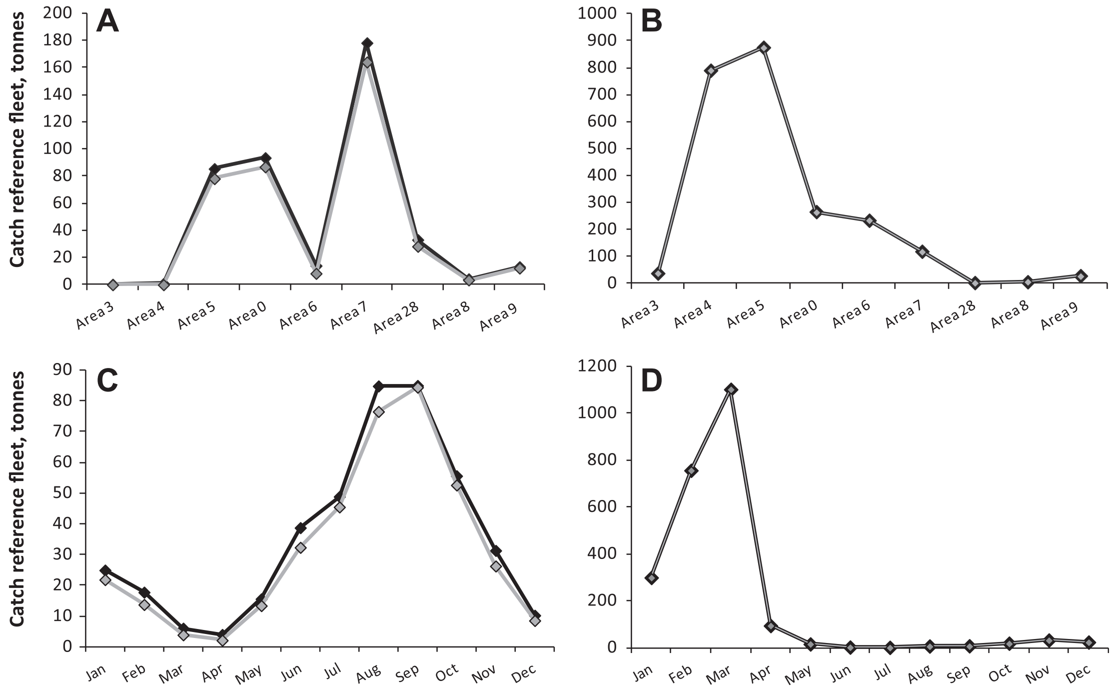

Fig. 3. Landings by reference fleet of monkfish and cod, in monkfish fisheries and cod fisheries, respectively. (A and C) Monkfish landings from monkfish nets (grey) and total landings (black), by area and month. (B and D) Cod landings from cod nets (grey) and total catch (black, almost completely overlapping).

a substantial increase in over-dispersion (dispersion factors >300) in these mixed models relative to models without year demonstrated a poor capability to estimate any random year effects. We therefore chose models that excluded year effects.

We used the bycatch rates from the best models to estimate the total number of porpoise bycatches in the commercial fisheries, based on catches of cod and monkfish by the commercial fisheries. The *predict.gam* function (mgcv package, R 2.10.1, R Development Core Team, 2011) was used to perform this extrapolation.

We used the best model in the *predict.gam* function to predict the total bycatch (in numbers) of harbour porpoise in the monkfish and cod fisheries based on the catches of these two species in the commercial fisheries. In the commercial catch statistics, net type is not specified and catches were therefore summed across net types. In the CRF data, 9.85% of the monkfish were caught in cod nets, while <1% of cod was caught in monkfish nets. Thus, to estimate the actual monkfish catch in the monkfish gillnet fishery, the total landings of monkfish required an adjustment for the proportion of monkfish caught in cod nets. According to Fig. 3, there were no pronounced geographic or temporal patterns in the proportion of catches between the two net types. Thus, we adjusted for catches of monkfish in cod nets by multiplying the total commercial monkfish catches by 0.901. No such adjustment was required for the cod catches.

