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What's the catch with lumpsuckers? A North Atlantic study of seabird bycatch in lumpsucker gillnet fisheries

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ABSTRACT

Worldwide, incidental bycatch in fisheries is a conservation threat to many seabird species. Although knowledge on bycatch of seabirds has increased in the last decade, most stems from longline fisheries and the impacts of coastal gillnet fisheries are poorly understood. Gillnet fishing for North Atlantic lumpsucker (*Cyclopterus lumpus*) is one such fishery. We collated and synthesized the available information on seabird bycatch in lumpsucker gillnet fisheries across the entire geographical range to estimate and infer the magnitude of their impact on the affected seabird populations. Most birds killed were diving ducks, cormorants and auks, and each year locally high numbers of seabirds were taken as bycatch. We found large differences in bycatch rates among countries. The estimated mean bycatch in Iceland was 2.43 birds/trip, while the estimates in Norway was 0.44 and 0.39 birds/trip, respectively. The large disparities between estimates might reflect large spatial differences in bycatch rates, but could partly also arise due to distinctions in data recorded by onboard inspectors (Iceland), self-administered registration (Norway) and direct observations by cameras (Denmark). We show that lumpsucker gillnet fisheries might pose a significant risk to some populations of diving seabirds. However, a distinct data deficiency on seabird bycatch in terms of spatio-temporal coverage and the age and origins of the birds killed, limited our abilities to fully assess the extent and population consequences of the bycatch. Our results highlight the need for a joint effort among countries to standardize monitoring methods to better document the impact of these fisheries on seabirds.

1. Introduction

Seabirds are one of the most threatened groups of birds globally, and many seabird populations are experiencing severe declines, although trends vary greatly among species and areas (e.g. Croxall et al., 2012; Gaston et al., 2012; Berglund and Hentati-Sundberg, 2015; Paleczny et al., 2015; Dias et al., 2019). To support conservation efforts, there is a continuous need for quantitative information on population trends and key drivers of change, especially in relation to the possible effects of human activities (e.g. Nordic Council of Ministers, 2010).

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Table 1
Overview of lumpsucker fishing activity in the countries included in the analysis.

	Greenland	Iceland	Norway	Denmark	Sweden	Canada
Fishing period	Varies with latitude, overall range is from early April to late June	Late March until August	April to July	Late January to May	Timing of fishing is unknown, but spawning takes place February to May	June to July
Main fishing area	West Greenland, north to 70 °N	West and north coast of Iceland	Norwegian mainland north of 65 °N	Kattegat, Skagerrak and the West coast of Jutland	Øresund (the narrow strait between Sweden and Denmark)	Gulf of St Lawrence (GSL) and around Newfoundland
Regulation	Lumpsucker management plan was implemented in 2015 and led to a shortening of the season length (44–47 consecutive days per vessel) and to the introduction of quotas	Limits placed on the total length of nets set, number of fishing days per boat and total number of licences	Lumpsucker can be commercially fished in the three northernmost counties. Fishing is not allowed after 20th June west of 26 °E or after 5th July further east. For 2019, total catch quota per boat is 5 t roe. Boats must be under 13 m.	Commercial operations require a license. There are mesh size regulations, but no management plan, input control or catch quota.	Commercial operations require a license. There are mesh size regulations, but no management plan, input control or catch quota.	There are Annual Integrated Fisheries Management Plans (IFMPs) produced for each NAFO subdivision for groundfish, which includes lumpsucker. Limits are in place on the maximum length of nets (50 fathoms), and number of nets (Max 50 nets per boat)
Fleet size	The fleet size varies among years and the highest number recorded was 700 dinghies in 2010. In 2016 the number was 420	Between 144-372 boats active over the last 20 years, with an average of 260 boats fishing over the past 5 years	Between 2005–2015, the active fleet size varied between 10 and 409 vessels	Between 1998–2018, the size of the commercial fleet varied between 23 and 67 vessels. From 2014 and onward, the yearly number of active vessels has been on average to 57	The fleet size has declined but varies between years, with around 55 active vessels since 2010.	Fleet is currently typically small with 65 fishers, but this has been greatly reduced since the early 2000s
Mesh size (min-max, mm)	Not regulated	267–292	267 – no max	None	120 – no max	267 – no max
MSC- certification year	2015	2014 (but suspended in 2018)	2017	Not certified	Not certified	Not certified
History of fishery	Landings increased from almost nothing in the early 1990's to ca. 2100 t of roe in 2013. Subsequently landings declined again due to market conditions and the implementation of a management plan. In 2016 ca. 750 t of roe was landed (ca. 2775 t of whole fish)	Landings peaked between late 1970's and 1980's, when landings fluctuated between 6000–12.000 tonnes annually. Between 1990 and 2017 landings have been 2000-6000 tonnes and was ca. 5000 tonnes in 2017–2018	Landings peaked in late 1980's and 1990's with highest harvest being 7300 t in 1987. Since 2000 the landings have declined due to market conditions. In 2018, after the fishery was MSC-certified, numbers of active boats increased	Landings in the Kattegat, the area contributing the most to landings for Denmark, have decreased by 90% from the late 1980s to 2003, stabilizing since to around 1000 tonnes per year. However, lumpsuckers remain important seasonally for many Danish small-scale fishermen	Landings vary from year to year with no apparent long-term trend. Vessel numbers are declining	Number of fishers dropped from 404 in 1986–2009 to 65 in 2010–2015. Peak landings of 1203 t in 1999 and has been on average 63 t annually since 2010

