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Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

DTU Aqua
National Institute of Aquatic Resources

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DTU Aqua Report no. 389-2021







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Colophon

Title:	Bycatch of marine mammals and seabirds. Occurrence and mitigation
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DTU Aqua Report no.:	389-2021
Year:	Scientific work finalized May 2021. Report published October 2021.
Reference:	Larsen, F., Kindt-Larsen, L., Sørensen, T.K. & Glemarec, G. (2021) Bycatch of marine mammals and seabirds. Occurrence and mitigation. DTU Aqua Report no. 389-2021. National Institute of Aquatic Resources, Technical University of Denmark. 69 pp.
Cover:	Photos from gillnets fisheries and bycatch of marine mammals and seabirds. Photos: Anne-Mette Kroner, Lotte Kindt-Larsen and Gildas Glemarec.
Published by:	National Institute of Aquatic Resources, Kemitorvet, 2800 Kgs. Lyngby, Denmark
Download:	www.aqua.dtu.dk/publications
ISSN:	1395-8216
ISBN:	978-87-7481-312-5

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Preface

This report is based on the project “Bifangst af havpattedyr og havfugle – forekomst og afværgning (no. 33113-I-16-040)” funded by the European Maritime and Fisheries Fund and the Danish Fisheries Agency.

European Union
European Maritime and Fisheries Fund

HAV & FISK

We thank all the scientists who participated during the course of the project, contributed to discussing the results and helped identify future challenges in research on bycatch and bycatch mitigation.

DTU Aqua, Kgs. Lyngby
July 2021

Content

Summary

Gillnet fisheries are generally considered environment-friendly, causing limited bottom-impact and generating high-quality fish. Nevertheless, gillnets are also associated with high risks of bycatch of non-target animals, including seabirds and marine mammals. To fulfil Denmark's obligations with regards to European legislations and other international agreements, the present report assesses for the first time the magnitude and the spatiotemporal distribution of marine mammal and seabird bycatch in Danish gillnet fisheries and proposes solutions to mitigate this bycatch.

Bycatch of seabirds and marine mammals in gillnets was estimated using electronic monitoring (EM) with videos on a sample of the Danish commercial gillnet fleet (Section 2). EM systems combined video data and fine-scale tracking data, allowing to record and analyse a census of the fishing activity of 16 vessels, including bycatches of vulnerable species, between 2010 and 2016, in the North Sea, Skagerrak, Kattegat, Belt Seas and Western Baltic Sea. Monitoring focused on seabirds, harbour porpoise and seals for which it was possible to document the temporal and spatial distribution of bycatches in gillnets in areas where data had been collected and to estimate mean quarterly bycatch rates in areas where enough EM data were available, *i.e.* the North Sea, the Skagerrak, the Øresund and the Belt Sea. Based on these estimates, bycatch mortality at fleet-level was calculated as the product of the estimated bycatch rates and the total fleet effort, for each area and per quarter. This work revealed important seasonal variations in bycatch rates within and between fishing areas for all the considered species. Notably, more than half of all seabird bycatches occurred in quarters 1 and 4 in the Western Baltic Sea, with a mean yearly estimate of 3,249 bycatches (95% CI: 1,439-5,759). Harbour porpoises and seals were generally more impacted by gillnet fishing in quarter 3, totalling on average 2,722 porpoise bycatches per year (95% CI: 1,323-4,518) and 890 seal bycatches per year (95% CI: 299-1,646).

The factors determining bycatch of seabirds, porpoises and seals in gillnets were evaluated based on interviews with commercial fishers and assessed using a modelling approach (Section 3). Skippers usually linked elevated bycatch risks to the overlap between fishing activities and marine mammal or seabird distribution. Moreover, depth, light and weather conditions, as well as the characteristics of the fishing gear (twine width, mesh size, net height and soak time) were often cited as important factors influencing bycatch. Using the EM data collected onboard Danish gillnet vessels, statistical modelling revealed that mesh size, fishing depth, distance to shore and time of the year were important contributors to the observed levels of bycatches both for seabirds and harbour porpoises.

Bycatch results from a failure of animals to detect gillnets, leading to entanglement, or a failure to identify gillnets as a danger. Section 4 focuses on the behavioural and sensory ecology of harbour porpoises and seabirds to explain gillnet bycatch. The foraging behaviour of porpoises and how this relates to bycatch was analysed in the Kattegat using passive acoustic loggers. Potential mitigation methods based on behaviour, sensory abilities and diet of seabirds and harbour porpoises are also discussed.

Based on the above, research was conducted to mitigate bycatch in gillnets in Denmark (Section 5). Novel mechanical alarms, or rattle pingers, were developed as a potential alternative to pingers. Low nets were trialled in the North Sea to reduce porpoise bycatches without affecting

target species catches. Gillnet illumination was tested in the Øresund to limit seabird bycatch, and 10 kHz pingers were installed in a pound net in Lillebælt to control great cormorant depredation.

This report concludes with recommendations to resolve the problem of bycatch of seabirds and marine mammals in Danish waters, both by increasing monitoring effort and developing appropriate mitigation methods.

1. Introduction

Gillnet fisheries are generally considered environment-friendly fisheries thanks to a high selectivity, low fuel consumption and low impact on the sea floor, while landing fish of high quality (Gislason *et al.* 2014). However, some gillnet fisheries have a negative side as well because of a high bycatch rate of air-breathing animals, such as marine mammals and seabirds (Lewison *et al.* 2014).

Prior to this project, there was no assessment of the total magnitude of the bycatch of vulnerable air-breathing megafauna in Danish gillnet fisheries, yet, earlier investigations had shown that *e.g.* the bycatch of harbour porpoises *Phocoena phocoena* in the Danish gillnet fisheries in the North Sea in the 1990s was very high (Vinther 1999; Vinther and Larsen 2004). Similarly, recent assessments of seabird bycatch in various gillnet fisheries in *e.g.* the Baltic Sea pointed to large bycatches of certain species (Žydelis *et al.* 2009). For Denmark, a few regional investigations on seabird bycatch had been conducted (*e.g.* Degel et al. 2010), but there was no assessment of the total bycatch of seabirds in Danish fisheries. The distribution of the bycatch in time and space was therefore not known, nor was it known which factors determine the distribution and magnitude of the bycatch.

In Denmark, ensuring a favourable conservation status for marine mammals and seabirds is enacted by European Union (EU) legislations like the Habitats Directive (92/43/EEC), the Birds Directive (2009/147/EC), the Marine Strategy Framework Directive (2008/56/EC), the Regulation on the conservation of fisheries resources and the protection of marine ecosystems through technical measures (2019/1241/EU), or through international agreements like ASCOBANS (Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas). In addition, the European Commission adopted in 2012 the 'Action Plan for reducing incidental catches of seabirds in fishing gears' (2012/665/COM), which among other things requires Member States to minimise and, where possible, eliminate the bycatches of seabirds. These obligations together require EU Member States to estimate the total bycatch for each population of marine mammals and seabirds and assess the effects of these bycatches at the population level. Additionally, Member States are required to develop and implement measures to reduce the bycatch.

The present project was aimed at contributing to Denmark fulfilling its obligations with respect to bycatch of marine mammals and seabirds by providing answers to two main questions:

- What is the magnitude of the bycatch of marine mammals and seabirds in Danish gillnet fisheries, and how is this bycatch distributed geographically and seasonally?
- How can this bycatch be mitigated?

For these purposes, the project was organized in five work packages (WPs) with WP-1 providing answers to the first main question, WP-2, WP-3 and WP-4 aimed at answering the second main question, while WP-5 took care of project management and dissemination of results.

2. Distribution and magnitude of bycatch (WP-1)

Prior to the project presented in this report, no assessment of the total bycatch of marine mammals and seabirds in commercial gillnets had been conducted in Danish gillnet fisheries. Since 2010, DTU Aqua had conducted a number of pilot studies using electronic monitoring systems (EM) with videos on a sample of commercial gillnet vessels, to record bycatch of marine mammals in the North Sea, Skagerrak, Kattegat, Belt Seas and Western Baltic Sea. The recordings from these pilot studies could also be used to identify seabird bycatch on the previously sampled vessels. However, there were very little data from the northern part of Kattegat and the North Sea, so additional EM data needed to be collected to assess the total bycatch of marine mammals and seabirds in Danish gillnet fisheries, as well as the seasonal and geographical distribution of the bycatch events. Identification of areas and seasons with elevated bycatch rates are of interest as they could form the basis of bycatch management in the shape of time-area closures.

In this section, we assess the total bycatch of marine mammals and seabirds in Danish gillnet fisheries, as well as the seasonal and geographical distribution of the bycatch events, based on the analysis of the EM data collected from 2010 to 2018.

2.1 Materials and methods

2.1.1 Monitoring of bycatch in Danish gillnet fisheries

Bycatch data collection of marine mammals and seabirds in gillnet fisheries was conducted using EM with videos onboard 16 Danish commercial gillnetters between 2010 and 2018. Each vessel was monitored for periods spanning from several consecutive months to years. Three groups of species vulnerable to bycatch in gillnets were recorded as bycatch: seabirds (all species), seals (grey seal *Halichoerus grypus* and harbour seal *Phoca vitulina*) and harbour porpoise.

We used two different EM systems to monitor the fishing activity and potential bycatch. Originally, in 2010, EM Observe (Archipelago Marine Research Ltd, Canada; http://www.archipelago.ca) equipped all participating vessels. From 2013, EM Observe was replaced with Black Box Video (Anchorlab, Denmark; http://www.anchorlab.dk/). Both EM systems were similar in terms of hardware, consisting of a central processing unit installed in the wheelhouse, integrating data from a position sensor (GPS) and a set of waterproof CCTV (Closed Circuit Television) cameras recording the activity on deck. Specifically, at least one camera was oriented outward to capture the footage of the net breaking the water surface during the hauling phase and at least one camera was placed above the sorting table to monitor target species catches and bycatch of marine mammals and seabirds.

Specialised software, specific to each EM system, were used to analyse the collected EM data. EM analysers displayed alongside the position of a vessel (on a map showing the GPS trace), the time of the day (on a timeline, which also indicated the instantaneous speed as a graph) and the video recordings from the different cameras. Data analysts were trained to identify fishing activity (net deployment and retrieval), as well as the bycatch of the species of interest (here, seabirds, harbour porpoise and seals). The software offered the possibilities to vary playback speed according to video quality, to pause and replay video sequences at will and to zoom onto distinctive anatomical features, providing an effective platform for the identification of bycaught animals. Weather conditions, luminosity or potential sun flares could affect image readability, but also the general cleanliness of the camera lenses. Moreover, fishers could sometimes place themselves in the visual field in a way that made the identification process difficult. Nonetheless, the vast majority of bycaught animals could be identified from the video footage, down to species level.

2.1.2 Estimating bycatch in Danish gillnet fisheries

Several methods can be used to estimate the total amount of bycatch in a fishery. In most cases, bycatches have been estimated by extrapolating observer data from the observed part of the fleet to the whole fleet, using either total days-at-sea (DAS) or total landings (Vinther 1999).

In this report, we estimated fleet-level bycatch mortality for three taxa vulnerable to bycatch in gillnets (seabirds, harbour porpoise and seals). First, using fine-scale EM data from Danish commercial gillnet vessels between 2010 and 2018, we estimated mean bycatch rates (bycatch per unit effort or BPUE) as the number of individuals of each taxon captured per fishing day per quarter per ICES statistical area. Then, we collated data from official fishing logbooks and sales notes for all the vessels, which had registered gillnets as their primary or secondary gear for the period 2010-2018, and we calculated mean fishing effort estimates as the mean total number of fishing days per quarter per ICES statistical area (Table 2.1). A fishing day was defined as a calendar day during which at least one hauling operation had been registered. Finally, we multiplied the stratified BPUE estimates for each taxon with the stratified fishing effort estimates to obtain the corresponding bycatch estimates per quarter per ICES statistical area.

Table 2.1. Mean number of fishing days per quarter in the North Sea, the Skagerrak, Kattegat, the Øresund and the Belt Sea for the period 2010-2018 in the Danish commercial gillnet fleet. Data compiled from official logbook and sales notes.

FISHING EFFORT					
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**	**Year**
North Sea	1,013	1,852	984	574	**4,423**
Skagerrak	1,278	1,952	1,257	1,240	**5,727**
Kattegat	1,048	1,527	1,027	347	**3,949**
Øresund	682	684	958	1,177	**3,501**
Belt Sea	2,243	2,697	2,088	1,883	**8,911**
All areas	**6,264**	**8,712**	**6,314**	**5,221**	**26,511**

Bycatch mortality in Danish commercial gillnet fisheries was estimated for the marine mammals and seabirds in the North Sea (ICES IVb), the Skagerrak (ICES IIIa20), the Øresund (ICES IIIb23) and the Belt Sea (ICES IIIc22), where enough EM data were available. Bycatch mortality was not estimated in Kattegat (ICES IIIa21), as only 33 days of electronic monitoring had been conducted in this area. In addition, no bycatch monitoring using EM had been conducted in

ICES areas IIId24, IIId25 and IIId26, so fleet-wide bycatch could not be estimated in the Baltic Proper.

The geographical distribution of the total fleet effort for the period 2010-2018 is shown in Fig. 2.1.

It should be noted that the total gillnet fleet effort has been going down during the period 2010-18 by between 10 and 40% depending on area and with a mean reduction of c. 25% for all areas combined.

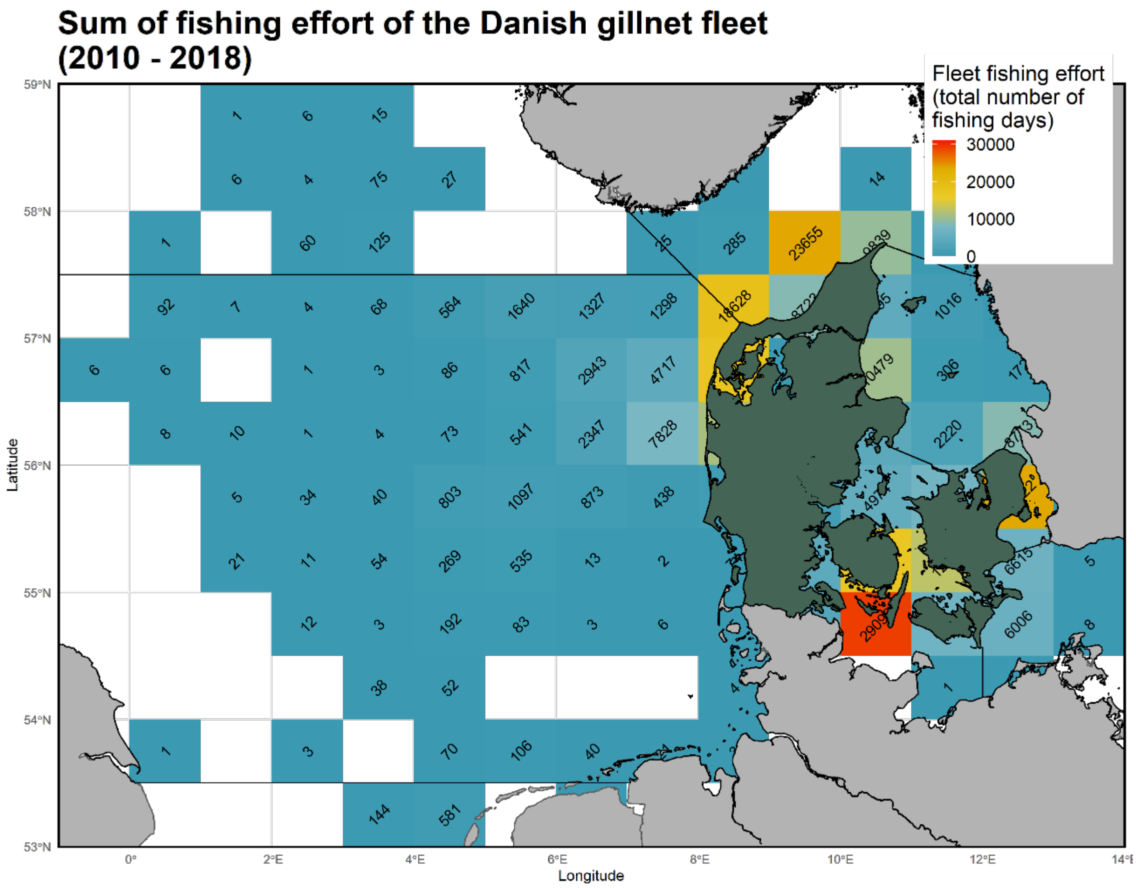


Figure 2.1. The figure shows the geographical distribution of the total gillnet fleet effort in fishing days for the period 2010-2018. Delimitations between ICES areas are marked as plain grey lines.

2.2 Results and discussion

Between 2010 and 2018, electronic monitoring of Danish commercial gillnetters resulted in a total of 4,730 fishing days observed. Fig. 2.2 shows the location of the hauls recorded from the 16 vessels. Table 2.2 shows how the total observation effort was distributed by year and area and Table 2.3 shows how the observation effort was distributed by quarter of the year. It is clear from Fig. 2.2 and Table 2.2 that with only 33 observed fishing days we did not succeed in getting a sufficient coverage of the Kattegat. We did manage to get some coverage of the North Sea, but with only 190 observed fishing days the resulting coverage is only c. 4%.

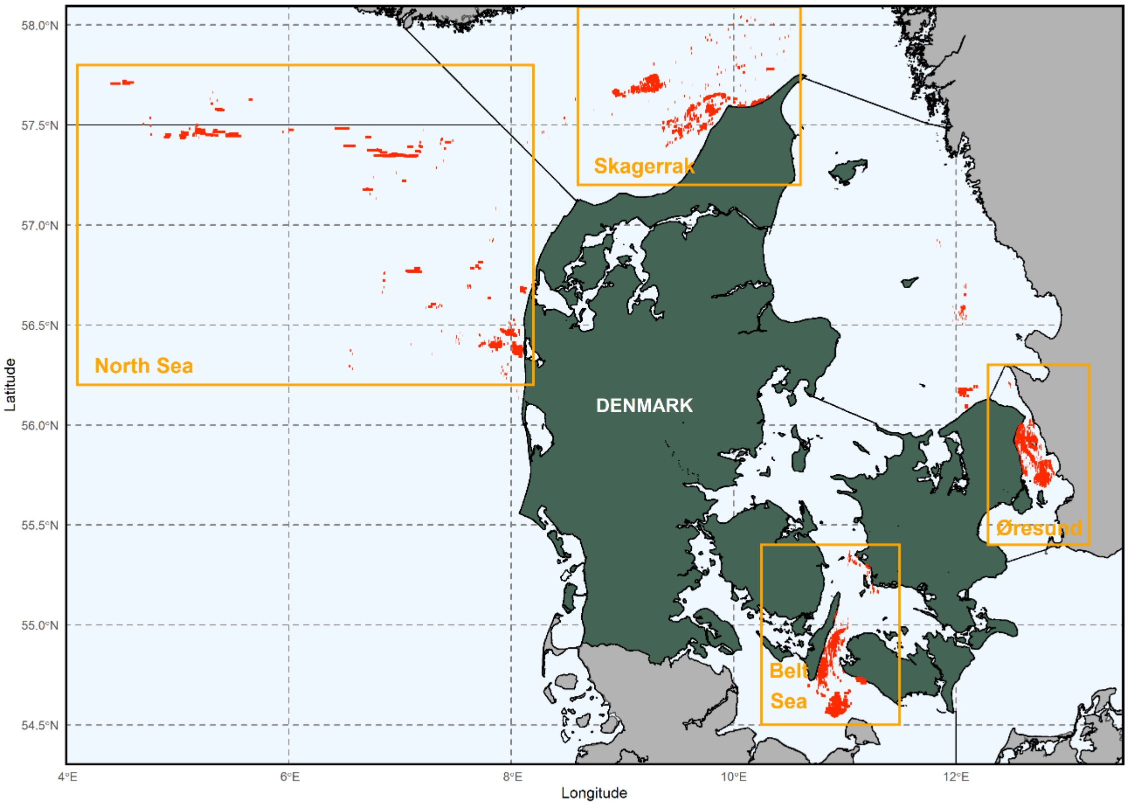


Figure 2.2. Location of the hauls recorded in the Danish bycatch monitoring programme, using electronic monitoring with videos on commercial gillnetters from 2010 to 2018. Observed hauls are represented as red lines. Delimitations between ICES areas are marked as plain grey lines. The orange squares indicate the areas where enough data were available to calculate mean quarterly bycatches and confidence intervals for the respective ICES area.

In general, bycatch in gillnet fisheries occurs where there is overlap in time and space between the distributions of vulnerable species and the fisheries, and observing such bycatch is only possible where these distributions overlap with the distribution of observer effort. This should be kept in mind when evaluating the seasonal and regional distributions of the bycatch events shown in Figs. 2.3-2.14.

Another important caveat is that the bycatch rates in this report were calculated from observations on a sample of fishing vessels that volunteered to participate in the study. Skippers and crews were informed of the presence of cameras onboard, which could have influenced their behaviour, resulting in an increased awareness of the issue of bycatch in fisheries, and a possible overall reduction of the number of bycatches. As such, although the sample of vessels monitored with EM may not be truly representative of the entire Danish gillnet fleet, the bycatch rates presented in this report are likely underestimating the risk of bycatch at the national level.