CVs for the predicted numbers of harbour porpoise bycatch were obtained through bootstrapping as in Orphanides (2009). Three years of CRF data (trips), summed by fishery, month and area, yielded $N = 648$ observations in the data set. In the bootstrapping procedure, we therefore randomly selected $N = 648$ observations with replacement. We replicated this selection 1000 times. For each replicated set of selected observations, we ran the best models and predicted the total number of bycatch. CVs were calculated from the resulting distribution of the predicted values.

2.5. Identifying factors influencing bycatch rates

The CRF data provided auxiliary information about fishing practices not available from the commercial fleet. This included details on spatial and temporal patterns of fishing, as well as information on the bottom depth of the net sets (minimum, average, and maximum bottom depths) and soak times. These data are available at the spatial and temporal resolution of landings. Using the new auxiliary data, we modelled the harbour porpoise catch rate (relative to number of nets set per landing) as a function of season, area, minimum bottom depth (as harbour porpoises generally inhabit shallow areas; Bjørge and Tolley, 2009), and soak time. We used log linear General Additive Mixed Models (GAMMs) with number of nets as an offset, year as a random factor, and with smooth functions of soak time and minimum bottom depth. The CRF data proved sufficient to include an interaction between season and depth. The full model was thus defined as

$$\begin{aligned}\text{No. harbour porpoises} = {} & \text{offset}(\log(\text{no.of nets})) \\ & + \text{random factor}(\text{year}) \\ & + \text{factor}(\text{regions}) + \text{s}(\text{soak time}) \\ & + \text{s}(\text{minimum depth}) * \text{season} \qquad (2)\end{aligned}$$

We ran model (2) and all models nested within (2) and selected the best model based on AICc values. As the cod and monkfish fisheries differ with respect to both soak time and depth, we analysed the fisheries separately. The separate models also enabled us to independently assess potential mitigation factors for each fishery.

All analyses were performed in R 2.10.1 (R Development Core Team, 2011) with the mgcv library (Wood, 2006).

3. Results

In the CRF data, harbour porpoise bycatch was significantly correlated with the landings of cod from the cod fishery (Pearson's $r = 0.36$, $p < 0.001$) and landings of monkfish from the monkfish fishery (Pearson's $r = 0.50$, $p < 0.001$).

3.1. Estimating total bycatch of harbour porpoise in two coastal gillnet fisheries

Model fit statistics for the various model formulations evaluated to estimate harbour porpoise bycatch rates using the CRF data

Table 4
Models tested for combined CRF fisheries to estimate harbour porpoise catches relative to total catches of cod and monkfish, respectively. Models in bold have the lowest AICc values.

Model		DF	Dev. expl.	Scale	AICc
Models with combined areas (four levels) and season					
1.1	Offset(log catch)	2	0.22	2.17	1654.76
1.2	Offset(log catch) + factor(comb. areas)	4	0.31	1.92	1492.51
1.3	Offset(log catch) + factor(season)	2	0.3	1.95	1509.36
1.4	Offset(log catch) + factor(fishery) + factor(season)	3	0.31	1.94	1502.13
1.5	Offset(log catch) + factor(fishery) + factor(comb. areas)	5	0.42	1.63	1306.88
1.6	Offset(log catch) + factor(season) + factor(comb. areas)	5	0.49	1.41	1165.72
1.7	Offset(log catch) + factor(fishery) + factor(season) + factor(comb. areas)	6	0.49	1.42	1167.62
1.8	Offset(log catch) + factor(fishery) + factor(season)+factor(comb. areas) + factor(fishery):factor(season)	7	0.5	1.4	1158.09
1.9	Offset(log catch) + factor(fishery) + factor(season)+factor(comb. areas) + factor(fishery):factor(comb. areas)	9	0.52	1.35	1129.73
1.10	**Offset(log catch) + factor(fishery) + factor(season)+factor(comb. areas) + factor(fishery):factor(comp. areas) + factor(fishery):factor(season)**	**10**	**0.53**	**1.33**	**1117.54**
Models with s(areas) and season					
2.1	Offset(log catch) + factor(fishery)	2	0.22	2.17	1654.76
2.2	Offset(log catch) + s(areas)	7.0	0.28	2.02	1554.6
2.3	Offset(log catch) + factor(season)	2	0.3	1.95	1509.36
2.4	Offset(log catch) + factor(fishery) + factor(season)	3	0.31	1.94	1502.13
2.5	Offset(log catch) + factor(fishery) + s(areas)	7.9	0.39	1.71	1355.14
2.6	Offset(log catch) + factor(season) + s(areas)	7.8	0.47	1.49	1214.75
2.7	Offset(log catch) + factor(fishery) + factor(season) + s(areas)	8.8	0.47	1.49	1216.74
2.8	Offset(log catch) + factor(fishery) + factor(season) + s(areas)+ factor(fishery):factor(season))	9.7	0.48	1.47	1202.7
2.9	Offset(log catch) + factor(fishery) + factor(season) + s(areas)+ factor(fishery):s(areas)	14.4	0.51	1.38	1151.93
2.10	**Offset(log catch) + factor(fishery) + factor(season)+s(areas) + factor(fishery):s(areas)+factor(fishery):factor(season)**	**15.14**	**0.52**	**1.35**	**1135.17**