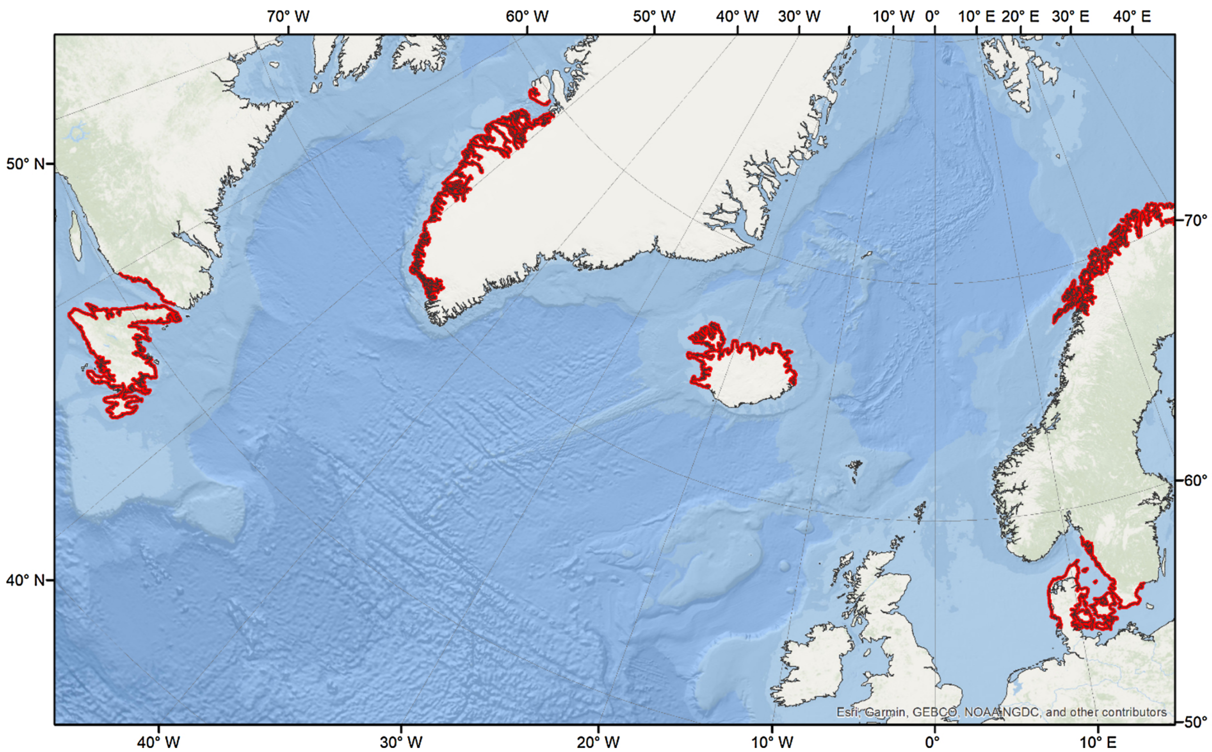

Fig. 1. Map of the North Atlantic showing with red the main areas where North Atlantic lumpsucker (*Cyclopterus lumpus*) is fished (based on Kennedy et al., 2019 and www.fao.org) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

North Atlantic seabirds are no exception and their populations share many characteristics that make them susceptible to excessive mortality. Many species are colonial during breeding and may also form large feeding aggregations in wintering and staging areas, meaning that large numbers of birds can be affected when human activities occur near such aggregations (Boersma et al., 2002). As predators often near the top of marine food webs, their populations may already be stressed by natural and human-induced changes in prey stocks (Frederiksen et al., 2004), climate-driven effects on habitats (Moe et al., 2009; Iverson et al., 2014), changes in fisheries discard practices (Votier et al., 2004) or contamination (Bustnes et al., 2003; Fisk et al., 2005). Moreover, most seabirds migrate significant distances, and their health and survival are therefore affected by human activities in a wide range of areas (Montevecchi et al., 2012; Reiertsen et al., 2014). Consequently, sound management and conservation of these populations requires multi-national, collaborative attention to reduce threats throughout the year.

Incidental bycatch of seabirds in fishing gear is one of the factors that may have detrimental effect on seabird populations (Dias et al., 2019), and has been reported in several fisheries in the North Atlantic region (Bakken and Falk, 1998; Dunn and Steel, 2001; Žydelis et al., 2009; Merkel, 2011; Fangel et al., 2015). Žydelis et al. (2013) estimated that on a global scale, 400 000 seabirds were killed as bycatch in gillnets annually, of which almost 200 000 were taken in the eastern North Atlantic. Gillnets are known to catch an array of non-target taxa (Wallace et al., 2010; Reeves et al., 2013) with the most susceptible seabird species being those that dive in pursuit of prey (e.g., seaducks, divers, alcids and cormorants). Unfortunately, there is still a severe lack of quantitative information on what species are most affected and the potential effects on their populations (Lewison et al., 2014; Pott and Wiedenfeld, 2017). The increased public demand for sustainably managed fisheries (Potts et al., 2016) has however led to increased awareness of the bycatch of non-target species. For instance, minimal bycatch of seabirds is one of the criteria that should be met for a fishery to be certified with the Marine Stewardship Council (MSC) ecolabel (MSC, 2018). Yet, there are evident limitations in the existing standard as to how this bycatch is evaluated (Crespo and Crawford, 2019). Regardless, quantifying and then tackling seabird bycatch (where relevant) are key elements in ensuring the sustainability of fisheries under such certification schemes. In this context, the MSC certification of the gillnet fishery for North Atlantic lumpsucker (*Cyclopterus lumpus*, hereafter lumpsucker), in Iceland (Petersen, 2002; Pálsson et al., 2015), Greenland (Merkel, 2011; Lassen et al., 2015) and Norway (Fangel et al., 2015; Gaudian et al., 2017) all highlighted seabird bycatch issues. This has motivated additional data collection in Iceland (Gascoigne et al., 2017) and Greenland (Lassen and Chaudhury, 2018), though only Iceland has done this through independent on-board observers/inspectors.