The extrapolation of bycatch rates to the whole fleet presented below is based on two important assumptions. The first assumption is that the observed part of the fleet is representative of the whole fleet with respect to seasonal and geographic coverage, and with respect to bycatch rates. Comparing Figs 2.1 and 2.2 suggests that our coverage has missed some areas with high gillnet effort, *i.e.* the area around the boundary between ICES areas IIIa20 and IVb, and the area in the Kattegat north of Djursland. These two concentrations could to some extent be an artifact of the way that we have distributed fleet effort of vessels that do not report a specific ICES square for their landings, as we have chosen to allocate their effort to the home harbour of the vessel. However, there are clearly parts of *e.g.* the North Sea that requires a better coverage. Comparing Tables 2.1 and 2.3 suggest that our seasonal EM-coverage has in general reflected the effort of the whole fleet. The bycatch rates of the observed fleet are probably not representative of the whole fleet, primarily because the bycatch rates are based on fishing vessels that volunteered to participate in the study as mentioned above.

The second important assumption is that the seabirds, harbour porpoises and seals are evenly distributed in the areas that we extrapolate to. This is clearly not the case for seabirds, where *e.g.* seaducks tend to aggregate in coastal areas, and we know from aerial surveys and satellite tracking that seals and harbour porpoises are also not evenly distributed either.

The solution to these problems is to collect bycatch data that are more representative of the fleet, *i.e.* not just from volunteering vessels, but also to collect fishing effort data at a finer spatiotemporal scale for all vessel length classes, as we know that small vessels represent a large fraction of the effort, especially in coastal waters where the risk of bycatch is very high for groups like seaducks.

Table 2.2. Total number of fishing days observed with EM by area and year for the period 2010-2018 in the Danish commercial gillnet fleet.

OBSERVATION EFFORT BY AREA AND YEAR										
Area	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**SUM**
North Sea	-	5	-	34	15	45	90	-	1	**190**
Skagerrak	-	96	25	1	-	13	110	215	189	**649**
Kattegat	-	-	-	29	-	4	-	-	-	**33**
Øresund	126	291	238	315	246	209	261	189	234	**2,109**
Belt Seas	-	-	72	166	353	248	414	284	212	**1,749**
All areas	**126**	**392**	**335**	**545**	**614**	**519**	**875**	**688**	**636**	**4,730**

Table 2.3. Total number of fishing days observed with EM by area and quarter for the period 2010-2018 in the Danish commercial gillnet fleet.

OBSERVATION EFFORT BY AREA AND QUARTER					
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**	**Year**
North Sea	33	90	48	19	**190**
Skagerrak	156	131	146	216	**649**
Kattegat	-	33	-	-	**33**
Øresund	566	563	517	463	**2,109**
Belt Seas	346	573	418	412	**1,749**
All areas	**1,101**	**1,390**	**1,129**	**1,110**	**4,730**

2.2.1 Distribution and scale of seabird bycatches

Observed distribution of seabird bycatches

Figs. 2.3-2.6 show the positions of all observed seabird bycatch events in the part of the Danish commercial gillnet fleet monitored with EM for the period 2010-2018. The maps detail quarterly bycatches in the four areas where enough data were collected to estimate bycatch rates in gill-nets, *i.e.* the North Sea, Skagerrak, Øresund and the Belt Sea.

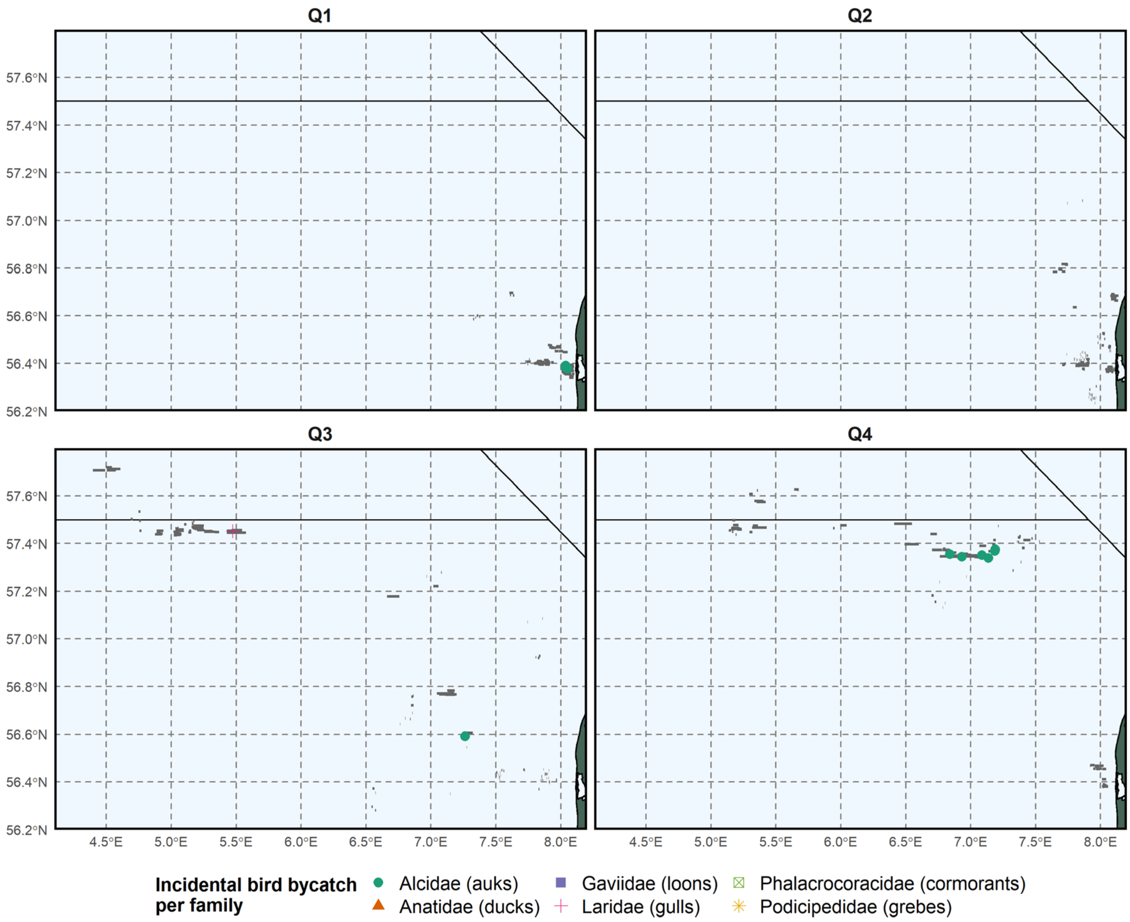


Figure 2.3. Quarterly seabird bycatch recorded using EM data on Danish commercial gillnet vessels (2010-2018), split by family (coloured markings) in the North Sea. Observed hauls are indicated as grey lines.

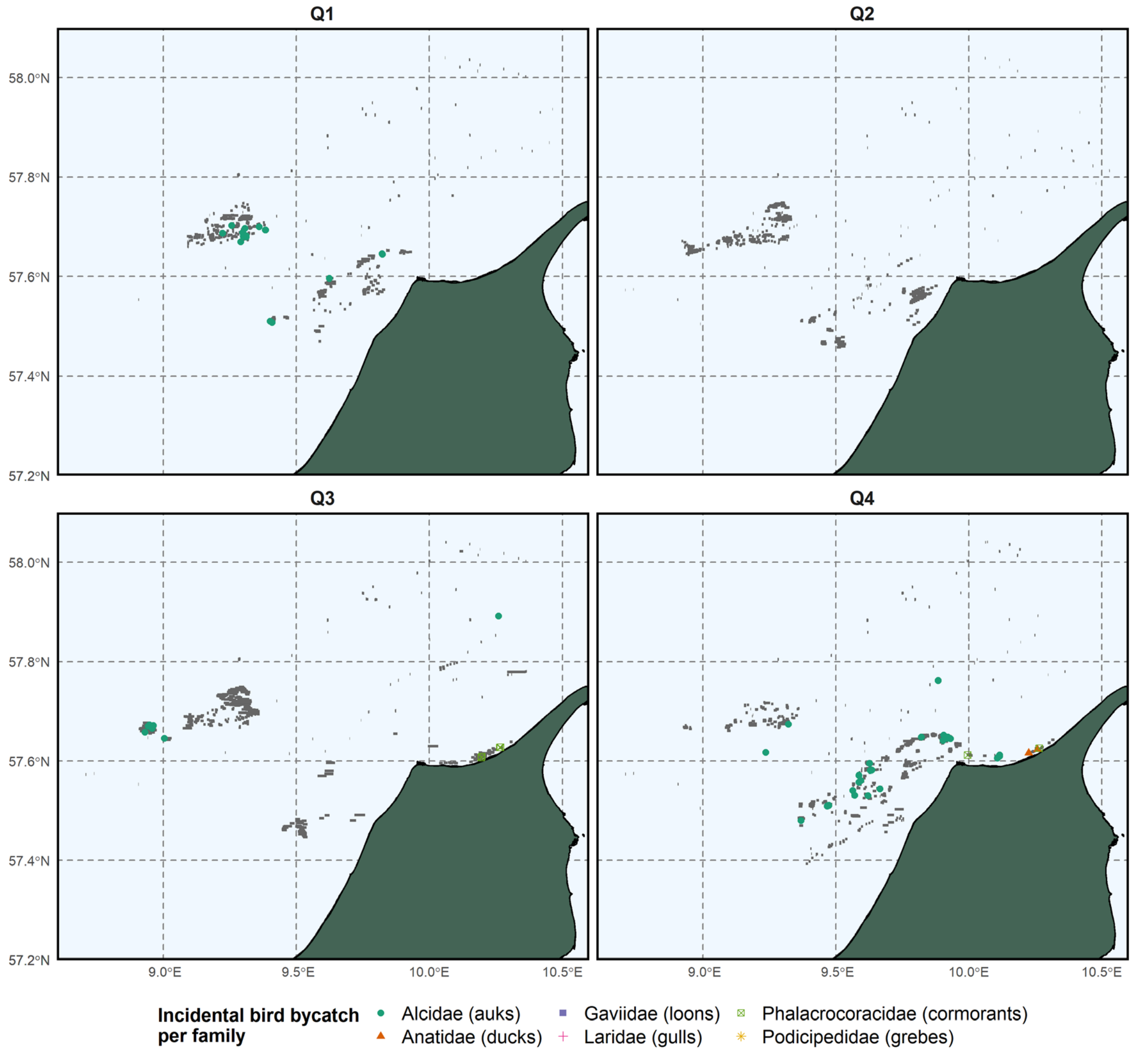


Figure 2.4. Quarterly seabird bycatch recorded using EM data on Danish commercial gillnet vessels (2010-2018), split by family (coloured markings) in the Skagerrak. Observed hauls are indicated as grey lines.

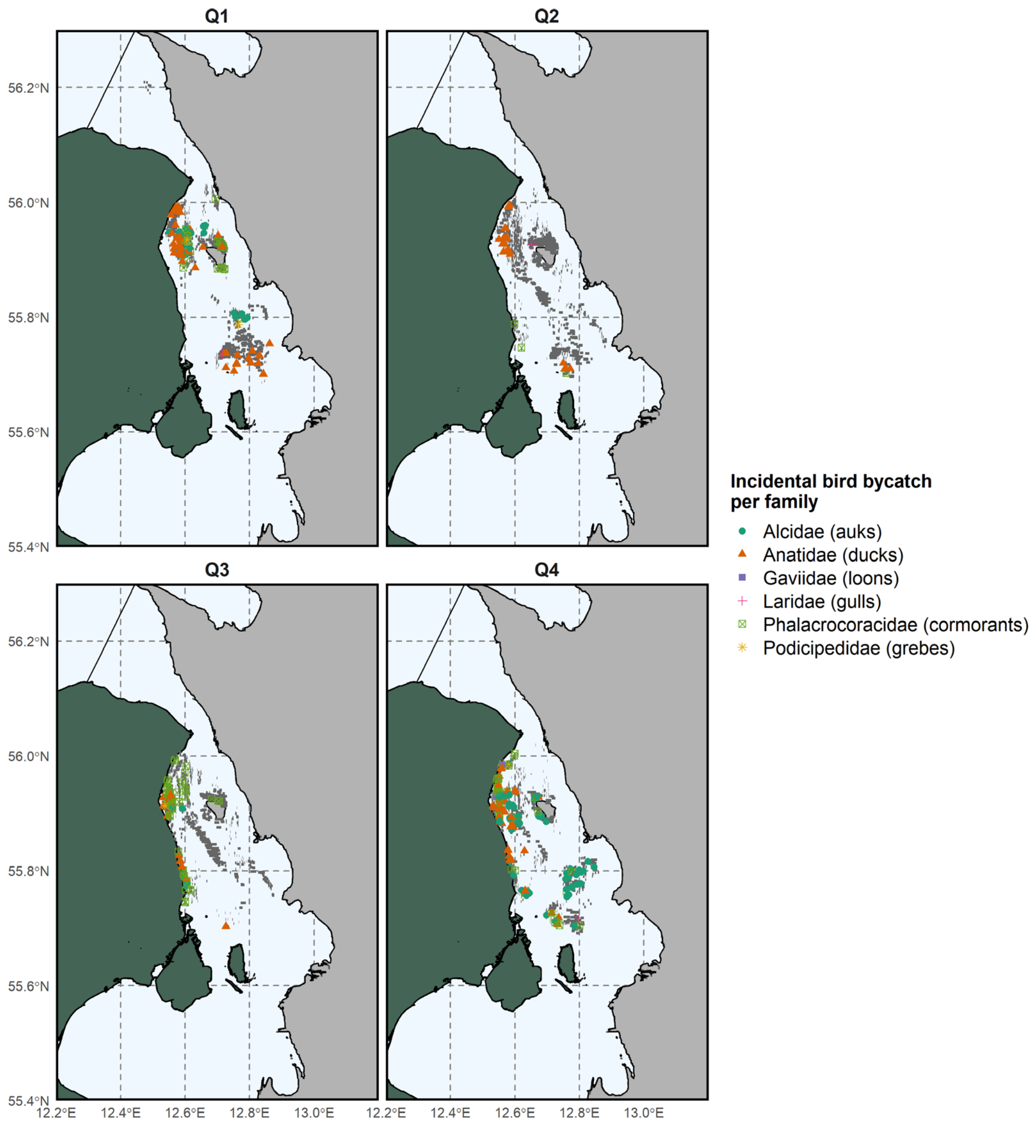


Figure 2.5. Quarterly seabird bycatch recorded using EM data on Danish commercial gillnet vessels (2010-2018), split by family (coloured markings) in the Øresund. Observed hauls are indicated as grey lines.

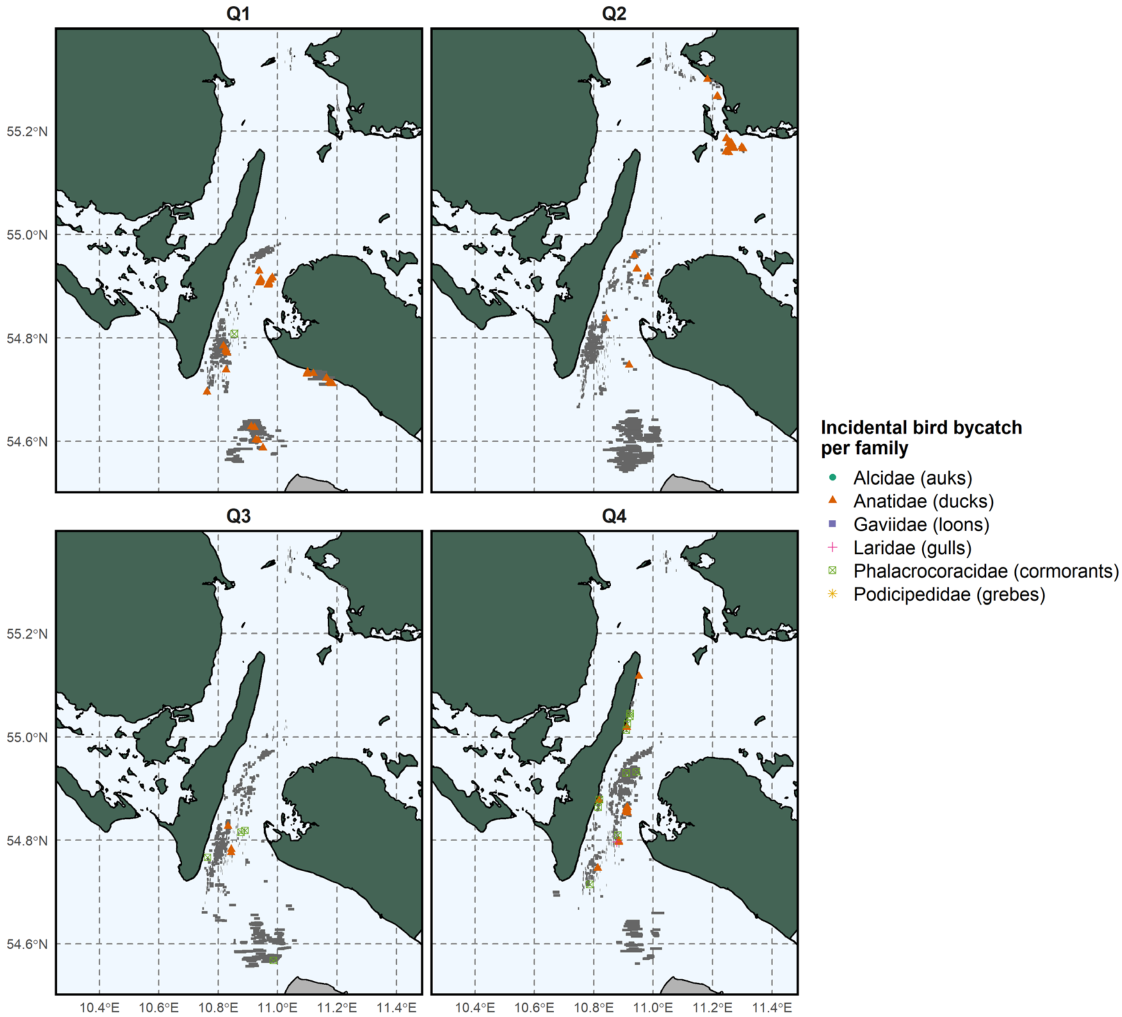


Figure 2.6. Quarterly seabird bycatch recorded using EM data on Danish commercial gillnet vessels (2010-2018), split by family (coloured markings) in the Belt Sea. Observed hauls are indicated as grey lines.

In Danish waters, where seabirds, *e.g.* bottom-feeding seaducks, are locally aggregated, the overlap between the birds' at-sea distribution and gillnet fishing effort distribution can result in large numbers of bycatch particularly in the wintertime. The analysis of the video monitoring data from Danish commercial gillnetters confirmed that wintering seabirds are more at risk of getting entangled in gillnets than are breeding seabirds. Bycatches were more frequent in quarters 1 and 4 in all the study areas, and the resulting bycatch rates were also higher than in quarters 2 and 3 (Figs. 2.3-2.6). Bycatch of seaducks were most common in coastal areas, as the Øresund and the Belt Sea, whereas in areas where fishing nets are set in deeper waters, for instance in the North Sea and Skagerrak, most bycaught species were pelagic feeders, *e.g.* alcids. Cormorants represented locally up to 20% of all bycatches and, unlike other families, were captured incidentally in small numbers yearlong. A few families were observed more rarely. Loons and grebes are pelagic-feeding birds, thus probably caught in nets during foraging dives. On the other hand, gulls are surface-feeding birds and were likely entangled in the nets during hauling while feeding on entangled or discarded fish.

Estimated fleet-wide seabird bycatch

Table 2.4 shows the mean quarterly fleet-wide bycatch rate estimates for seabirds captured in the Danish commercial gillnet fleet in ICES areas IVb (North Sea), IIIa20 (Skagerrak), IIIb23 (Øresund) and IIIc22 (Belt Sea) for the period 2010-2018, and Table 2.5 shows the mean fleet-wide bycatch estimates for the same areas and period.

Table 2.4. Mean (and 95% CI) quarterly fleet-wide seabird bycatch rate estimates (number of seabirds per fishing day) in the North Sea, Skagerrak, Øresund and the Belt Sea in the Danish commercial gillnet fleet between 2010 and 2018.

SEABIRDS				
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**
North Sea	0.21 (0-0.49)	0	0.10 (0.02-0.23)	0.37 (0-0.90)
Skagerrak	0.11 (0.04-0.18)	0.01 (0-0.02)	0.09 (0.04-0.15)	0.14 (0.08-0.20)
Øresund	0.36 (0.25-0.48)	0.08 (0.02-0.17)	0.23 (0.17-0.29)	0.80 (0.49-1.19)
Belt Seas	0.22 (0.06-0.49)	0.05 (0.02-0.09)	0.03 (0.01-0.05)	0.08 (0.04-0.14)

The highest bycatch rate and total estimate originated from the Øresund in quarter 4 (935 birds). No bird was registered as bycatch in the North Sea in quarter 2, so the estimate was null for this stratum. Total bycatch estimates summed up to 3,249 seabirds per year. These numbers are based on the mean fishing effort of the gillnet fleet for the period 2010-18. If we instead use the fleet effort from the most recent year in the series, the total seabird bycatch is estimated at 2,568 (95% CI: 1,132-4,536).

Table 2.5. Mean (and 95% CI) quarterly fleet-wide seabird bycatch estimates in the North Sea, Skagerrak, Øresund and the Belt Sea in the Danish commercial gillnet fleet between 2010 and 2018.