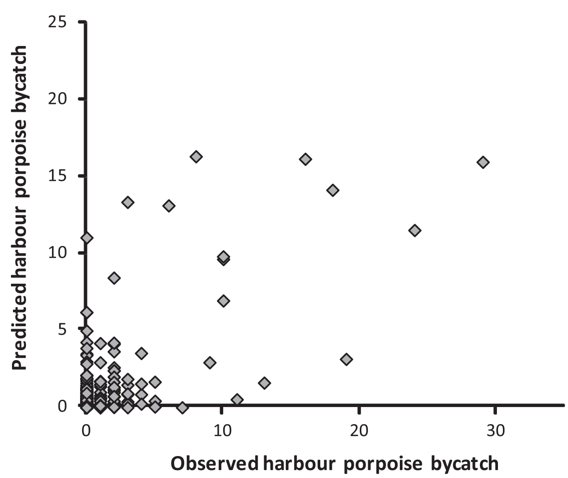

Fig. 4. Observed versus predicted bycatch numbers. Predicted values are from the best model (model 1.10).

are given in Table 4. The best model in terms of AICc was model 1.10, which included region and two interaction terms: fishery × region and fishery × season. This model accounted for 53% of the deviance; thus half of the variation in the observed bycatch rates could be explained by the predictor variables used. The dispersion parameter of 1.35 indicates that the Poisson approximation was relatively good, and the plot of observed versus fitted values from model 1.10 demonstrates that the model captured the major trends, although considerable variability still exists between predicted and observed values (Fig. 4). The correlation coefficient between fitted and observed values was 0.70. The second best model was the one in which geographic patterns were modelled as a nonlinear, continuous variable (model 2.10). This model accounted for 52% of the variation, with a dispersion parameter of 1.35.

Fig. 5 shows the total predicted harbour porpoise bycatch during 2006–2008, by area and month, for the commercial fleet of gillnetters <15 m based on their landings, using the two best models (model 1.10 and model 2.10). Both models predict highest bycatches in Area 00 and in spring. For the 3-year period (2006–2008), the total predicted number of harbour porpoise bycatch was 20,719 and 20,989 porpoises based on model 1.10 and model 2.10, respectively. The bootstrap generated CVs associated with the predicted numbers were 36% and 27%, respectively. Thus, the models predict total annual bycatches of ~6900 harbour porpoises in the Norwegian coastal cod and monkfish gillnet fisheries.