With this background, the main aims of this study are to collate, review, and quantify relevant information on seabird bycatch in lumpsucker fisheries in the North Atlantic to: 1) promote an ocean basin scale approach to assess potential conservation issues; 2) assess bycatch in relation to the status and trends of the most susceptible species across countries and regions; 3) assess the results in relation to differences in methods and sources of bias; and 4) identify priorities for future fisheries management.

Our study constitutes a first attempt to quantify, in the most proper statistical terms, the potential direct impact on seabird populations of a species-specific fishing activity across its entire range. This work will contribute to a better understanding of the overall effects of coastal gillnet fisheries on seabird populations and serve as a base to motivate bycatch reduction efforts.

2. Material and methods

2.1. Description of the fishery

The lumpsucker is found throughout the North Atlantic and migrates considerable distances between offshore feeding habitats and inshore spawning areas (Davenport, 1985; Kennedy et al., 2015). Spawning occurs in spring and early summer, and commercial fishing takes place in inshore waters during the spawning migration, using demersal large-mesh gillnets (Table 1) set close to shore and in shallow waters (Tún, 2014; Lassen et al., 2015; FAO, 2017; Gaudian et al., 2017; Kennedy et al., 2019). The soak time of the nets is usually at least one night, but often longer. The commercial lumpsucker fishery primarily targets females for roe, but there is also a small commercial fishery in Iceland for male lumpsuckers (Kennedy et al., 2019).

The commercial lumpsucker fishery began in earnest in the North Atlantic after the Second World War (Davenport, 1985; Kennedy et al., 2019). Since then, vessels have targeted this species across much of its range in the North Atlantic, spanning from Newfoundland and Labrador, Canada in the west, the Barents Sea in the northeast and Denmark in the southeast (www.fao.org, Fig. 1). Prior to 2000, most of the lumpsucker was fished in Iceland and Canada, but the Canadian catch has since declined dramatically (Table 1). In turn, Iceland, Greenland and Norway have accounted for most of the landings of lumpsucker in the last decade (Kennedy et al., 2019, Table 1). Traditionally, lumpsuckers are caught using small fishing vessels (< 13 m) with only one fisherman on board, but in recent years, boats with crews of two to three people have also been in operation (Johannesson, 2006). The fishing period and intensity varies among and within countries (Table 1).

2.2. Data on seabird bycatch

We reviewed the available published and unpublished information related to lumpsucker fisheries, as well as seabird interactions reported in these fisheries. We also assembled an overview of seabird species documented to be taken as, or expected to be susceptible to, bycatch in these fisheries. In addition, we collated all available quantitative data on seabird bycatch in the lumpsucker fisheries in order to estimate the overall bycatch of the most commonly killed species.

2.2.1. Bycatch sampling: Norway

The Norwegian bycatch data originate from self-administered registration conducted by lumpsucker fishers during 2012, 2013, and 2015. The data comprised bycatch records for 177 fishing trips targeting lumpsucker, from 18 different vessels. These data represented 11.6% of the total number of fishing trips recorded for the lumpsucker fishery in the official Norwegian fishery statistics for the same period. All fishers included in the survey voluntarily reported their catch through standardized forms developed for the project, and received a small economic compensation for the extra work associated with this. Through participation in the study the fishers also recorded all seabirds caught. As more than 96% of the recorded commercial lumpsucker fishery in Norway (2012–2015) was situated in the two northernmost counties, Troms and Finnmark, our data only included bycatch records from vessels operating within this area.

2.2.2. Bycatch sampling: Iceland

The Icelandic bycatch data came from two independent sampling projects using on-board observers/inspectors. One study covered 31 fishing trips joined by observers hired by Birdlife International in 2016. These trips were conducted in collaboration with individual fishers that allowed observers on their boats. The boats were selected opportunistically. The other study covered 192 trips monitored by on-board inspectors from the Icelandic Directorate of Fisheries in 2014–2017. The main objective of the latter project was to enforce regulations concerning discards and gear. From 2014 onwards, the inspectors recorded all bycatch of marine mammals and birds, but before 2014, reports of bycatch events were only sporadic. Inspection trips were generally not selected randomly, as the process was often guided by anomalies in landings, or by the need to check for maximum number of nets, bycatch of cod (*Gadus morhua*), or potential infractions.