SEABIRDS					
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**	**Year**
North Sea	215 (0-491)	0	102 (20-225)	211 (0-513)	**528 (20-1,230)**
Skagerrak	136 (57-228)	11 (0-33)	112 (49-182)	169 (101-246)	**428 (207-689)**
Øresund	243 (169-332)	54 (16-116)	227 (174-285)	935 (576-1,399)	**1,450 (927-2,120)**
Belt Seas	474 (125-1,072)	144 (57-263)	64 (23-117)	159 (80-260)	**843 (284-1,720)**
All areas	**1,077 (353-2,145)**	**204 (71-403)**	**493 (258-790)**	**1,475 (758-2,420)**	**3,249 (1,439-5,759)**

There was a clear temporal shift between the colder and the warmer times of the year, with more than 78% of all seabird bycatches in gillnets occurring during quarters 1 and 4, even though the overall fishing effort in the same period represented on average only 43.5% of the yearly effort (Table 2.1). The larger bycatch estimates in the Øresund and, to a lesser extent, in the Belt Sea, compared to the North Sea and Skagerrak results from a greater number of sea-ducks in these areas. In particular, common eiders, common scoter and velvet scoter were frequently observed as bycatch, occasionally alone, often in small groups of two to six, but at times with more than 50 individuals captured in a single haul. Although uncommon, these extreme bycatch events considerably increased the average bycatch rate of seabirds in inner Danish waters.

Even though the estimates presented here represent only a fraction of the bird population numbers occurring in Denmark, the current level of bycatch in gillnets may be unsustainable for some threatened species. For instance, in the Øresund, 90 % of the bycatch of seabirds was made of only three species: the common eider *Somateria mollissima*, the great cormorant *Phalacrocorax carbo*, and the common guillemot *Uria aalge* (Glemarec *et al.* 2020). These species are respectively listed as near threatened, least concern (LC) and vulnerable on the International Union for the Conservation of Nature (IUCN) Red List and on the Danish national Red List.

2.2.2 Distribution and scale of harbour porpoise bycatches

Observed distribution of harbour porpoise bycatches

Figs. 2.7-2.10 show the positions of all observed harbour porpoise bycatch events in the part of the Danish commercial gillnet fleet monitored with EM for the period 2010-2018. The maps detail quarterly bycatches in the four areas where enough data were collected to estimate bycatch rates in gillnets, *i.e.* the North Sea, Skagerrak, Øresund and the Belt Sea.

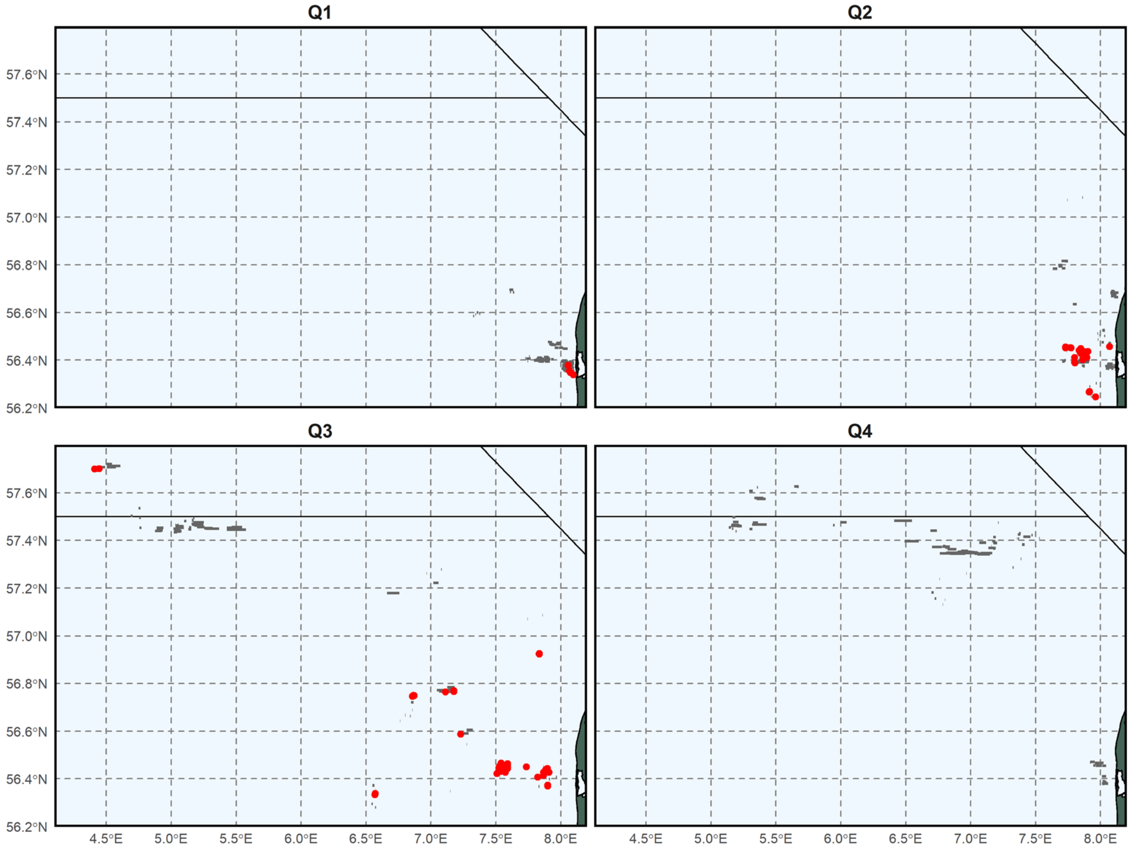


Figure 2.7. Quarterly harbour porpoise bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the North Sea. Observed hauls are indicated as grey lines.

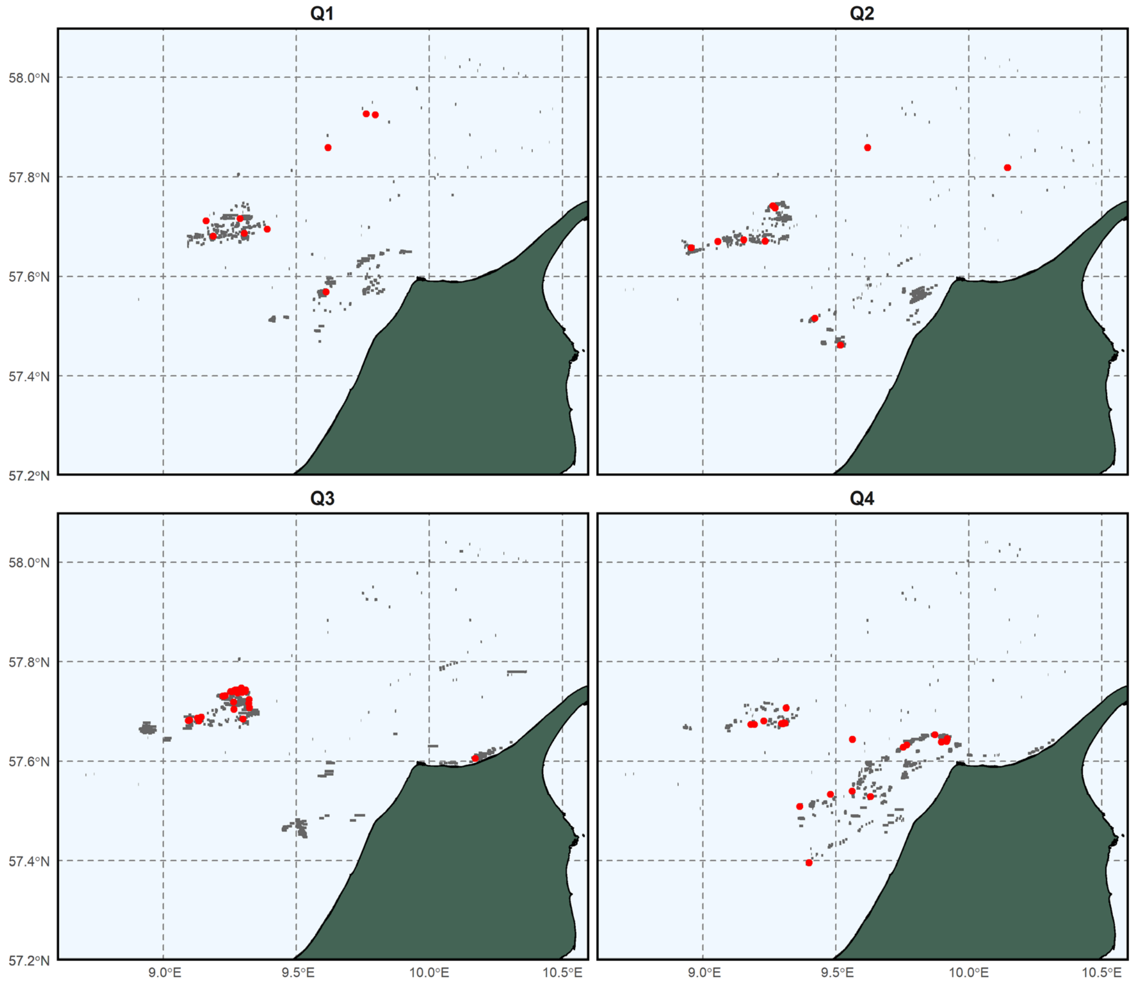


Figure 2.8. Quarterly harbour porpoise bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the Skagerrak. Observed hauls are indicated as grey lines.

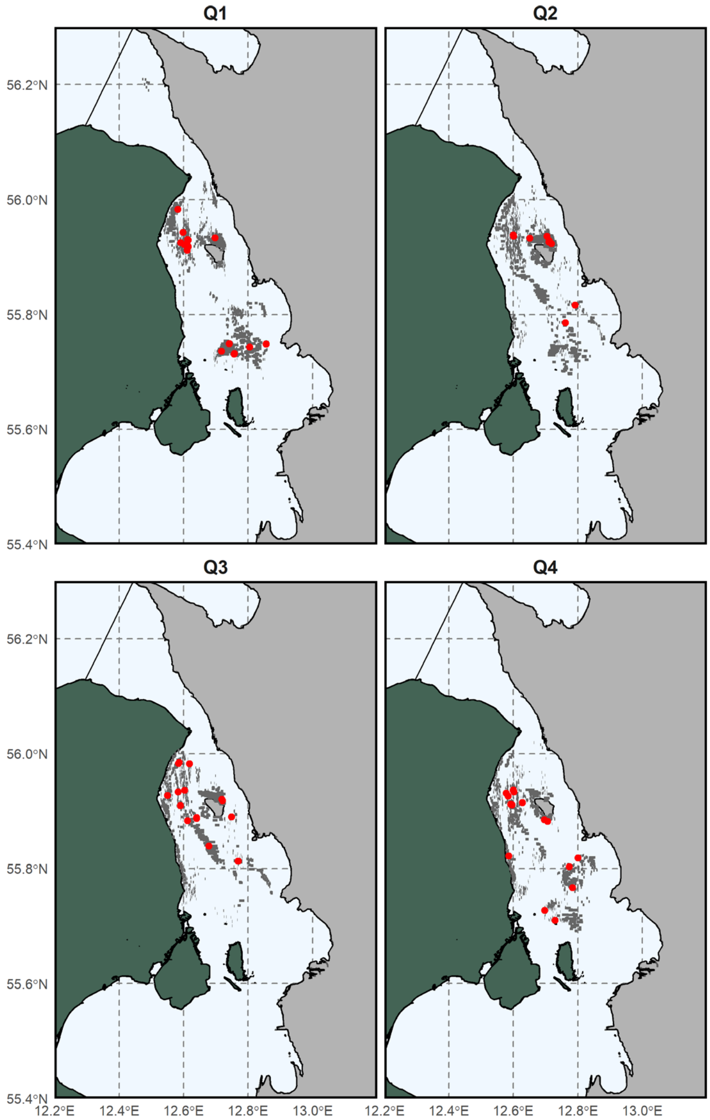


Figure 2.9. Quarterly harbour porpoise bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the Øresund. Observed hauls are indicated as grey lines.

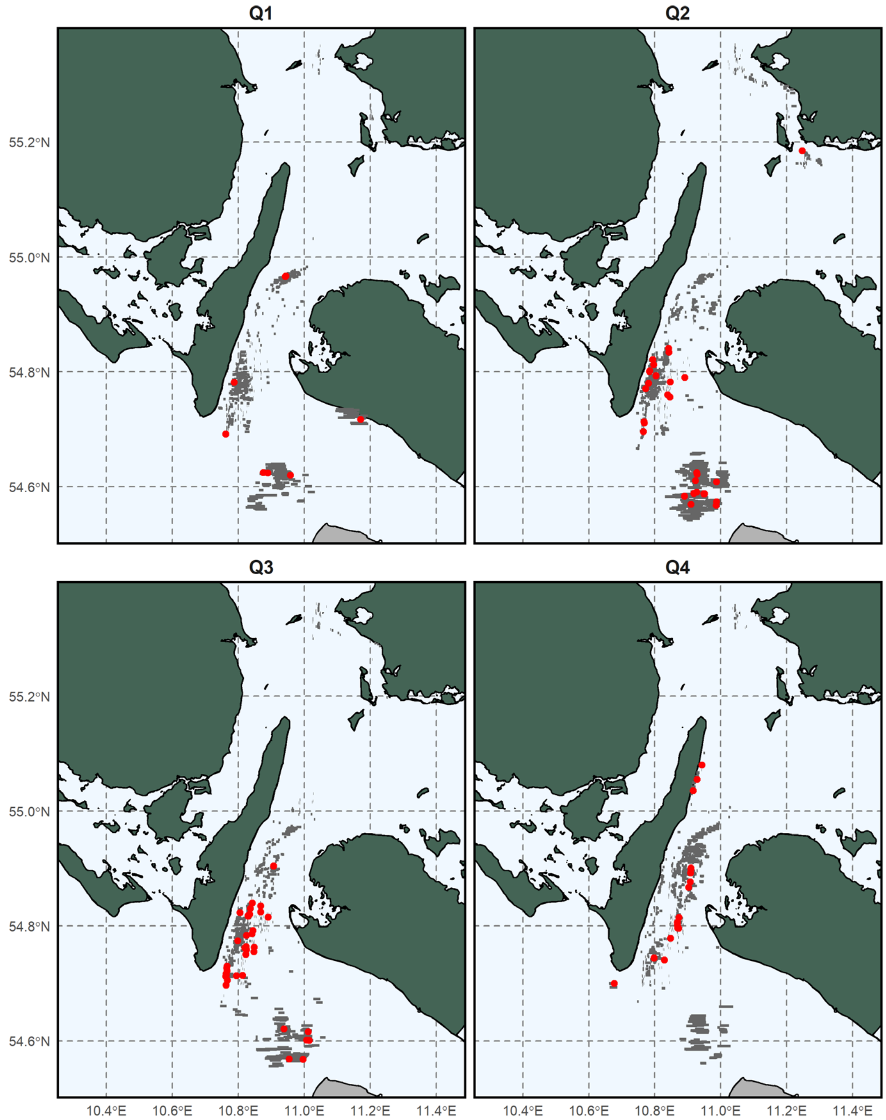


Figure 2.10. Quarterly harbour porpoise bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the Belt Sea. Observed hauls are indicated as grey lines.

Estimated fleet-wide harbour porpoise bycatch

Table 2.6 shows the mean quarterly fleet-wide bycatch rate estimates for harbour porpoise in the Danish commercial gillnet fleet in ICES areas IVb (North Sea), IIIa20 (Skagerrak), IIIb23 (Øresund) and IIIc22 (Belt Sea) for the period 2010-2018, and Table 2.7 shows the mean fleet-wide bycatch estimates for the same areas and period.

Table 2.6. Mean (and 95% CI) quarterly fleet-wide harbour porpoise bycatch rate estimates (number of porpoises per fishing day) in the North Sea, Skagerrak, Øresund and the Belt Sea in the Danish commercial gillnet fleet between 2010 and 2018.

HARBOUR PORPOISE				
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**
North Sea	0.12 (0-0.33)	0.28 (0.13-0.44)	1.00 (0.50-1.67)	0
Skagerrak	0.05 (0.02-0.08)	0.07 (0.03-0.11)	0.17 (0.08-0.27)	0.08 (0.04-0.12)
Øresund	0.03 (0.01-0.04)	0.02 (0.01-0.03)	0.03 (0.02-0.05)	0.04 (0.02-0.06)
Belt Seas	0.03 (0.01-0.04)	0.05 (0.04-0.07)	0.10 (0.06-0.14)	0.05 (0.03-0.08)

The highest bycatch estimates originated from the North Sea in quarter 3 (984 animals). No animal was registered as bycatch in quarter 4 in the North Sea, so the estimate was null for this stratum. Total bycatch estimates summed up to 2,722 harbour porpoises per year. These numbers are based on the mean fishing effort of the gillnet fleet for the period 2010-18. If we instead use the fleet effort from the most recent year in the series, the total harbour porpoise bycatch is estimated at 2,343 (95% CI: 1,128-3,895).

Table 2.7. Mean (and 95% CI) quarterly fleet-wide harbour porpoise bycatch estimates in the North Sea, Skagerrak, Øresund and the Belt Sea in the Danish commercial gillnet fleet between 2010 and 2018.

HARBOUR PORPOISE					
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**	**Year**
North Sea	123 (0-337)	515 (246-822)	984 (492-1,644)	0 (0-0)	**1,622** (739-2,804)
Skagerrak	64 (28-106)	134 (56-223)	211 (105-344)	96 (48-154)	**505** (238-827)
Øresund	19 (10-30)	10 (5-18)	30 (15-46)	43 (23-69)	**102** (52-163)
Belt Seas	57 (21-100)	145 (95-199)	201 (130-282)	90 (48-144)	**493** (294-752)
All areas	**263** (59-573)	**804** (402-1,262)	**1,426** (743-2,317)	**229** (119-366)	**2,722** (1,323-4,518)

In the North Sea, observer data includes only 190 fishing days, so there is a limit to what can be concluded about where and when bycatch occurs. However, it is clear from Figs. 2.7-2.10 that there is both a seasonal difference in bycatch of harbour porpoises as well as a geographical difference, with the majority of bycatches taking place in quarter 2 and quarter 3 and very little in quarter 1 and quarter 4.

In Skagerrak, bycatches occur all year round with the highest bycatches in quarter 3 and particularly at the offshore bank Store Rev. This is also where the majority of the fishing effort of the observed vessels is placed, except in quarter 4, where the effort is more spread out.
In the Øresund, bycatches occur all year round and geographically spread out over the areas covered by the EM effort, with the largest bycatches in quarters 3 and 4.

In the Belt Seas, bycatches occur all year round and are geographically spread out over the areas covered by the EM effort, except for the area north of the island of Rügen, where bycatches occur in quarters 1-3 but not in quarter 4 despite a substantial observer effort. Highest bycatches are found in quarter 3.

Looking at bycatch rates (Table 2.6), the Øresund and the Belt Seas are generally at the same level, Skagerrak is slightly higher, and the North Sea is at a much higher level. Quarter 3 generally shows a higher rate than the other periods except in the Øresund, where quarter 4 is slightly higher than quarter 3. For the North Sea, the bycatch rate in quarter 3 is by far the highest for all the areas and periods sampled here. This agrees with the results of earlier assessments of porpoise bycatch in the North Sea, where Vinther (1999) found the highest bycatch rates in quarter 3. Kindt-Larsen *et al.*(2016) found that bycatch risk was primarily determined by porpoise density and fishing effort, but other studies (Northridge et al. 2017) have found that technical factors such as *e.g.* mesh size and net height also plays a role. In section 3, we will look more into the effects of the various factors on bycatch.

Vinther and Larsen (2004) estimated the mean bycatch of harbour porpoises in the North Sea for the period 1987-2001 at 5,591 animals per year. However, the estimate for the most recent year of that period was only 3,887 animals because of reductions in fishing effort during the period. Our estimate is considerably lower at 1.,622 porpoises per year, but it is difficult to compare the two results since the methods used for both sampling and for extrapolation are quite different.

2.2.3 Distribution and scale of seal bycatches

Observed distribution of seal bycatches

Figs. 2.11-2.14 show the positions of all observed seal bycatch events (both grey and harbour seal) in the part of the Danish commercial gillnet fleet monitored with EM for the period 2010-2018. The maps detail quarterly bycatches in the four areas where enough data were collected to estimate bycatch rates in gillnets, *i.e.* the North Sea, Skagerrak, Øresund and the Belt Sea.