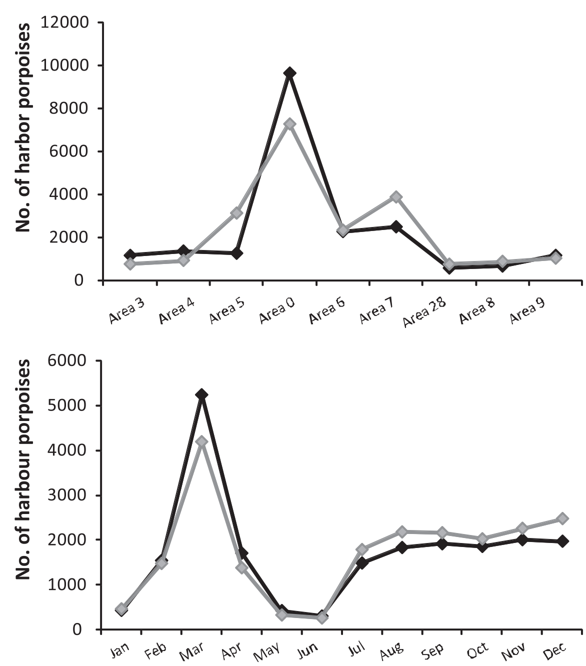

Fig. 5. Predicted harbour porpoise bycatches for the period 2006–2008 from two best models (model 1.10 in black, model 2.10 in grey) by area and month.

3.2. Factors influencing bycatch rates

Soak time, minimum bottom depth per trip, number of nets, area and date were available for $n = 2330$ and $n = 997$ trips in the

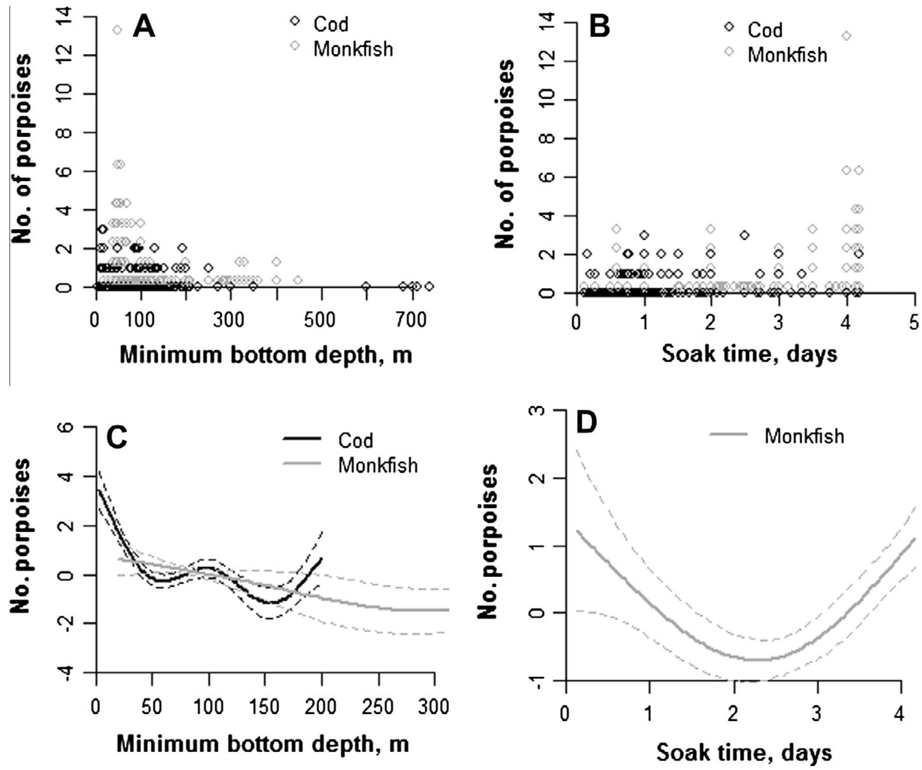

Fig. 6. Catches of harbour porpoises in the CRF. Number of harbour porpoises caught relative to (A) minimum bottom depth of cod and monkfish nets and (B) soak time of cod and monkfish nets. Predicted number of harbour porpoise bycatch relative to minimum bottom depth (C) and soak time (D) from selected GAMM-models. A small number (0.15) is added (monkfish fisheries) or subtracted (cod fisheries) to the harbour porpoise numbers in A and B for better visualisation of the data.

cod and monkfish gillnet fisheries, respectively. Minimum bottom depth is the depth at the shallowest end of the net.

Monkfish gillnets were predominantly set for a longer time period and at greater depths than cod gillnets (Fig. 6A and B). The minimum bottom depth at which cod nets were set ranged from 5 to 200 m, while the minimum bottom depth for setting monkfish nets ranged from 20 to 400 m (Fig. 6A). The average soak time for cod nets was 1.1 days (s.d. = 0.61), while the average soak time for monkfish nets was 2.7 days (s.d. = 1.1).