The two datasets were combined for this analysis, totalling 223 trips, which represent 1.6% of the total number of landings of catch registered in those years. The spatial distribution of the sampling accorded well with the spatial distribution of the fishery (Marine and Freshwater Institute, 2018). Total number of landings by the fleet was used as the metric for effort rather than data on the number of nets and soak time from the fleet/logbooks, as the reporting of these data in the logbooks has been inadequate. For example, only 604 out of 3309 landings in 2016 (18%) included soak time and number of nets set, highlighting one of the issues with self-reporting, namely low compliance.

2.2.3. Bycatch sampling: Denmark

In Denmark, lumpsucker gillnet fishing was not covered by a dedicated observer programme. Nevertheless, an estimation of the overall bycatch of seabirds in gillnet fisheries is currently ongoing, using CCTV cameras and a remote electronic monitoring (REM). Since 2010, 17 gillnet vessels have been equipped with REM systems. The vessels originated from all major fishing areas of Denmark, except for Bornholm, where no fishers volunteered to participate. The spatial and temporal coverage was highest for Øresund, Skagerrak and the inner Danish waters. Kattegat and the North Sea were only partially covered, i.e. with fewer vessels and/or shorter data collection. The Danish data were therefore not considered representative of the whole Danish lumpsucker fleet. From 2010 to 2018, 816 fishing trips (i.e., < 4% of all the recorded trips) were identified as targeting lumpsuckers specifically, or targeting multiple species, with lumpsuckers constituting the most valuable part of the catch.

Information on bycatch of seabirds was collected for each trip by analysing video data. Each vessel was equipped with at least two cameras, one filming the sorting table and the other the areas where the net breaks the water during the fishing operation (see Kindt-Larsen et al., 2012 for more details). For each haul, the date, position of the boat, net length, soak time, target species, and bycatch events were recorded. Birds were identified to species, unless the video quality was too poor (9% of the cases). In rare cases (< 1%), identification to family level was not possible, and these bycatches were marked as unidentified.

2.2.4. Bycatch sampling: Sweden

In Sweden there is no observer program targeting the lumpsucker fishery. Incidental bycatch may be reported by fishermen, using logbooks, but identification to species level is typically not recorded, precluding quantification of bycatch rates. Logbook data are confidential, and consequently not easily accessible. For this study, it was therefore not possible to include bycatch data from Sweden.

2.2.5. Bycatch sampling: Greenland

Reports on bycatch of seabirds in Greenland are part of the Greenland harvest statistics and were made available by the Greenland Home Rule Department of Hunting and Fisheries. Information on harvest (including hunting and bycatch in the fishery) was collected on a national scale by means of hunters/fishers mandatory self-reporting of their monthly harvest for the period 2013–2016. For commercial fishers, a supplementary reporting system was introduced by the Greenland Fisheries Licence Control Authority in 2015, where fishers have to report bycatch when landing the catch at the fish factory. However, data from this system were not included in this study, as they were still limited.

2.2.6. Bycatch sampling: Canada

Bycatch data for the lumpsucker fishery in Canada was accessed via the Department of Fisheries and Oceans. There is a target to have 10% observer coverage for all lumpsucker fisheries in Canada (Gauthier et al., 2017), but in at least some management areas only self-reported logbooks or dockside monitors are used. As a result, there is minimal observer coverage, and therefore very limited data for incidental bycatch available. The data reported here are from third-party at-sea

Table 2

Bycatch of seabirds in the Icelandic, Danish and Norwegian lumpsucker fisheries in 2014–2017, 2010–2018 and 2012–2013, 2015, respectively. Observed numbers refer to the total bycatch recorded by inspectors/observers/fishers over those years (with estimated mean bycatch per trip in parentheses), whereas extrapolated numbers are estimates of annual bycatch raised by total fishing effort of the whole fleet. Species with small number of observed birds (< 5 birds) were not raised by effort separately. The Danish data were not extrapolated to the whole fleet, due to their non-representative nature.

Species	Iceland: Observed	Norway: Observed	Denmark: Observed	Iceland: Extrapolated annual (95% CI)	Norway: Extrapolated annual (95% CI)
Great northern diver	3		1	–	
Northern gannet	1		0	–	
Cormorant/Shag	58 (0.26)	30 (0.10)	3	898 (671–1174)	50 (16–84)
Long-tailed duck	5 (0.02)	–	0	–	–
Common eider	260 (1.17)	–	133 (0.33)	4030 (2863–5241)	–
Velvet scoter			3 (0.001)		
Unidentified scoter			4 (0.003)		
Black-legged kittiwake	1		0	–	
Razorbill	2	–	0	–	–
Common guillemot	79 (0.35)	–	21 (0.003)	1185 (673–1750)	–
Brünnich's guillemot	4	–	0	–	–
Black guillemot	126 (0.57)	71 (0.11)	0	1930 (1449–2409)	60 (15–94)
Atlantic puffin	3	–	0	–	–
Unidentified auk			4		
Species not identified	–	40 (0.11)	3	–	55 (13–97)
Total	**542 (2.43)**	**141 (0.44)**	**172 (0.39)**	**8290 (6694–9992)**	**218 (94–329)**

observers and likely represents less than 1% of coverage in only a handful of years. As in other regions discussed above, the self-reported logbooks are not easily queried. Data on fishing effort were not available from this fishery.

2.3. Statistical modelling

Data from all countries were compiled and compared. The data were sampled independently of each other in the different countries and using different sampling procedures (see 2.2). This warranted variations in the data analysis applied to the different data sources to extract valid information. For all countries with available data, the species documented as bycatch were summarised. However, data on fishing effort were only available for Iceland, Norway and Denmark, and estimates of bycatch rate were therefore only produced for these datasets.