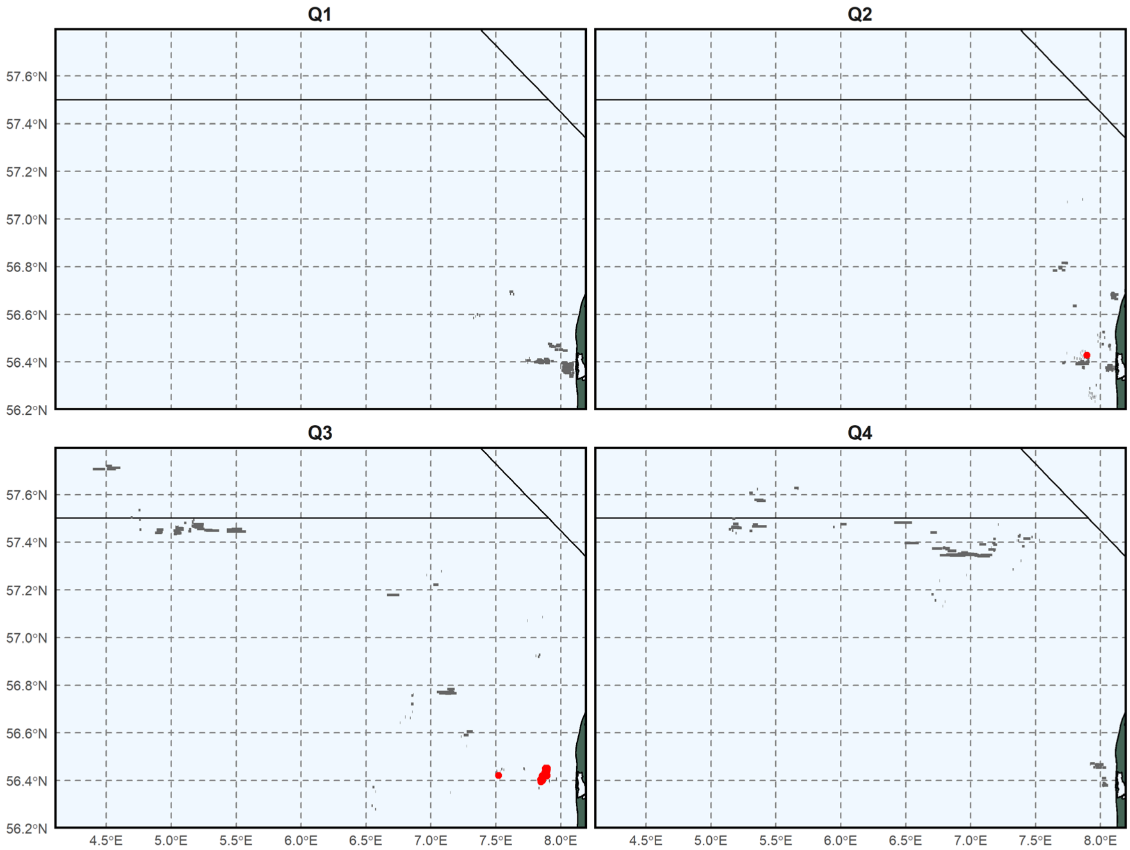


Figure 2.11. Quarterly seal bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the North Sea. Observed hauls are indicated as grey lines.

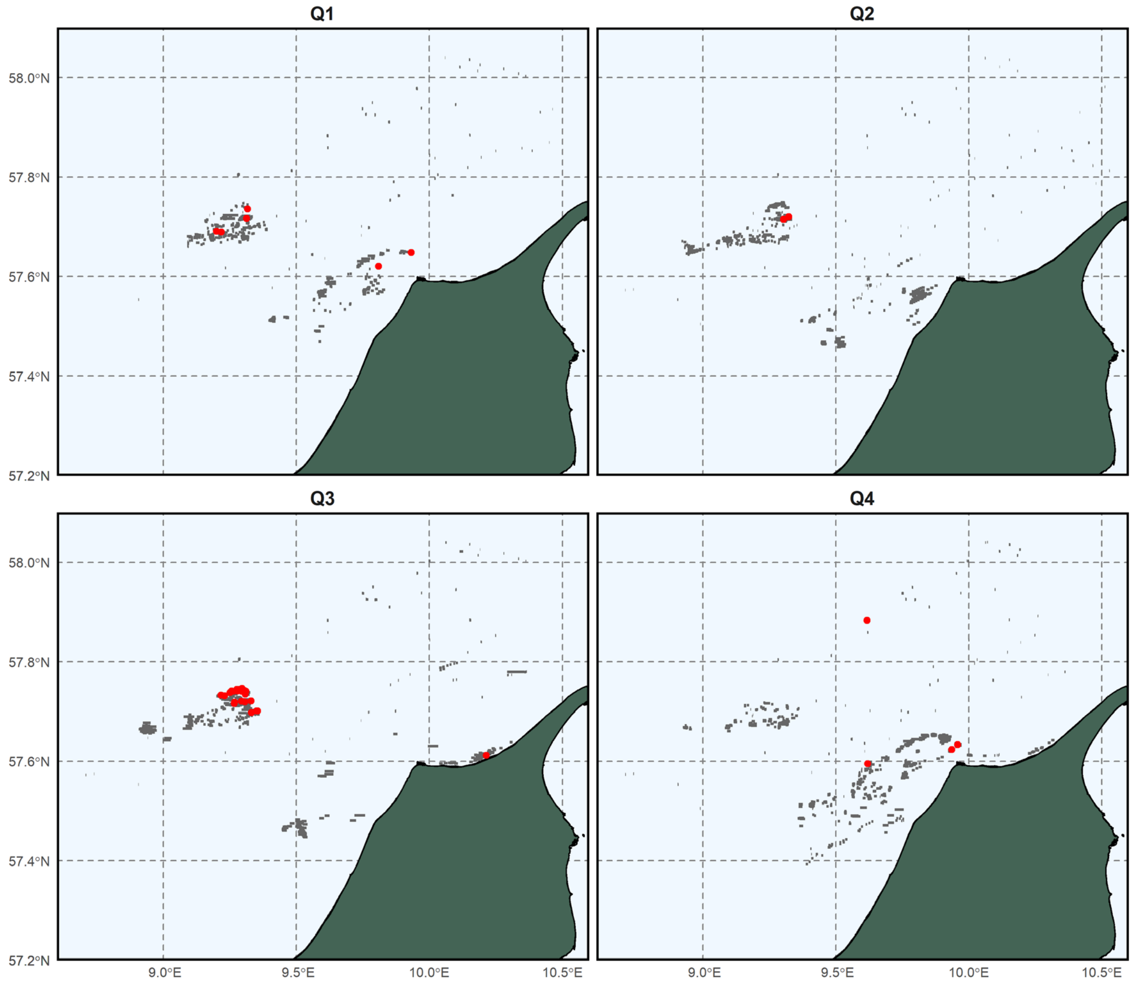


Figure 2.12. Quarterly seal bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the Skagerrak. Observed hauls are indicated as grey lines.

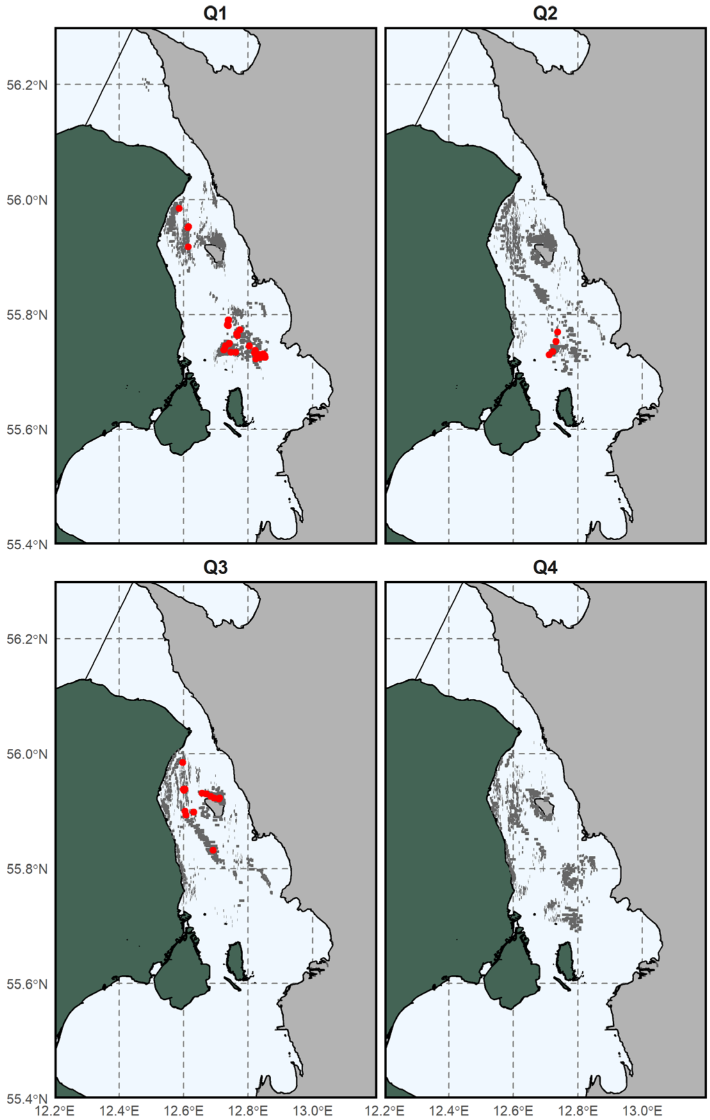


Figure 2.13. Quarterly seal bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the Øresund. Observed hauls are indicated as grey lines.

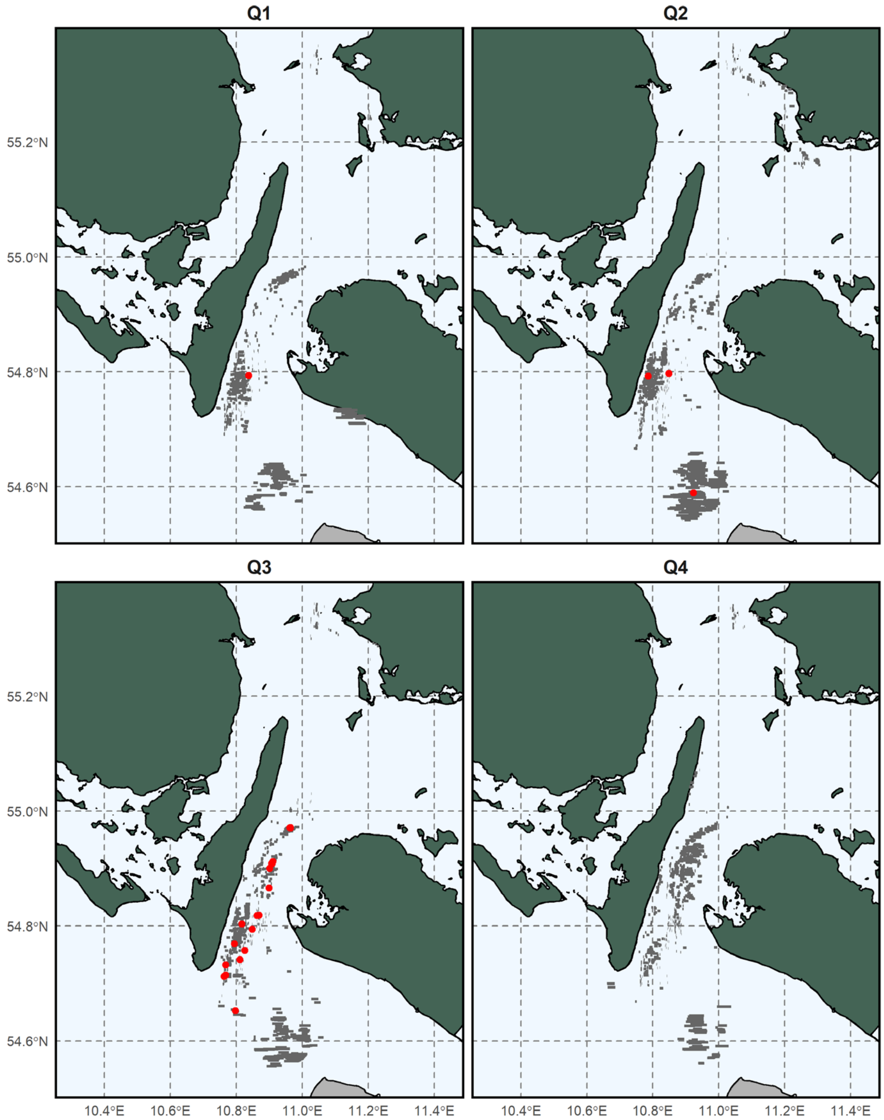


Figure 2.1 Quarterly seal bycatch (red) recorded using EM data on Danish commercial gillnet vessels (2010-2018) in the Belt Sea. Observed hauls are indicated as grey lines.

Estimated fleet-wide seal bycatch

Table 2.8 shows the mean quarterly fleet-wide bycatch rate estimates for seals in the Danish commercial gillnet fleet in ICES areas IVb (North Sea), IIIa20 (Skagerrak), IIIb23 (Øresund) and IIIc22 (Belt Sea) for the period 2010-2018, and Table 2.9 shows the mean fleet-wide bycatch estimates for the same areas and period.

Table 2.8. Mean (and 95% CI) quarterly fleet-wide seal bycatch rate estimates (number of seals per fishing day) in the North Sea, Skagerrak, Øresund and the Belt Sea in the Danish commercial gillnet fleet between 2010 and 2018.

SEALS				
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**
North Sea	0	0.01 (0-0.03)	0.40 (0.08-0.79)	0
Skagerrak	0.03 (0.01-0.07)	0.01 (0-0.02)	0.16 (0.10-0.24)	0.02 (0-0.03)
Øresund	0.05 (0.03-0.07)	0.01 (0-0.02)	0.03 (0.01-0.04)	0
Belt Seas	0 (0-0.01)	0.01 (0-0.01)	0.05 (0.03-0.08)	0

The highest bycatch estimates originated from the North Sea in quarter 3 (390 individuals). No animal was registered as bycatch in quarter 1 in the North Sea, and in quarter 4 in the North Sea, the Belt Sea and the Øresund, so the estimates were null for these strata. Total bycatch estimates summed up to 890 seals per year. These numbers are based on the mean fishing effort of the gillnet fleet for the period 2010-18. If we instead use the fleet effort from the most recent year in the series, the total harbour porpoise bycatch is estimated at 746 (95% CI: 247-1,388).

Table 2.9. Mean (and 95% CI) quarterly fleet-wide seal bycatch estimates in the North Sea, Skagerrak, Øresund and the Belt Sea in the Danish commercial gillnet fleet between 2010 and 2018.

SEALS					
Area	**Quarter 1**	**Quarter 2**	**Quarter 3**	**Quarter 4**	**Year**
North Sea	0	21 (0-62)	390 (82-780)	0	**411** (82-841)
Skagerrak	43 (7-85)	22 (0-56)	204 (119-302)	19 (5-38)	**288** (131-481)
Øresund	35 (20-51)	5 (0-11)	26 (11-43)	0	**66** (32-104)
Belt Seas	7 (0-21)	15 (0-35)	103 (54-163)	0	**125** (54-219)
All areas	**85** (28-157)	**63** (0-163)	**723** (267-1,287)	**19** (5-38)	**890** (299-1,646)

Bycatches were not evenly distributed. In the North Sea, Skagerrak and the Belt Seas 85% of the bycatches happened in quarter 3, whereas in the Øresund bycatches were highest in quarter 1, and at the same level in quarter 3. Most bycatches were found in the North Sea, but because of the low observer coverage, this estimate has wide confidence limits. The bycatch estimates in quarter 4 was null in all areas except for Skagerrak, which was intermediate between the North Sea and the Inner Danish waters.

Similar to the harbour porpoise, the bycatch rate in the North Sea in quarter 3 was an order of magnitude higher than in the other strata, which were all at approximately the same level except for Skagerrak in quarter 3.

3. Factors determining the level of bycatch (WP-2)

Several factors are known to or suspected to affect bycatch rates – here taken to mean bycatch per unit of fishing effort – and these factors can be divided into four groups. Environmental factors include *e.g.* wind/weather, turbidity and water depth. Operational factors include location, season and soak duration. Gear specific or technical factors include net height, mesh size, twine size, twine type (mono-, multi- or multimono-filament), stiffness, float line type, tie-downs and hanging ratio. And behavioural factors include *e.g.* acoustic and visual deterrents, although the latter have not yet been shown to have an effect (see Northridge *et al.* 2017 for a review of controlling factors). Finally, the density of porpoises in a given area will also affect the bycatch rate (Kindt-Larsen et al. 2016). It is important to realise that many of these factors are confounded and can be very difficult to disentangle. There are, however, similarities among the fisheries responsible for the majority of harbour porpoise bycatch in the various regions of the North Atlantic. These fisheries tend to be those using medium to large mesh size gillnets set for species such as cod, hake, turbot, monkfish and lumpfish. The reason for this is not only the gear they use but also the large total effort of these fisheries.

Better knowledge about the factors affecting the bycatch rates in the gillnet fisheries is important in identifying the best mitigation measures for these fisheries. Thus, in this section, we will attempt to identify which factors are important for determining the bycatch rates in the Danish gillnet fisheries. This will include interviews with experienced gillnet fishermen to obtain their views on which factors are important, and analyses of fine-scale EM data from the commercial gillnet fleet.

3.1 Interviews with commercial gillnet fishers

3.1.1 Introduction

The following is a summary of the results of a number of semi-structured and open-ended interviews with 7 commercial gillnet skippers concerning the effects of weather conditions, locality and fishing gear on the frequency of bycatch of seabirds and harbour porpoises. The purpose of these interviews was to find out if the fishers experience if certain conditions increase the risk of bycatch. The skippers interviewed includes fishers from both the North Sea, Skagerrak, Kattegat, Øresund and the Western Baltic. The fishers are anonymous in this report, but their identities are known by DTU Aqua.

3.1.2 Résumé

The magnitude of bycatch
All the fishers interviewed expressed that they only rarely experienced bycatch of seabirds. Several said that they had not had bycatch of seabirds in the last 1-2 years. A fisher from Thyborøn was prepared to put numbers to the claim and considered bycatch of 10-15 seabirds per year (incl. cormorants, guillemots, and sea ducks) as ‘unbelievably little’. Species specifically listed by the fishers as bycatch were common scoter *Melanitta nigra*, velvet scoter *Melanitta fusca*, common eider, great cormorant and common guillemot.

There were large differences in the fishers’ experiences and views on the bycatch of harbour porpoises. Several of the fishers catch very few (1-2) porpoises per year, while others reported that they caught up to 20 porpoises yearly (North Sea/Skagerrak). The bycatches were generally viewed as sporadic in both time and place. One fisher from Øresund/Kattegat reported that he used to catch on average 1-1½ porpoises yearly, but in 2016 had so far in July caught 7 porpoises. This fisher had the impression that he observed increasing numbers of porpoises in Øresund/Kattegat and believed that an increase in the number of porpoises would inevitably lead to an increase in the number bycaught.

Overlap between fishing and the distribution of seabirds and porpoises

Most of the interviewed fishers consider the overlap between fishing grounds and the areas where seabirds and porpoises forage as the most important factor determining bycatch. The fishers will normally try as much as possible to avoid setting their nets in places where they have observed high densities of seabirds and porpoises. These localities are often well known, particularly with respect to seabirds, where mussel banks were mentioned by several fishers as areas with increased risks of bycatch. One fisher mentioned that he consciously avoids certain areas in the North Sea, where the risk of porpoise bycatch is particularly high in lumpfish and turbot nets. The fishers mentioned that some of the seabird species are only present on their fishing grounds at certain times of the year, and that periods with increased bird densities naturally could result in increased bycatches.

Depth

Relating to bird bycatch, the fishers said that the bycatches were more common in shallow areas. Shallow areas seemed to be depth down to c. 15 m. This is probably related to the diving abilities of the birds. Depth was not mentioned as a determining factor for porpoises.

Light conditions

The fishers usually set their nets at night and haul them during daytime, which means that they do not have any basis for saying if light conditions affect the bycatch rates. However, a fisher from Øresund mentioned that darkness could have an effect. He based this on his observation that the cormorants often would dive into the nets while they were being hauled to steal fish. Thus, the cormorants are able to see the nets clearly in daylight. He thought that cormorants were caught in the nets during night-time when hunting fish schools.

Weather conditions

In relation to weather conditions, 3 of the 7 fishers suggested that murky water resulting from strong winds could lead to increased bycatches, particularly of seabirds. One of the fishers mentioned that cormorants during winter were more ‘desperate’ for food and thus came closer to the nets to steal fish. According to two fishers from the west coast of Jutland, during winter, sea ducks will approach much closer to the coast because of ice cover and adverse weather – sometimes all the way into the harbours. Here they aggregate in close flocks and may in this way become more susceptible to bycatch.

Fishing gear and fishing

According to several of the fishers, the twine size and breaking strength of the nets influences the bycatch of harbour porpoises. Two fishers from Øresund/Kattegat are using very light gear for both sole and other species. Porpoises (and very large cod) can easily break through these thin nets, and bycatch most often happens when the tail of the porpoise gets entangled in the float line. A fisher from the west coast of Jutland mentioned that there is a lower limit to how thin twine you can use in the North Sea.

Mesh size also influences the bycatch, particularly for porpoises. Turbot nets have large meshes and therefore pose a greater risk to porpoises.

The height of the nets was mentioned by almost all fishers as influencing the bycatches of both seabirds and porpoises. A fisher from Langø attributed his few bycatches to the fact that he uses lower nets (1.6-2 m). A sole fisher from Kattegat attributed his low bycatches to his low sole nets, which are also of very thin twine.

Several of the fishers furthermore expressed that the soak time plays a major role with respect to bycatch in general. Turbot fishing was mentioned as a fishery where a large number of nets are fishing for very long periods of time.

There were quite different views on the efficiency of pingers. One fisher claimed that they did not work at all, whereas another fisher said that they were very efficient.

3.2 Modelling approach

Assessing the factors associated to elevated bycatch of Protected Endangered and Threatened species (PETS) in gillnets has been attempted in different parts of the world, sometimes with information collected opportunistically, *e.g.*, using carcass collection and interviews with fishers (*e.g.* Bellebaum *et al.* 2013), or in a more systematic manner with data from fisheries observers or a national reference fleet (Vinther and Larsen 2002, Bjørge and Moan 2013, Orphanides and Palka 2013; Bærum *et al.* 2017, Moan *et al.* 2020, Bertram *et al.* 2021). Long-term electronic monitoring data with video, however, have rarely been used for this task (but see for instance Tremblay-Boyer & Abraham 2020). In Danish waters, the analysis of the long-term EM data with video from the commercial gillnet fleet allowed us to unveil factors associated with seabird and harbour porpoise bycatches in gillnets. EM data were used to determine the exact position of each individual haul and bycatch events in every recorded fishing trip. These fine scale spatial and temporal data were associated with operational parameters such as soak time and net length. Other important parameters like mesh size were recovered from official logbook and sales notes. In addition, the data were augmented with environmental parameters as depth at immersion, distance to the nearest shore, as well as temporal dummies (year, quarter of the year, month). The amount of data collected with EM on Danish fishing vessels were sufficient to determine the factors associated with variations in bycatch rates of seabird and harbour porpoise in commercial gillnets.