The best model, in terms of AIC-fit, for harbour porpoise bycatch rates in cod nets included a random intercept by year, fixed intercepts by region, and a smooth of minimum bottom depth (Table 5). Data from nets set at depths greater than 200 m were very limited (only 38 observations), so these data were excluded from the analysis. The highest bycatch rates of harbour porpoises occurred in region 2 (mean 2.72×10^{-3} porpoises per net, s.e. 0.97×10^{-3}), followed by region 1 (mean 0.47×10^{-3} porpoises per net, s.e. 0.12×10^{-3}), region 3 (mean 0.39×10^{-3} porpoises per net, s.e. 0.09×10^{-3}) and region 4 (mean 0.06×10^{-3} porpoises per net, s.e. 0.02×10^{-3}). Bycatch rates were highest in shallower areas and decreased steeply towards 50 m bottom depth before levelling out (Fig. 6C).

The best model for predicting harbour porpoise catch rates in monkfish nets included a random intercept of year, fixed intercepts of region and season, and smooth functions of depth and soak time (Table 5). No bycatch of porpoise occurred in region 1 and so catches from this region were excluded from the analysis. Also excluded were nets set at bottom depths >400 m because of limited

Table 5
General Additive Mixed Models for cod and monkfish CRF fisheries (analysed separately) for testing porpoise catch rate per net as a function of depth and soak time. Values in bold demonstrate models with lowest AIC values.

Model		Cod nets		Monkf. nets	
		Dev expl	AIC	Dev expl	AIC
3.1	Offs(log n nets)	0.00	973.1	0.00	805.2
3.2	Offs(log n nets) + f (comb. areas)	0.07	921.4	0.11	740.4
3.3	Offs(log n nets) + f (season)	0.00	974.9	0.07	763.4
3.4	Offs(log n nets) + s(soak time)	0.02	962.4	0.17	706.7
3.5	Offs(log n nets) + s(min depth)	0.15	868.2	0.11	741.4
3.6	Offs(log n nets) + f(comb. areas) + f (season)	0.07	923.4	0.15	717.1
3.7	Offs(log n nets) + f(comb. areas) + s(min depth)	**0.18**	**848.9**	0.17	604.7
3.8	Offs(log n nets) + f(season) + s(soak time)	0.02	964.3	0.21	678.9
3.9	Offs(log n nets) + f(season) + s(min depth)	0.15	870.1	0.17	709.7
3.10	Offs(log n nets) + s(soak time) + s(min depth)	0.15	864.7	0.22	677.5
3.11	Offs(log n nets) + f(comb. areas) + f (season) + s(soak time)	0.08	923.3	0.22	677.3
3.12	Offs(log n nets) + f(comb. areas) + f (season) + s(min depth)	0.18	850.9	0.20	691.8
3.13	Offs(log n nets) + f(comb. areas) + s(soak time) + s(min depth)	0.18	849.7	0.25	661.8
3.14	Offs(log no. of nets) + f(season) + s(soak time) + s(min depth)	0.15	866.65	0.25	660.9
3.15	Offs(log n nets) + f(comb. areas) + f(season) + s(soak time) + s(min depth)	0.18	851.61	**0.26**	**657.8**
3.16	Offs(log n nets) + f(comb. areas) + s(soak time) + s(min depth * season)	0.11	911.1	0.23	678.7

number of observations. Hence, the analyses included 959 out of 997 observations.

Harbour porpoise bycatch catch rates in monkfish nets were similar in regions 2 (mean 1.43×10^{-3} porpoises per net, s.e. 0.25×10^{-3}) and 4 (mean 1.23×10^{-3} porpoises per net, s.e. 0.63×10^{-3}), and greater than in region 3 (mean 0.54×10^{-3} porpoises per net, s.e. 0.12×10^{-3}). Bycatch rates were much higher in the second half of the year (mean 1.16×10^{-3} porpoises per net, s.e. 0.7×10^{-3}) when monkfish landings were highest, relative to the first half of the year (mean 0.03×10^{-3} porpoises per net, s.e. 0.14×10^{-3}). Bycatch rates decreased linearly with minimum bottom depth, and the rate of decrease was less than that for the cod nets in shallow waters (Fig. 6C). However, monkfish nets were typically set at slightly deeper minimum depths than cod nets. The shallowest end of cod nets was typically shallower than the shallowest end of monkfish nets. The bathymetry of Norwegian coastal waters is very complex and a string of nets may cover a wide depth range.