2.3.1. Norwegian and Danish bycatch estimates

To produce representative bycatch estimates that account for the nested structure (i.e. trips nested within vessel), non-normal and zero-inflation in the data, we used generalized linear mixed models (GLMM). Specifically, we modelled seabird bycatch as intercept only models in the statistical software R, version 3.4.3 (R Core Team, 2017), utilizing the *glmmADMB* package (Fournier et al., 2012; Skaug et al., 2014). Fishing vessel ID was used as a random intercept. The GLMM aimed to produce estimates for all seabirds combined, together with separate estimates for the most common species caught in the fisheries.

For the models, we considered response distributions such as Poisson, negative binomial, zero-inflated Poisson, and zero-inflated negative binomial distributions. We used a negative binomial distribution and zero inflation to accommodate overdispersion, and the excess of zeros, due to patchiness in occurrence of seabirds and bycatch. To assess the most appropriate distribution and model, we first tested and graphed the response to consider whether the negative binomial distribution could be preferred over the Poisson distribution (following Friendly and Meyer, 2015). We then compared the Akaike Information Criteria (*AIC)* values (Burnham and Anderson, 2002) for each model with different response distributions, as well as model rankings, utilizing the *bbmle* package (Bolker, 2016). The highest ranked model (i.e., lowest AIC value) was considered having most support. Both procedures favoured a negative binomial GLMM, without a zero inflation parameter. We validated the final model by plotting the Pearson residuals against the fitted values. We also estimated the number of birds/1000 m of nets set/24 h, based on the same model approach, using recorded fishing effort as an offset. We were only able to extrapolate seabird bycatch rates for the whole fishery based on the per trip estimator.

2.3.2. Icelandic bycatch estimates

Due to zero inflation, we used a Gamma Hurdle intercept only model to estimate bycatch rates (Zuur et al., 2009). This two-step process first estimates the probability of a bycatch event, and then their intensity (Hilborn and Mangel, 1997). Multiplying these values together results in an overall bycatch rate for all the trips (Hothorn et al., 2008). Bycatch probability (i.e. the probability of a non-zero bycatch event) was estimated with a binomial generalized linear model with logit-link function while the bycatch intensity (number of birds) was estimated with a gamma-generalized linear model with log-link function (R Core Team, 2018, Achim Zeileis and Hothorn, 2002).

2.3.3. Extrapolation of bycatch estimates to national fleets

The data from Norway and Iceland had sufficient spatio-temporal coverage to extrapolate the bycatch rate estimates to the fleet level, whereas the Danish data were not considered representative for the whole Danish lumpsucker fleet due to low spatial coverage. Extrapolation was therefore only possible for Norway and Iceland and was done by a bootstrapping procedure which randomly sampled (10,000 iterations) bycatch rate estimates, which again was multiplied with total number of national landings in the respective fleet. This included the years 2012, 2013 and 2015 for Norway, and 2014–2017 for Iceland, representing respectively in total 1531 and 13,710 landings of catch. As there were no recordings of fishing effort at a better resolution than landings (normally representing one trip in these fisheries) in the national records of catches, extrapolations to the whole fishery were also based on these estimators. Upscaled bycatch predictions are presented as annual means with 95% confidence intervals, based on the results from the bootstrapping procedure.

2.4. Population effects of bycatch

One of the ultimate goals of characterizing and quantifying the extent of seabird bycatch is to assess the impact of additional fishery-induced mortality on seabird population dynamics. This, however, requires not only reliable bycatch estimates but also detailed demographic and life history information on the affected species (e.g., Arnold et al., 2006; Le Bot et al., 2018). In order to assess the estimated bycatch in relation to the status and trends of the most susceptible seabird species across countries and regions, we summarized the most recent published estimates of population sizes (number of breeding pairs), population trends, and apparent adult survival rate for the four seabird species most often taken as bycatch in the fisheries studied. Based on the corresponding bycatch estimates derived in our analysis, we subsequently calculated the resulting proportions of populations killed annually (minimum and maximum value), both on the national level and summarized for the whole North Atlantic Ocean.

3. Results

3.1. Species composition

In total, 20 different seabird species were documented taken as bycatch in the lumpsucker fisheries in the five countries (Table S1). Most birds taken were diving species of ducks (Anatidae), cormorants (Phalacrocoracidae), and auks (Alcidae). Iceland had the highest diversity of species affected (19 species). The overall prevalence of species documented as bycatch however likely reflects both the distribution of diving seabird species within the study area, and the intensity of registration of bycatch of seabirds in each fishery. For example, in Canada only three species were documented as bycatch, while 15 others were suggested as being susceptible (Table S1).

3.2. Bycatch estimates for Norway

About 38% of the fishing trips were reported to have seabird bycatch, of which 90% involved < 5 birds caught per trip. Estimated mean seabird bycatch/1000 m of nets set/24 h was 0.40 (SD = 0.12) and estimated seabird bycatch per trip was 0.44 (SD = 0.13). Upscaling to the whole Norwegian lumpsucker fishing fleet, an estimated 230 (95% CI = 112–359) seabirds were caught annually between 2012 and 2015. This assumes a total of 1530 fishing trips, the number of fishing trips that were recognised in the official Norwegian fishery statistics as specifically targeting lumpsuckers within the same time period. The bulk of seabirds taken as bycatch were black guillemots (*Cepphus grylle*) and cormorants (Table 2).