We evaluated the most influential factors determining seabird and harbour porpoise bycatch in Danish commercial gillnet fisheries using the extensive EM with video dataset from the Danish gillnet fishery, where we monitored 16 gillnetters for periods spanning from months to several years, from 2010 to 2018. The dataset compiled 4,733 unique fishing trips, 23,819 individual hauls, 952 seabird bycatch registrations and 336 harbour porpoise bycatch registrations. A generalised linear model (GLM) was developed for each target group, to help determine the parameters that explained most of the observed variability in bycatch rates. The response variable was defined as the number of birds or harbour porpoise captured per haul. With the response variable being a count, Poisson and negative binomial distributions were considered. Different candidate models were compared to a model including all relevant fixed variables and interactions (Zuur *et al.* 2009), using the Akaike Information Criterion (AIC). It seemed reasonable to assume that all other things being equal, the number of birds or harbour porpoise captured in a haul is higher if the length of the net fleet is larger and it is soaked for a longer duration. Therefore, we used the product of net fleet length times soak duration (in meter.hour) as an offset in the models. We included the following explanatory variables in the full model: stretched mesh size (in mm), fishing depth (in meter), distance to the nearest coastline (in meter), the interaction between depth and distance to the nearest coastline, month, and year. We noted frequent spatial clustering of bycatch events, *e.g.* hauls in which more than one bird or harbour porpoise was captured, so we also considered models including a spatial autocorrelation component. The goodness-of-fit of the best-fitting models were checked using simulation-based tests and controlled for potential misspecifications. The analyses were written in the R language (R Core Team 2020), using the package *glmmTMB* for fitting the models (Brooks *et al.* 2017), *bblme* for comparing the models' information criterion (Bolker and R Development Core Team 2020), and *DHARMa* for running residuals diagnostics (Hartig 2020).

3.2.1 Bird bycatch model

The model selection favoured a negative binomial over a Poisson distribution, indicating a relatively wide overdispersion in our dataset. The inclusion of a spatial autocorrelation term increased the fit of the full model importantly (ΔAIC = 98.4). The backward model selection favoured a parsimonious model including the spatial autocorrelation term, together with the fixed parameters *mesh*, *depth*, the interaction between *depth* and *distance to the nearest coastline*, and *month*. All the parameters in the parsimonious model were significant. Nevertheless, the difference in AIC scores between the full and parsimonious models was small (ΔAIC = 3.4).

3.2.2 Harbour porpoise bycatch model

The model selection favoured a negative binomial over a Poisson distribution, indicating a relatively wide overdispersion in our dataset. The inclusion of a spatial autocorrelation term increased the fit of the full model importantly (ΔAIC = 33.4). The backward model selection favoured a model without the parameter *mesh*, however, the gain was only marginal in terms of AIC (ΔAIC = 1.7). Therefore, the full model was preferred to simpler models.

3.2.3 General results of the modelling approach

The model selection indicated that for both species groups, the parameters *mesh*, *depth*, *month* and the interaction between *depth* and *distance to shore* were important contributors to the response. However, unlike the bird bycatch model, the parameters *year* and *distance to shore* were kept in the selected harbour porpoise bycatch model. In the case of the harbour porpoise bycatch model, the variable *mesh* was not statistically significant (z-value = -0.50) but removing it did not improve the AIC score importantly, and it was kept in the final model.

3.2.4 Discussion

The seabird and harbour porpoise bycatch models highlight the factors associated with bycatch in bottom-set gillnets in the Danish commercial fleet and reveal that a combination of ecological and operational parameters determines the number of seabirds and harbour porpoise bycatches. The most influential parameters in both models were time of the year (*month*), but depth and distance to shore (and/or their interaction) were significant and strongly influencing the response variable both for seabirds and porpoise. We found that the size of the meshes had a lesser contribution to bycatch numbers in both groups, yet the parameter *mesh* was not statistically significant in the harbour porpoise model. This may seem contradictory with previous studies that indicate that large meshes are more likely to lead to higher bycatch rates of marine mammals (Northridge *et al.* 2017). However, because we pooled together information from different fishing areas – where the populations of birds and porpoise and the typical fishing activity could differ widely – the findings presented here may have ignored local bycatch rate specificities. Moreover, the proportion of hauls using gillnets with a stretched mesh width <160 mm – typical of gillnet fisheries targeting cod and flatfish in Denmark – was much higher than hauls using large-meshed nets – typically targeting lumpsucker *Cyclopterus lumpus* or turbot *Psetta maximus* – which may have impeded our ability to detect a significant effect of mesh size on bycatch rates, notably for harbour porpoise. We tried to control for these known caveats by checking the correlations between the parameters but found no red flag in the dataset. Nevertheless, provided enough data are available, more advanced models could integrate specific areas, fishing vessels, or main target species, *e.g.* by using a mixed modelling approach. Likewise, the strong influence of the time of the year on the response variable suggests that a generalised additive model (GAM) may be an appropriate alternative to a GLM.

The results from the bycatch models, although general in their scope, emphasize the need to collect precise data from gillnet fishing fleets to estimate bycatches of vulnerable taxa with accuracy at fleet level. The parameters used in the bycatch models presented in this section were only accessible thanks to the use of electronic monitoring on a sample of the Danish fleet. However, information on the exact length and soak time of the fishing fleets, their precise location, the technical characteristic of the nets (*e.g.* mesh size, net height, colour of the thread), or the number of bycatches in each haul is typically not reported by most commercial vessels. Therefore, these models are useful for making inference, but not for predictions. On small-scale vessels, which constitute a large fraction of the gillnet fleet in Denmark, reporting fishing effort data in meaningful units and at a fine spatial and temporal resolution may be difficult for fishers using traditional pen and paper methods. Alternatively, the use of modern accessible electronic technologies, including the semi-automatic tracking and reporting of the fishing activity using dedicated smartphone apps could facilitate data collection both for fishers and fisheries managers, and would constitute a way forward to assess the factors influencing bycatch rates, as well as estimate the total number of bycatches in Danish fisheries.

4. Behaviour of seabirds and harbour porpoises around gillnets (WP-3)

For both marine mammals and seabirds, we know little about which circumstances and behaviours are important for determining whether bycatch occurs, and this means that the development of mitigation measures has been done to some extent in the dark. There is thus a need to investigate which circumstances and behaviours lead to marine mammals and seabirds being caught incidentally in gillnets to enable us to better focus on specific solutions to the bycatch problems.

4.1 Behaviour of harbour porpoises at Store Middelgrund

4.1.1 Introduction

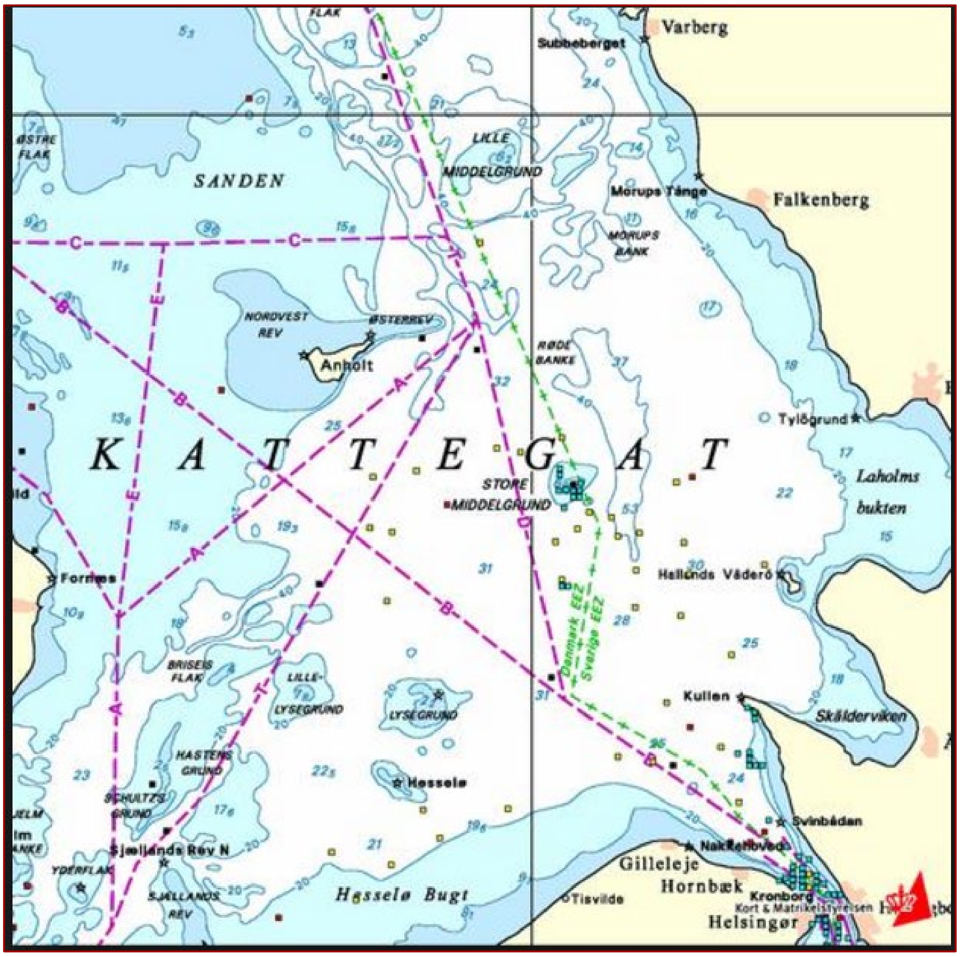
Preliminary data on the bycatch of harbour porpoises in Kattegat suggested that bycatch rates were very high in gillnet fisheries at Store Middelgrund, a shallow offshore bank in Kattegat. It was proposed that this could be related to the foraging activities of the porpoises at the bank and that the situation could represent an opportunity to investigate how porpoise behaviour affects bycatch risk. More specifically, we wanted to analyse the acoustic behaviour of the porpoises in an area with high bycatches and compare this to the acoustic behaviour in nearby areas with much lower bycatches. We expected to find differences in the acoustic behaviour of the porpoises that could indicate differences in how the porpoises utilise different areas and ultimately assist in developing bycatch mitigation measures.

The harbour porpoise belongs to a group of porpoises and dolphins called Narrow-Band, High Frequency (NBHF) echolocators, generating stereotyped sonar clicks, centred at 130 kHz (Villadsgaard *et al.* 2007; Kyhn et al. 2013). These clicks are also used for communication as the harbour porpoise cannot whistle (Amundin 1991). It has been shown that the sonar behaviour of harbour porpoises varies between diel phases (Carlström 2005; Todd et al. 2009; Linnenschmidt et al. 2013) and that foraging activity is higher during dawn and night, than during day and dusk (Kyhn et al. 2018).

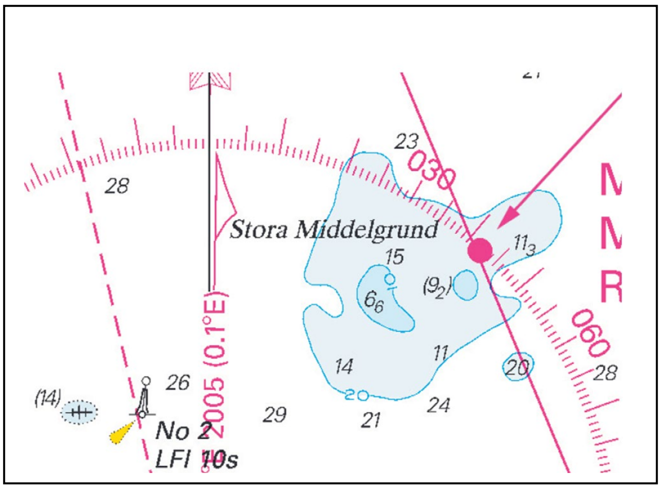
4.1.2 Materials and methods

In connection with mapping the temporal and spatial distribution of bycatch, the acoustic behaviour of porpoises was recorded, using passive acoustic loggers (C-POD; Chelonia Ltd, UK) deployed on and around Store Middelgrund (Sveegaard et al. 2017). These loggers recorded and stored selected measures, such as the inter-click intervals, ICIs, of the sonar click trains generated by porpoises in the area. Characteristic, very short ICIs, so called “buzzes”, are associated with fish catching (Miller 2008; Verfuß et al. 2009; Wisniewska et al. 2016) and can thus be used as a proxy for foraging. These logger data have already been used to model the temporal and spatial presence of porpoise on and around Store Middelgrund (Sveegaard et al. 2017).

One limitation of using stationary acoustic loggers is that the sonar sounds of porpoises – and of all known echolocating odontocetes – are contained in a narrow beam. The -3dB horizontal beam width is 13-16 degrees in the harbour porpoise (Au et al. 1999; Koblitz et al. 2012), projected forward along the body axis of the animal. If the beam is not pointed at the logger, the clicks are not recorded. The ensonified sector is enlarged by the scanning movements of the head, but it is still only a fraction of the sounds from passing porpoises that are logged.



a)



b)

Figure 4.1. Maps showing Store Middelgrund. a) Overview; b) Close-up with depth. Arrow points at a measuring mast (position: 56.563133 N (56°33,788N), 12.105733 E (12°06,344E); Ufs nr 229, 2008), on the Swedish side of the EEZ border, which is marked by the pink straight line.

There is a species-specific foraging behaviour, called bottom grubbing, in the harbour porpoise, where the animal holds a vertical body orientation, with the head close to the bottom, while searching for fish (Desportes *et al.* 2000). It uses the sonar extensively, with high click repletion rates, during this activity, but naturally these sounds cannot be picked up by a logger suspended some meters above the seabed. This will thus also affect the total number of logged click trains. However, observations of this behaviour in captivity have shown that fish hidden among the rocks on the bottom were forced out in open water above the rocks by the porpoise squirting water on it (Mats Amundin, pers. obs. at the Fjord&Belt Center, Kerteminde, DK). Then, the porpoise chased the fish in a horizontal pursuit, with an increased chance of the sonar click trains being logged by a C-POD.

The data set comprised 20 C-POD files from 10 positions on Store Middelgrund (Figs 4.1 and 4.2), covering a total logging period from February 2016 until March 2017 (Table 4.1), but with a useful range limited to February 2016 until December 2016 (further details in Sveegaard *et al.* (2017)). The depths at the C-POD stations were 14-30m (Fig. 4.1.b).

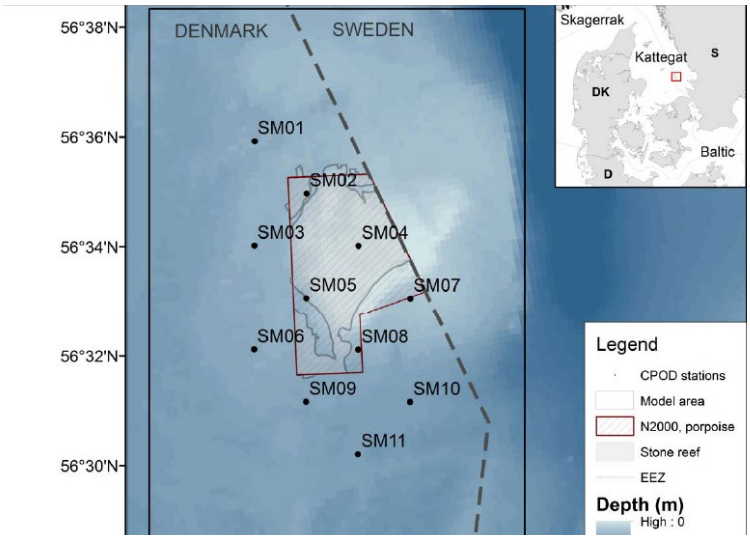


Figure 4.2. The C-POD positions. The NW/NE distance between each position was ca. 2.5 km, and 3.5 km in EW/NS directions (copied from Sveegaard et al. 2017).

4.1.3 Analysis

The raw C-POD CP1 files were run through the custom-made CPOD analysis software (Chelonia Ltd, UK) to only extract NBHF (porpoise) clicks of high to moderate quality. The output files were then run through a custom-made MatLab script (Mathworks Inc., R2018b), courtesy of Jakob Tougaard, Aarhus University, to extract Inter-Click Intervals (ICI) together with their time stamps. Another custom-made Matlab script, courtesy of Eskil Amundin, Amundin Tech AB, calculated the Buzz ratio, *i.e.* the ratio between the number of BuzzICIs and the total number of ICIs<250ms within each day's diel phases (Night, Dawn, Day and Dusk). BuzzICI was defined as ICI<15ms; ICI's>250ms were considered as Inter-Train Intervals and hence were excluded from the Buzz ratio calculations.

Table 4.1. Copied from Sveegaard *et al.* (2017)

Table 4-1. Station name, positions, depth, CPOD ID and CPOD sensitivity at calibration of the 11 monitoring stations deployed at St. Middelgrund 2016-2017. Deployment A refers to the first deployment period from February-July 2016 and deployment B refers to the second period: July 2016-Jan 2017.

Station	Position (WGS84)		Depth (m)	Deployment period with usable data (day /month /year)	CPOD ID Dep. A / B	CPOD Detection threshold (dB re 1 μPa (pp))
SM01	56° 35,822' N	12° 01,476' E	27	12/2/16-8/7/16 & 16/7/16-5/1/17	1984/1984	112.3
SM02	56° 34,826' N	12° 03,119' E	22	12/2/16-8/7/16 & 16/7/16-25/12/16	908/908	114.3
SM03	56° 33,919' N	12° 01,315' E	26	12/2/16-8/7/16 & 16/7/16-25/12/16	1988/1988	115.8
SM04	56° 33,829' N	12° 04,761' E	14	12/2/16-8/7/16 & 16/7/16-25/12/16	1687/1687	117.3
SM05	56° 32,923' N	12° 02,957' E	25	12/2/16-8/7/16 & 16/7/16-25/12/16	898/898	111.9
SM06	56° 32,016' N	12° 01,154' E	27	12/2/16-8/7/16 & 16/7/16-6/1/17	2117/2117	112.0
SM07	56° 32,833' N	12° 06,402' E	21	12/2/16-8/7/16 & 16/7/16-1/12/16	909/909	113.7[a]
SM08	56° 31,927' N	12° 04,598' E	24	12/2/16-8/7/16 & 16/7/16-25/12/16	1974/1690	114.5/113.3
SM09	56° 31,020' N	12° 02,795' E	29	12/2/16-8/7/16 & 16/7/16-17/1/17	1690/1974	113.3/114.5
SM10	56° 30,930' N	12° 06,237' E	30	12/2/16-8/7/16 & Lost	1693/1693	113.7[b]
SM11	56° 30,024' N	12° 04,435' E	30	12/2/16-27/5/16 & 16/7/16-17/1/17	1986/1776	113.7[a] /112.0

a) CPOD not calibrated due to redeployment. In the analysis this CPOD were given the average sensitivity of the calibrated CPODs.
b) CPOD lost at sea and thus not calibrated. In the analysis this CPOD were given the average sensitivity of the calibrated CPODs.

4.1.4 Results and discussion

There were quite some variations in the monthly average Buzz ratio over time and between diel phases and positions. Fig. 4.3 shows the monthly Buzz ratio averages per diel phase for each position in first period (February-July) and Fig. 4.4 shows the same for the second period (July-January). In period one, dawn had very low averages during the whole period, whereas night had relatively much higher values. Period two showed a similar picture, with the highest values during night, although during July-September the day averages were also rather high. The latter was also reflected, although to a lesser degree in the dawn and dusk values. The data for January-March were incomplete and should be disregarded. There does not appear to be any consistent differences in Buzz ratio between the individual positions, although SM04 is different from the other positions. The low number of detections at SM04 most likely reflects a much lower presence of porpoises here. This conclusion was also reached by Sveegaard *et al.* (2017). It was also the shallowest position, which may have had an influence.