Porpoise bycatch rates in monkfish nets were high for both the shortest (<1 days) and longest (>3 days) soak times (Fig. 6D). While the elevated bycatch rates at short soak times were associated with large standard errors caused by relatively few nets soaked <1 day and few catches of porpoises (Fig. 6B), the elevated bycatch rates for the longest soak times were associated with smaller standard errors, reflecting the higher proportion of nets with longer soak time.

4. Discussion

4.1. Uncertainties in the estimate

Seasonal and geographical catch patterns were similar in the CRF and the coastal monkfish and cod gillnet fisheries (Fig. 2). However, the patterns deviated in some months and areas because of low CRF catches (e.g., the monkfish fishery in area 06). These low catches in some months and areas likely increased the heterogeneity in observed porpoise bycatch rate by month and area (Fig. 2E and F). As an example, the low monkfish catch by the CRF in area 06 resulted in very low porpoise bycatch estimates in this area, despite high bycatch numbers in the neighbouring area 00 (Fig. 2E). Similarly, the few bycatches in area 28 by cod fisheries resulted in higher estimated bycatch rates than in neighbouring areas, due to the low cod landings in this area.

Coefficients of variation (CV) of 0.36 in model 1.10 and 0.27 in model 2.10 are close to the 0.30 CV limit for bycatch estimates established in EU Regulation 812/2004. Based on the geographic and seasonal variability observed in catches in the coastal cod and monkfish gillnet fisheries and also in the CRF porpoise bycatch rate (Fig. 2), bycatch models must take space and time into account. However, the data available for our study only allowed temporal and spatial patterns to be modelled at very coarse scales. More precise bycatch estimates, and a greater understanding of bycatch trends in space and time, will only be achieved when more data become available from the monitoring programme.

A more general critique of this method for estimating bycatches is the use of cod and monkfish catch as a unit of effort proxy (i.e., the denominator in the harbour porpoise bycatch rate: number of porpoise caught per kg of cod [or monkfish] caught) as there is often a poor relationship between target species catches and non-targeted bycatch (Orphanides, 2009). In the CRF fisheries for cod and monkfish, however, a relatively good relationship, as assessed by the significant correlations (Pearson's $r \geqslant 0.36$), was observed between landings and porpoise bycatches.

An associated concern when using catches as a proxy unit of effort is changing availability of the target species within the period of the study (e.g. a declining availability of the target species may require more fishing effort [more time or more gear] to land the same quantity of fish (Orphanides, 2009). In our case, the availability of cod was relatively stable during 2006–2008. The population size and landings of Northeast Arctic cod were high and stable during the period (Bogstad, 2010), while the abundance and catch of coastal cod north and south of 62°N remained low (Berg, 2010; Gjøsæter, 2010, respectively). Norwegian gillnet landings of monkfish were stable at approximately 5000 tonnes per year during 2006–2008, but the population status of monkfish is less well documented (Bjelland, 2010). Overall, it seems unlikely that availability of either cod or monkfish changed much during the study period.

4.2. Observer coverage

The US Marine Mammal Protection Act of 1972 recommends 20–30% observer coverage to monitor marine mammal bycatches. Annex III of EU Regulation 812/2004 recommends minimum observer coverage of 5% of the effort, and for fleets numbering more than 400 vessels, the effort of 20 vessels should be monitored. The combined Norwegian coastal fisheries for cod and monkfish comprise more than 400 vessels. In our study, 18 vessels were monitored, which approximates the 20 vessels requirement of the EU regulation. However, with respect to target catches, the CRF vessels accounted for only 1% and 3% of the total landings of cod and monkfish, respectively. This does not fulfil the requirements of the regulation, but is concordant with many at-sea monitoring programmes in the US, which have observer coverage between 1% and 5% (Moore et al., 2009). Globally, most fisheries operated by small vessels are not subject to monitoring for estimating marine mammal bycatches. Nevertheless, the Norwegian coastal gillnet monitoring programme should seek to increase observer coverage.