3.3. Bycatch estimates for Iceland

In Iceland, about 47% of the observed fishing trips had seabird bycatch, and of these, 85% of the bycatch events involved < 5 birds per trip. However, mean seabird bycatch per trip was much higher than in Norway amounting to 2.43 birds/trip (SD = 4.84). When extrapolated to the entire Icelandic fishing fleet, the estimate was around 8290 seabirds annually (95% CI = 6694–9992) for the 2014–2017 fishing seasons. The most frequent seabird taken was common eider (*Somateria mollissima*), followed by black guillemot, cormorant species (great cormorant *Phalacrocorax carbo* and European shag *P. aristotelis*) and common guillemot (*Uria aalge*). Other species caught with lower frequency included Brünnich's guillemot (*Uria lomvia*), long-tailed duck (*Clangula hyemalis*), great northern diver (*Gavia immer*), black-legged kittiwake (*Rissa tridactyla*), Atlantic puffin (*Fratercula arctica*), northern gannet (*Morus bassanus*) and razorbill (*Alca torda*) (Table 2).

3.4. Bycatch estimates for Denmark

The frequency of bycatch events in the Danish fishery was lower compared to Norway and Iceland. Only 11% of the trips had registered seabird bycatch, of which 85% involved < 5 seabirds per trip. Mean seabird bycatch per trip was however similar to the Norwegian data and estimated to 0.39 birds (SD = 0.10). It must however be stressed that

Table 3

Published estimates of most recent population sizes, trends and adult survival rates for the four seabird species that most often are taken as bycatch in lumpsucker fisheries in Greenland, Iceland, Norway and the North Atlantic as a whole, with the corresponding total bycatch estimates derived in this study (Table 2) and the resulting proportions of the breeding populations killed annually as bycatch if all birds taken were established breeders (i.e., 'worst case' scenario). For common eider, Canada/Greenland refers to the sum of the source populations in West Greenland and East Canada, which winter mainly in Greenland. As bycatch of cormorants were not identified to species, the estimates for European shags and great cormorants (*P. c. carbo)* were made assuming the bycatch was distributed proportionally to their national population sizes. Conservation status is indicated according to the latest national assessments or, in case of the North Atlantic as a whole, the IUCN global red list of threatened species (EN = endangered, VU = vulnerable, NT = near threatened, LC = least concern).

Species	Area	Conservation status	Breeding pairs/ Source pop§ (thousands)	Trend % p.a.	Adult survival % p.a	Estimated bycatch p.a. (range* or 95% CI)	Proportion taken % p.a. (min-max)
Black guillemot	Greenland	LC [4]	200 [3]	Stable? [3]	?	13 (0–20*)	0.00 (0–0.01)
	Iceland	EN [11]	10–15 [19]	−3.5 [20]	87.0 [6]	1930 (1449–2409)	7.72 (4.8–12.1)
	Norway	VU [9]	35 [2]	+4.7 [22]	85.3 [22]	60 (15–94)	0.09 (0.02–0.13)
	Other		118–195 [1,18-21]	?	?	0 (?)	0?
	All North Atlantic	LC [12]	363–445 [18]	Unknown	86.0 [10]	2003 (1466–2523)	0.25 (0.2–0.4)
Common eider	Canada/Greenland	LC [1,4]	460§ [16]	Increasing [15,17]	?	4128 (3789–4541*)	0.90 (0.8–1.0)
	Iceland	VU [11]	300 [23]	Stable? [13]	90.0 [24]	4030 (2863–5241)	0.67 (0.5–0.9)
	Norway	NT [9]	87 [14]	−4.3 [22]	77.9 [22]	0 (0–0)	0.00
	Other		960–1160 [23]	?	?	0 (?)	0?
	All North Atlantic	NT [12]	1577–1877 [14]	Decreasing [23]	86.0 [10]	8158 (6652–9782)	0.23 (0.2–0.3)
Great cormorant	Greenland	LC [4]	> 5 [14]	Increasing [3]	?	5 (0–10*)	0.05 (0–0.1)
	Iceland	LC [11]	5.0 [8]	+3.5 [8]	85.0 [8]	454 (339–593)	4.63 (3.5–6.1)
	Norway	LC [9]	19 [5]	−7.3 [22]	?	20 (6–34)	0.05 (0.02–0.09)
	Other		22 [18,21]	?	?	0?	0?
	All North Atlantic	LC [12]	51 [18]	Unknown	87.0 [10]	479 (345–637)	0.47 (0.3–0.6)
European shag	Iceland	VU [11]	4.9 [7]	−2.4 [7]	?	444 (332–581)	4.53 (3.4–5.9)
	Norway	LC [9]	28 [5]	−10.8 [22]	82.4 [22]	30 (10–50)	0.05 (0.02–0.09)
	Other		40–41 [18]	Decreasing [12]	?	0?	0?
	All North Atlantic	LC [12]	74–75 [18]	Decreasing [25]	85.0 [10]	474 (342–631)	0.32 (0.2–0.4)