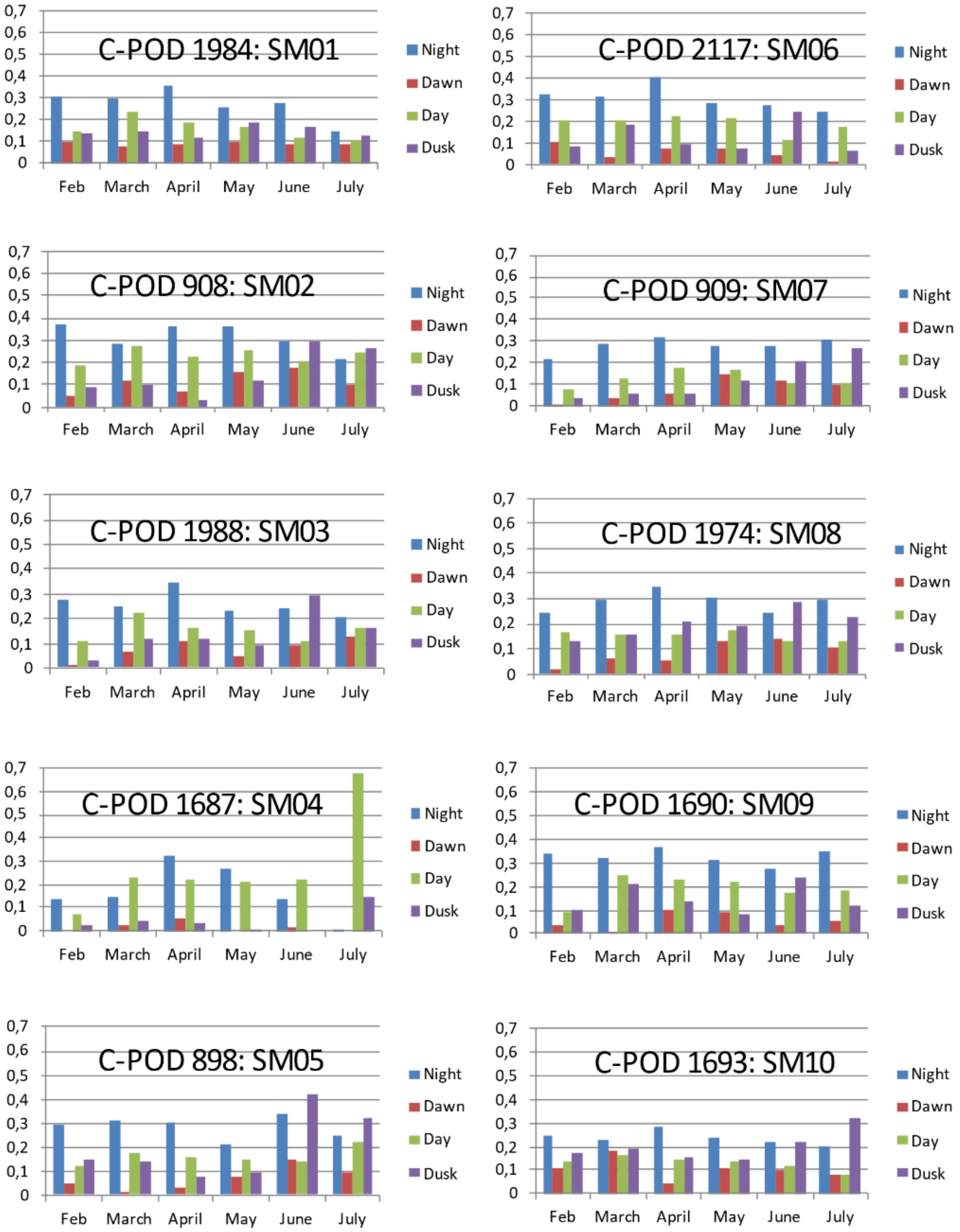


Figure 4.3. Monthly average Buzz ratios per diel phase in all positions (except SM11) in first period.

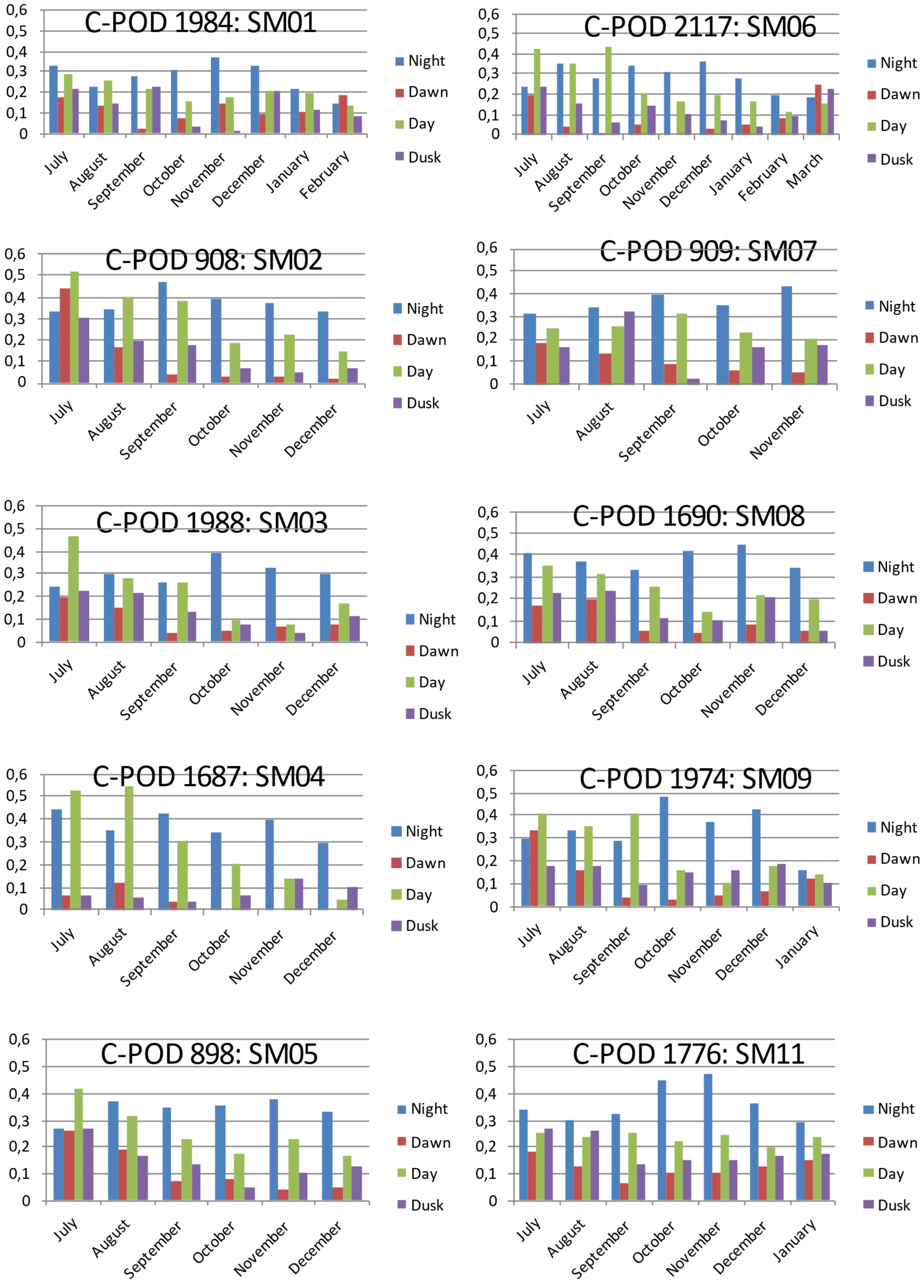


Figure 4.4. Monthly average Buzz ratios per diel phase in all positions (except SM10) in second period.

Our EM data set includes observations from St. Middelgrund in 2013 and 2015, but bycatches occurred only in 2015. Fig. 4.5 shows the observed effort in the two years and the positions of the bycatches together with the positions of the C-PODs in 2016-17. Most bycatches occurred just north of St. Middelgrund, but 10 porpoises were caught at the bank; all along the north-western slope of the bank, which probably reflects primarily where the fishing took place. A more in-depth modelling will be necessary to determine the reasons for the observed distribution of bycatches, but such a modelling exercise is beyond the scope of the present project.

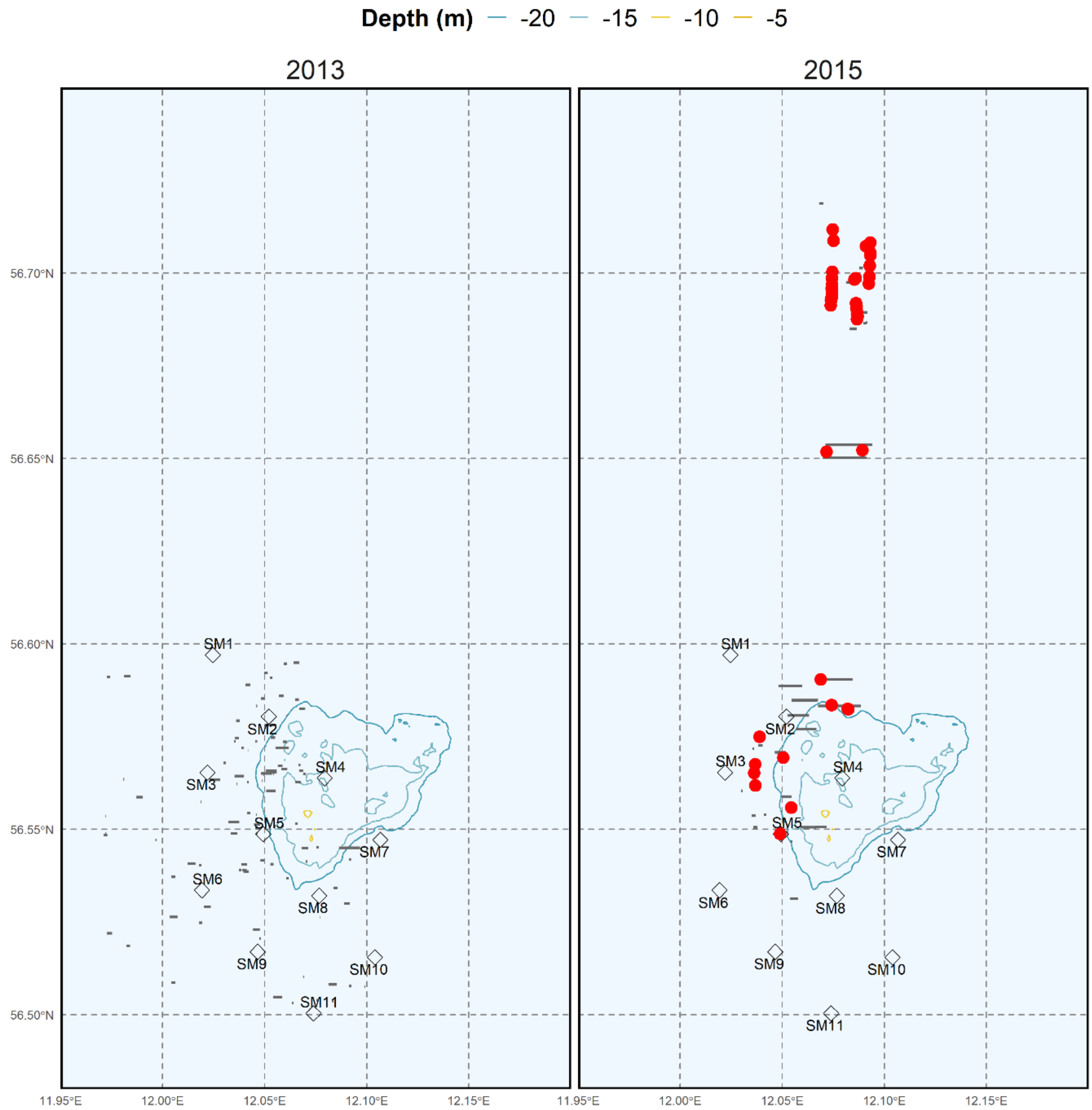


Figure 4.5. The figures show the observed effort in 2013 and 2015 (grey lines), the positions of the bycatches of harbour porpoises and the positions of the C-PODs in 2016-17.

4.2 Behaviour of seabirds around gillnets

To the best of our knowledge, no study has specifically explored the behaviour of wild diving seabirds in the vicinity of nets in the field. In the last century, Melvin *et al.* (1999) observed several hundreds of seabird bycatch events in a salmon driftnet fishery in the US. However, their experiment consisted of testing methods to reduce bycatch, so specific bird behaviour near nets was not analysed. In most gillnet fisheries, the gear is not visible from the surface, and it is assumed that seabirds foraging underwater are simply failing to perceive nets as obstacles, which sometimes result in entanglement. A study conducted in a controlled environment on captive birds confirmed this hypothesis for at least one species, the little penguin *Eudyptula minor* (Hanamseth *et al.* 2018).

Initially, we had planned to set up an experiment to record the behaviour of wild seabirds during foraging dives in the presence of a bottom-set monofilament gillnet fleet. Specifically, we wanted to observe if at least some of the birds were able to detect the net and avoid it, or if all the birds captured in the net had exhibited no difference in foraging behaviour prior to entanglement. However, the technical constraints we faced for such an experiment forbad its execution. In particular, the spatiotemporal patterns described in previous sections of this report show that seabird bycatch events are rare, and their occurrence is difficult to predict in Danish commercial fisheries. We would thus have had to collect a lot of data to obtain an exploitable sample. Using video recordings was quickly abandoned. Assuming a horizontal water visibility of 7 meters in the study area, and provided that the field of view of the cameras was able to record the action from both sides of the net, it would have required more than 140 cameras per 1000 meters of net fleet. Since we were interested in observing the potential avoidance of nets by diving seabirds, this would have required to watch and analyse a census of the collected video data, a task which would have been overly time consuming and expensive to conduct. Alternatively, we considered using a fish finder placed on a buoy attached to the floatline to record the activity of the animals swimming directly underneath. Nevertheless, because of the low mean number of interactions expected on a typical bottom-set gillnet in Danish fisheries, we would have had to use several fish finders to cover a sensible fraction of the net fleet length. Preliminary budget estimates showed that the full experiment would be largely above what we could spent for this work package, and the idea was therefore abandoned for the time.

4.3 Stomach analyses of seabirds

Between 2017 and 2019, two gillnet vessels fishing in the Øresund (ICES IIIb23), both equipped with EM systems, brought back to shore the seabirds taken as bycatch and handed the carcasses to DTU Aqua. A total of 236 birds were collected and kept in freezers (Table 4.2). However, in the winter 2017, the bird flu was detected in wild birds in Denmark. DTU Aqua labs were not equipped to carry on necropsies on potentially contagious carcasses, so the work was postponed. In early 2020, the frozen animals were transferred to the Institute for Terrestrial and Aquatic Wildlife Research (ITAW) in the University of Veterinary Medicine in Hanover (Germany) where the laboratories were equipped to handle a bird flu-safe protocol. All dead animals were tested for bird flu and the stomachs, oesophagus and gizzard of each bird was extracted for later examination. Further health investigations, including parasite loads and marks of chronic diseases, were conducted on the birds. Because of the delay caused by the bird flu and the COVID-19 pandemic, the analyses planned originally could not be conducted in time for this report. The digestive tracts samples prepared in Germany are planned to be ready by the end of quarter 1 of 2021 and the analyses of the drowned birds' diet will start in Denmark in quarter 3 of 2021.

Table 4.2. The number of individuals of each seabird species collected from the Øresund.

Vernacular name	Scientific name	Number of individuals
Arctic loon	*Gavia arctica*	6
Common eider	*Somateria mollissima*	133
Common guillemot	*Uria aalge*	55
Common scoter	*Melanitta nigra*	3
Great cormorant	*Phalacrocorax carbo*	31
Great crested grebe	*Podiceps cristatus*	2
Merganser	*Mergus sp.*	1
Razorbill	*Alca torda*	2
Velvet scoter	*Melanitta fusca*	3
TOTAL		**236**

4.4 Stomach analyses of harbour porpoise

Only 4 harbour porpoises were obtained as bycatch during the project. They were necropsied together with the seabirds at the Institute for Terrestrial and Aquatic Wildlife Research (ITAW) in the University of Veterinary Medicine in Hanover (Germany). Because of the low number, the stomachs have not been analysed.

4.5 Behaviour determining bycatch

4.5.1 Harbour porpoise

The question of why porpoises are bycaught in gillnets has received a lot of attention and many hypotheses have been proposed, which could help in the development of better mitigation methods. An important question is whether porpoises can detect gillnets at a distance sufficient to react and prevent entanglement. Several studies have shown that porpoises are in fact able to detect gillnets at a distance sufficient to avoid them (Villadsgaard, Wahlberg, and Tougaard 2007; Mooney, Nachtigall, and Au 2004). However, since porpoises despite this become entangled in gillnets, it may be that the net echoes received by the animals were masked by other incoming echoes or by background noise, thus preventing detection.

It could also be that although porpoises have the ability to detect gillnets, they do not use their sonar all the time. Verfuß *et al.* (2005) recorded harbour porpoises clicking continuously even in daylight conditions with good visibility and in familiar surroundings. Wisniewska *et al.* (2012) confirmed this on an even finer scale. In a controlled environment, entanglement of porpoises was observed in a pool by Kastelein *et al.* (1995). The authors documented that when introducing live fish or other porpoises in the pool, the tested porpoise became distracted, which resulted in a higher chance of entanglement. Their observations imply that porpoises may have been having their sonar locked on other targets. In the wild, it is possible that foraging porpoises had their sonar locked on prey, other group members or nearby obstacles, thereby failing to detect the nets.

There is also the possibility that porpoises classify gillnets incorrectly and regard gillnets as elements that they normally can swim through, like bottom vegetation. In their controlled setup, Kastelein *et al.* (1995) observed a learning process through a decline in entanglement frequency with time. Therefore, the studied porpoises may not have identified gillnets as a barrier in the first stages of the study but did eventually after a certain learning period. This study suggests that gillnets are not classified as barriers by the porpoises upon first encounter. In the wild however, porpoises would not have the possibility of such a learning process, as they will likely drown if they become entangled.

It has been suggested that porpoises use the gillnets to herd fish. However, porpoises are not known depredate fish caught in gillnets. Moreover, since they swallow fish whole, most net-caught fish would be too large for them to eat (Recchia and Read 1989). It is nevertheless a possibility that porpoises forage on the same prey items as the target species of the gillnet fisheries and therefore are found in the same areas, which is confirmed by feeding studies of porpoises and *e.g.* cod (Daan 1973; Andreasen et al. 2017).

Disentangling the reasons why porpoises are caught in gillnets remains an ongoing field of research. Recently, a group of researchers from the UK succeeded in tracking porpoises along a gillnet on a very fine scale using 4 channel hydrophones (Macaulay et al. 2021). In that study, the authors could for the first time track how wild porpoises behave around gillnets for extended periods. Hopefully, such studies will help getting one step closer to understanding the underlying reasons of porpoise bycatch in gillnets.

4.5.2 Seabirds

Understanding the cognitive abilities of seabirds, *i.e.* how the animals perceive the environment both in and out of the water and interpret the various stimuli they receive, is important to determine the best bycatch mitigation approaches and reduce incidental captures. Seabird species foraging underwater use a variety of techniques to detect and capture preys, but it is generally admitted that vision constitutes the primary sense for most species (Martin 2017). Melvin *et al.* (1999) demonstrated that opacifying the upper section of the net in a driftnet salmon fishery resulted in an important reduction of the bycatch of alcids. The authors hypothesized that making the net visible to diving birds allowed the animals to perceive the modified net as a barrier, so that they were dissuaded from swimming anywhere close to it. Nevertheless, illuminating gillnets with artificial lights has not resulted in reducing the bycatch of several seaduck species (Field *et al.* 2019), while white flashing lights may even have made the illuminated areas more attractive to at least one species, the long-tailed duck *Clangula hyemalis* (Cantlay *et al.* 2020). Moreover, in Peru, an 84% reduction of seabird bycatch per unit effort was observed on net fleets illuminated with green LED lights (Bielli *et al.* 2020). However, the authors concede that the low number of seabirds bycaught during the experiment forbad to draw definitive conclusions on the effect of lights on seabird bycatch rates. These studies seem to confirm the predominance of vision to detect prey for diving seabirds. However, the underwater visual acuity of seabirds is generally poor, and is comparable to the one of a human diving without goggles for a number of species (Martin *et al.* 2008, White *et al.* 2008, 2007). For pursuit diving species foraging at depth like penguins, cormorants, or alcids, light conditions can be too low to rely on vision alone, so that these species may have to count on random encounters with prey that they detect by swimming into them or by seeing and chasing a "moving blur" at short range (Martin 2017, White *et al.* 2007). As a result, and as the amount of light decreases rapidly with increasing depth, the capacity for diving birds to see – and avoid – obstacles like nets placed on their way is greatly reduced the deeper the fishing gear is set.

Seabirds may also rely on other senses than vision to interpret their surroundings. Seaducks feeding on organisms like bivalves utilise the touch-sensitive areas on and around their bill, as well as taste cues, to discriminate prey from the rest of the environment *(*Martin 2017, Martin *et al.* 2007). Additionally, the ability for seabirds to hear sound underwater has been shown for a few species like the great cormorant (Hansen *et al.* 2017, Johansen *et al.* 2016, Larsen *et al.* 2020). Recent work analysing the reaction of captive common guillemots to various levels of sound underwater suggests that the tested birds were capable of identifying the origin of a sound source in a pool (Hansen *et al.* 2020).

Moreover, social behaviour may influence bycatch rates for some species. In the marine environment where it can be difficult for seabirds to locate preys, several seabird species exhibit flocking behaviours to maximise their foraging success. The European shag *Phalacrocorax aristotelis*, a close relative of the great cormorant, uses social information in order to determine where and when to dive (Evans *et al.* 2019). In groups of socially foraging shags, the probability for a member of the group to dive is doubled if it has seen at least one of the other birds in the group dive immediately before. As such, for large groups of socially interacting foraging seabirds, the risk of capture may be higher in areas where gillnet fisheries operate, than for more solitary bird species.

4.6 Potential mitigation methods based on behaviour

Bycatch of marine mammals and seabirds in gillnets depends on an array of determinants, including environmental, operational, technical and behavioural or physiological factors (Northridge *et al.* 2017). In this section we will focus on whether specific aspects of their behaviour, as described in section 4.5, lead to an increased risk of bycatch for harbour porpoises and seabirds.

4.6.1 Harbour porpoise

Harbour porpoises rely primarily upon echolocation both for orientation and to find prey (Verfuß et al. 2009), although vision may also be used when light levels permit. The acoustic behaviour of harbour porpoises is well known, and it was shown by Villadsgaard *et al.* (2007) that harbour porpoises are able to detect gillnets at a distance of 13 to 26 m, which is sufficient to avoid the nets. Since harbour porpoises rely primarily on acoustic cues, mitigation has been focussed on either increasing the detectability of the gillnets or on deterring the animals from the nets by means of acoustic signals. Increasing the detectability of the nets without reducing the target species catch has not met with great success, although recent work by Kratzer *et al.* (2020) using acrylic glass pearls to induce resonance is promising, whereas acoustic alarms (pingers) have been shown in a number of studies to be very efficient when used correctly (Kraus et al. 1997; Larsen and Eigaard 2014; Dawson et al. 2013). Pingers have the advantage that they will work independently of the reason why the porpoises get caught in the nets, but pingers have a number of potential drawbacks including costs, noise pollution, potential habituation and habitat exclusion, making them a sub-optimal solution to the bycatch problem. Increasing the detectability of the nets does not suffer from these drawbacks, but will only be a solution if the reason for the bycatch is that the porpoises do not perceive the nets as a barrier, and it will probably not be a solution if the reason for the bycatch is that the porpoises are distracted by prey.