4.3. Sustainability and conservation concerns

The population structure of harbour porpoises in Norwegian waters is not well documented. Gaskin (1984) assumed that there were two populations, divided by the deep waters of Vestfjorden (corresponding to Area 00 in this study). Bjørge and Øien (1995) found a hiatus in the offshore distribution of porpoises off central Norway suggestive of two population components: a southern component associated with the shelf waters of the North Sea, and a northern component associated with the shelf waters of the Barents Sea. Based on analysing mtDNA samples from 45 porpoises from the North Sea and 38 porpoises from the Barents Sea, Tolley et al. (1999) concluded that porpoises along the entire Norwegian coast constituted a single population unit. In a review paper, Andersen (2003) supported the conclusion of Tolley et al. (1999), but noted that results from wider studies using mtDNA and nuclear DNA samples indicated that the Norwegian harbour porpoise population was distinct from populations in the rest of Scandinavian and European waters. However, within Norwegian waters, seasonal movements and the relationship between coastal and offshore porpoise groups are not known.

The abundance of porpoises in the wider North Sea area was estimated at 341,366 animals (CV 0.14) in 1995 (Hammond et al., 2002), and at 334,948 individuals (CV 0.16) in 2005 (SCANS II, 2006). About 1/3 of the Norwegian coast borders the North Sea. Bjørge and Øien (1995) estimated that 11,000 porpoises (CV 0.44) inhabited part of the offshore Barents Sea area. This estimate assumed that all porpoises on the track line were observed, and thus underestimates the true abundance. The abundance of porpoises in the large and complex coastal and fjord waters of Norway is still unknown.

According to the criterion advised by ASCOBANS (i.e., bycatches should not exceed 1.7% of the best population estimate), a population in excess of 400,000 is required to sustain an annual bycatch of

6900 harbour porpoises. Although no abundance estimate exists for the harbour porpoise that occur along the Norwegian coast, it is unlikely that the population can sustain this level of bycatch. As such, incidental takes in the coastal fisheries should be reduced and specific management objectives for harbour porpoise developed.

4.4. Recommendations for mitigation

Currently no porpoise bycatch mitigation measures exist in Norway. However, a variety of approaches are available for mitigating bycatches of small cetaceans including time and area closures (Dawson and Slooten, 1993), the use of acoustic deterrent devices (pingers) (Kraus et al., 1997; Gearin et al., 2000; Barlow and Cameron, 2003; Gönener and Bilgin, 2009), and deployment of acoustic reflective nets (Trippel et al., 2003; Larsen et al., 2007).

To test the operational aspects of pingers under conditions typical for Norwegian coastal gillnet fisheries, we plan to conduct a controlled experiment using the pinger AQUAmark 100 in the area of highest harbour porpoise bycatch rates (area 00). The AQUAmark 100 has an undulating bandwith of 20–160 kHz, and using a spacing of 400 m between pingers has successfully reduced harbour porpoise bycatch (ICES, 2011b; Larsen and Krog, 2007). The AQUAmark 100 has been tested to 200 m depth, but is anticipated to work at depths of 400 m (information from producer).

If the experiment demonstrates that ADDs significantly reduce porpoise bycatches, we will recommend a combination of ‘closed areas’ and the use of pingers. Porpoise bycatch rates increase with decreasing depth in the coastal gillnet fishery for monkfish (Fig. 6A). We therefore recommend the prohibition of large-mesh gillnets in waters shallower than 50 m as a proxy for the closed area approach. For gillnets in waters exceeding 50 m depth, we recommend the use of pingers, and we recommend pingers with the specifications outlined in EU Regulation 812/2004.

We also recommend the continuation of the bycatch monitoring programme, but with increased coverage. To increase the coverage on small vessels, we will increase the number of vessels in the CRF.

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