References: 1) Asbirk, 2013, 2) Barrett et al., 2006, 3) Boertmann et al., 2010 (rough assessment), 4) Boertmann and Bay, 2018, 5) Fauchald et al., 2015, 6) Frederiksen and Petersen, 1999, 7) Garðarsson and Petersen, 2009, 8) Gardarsson and Jónsson, 2019, 9) Henriksen and Hilmo, 2015, 10) ICES, 2017, 11) Icelandic Institute of Natural History 2017, 12) IUCN, 2018, 13) Jónsson et al., 2015, 14) Kuletz et al., 2017, 15) Maftei et al., 2015, 16) Merkel et al., 2002, 17) Merkel, 2010, 18) Mitchell et al., 2004, updated by more recent estimates from some countries, 19) Petersen, 2000, 20) Petersen et al., 2016, 21) Rail and Cotter, 2007, 22) SEAPOP database, www.seapop.no, 23) BirdLife International, 2018, 24) Wood et al. (submitted), 25) Based on the other estimates give.

due to the low spatial coverage of the Danish sampling, the Danish data were not representative of the fishery. The estimates should therefore be treated with caution, and we did not extrapolate the bycatch estimates to the whole Danish fleet.

3.5. Bycatch in relation to seabird population status

When compared with the sizes of breeding populations, the estimated annual bycatch of the most frequent inshore species taken in the lumpsucker fishery in Norway, Iceland and Greenland corresponded to between 0.23–0.47% of their total North Atlantic populations (Table 3). When considering the national populations, black guillemot in Iceland was most affected, with an estimated 7.72% of the population being killed every year. This was followed by great cormorants and shags in Iceland with an estimated 4.63% and 4.53% of the population being killed every year respectively (assuming that shags and great cormorants were equally abundant in the bycatch). For the remaining species and countries, the estimated bycatch was < 0.54%. Note that this comparison does not consider numbers of immature birds or birds that move across national borders, except for bycatch of eiders in Greenland where the whole overwintering population of eiders is considered.

4. Discussion

This study is the first to estimate the number of seabirds killed in the commercial gillnet fisheries targeting lumpsuckers across the entire North Atlantic. We found that these fisheries might pose a significant risk to some populations of diving seabirds, although this risk varied considerably among countries and areas. The bycatch consisted of a variety of species, but the most abundant were diving ducks, cormorants and auks, which is consistent with these birds being considered the most susceptible of getting entangled in fixed nets (Žydelis et al., 2013). As gillnets for lumpsuckers are often placed in shallow waters close to the shoreline, it is not surprising that coastal foraging seabird species appear to be the most vulnerable. Less expected were the apparent large spatial differences in species composition in the reported bycatch, and that the estimated bycatch rates for Iceland were orders of magnitude greater than for Norway. The limited quantitative information from Denmark indicated a bycatch rate comparable to the Norwegian fishery, but as the most important fishing areas in terms of landings of lumpsuckers in Danish waters were largely under-sampled for seabird bycatch, this estimate should be treated with caution.

There are several potential reasons for the observed differences in species composition and bycatch rates between countries. Firstly, the occurrence of more extreme bycatch events (i.e., many birds caught on a single trip) was much more frequent in Iceland. The estimated bycatch per trip in Iceland was 5–6 times that in Norway, although the proportion of trips without bycatch was similar between the two countries. This could be due to differences in the occurrence, abundance and species composition of birds, as well as how and where gillnets were set. As we here only have enough information to estimate bycatch per trip, we also disregard potentially important factors (e.g. fishing depth, number of nets set, and distance to shore) determining the amount of seabird bycatch (Marine and Freshwater Institute, 2018; Bærum et al., 2019). It is also possible that bycatch rates were underestimated by the Norwegian and Danish sampling schemes due to lower spatial and temporal coverage. Lower coverage is likely to result in fewer recorded incidents of extreme bycatch events, as these events are rare, and probably not evenly distributed in space and time (Bærum et al., 2019).

Another likely explanation is that in Norway, the bycatch rate estimates could have been biased by the reliance on self-reporting of bycatch by fishers. Conversely, the Icelandic data were collected by independent on-board observers/inspectors. The substantial difference in estimated bycatch per trip, despite large aggregations of diving seabirds in both countries, suggests that there may have been underreporting of bycatch in Norway, an effect which is well established when comparing self-reported bycatch data to observed bycatch data (Northridge, 1996; NMFS, 2004). For example, in Iceland, self-reported seabird bycatch rate based on logbooks in 2017 (the year where most seabirds were reported in logbooks) was 0.66 birds per trip, while the bycatch rate reported in the same year from vessels carrying an observer was 2.04 birds/trip (Marine and Freshwater Institute, 2018). Underreporting may be the result of fishers perceiving that accurate reporting could result in sanctions (NMFS, 2004). Underreporting of bycatch is also a likely scenario in Greenland (Merkel, 2011). However, the magnitude of underreporting is uncertain and may have changed over time as a result of increasing awareness of the potential sanctions associated with bycatch. On the other hand, Merkel (2011) also argued the possibility that some hunters in Greenland incorrectly report hunted birds as bycatch, which to some extent could counterbalance the expected underreporting. The Danish data were independently collected using cameras, so factors like bird abundance likely explain the difference here.