Comparatively little is known about vision in harbour porpoises and particularly how the animals use this sense for orientation and to find prey, and we are aware of only one other study that employed visual means to reduce bycatch of a cetaceans. In that study, Biellli *et al.* (2020) deployed green LED lights on gillnets in a Peruvian fishery and found that the lights reduced the bycatch of three species of small cetaceans by c. 70% without affecting the target species catch rates. This suggest that mitigation through visual means could be worth pursuing. In section 5.5, we will present the results of a similar experiment conducted in Danish waters in the present project.

4.6.2 Seabirds

Incidental captures of seabirds in fishing nets results either from the failure for the animals to detect a net in time to avoid it or from the failure to associate the net with a danger. Research on mitigation measures to prevent seabird bycatch in gillnets have taken place in different areas of the globe, but, to this day, no universal way of tackling this issue has emerged. The vast number of bird species vulnerable to bycatch in gillnets and the variety of seabird feeding behaviours suggest that efficient solutions to stop bycatch are likely fisheries-specific (Wiedenfeld *et al.* 2015). For species feeding on preys right below the surface (*e.g.* gannets, gulls, terns), vision plays a major role in prey detection and capture (Martin 2017). Pelagic-feeding species (*e.g.* penguins, cormorants, auks) can dive much deeper to find and capture preys. For these birds, vision is likely essential to locate preys, however, they also probably rely on other senses when foraging in total darkness, including sounds (Hansen *et al.* 2020, 2017, Martin 2017, Regular *et al.* 2011). In addition, bottom feeding seaducks that prey upon fixed or mobile species on the sediment can detect preys by touch, thanks to their highly sensitive bill, and by taste (Martin *et al.* 2007).

The development of mitigation methods to reduce bycatch of seabirds in gillnet fisheries has focused on two main axes: visual and acoustic signals. Early positive results using bycatch reduction devices were reported in the salmon driftnet fishery in the Puget Sound (USA), where gear modification to make the upper section of the net highly visible from the surface were shown to reduce, at least partially, seabird bycatch rates (Melvin *et al.* 1999). Similarly, bycatch of greater shearwaters *Puffinus gravis* was significantly reduced in an experiment with gillnets treated with barium sulphate. These experimental nets, tested to reduce the bycatch of echolocating cetacean, appeared dark blue and were therefore highly visible from the surface to the predatory seabirds feeding on discards during net fleets setting (Trippel *et al.* 2003). In the Peruvian coastal gillnet fishery, LED lights attached to the nets reduced the bycatch rates of at least one pelagic-feeding species, the guanay cormorant *Leucocarbo bougainvilliorum* (Bielli *et al.* 2020, Mangel *et al.* 2018). However, Martin and Crawford (2015) argued against the use of lights on the nets as they could temporarily blind diving seabirds foraging in very low light conditions. Instead, the authors suggest attaching to the nets high-contrast panels, to warn birds of the presence of an obstacle, without altering their foraging abilities. Recently, such high-contrast panels, as well as green and white artificial lights to illuminate gillnets, were tested in the southern and eastern Baltic Sea, in order to reduce seabird bycatch, but showed mixed results (Field *et al.* 2019).

Moreover, the results obtained in the Puget Sound two decades ago suggest that at least some seabirds are deterred from fishing gears when using acoustic alarms (Melvin *et al.* 1999). In that study, the pingers were tuned to operate at a nominal frequency of 1.5 kHz, based on general knowledge of hearing of birds and of salmon gathered in the literature. Since then, however, although important progress has been made to understand their in-air and underwater auditory capabilities, seabirds remain largely understudied compared to land birds (Crowell 2016). Recently, in-air and underwater hearing sensitivities of the great cormorant were investigated using auditory brainstem response (ABR) and psychophysical responses (Hansen *et al.* 2017, Johansen *et al.* 2016, Larsen *et al.* 2020, Maxwell *et al.* 2016*)*. Psychophysical experiments conducted on an adult male great cormorant revealed that his underwater hearing peak sensitivity was situated at approximately 2 kHz with a threshold of 71 dB re 1 µPa (Hansen *et al.* 2017), while ABR measurements on a sample of 8 great cormorants found an average peak at 1 kHz with a threshold of 85 dB re 1 µPa (Larsen *et al.* 2020). For comparison, the psychophysical threshold of the long-tailed duck is above 90-95 dB re 1 µPa (Crowell 2014, cited in Hansen *et al.* 2017). We could not find equivalent measurements of the underwater hearing sensitivity for other bird species, but in-air ABRs of 10 seabirds indicated that the best hearing frequencies were in the range of 1.7 kHz to 3 kHz (Crowell *et al.* 2015). Additionally, behavioural studies on common guillemots demonstrated that these birds react to underwater sounds, suggesting that they may use hearing during foraging dives (Hansen *et al.* 2020). The recent results from Larsen *et al.* (2020) also show possible anatomical adaptations to underwater hearing in the great cormorant. Nevertheless, none of these studies resolved the question of the ability for seabirds to hear directionally while diving. Therefore, sounds may be heard but the birds may not be able to know where they come from, making the capacity for sounds to deter birds from gillnets uncertain.

5. Developing and testing mitigation methods (WP-4)

Even though the total Danish fleet-wide bycatch of marine mammals and seabirds is not fully known, we know that the bycatches of harbour porpoises and seabirds are at levels that require mitigation measures to be implemented. For harbour porpoises, using acoustic alarms (pingers) is at the moment the most efficient mitigation tool that will allow gillnet fishing to continue, but pingers have a number of disadvantages including potential habituation, habitat exclusion, noise pollution and the cost of the devices. There is thus a need to develop and test alternative mitigation tools like *e.g.* deploying lights on the nets, using mechanical alarms and fishing with lower nets.

Development of mitigation tools for seabirds has been focussed primarily on increasing the visibility of the gillnets either by deploying lights on the nets or by using net panels with contrast colouring. Deploying lights have met with some success in Peru (Bielli et al. 2020) but not in the Baltic Sea (Field et al. 2019). The contrast-coloured net panels were tested in the Baltic Sea, but did not reduce bycatch (Field et al. 2019). Pingers deployed to reduce seabird bycatch were tested in the Puget Sound two decades ago, and the results suggested that at least some seabird species can be deterred from fishing gears by using pingers (Melvin *et al.* 1999). The lack of a clear picture of what works and what does not, suggests that more experiments need to be conducted to determine if pingers or lights could reduce bycatch of seabirds in Danish waters.

The following sections describe the pilot experiments that have been carried out in the present project to reduce bycatch of harbour porpoises and seabirds.

5.1 Mechanical alarms to reduce bycatch of harbour porpoises

There is scientific evidence available from fisheries in the US and Europe that acoustic deterrents are effective in reducing gillnet bycatch of harbour porpoises (see section 4.6.1). Different pingers were used in the documented trials, however, most are centred around 10 kHz or have shifting frequencies from 20-160 kHz. Pinger effectiveness, however, appears to be species- or even fishery-specific. Acoustic deterrents require maintenance, *e.g.* ensuring batteries are working and the cost varies in general between 50-250 Euros (Dawson et al. 2013).

Due to the high cost of pingers, new ideas for low-cost mitigation measures to reduce cetacean bycatch in gillnets are required. One idea is the glass bottle pinger, which was developed in Tanzania as a low-cost way to reduce bycatch of dolphins in gillnets (IWC 2019). Here, small metal bolts were put in sealed glass bottles and the bottles were attached to gillnets at regular intervals (Fig. 5.1) The idea was that the bolts would make a noise when the wave action moved the bottle. Test results from Tanzania with glass bottles were, however, inconclusive as no dolphins were caught in either control nets or nets with attached glass bottles (IWC 2019).

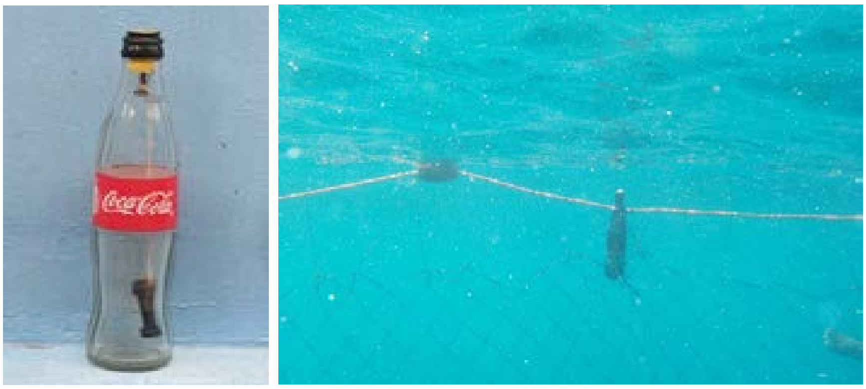


Figure 5.1. Examples of experimental glass bottle alarms. Photos © Per Berggren.

Even though the glass bottle trials were inconclusive, the idea was initiated to produce so-called rattle pingers. A low-tech rattle pinger could be a cheap alternative to standard pingers and have no need for battery power.

5.1.1 Rattle pinger tests

The focus of the present study was to make prototype rattle pingers and test their acoustic properties and suitability for field trials. Therefore, different rattle materials and housing thickness were tested. In total, 3 rattle pinger types were manufactured and tested.

Rattle pinger 1
Rattle pinger 1 was a 15 cm long stainless-steel cylinder of 4.5 cm in diameter, with a wall thickness of 2 mm. Inside the cylinder, seven small metal sticks were welded to the sides to create barriers for ten 8 mm stainless steel balls. The rattle pinger was then sealed in both ends with a metal disc with the diameter of the cylinder. The movement of such a rattle pinger attached to a net panel would ensure the constant shaking of the balls inside the metal cylinder and produce a sound that could potentially deter porpoise from the net (Fig. 5.2).

Rattle pinger 2
Rattle pinger 2 was a similar 15 cm long stainless-steel cylinder of 4.5 cm in diameter, with a wall thickness of 3.2 mm. Inside the cylinder, four small metal sticks were welded to the sides to create barriers for four 8 mm stainless steel balls. The rattle pinger was then sealed in both ends with a metal disc with the diameter of the cylinder.

Rattle pinger 3
Rattle pinger 3 was a similar 15 cm long stainless-steel cylinder of 4.5 cm in diameter, with a wall thickness of 3.2 mm. Inside the cylinder, four small metal sticks were welded to the sides to create a barrier for four 8 mm glass balls. The rattle pinger was then sealed in both ends with a metal disc with the diameter of the cylinder.

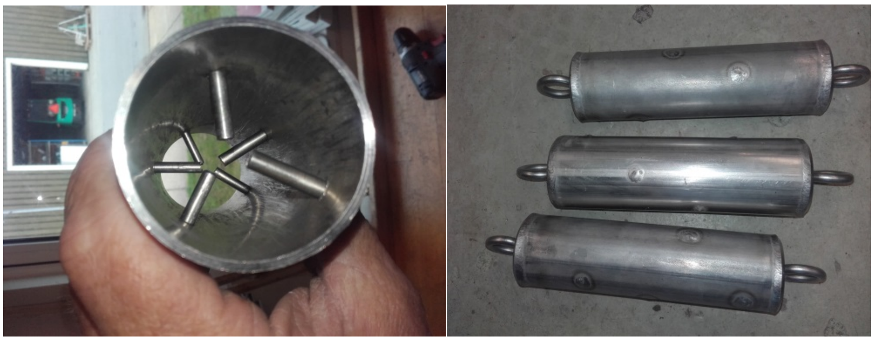


Figure 5.2. Left side: sticks welded to the inside of the pinger. Right side: the three rattle pingers.

Acoustic measurements were made to determine the peak frequency of the three pingers. This was done in the harbour of Kerteminde, Denmark. Here, the pingers were lowered to 1 meter under the surface and pulled up and down 30-50 cm to mimic wave action. A Reson TC 4032 hydrophone (Reson A/S, Slangerup, Denmark) with a sensitivity of -170dB re 1V/1μPa (at 250Hz) in a frequency range from 5Hz to 120kHz was used to record the pinger sounds. A pistonphone (Reson 4223) calibration of the hydrophone was performed before the recordings. The pingers' sound pressure levels (SPL) were measured at 1, 2, 5, 10, 20 and 40 m distance where also the peak frequencies were determined.

The measurements from pingers 1, 2 and 3 showed a peak frequency at 4.5 kHz, 7.8 kHz and 9.9 kHz, respectively. Table 5.1 shows the results of sound pressure level measurements (SPL) at increasing distances from the experimental pingers.

Table 5.1. Sound pressure level (SPL) of the three experimental rattle pingers with their associated peak frequencies.

	Sound pressure level (dB re 1 uPa)		
Distance (m)	Pinger 1 (peak frequency = 4.5 kHz)	Pinger 2 (peak frequency = 7.8 kHz)	Pinger 3 (peak frequency = 9.9 kHz)
1	*Invalid*	*Invalid*	*Invalid*
2	*Invalid*	164.34	169.19
5	165.4	152.99	160.8
10	160.04	153.62	155.75
20	154.2	147.97	154.51
40	137.47	155.4	148.19

The result from the peak frequency measurements of the three rattle pinger indicated levels from 4.5-9.9 kHz. Especially, pinger 3's (glass balls) frequencies peaked at a level close to a standard 10 kHz pinger, which has been shown to reduce harbour porpoise bycatch in gillnets. It is possible that this type of rattle pinger could reduce bycatch of porpoise, while there would be minimal or no maintenance required. Besides, with an estimated production cost around 25 Euro, this solution would likely be more affordable than traditional electronic pingers. However, before rattle pingers can be tested in operative fisheries, some technical aspects require attention. Rattle pingers produce sounds passively and rely only on external forces to ensure the movement of the elements – bolts or glass spheres – inside the hollow cylinder. To maximise the circulation of these elements and thus to maximise sound production, such pingers should be attached to the nets in a way that enable their rotation around the diameter of the cylinder. If the pinger does not move, no sound will be produced. If there is a lot of water current and the pinger is attached correctly, this will not be a problem. Yet, in very calm waters, where gillnets are mostly still in the water column, it is possible that water movements are simply not sufficient for the rattle pingers to rotate and produce sounds to deter porpoises. In general, however, Danish waters are subject to strong currents, and the North Sea Danish waters would be an ideal study area to test rattle pingers.

5.2 Trial of low nets to reduce bycatch of harbour porpoises

It has been proposed to mitigate bycatch of harbour porpoises by lowering the gillnet height to minimize the amount of net in the water column (Northridge et al. 2017). If porpoises are evenly caught in the gillnets, reducing the height of the net would reduce the number of bycatches. If porpoises are caught in the upper part of the net, a reduction in net height would lead to a larger reduction. If, however, the porpoises are caught primarily in the lower part of the net, a reduction in the net height would result in only a small reduction in bycatch if any at all.

5.2.1 Low net trials

The aim of this study was to test if lowering the net height could reduce the number of porpoises bycaught in the Danish turbot gillnet fishery. A trial was conducted from 8th June to 5th July 2016 in the commercial turbot gillnet fishery in the North Sea from the harbour of Thorsminde. The turbot fishery in the North Sea has been shown to have high bycatch rates of harbour porpoises (Vinther 1999), which makes it more efficient to test mitigation tools in this fishery. The trial was conducted on board a Danish commercial gillnet vessel operated by 2 fishers. The trial was conducted using 10 standard gillnets (6.5 meshes in net height, full mesh size 260 mm) and 10 modified gillnets, which were lowered by 2 meshes in net height (4.5 meshes in net height, full mesh size 260 mm). For each net haul, data were collected on net type (standard/low), soak time, position of setting, number of porpoises bycaught and amount of turbot caught (weight and numbers). The nets were set in the same areas, with similar soak times to compare the bycatch rates of porpoises from high and low nets.

A total of 12 net hauls were conducted with standard nets and 8 net hauls with low nets. For the standard nets, the mean soak time was 7 days with an upper limit of 8 days and a lower limit of 3 days. For the low nets, the mean soak time was 6.4 days with an upper limit of 8 days and a lower limit of 5 days.

A total of 7 porpoises were bycaught during the trial: 3 in the low nets and 4 in the standard nets (Table 5.2). The bycatch rates were not statistically different whether measured per trip or per soakday. Catch rates of turbot were also not statistically different, no matter how they were measured (Table 5.3).

Table 5.2. Bycatch and bycatch rate of harbour porpoises in low and standard nets, June-July 2016.

	Harbour porpoise by-caught in total	Porpoise bycatch per trip	Porpoise bycatch per soakday
Low nets	3	0.37	0.06
Standard nets	4	0.33	0.05

Table 5.3. Catch rates of turbot during the trial, June-July 2016.

	Mean weight of turbots per haul	Mean number of turbots per haul
Low nets	22.6	16.2
Standard nets	23.6	14

The results showed that by lowering the net height by 2 meshes it was still possible to catch the same amount of turbot as in the standard nets. However, the reduction in height was not sufficient to reduce the number of porpoise bycatches as both bycatches per trip and bycatches per soakday for high and low nets were similar. The main reason for this is most likely that even though the net height was reduced the nets were still too high to avoid porpoise bycatch. To test if low nets can reduce bycatch of porpoises one would need to continue with similar experiments but making the nets even lower. At some point the net height will affect the bycatch rate of porpoises. The question is, however, if nets with that height will still be able to catch sufficient amounts of turbot.

It should be mentioned that even though lowering the net height is a very simple solution, it can be a difficult task to find the optimal height. A lot of data is needed to find statistical significance, which is a time consuming and expensive process. The optimal net height will also depend on the target species. The higher in the water column the target species moves, the more difficult it will be to lower the net height without losing catch as the fish will simply swim over the net. Flatfish fisheries will thus have the best chance of reducing bycatch by using lower nets as flatfish species mainly moves on the seabed. It is, however, possible that a lowering of the net height will have no effect at all if the porpoises move too close to the bottom themselves, and thus even very low nets will still catch porpoises.

5.3 Lights and sounds against seabirds and harbour porpoises

In the winter 2018-2019, we tested light and sound as potential seabird deterrent methods in a commercial fishing setup. Two candidate seabird bycatch reduction devices (BRD) were trialled on a Danish gillnetter carrying a video-based EM system and operating in the coastal gillnet fishery for cod and flatfish in the Øresund: a flashing white LED light identical to the one in Field *et al.* (2019) (luminous flux = 10 lumen; wavelength: 430 – 630 nm; maximal intensity at 480 nm, “Netlight” manufactured by Fishtek, UK) and a pinger operating at a 3 kHz frequency with a source level of 145 dB re 1μPa @ 1m ("Whale Pinger" manufactured by Future Oceans, Australia). Additionally, since bycatches of harbour porpoises are frequent in the study area, we planned to measure the potential for these BRDs to reduce harbour porpoise bycatch rates.

This research consisted of a simple paired design experiment. BPUE of seabirds and of harbour porpoises, as well as target species catch per unit effort (CPUE) were compared between treatment net fleets and control fleets. The experimental net fleets were identical for controls and treatments and typical of the gears used in this fishery to target cod *Gadus morhua* and European plaice *Pleuronectes platessa*. The entire net fleet measured approximately 500 m in length and 3.6 m in height. The panels consisted of transparent nylon monofilament nets with a stretched diagonal mesh size of 120 mm. Treatment fleets had one of the two types of candidate BRDs attached at regular intervals to the gear as shown in Fig. 5.3. Based on the hearing capabilities of the great cormorant, we evaluated that the signal from the pingers could be perceived by a diving bird at a distance of 100 m (Hansen *et al.* 2017). To maximise their potential deterring effect, the pingers were attached to the floatline every 12.5 m. The LED lights were attached alternatively on the floatline and on the leadline with a horizontal distance of 10 m. That is, the interval between two consecutive net lights on the floatline (leadline) was 20 m.

The choice of fishing locations and soak duration of the net fleets was left to the fisher and varied depending on the weather conditions and currents. Controls and treatments were set in sequence with a spacing of approximately 200 m between each and retrieved together to ensure comparable soak durations. All fishing trips were monitored using an electronic monitoring system with videos, identical to the one described in Section 2. Observers were also present on half of the trips. Data collection consisted of counting the number of bycaught animals captured in each net fleet and identifying each individual at species level. The weight of target catch was estimated for each net fleet for each fish species. Confidence intervals around the mean estimates were calculated using a bootstrapping technique.

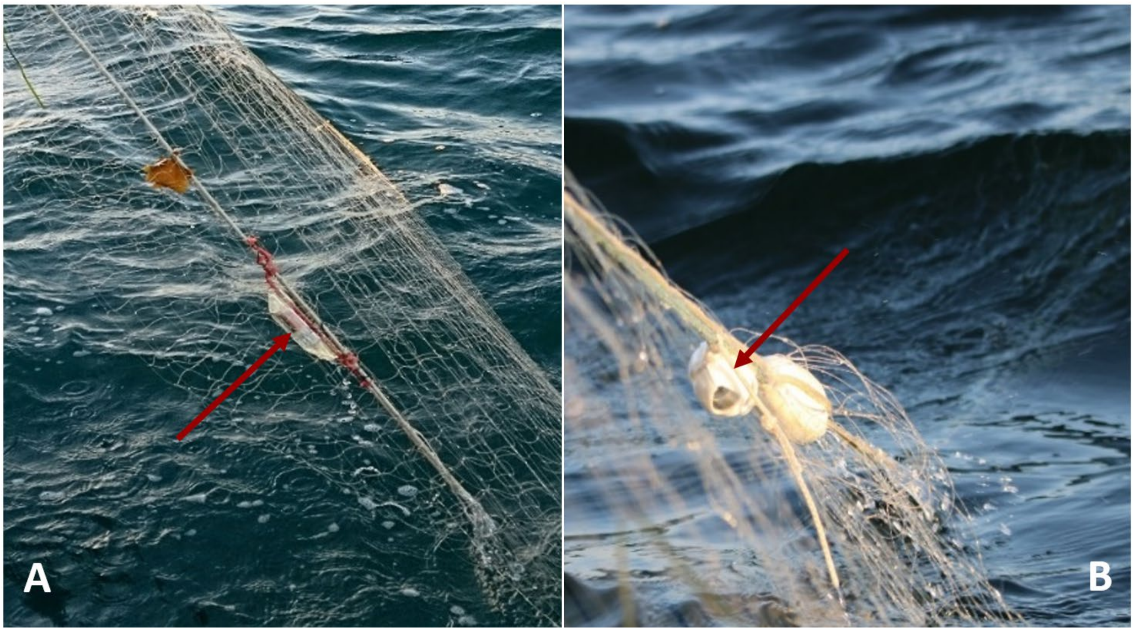


Figure 5.3. Trialled bycatch reduction devices. A. Flashing white LED light. B. 3 kHz pinger attached on the headrope (next to a float).

During the course of the experiment, seabirds were captured both in control and treatment net fleets. However, no harbour porpoise was caught either in control or in experimental nets. The birds taken as bycatch during the experiment belonged to six species and three families (Table 5.4). We classified these birds according to their feeding behaviour into two categories: benthic foragers (common eider, common scoter and velvet scoter) and pursuit divers (great cormorant, common guillemot and razorbill).

Table 5.4. Number of seabird incidental catches per species observed in each pair of experimental and control gillnet fleets between November 2018 and February 2019.

	Flashing White Netlights		3 kHz Pingers	
	Experiment	**Control**	**Experiment**	**Control**
Common eider (*S. mollissima*)	5	7	8	9
Common scoter (*Melanitta nigra*)	3	0	0	0
Velvet scoter (*Melanitta fusca*)	1	2	0	0
Great cormorant (*P. carbo*)	2	1	0	2
Common guillemot (*Uria aalge*)	1	4	2	1
Razorbill (*Alca torda*)	0	1	0	0
TOTAL	12	15	10	12

In order to conclude whether the candidate BRDs were effective at reducing bycatch in gillnets, we used a randomisation test (Manly 2018), under the null hypothesis that there was no difference between BPUE in experimental and control net fleets. Because no harbour porpoise was captured, we could only run randomisation tests for seabirds. We ran these tests for all birds pooled together, for pursuit-diving birds only and for benthic-foraging birds only. Confidence interval around the mean estimates were calculated using a bootstrapping technique (10.000 repetitions). We rejected the null hypothesis if the 95% CI of the difference in mean BPUE between experimental and control sets did not overlap zero. The same method was used to compare the difference in catch rates of target species between control and experimental net fleets.

Fig. 5.4 presents the results of the randomisation tests. There was no significant difference in seabird bycatch rates between controls and treatments for both candidate BRDs (Netlights and 3 kHz pingers) for all seabirds together and for benthic foragers only. Likewise, pingers did not significantly reduce the bycatch rates of pursuit divers in our experiment. However, we observed a small yet significant reduction in BPUE of pursuit-diving seabirds in the net fleets equipped with Netlights. Moreover, the difference in CPUE for target fish species was not significant between controls and treatments.

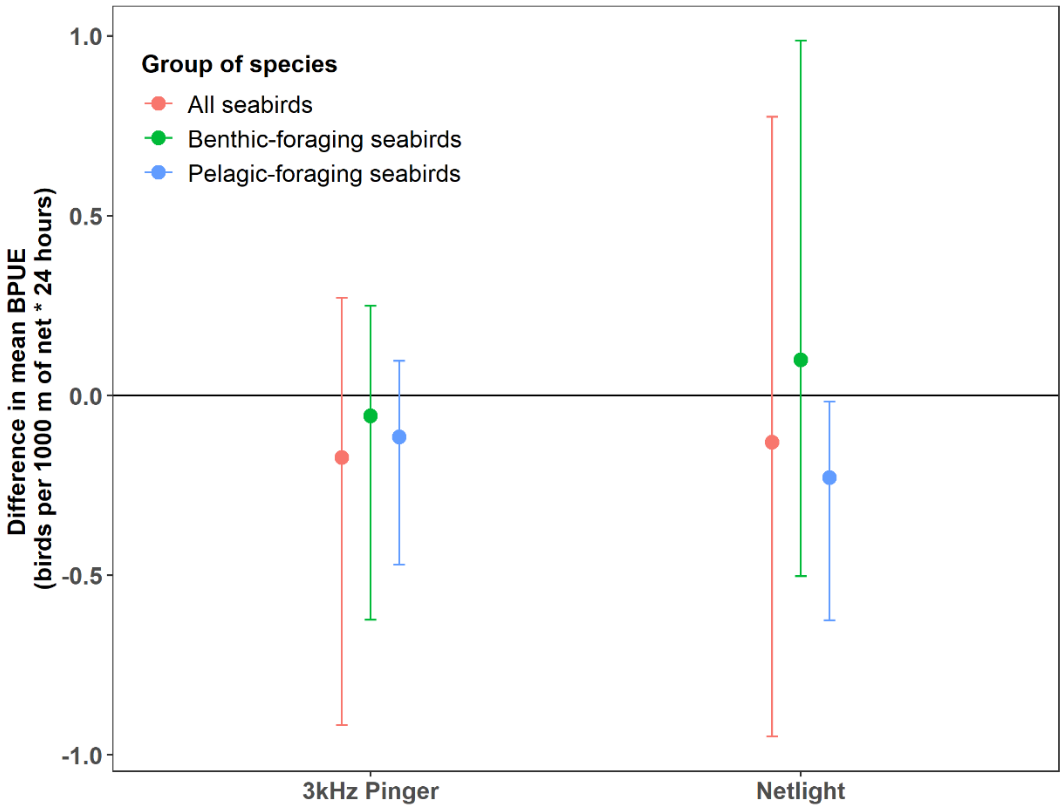


Figure 5.4. Difference in bycatch per unit effort (BPUE) of birds between paired experimental vs. control gillnet sets. Mean BPUE (coloured dot) and 95% confidence intervals (error bars) estimated using bootstrap (10.000 repetitions).

5.4 Pingers against great cormorant *Phalacrocorax carbo*

In the last 20 years, gear modifications and deterring devices using sound or light have been tested in various fisheries worldwide to reduce seabird bycatch, with contrasting results depending on the gear type, the nature of the mitigation tools, the affected species, and the location of the trials. Still, the use of sound underwater has generally received less attention as a bird by-catch mitigation method than have visual alerts, with the exception of encouraging results obtained in the United States on common murres (Melvin *et al.* 1999).

In the summer 2018, the effects of underwater sounds on great cormorants were tested in pound nets located in the Lillebælt (ICES area IIIc22). A pound net is a fixed at-sea structure, consisting of a small-meshed encircling net the height of the water column (here, approx. 5 m), with a narrow opening on one side. Passing migratory fish are channelled towards the trap with a long, small-meshed net extending from the entrance of the pound net and all the way to the shore. The structure is maintained in place with long wooden poles, used by numerous seabirds (*e.g.* great cormorant, herring gull, lesser black-backed gull, sandwich tern, common tern) for resting (Fig. 5.5). Great cormorants are commonly seen diving in these pound nets to prey on the fish captured in the traps. The fish disappearing to the birds reduces pound nets profitability and the fishers operating these fishing gears are keen to find a solution to stop cormorant depredation.

Figure 5.5. Detail of a pound net in the Lillebælt where the experimental trial took place. European herring gulls and great cormorants gather on the protruding poles in high numbers.

The goal of the experiment was to determine if acoustic deterrents (pingers) could affect the foraging behaviour of great cormorants. Specifically, we selected two pound nets to conduct experimental trials. The first part of the data collection took place in end of July to early August 2018 in a large pound net situated in a quiet area of the Lillebælt. The net enclosure, *i.e.,* the trap in which the target species are captured, roughly corresponded to a circle of 10 m in diameter. The netting was maintained in place by surrounding wooden poles, placed approximately 2 m from the netting. For the second part of the experiment, from mid- to end of August 2018, the setup was moved to a location approximately 2 km north of the initial one, using a smaller pound net (6 m in diameter). The reason was that the fisher stopped using the first trap (targeting mackerel) in mid-August, to focus on catching shore crabs in the smaller nearby trap.

The aim of the experiment was to measure the difference in the mean duration of dives of the great cormorants present in the trap enclosure when the acoustic devices were turned on and when they were off. Specifically, we tested a pinger centred at a frequency of 3 kHz, emitting at a source level of 145 dB re 1µPa @ 1m ("Whale Pinger" manufactured by Future Oceans, Australia). Previous work on psychoacoustics of the great cormorant had demonstrated that these birds are able to perceive these frequencies while diving (Hansen *et al.* 2017, Maxwell *et al.* 2017). To maximise the chance that the sounds would be heard by the birds diving in the trap, we placed four pingers at equidistance around the net enclosure. The pingers were immerged at a depth of 2.5 m using a rope attached to the headline of the net enclosure.

We monitored the behaviour of cormorants using a video camera able to record for several days in a row, *i.e.* a GoPro 7 with a 128 Gb SD card, equipped with two additional high-capacity 20.000 mA-hour external batteries in a rugged waterproof case, allowing the camera to film continuously for 71 to 97 hours. No human was present in the vicinity of the pound net during the observation period to limit the observer effect, except for occasional passing ships and bi-weekly visits of the fisher to collect the catch. The observations were grouped into two paired sessions, each pair consisting of video recordings made with and without pingers in the same pound net at a few days' interval. The first paired session was recorded in the large pound net from July 30th to August 2nd 2018, and from August 13th to 16th 2018. The second paired session was recorded in the smaller pound net from August 21st to 24th 2018, and from 28th to 31st August 2018. The video recordings for each session started around noon, and only the first 71 hours of each session were analysed. Furthermore, additional parameters such as temperature, wind speed, sea state, and general weather conditions, were registered during the setup of the equipment and for the whole duration of the monitoring of the pound net.

Several great cormorants were frequently present inside the net enclosure at once, so that different birds could be underwater together at the same time. As the video resolution was too low to differentiate individuals from the footage, we registered the time each bird dove and the time each bird surfaced and developed an algorithm to calculate the minimum average duration of a dive. We could thus compare statistically the difference in the mean dive duration while pingers were on and off for each pound net (Fig. 5.6).

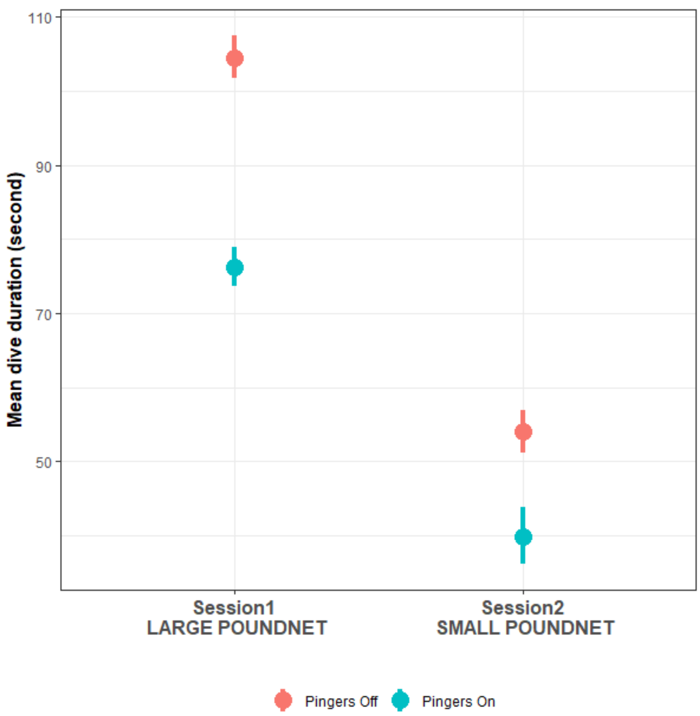


Figure 5.6. Comparison between the average duration of dives for great cormorants in pound nets when pingers are active and not active. The error bar represents 2 standard deviations around the mean values.

Recorded temperature, wind speed, sea state and general weather conditions were similar within each paired session, without large shifts that may have influenced the number of birds present in and around the trap enclosure, or the diving activity of the great cormorants present in the pound net. We estimated that the average duration of the dives of great cormorants was reduced significantly in both pound nets when the 3 kHz pingers were on compared to when the pingers were off (Fig. 5.6). Nonetheless, our results may also reflect unmonitored natural variability of mean dive duration of cormorants or other unmeasured confounding factors.

Additionally, we registered when cormorants ended their dives with a prey (*successful dive*) or without (*unsuccessful dive*). Success rates were defined as the fraction of successful dives over the total number of dives for each session. Because of *e.g.* sun reflections, water drops or salt crust on the lens, the quality of the videos was not constant over time, and it was often not possible to distinguish the outcome of a dive with certainty. Unclear observations were always considered as unsuccessful, which may have resulted in lowering success rates artificially. Additionally, although being generally admitted that cormorants swallow their prey at the surface, it cannot be excluded that they also do it occasionally while still being underwater (Carss *et al.* 1997). As such, we may have underestimated real success rates by an unknown amount. Nevertheless, during “pinger on” sessions, success rates were not null, indicating that at least some great cormorants could capture fish when pingers were active. However, cormorants spent on average less time underwater when 3 kHz pingers were on (Fig. 5.6). For the crested grebe *Podiceps cristatus*, a fish-eating species whose foraging behaviour is comparable to the one of the great cormorant, successful dives are significantly longer than unsuccessful ones (Ulenaers *et al. 1992)*. If the same applies to great cormorants, our observations of mean dive durations in pound nets suggest that the presence of pingers could have significantly reduced the foraging success of great cormorants. However, because of the impossibility to estimate success rates with certainty, this reduction was not quantified.

5.5 Conclusions and recommendations

5.5.1 Bycatch estimation

The results presented here is the first attempt to assess the scale of bycatch of marine mammals and seabirds in Danish gillnet fisheries. The results are based on a data set including EM data collected in the years 2010-2018 from 16 vessels and totalling 4.730 observed fishing days. This corresponds to a mean coverage of c. 18% of the total Danish gillnet fleet effort in 2018, but with large variations between years and areas. In the Øresund, the coverage is c. 60% while the North Sea has a coverage of only c. 4% and the Kattegat a coverage of less than 1%. These differences reflect primarily the difficulties in getting fishermen to accept having EM-systems onboard their vessels, which varies between regions. Having EM-systems onboard more vessels is needed to get a better and more even coverage of the total effort and would also results in a more even geographical coverage. Comparing Figs. 2.1 and 2.2, it appears that our coverage has missed some areas with high gillnet effort, *i.e.* the area around the boundary between ICES areas IIIa20 and IVb, and the area in the Kattegat north of Djursland. However, as explained in Section 2.1, these two concentrations could to some extent be an artifact. Ideally, the EM coverage should reflect the coverage of the total gillnet fleet, but this will probably not be possible as long as it is voluntary to accept the EM-systems on board.

The mean bycatch of harbour porpoises in 2010-18 was estimated at 1.628 for the North Sea, 507 for Skagerrak, 104 for the Øresund and 511 for the Belt Sea. Combining these based on the relevant porpoise populations, the estimated Danish gillnet bycatch from the North Sea/Skagerrak population is 2,135 animals and for the Kattegat/Belt Sea/Western Baltic it is 615 animals. However, this last figure does not include an estimate for the Kattegat, as we did not have sufficient EM-coverage to estimate bycatch rates for this area. If we used the bycatch rate for the Belt Sea and applied it to the mean Kattegat effort for 2010-18, the estimated porpoise bycatch for the Kattegat would be c. 160 animals, resulting in a total of 775 animals for the Kattegat/Belt Sea/Western Baltic population. It is important to note that these numbers refer to only the Danish gillnet fleet and that other nations (UK, Germany, Norway and Sweden) have bycatch of porpoises in these areas. To assess whether the bycatch is sustainable requires that the bycatch of these other nations be known.

The same concerns with respect both to EM-coverage and to inclusion of other nations' bycatch applies to bycatch estimates for both seabirds and seals given in this report. Specifically for seabirds, it will be necessary to estimate bycatch at the species level as some of the species recorded as bycatch are listed as near threatened and vulnerable on the IUCN Red List and on the Danish national Red List. For seals, it will also be necessary to distinguish between common and grey seals in the EM videos, which can be a challenge.

Recommendations
The following recommendations are necessary to improve the reliability and precision of the bycatch estimates:

- Collect bycatch data that are more representative of the whole gillnet fleet.
- Collect fishing effort data at a finer spatiotemporal scale for all vessel length classes.
- Collect data on the distribution of bycatch species at a finer spatiotemporal scale.

5.5.2 Mitigation measures

This report documents a level of bycatch of PET species in gillnets in Danish waters that is far from negligible. Reducing bycatches of PET species in gillnets while maintaining the viability of these fisheries is a challenge that could be addressed using one or a combination of several mitigation strategies. These approaches need to be tailored to the local specificities of the fisheries under scrutiny and/or of the vulnerable species or populations under threat. To achieve conservation goals, mitigation strategies may aim at reducing the intensity of fishing effort of high-risk gears, or to ensure *via* technical measures that the high-risk gears minimise the risk of entanglement of PET species. Both types of strategies have been trialled in gillnet fisheries around the world with various success, however sometimes leading to unintended consequences (O'Keefe *et al. in review*).

Time-area closures and switching gillnets to alternative bycatch-safe gears are often praised as solutions to end bycatches in the fisheries identified as problematic. The data collected during this project showed high seasonal bycatch risks in some areas and for all the studied groups (Section 2 of this report). We believe that this work could serve as a basis for future fine-scale time-area closures in Denmark, or for requiring the use alternative gears in areas and time of the year where the risk of bycatch is high. However, this will require data that are more representative of the whole fleet and at a finer scale than was possible in the present project (see Section 2). Nevertheless, the effectiveness of time-area closures and gear-switching measures should be carefully evaluated beforehand both in terms of benefits to conservation and potential economic loss to the fishing sector, as they might generate a number of unintended consequences including *e.g.* a displacement of the fishing effort to areas where bycatch was previously not an issue that may cancel the benefits of the closures for the vulnerable populations (O'Keefe *et al.* 2014), or a net economic loss for fishers that could in turn affect entire coastal communities (O'Keefe *et al.* 2014, Smith *et al.* 2003).

In many cases, closing areas to gillnets may be a less than optimal option. For a number of years, pingers have been mandatory in Danish gillnet fisheries to reduce the bycatch of harbour porpoises, but pingers have a number of potential drawbacks including costs, noise pollution, potential habituation and habitat exclusion, making them a sub-optimal solution to the bycatch problem. We presented in this report some examples of gear modifications (low nets) and bycatch reduction devices (mechanical pingers, gillnet illumination with LED lights, 10 kHz pingers), which could potentially be used as complementary technical measures in fisheries where closures or switching to alternative gears are not acceptable. Nevertheless, the results of the mitigation trials for these methods were inconclusive and will require more data to be collected in operational fisheries to confirm their efficacy at reducing bycatches of PET in gillnets. Other mitigation methods that could be effective includes aerial scarers like the bobby (looming-eye buoy), which has shown some success in trials in Lithuania and at present are tested in Denmark, and the acrylic glass pearls mentioned in Section 4.6.1, which are also at present undergoing further tests in Denmark and Germany.

In Denmark, gillnets are the principal fishing gear in terms of number of vessels (Fiskeridirektoratet 2020a), despite representing a small fraction of the total landings (Fiskeridirektoratet 2020b). Together with other passive gears, gillnets are particularly energy efficient and their effect on the marine habitat is generally much lower than active gears (Cochrane 2002; Gislason et al. 2014). An ecosystem-based approach to fisheries management requires to consider all components of the marine ecosystem and thus to reduce bycatch of PET species to negligible amounts. Combining the fine-scale spatiotemporal knowledge of the fishing activity of gillnet vessels with specific local mitigation strategies, while establishing quantifiable bycatch reduction targets agreed upon with fishers, may be the way forward to ensure the long-term viability of gillnet fisheries in Denmark.

Recommendations

The following mitigation measures should be subjected to more research to establish their efficacy:

- Fine-scale analyses of the basis for time-area closures.
- Trials of mechanical pingers in the commercial gillnet fishery to reduce bycatch of harbour porpoises.
- Trials of low nets in the commercial gillnet fishery to reduce bycatch of harbour porpoises.

Other mitigation measures that are being tested at present includes acrylic glass pearls, LED-lights, looming-eye buoys and thin nets that harbour porpoises can break free of.

6. References

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7. Acknowledgements

We would like to express our sincere gratitude to the fishers who accepted to have the EM-systems onboard and to the fishers who helped with the experiments.

We are also grateful to the Danish Ministry of Food, Agriculture and Fisheries and to the EU for financial support of the project through the European Maritime and Fisheries Fund.

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