It is also surprising that no common eiders were reported in the Norwegian bycatch, given that they are among the most common and widespread seabirds breeding all along the Norwegian coast (Fauchald et al., 2015), and are commonly captured in lumpsucker nets elsewhere (Table 3). This also contradicts local knowledge that "considerable quantities" of common eiders, king eiders (*Somateria spectabilis*) and long-tailed ducks were taken in lumpsucker nets off the coast of Troms and Finnmark in the 1980s (Bustnes and Erikstad, 1988; Follestad and Strann, 1991). Indeed, dialogue with Norwegian lumpsucker fishers revealed that common eiders are still taken as bycatch, although the extent is not known. The lack of eider bycatch in our data set may therefore be a consequence of underreporting. The timing of the Norwegian lumpsucker fishery may also be a factor, as female common eiders do not feed much in the incubation period (e.g. Gabrielsen et al., 1991), during which most males in this area congregate in flocks at the outermost shoals and skerries to prepare for the moulting period.

In recent years, the apparent low seabird bycatch in the Canadian lumpsucker fishery may be attributable to a dramatic decline in fishing effort and catch (Kennedy et al., 2019), following a decline in the Canadian lumpsucker population (Government of Canada, 2019). Consequently, we suspect that seabird bycatch was much greater in Canada in the past. It is important to note that the seabird bycatch data from Canada were very sparse with only a handful of records since 2003. Notably, the coverage of at-sea observers in the Canadian fishery (NAFO management divisions 3Pn and 4R off western and southwestern Newfoundland) also changed over this time period with a 10% observer coverage target included in the fishing plan in 2010 then later removed from the plan. Therefore, while seabird bycatch appears to decline in the data available, so has the at-sea observer coverage. As such, the data for the Canadian lumpsucker fishery represent a large underreporting of seabird bycatch.

The population level effect of the mortality from bycatch in the lumpsucker fishery is highly dependent not only on the number of birds caught, but also on the sex and age structure of the birds killed, the source populations to which they belong, and the status of these populations (Tasker et al., 2000; Genovart et al., 2017). The black guillemots taken in the Norwegian bycatch were predominantly adults (Barrett et al., 2016) whereas both adult and immature black guillemots were caught in Iceland (Frederiksen and Petersen, 1999). In Greenland, 66% of common eider bycatch was adults (Merkel, 2004). For the remaining species/areas no information is available. Relative to the most recent published estimates of their breeding population sizes, the most affected species were black guillemots and cormorants in Iceland with an estimated annual catch proportional to around 7.7% and 4.5% of the breeding population, respectively. To put these figures in a demographic perspective, the annual survival rate for all these species are documented to be around 85–87% (see e.g. Table 2.1 in ICES, 2017 and references therein). Therefore, the Icelandic bycatch estimate for black guillemots, the most resident species taken as bycatch (Petersen, 2002), may account for as much as half the normal mortality in this population, which is now in severe decline (Petersen et al., 2016). The actual level of mortality is, however, probably somewhat lower as these estimates do not account for the unknown proportions of immature birds among those taken. In this context, it should be noted that the population estimates used for comparison here cannot be considered very accurate, given the lack of a consistent census and monitoring scheme for the populations in question.

Most of the bycatch of common eiders in southwestern Greenland occurs before the spring migration, and therefore to a large extent affects Canadian birds wintering in the area rather than birds breeding in Greenland. Bycatch in this region therefore affects a large metapopulation, and though the yearly bycatch is quite high, the overall population effect is likely to be low. For the Norwegian fishery, the estimated levels of bycatch were < 0.13% of the breeding population for all species affected. It is, however, worth noting that the effects on local sub-populations might be much higher, especially for a species like the black guillemot which is relatively sedentary all year round (Ewins and Kirk, 1988).

In this context, it is also important to emphasize that our study focuses on bycatch of seabirds in only one specific fishery. Gillnets targeting other fish species also take an array of seabird species (e.g. Petersen, 2002; Merkel, 2011; Žydelis et al., 2013; Bærum et al., 2019), thus some of these populations may be subjected to multiple stressors from bycatch. This calls for an assessment of the total effects of seabird bycatch on a wide range of seabird species across multiple types of fisheries and fishing gear to evaluate the cumulative impact of the fishing activity, integrated across populations (Bærum et al., 2019).

When evaluating the lumpsucker fishery across the North Atlantic there was a distinct data deficiency on seabird bycatch, which restricted the possibility to assess the extent of the bycatch and the population consequences. Our results, and specifically the large variation in estimated bycatch rates between countries, highlight the need for a joint effort among countries to standardize monitoring methods and analysis to further assess the impact of these fisheries. It is perhaps telling that the highest bycatch rate was demonstrated in the Icelandic fleet, from which the largest independent dataset has been collected among the countries assessed. There is also clearly a need to ensure that self-reporting schemes are supported by independent observer- or camera-based monitoring to determine bycatch rates and levels adequately. There were several layers of uncertainty in the estimates, where perhaps the most important variation to account for was due to a large variation in the frequency of incidents with high bycatch intensity. A priority should therefore also be to obtain representative sampling coverage, to illustrate the frequency of extreme bycatch events, and also where and how these events occur. Ensuring expanded data collection in this fishery across the Atlantic, alongside common approaches to methods and analyses, will help better establish the true scale of the issue. This might prove increasingly important if the MSC-certification leads to an increase in fishing intensity, which appears to be the case in Norway (Norwegian fishery statistics, www.fiskeridirektoratet.no).

Unlike longline and trawl fisheries (ACAP, 2019), there are presently no best practice technical mitigation measures that demonstrably reduce seabird bycatch in gillnets, though research is being carried out on the use of visual alerts (Martin and Crawford, 2015; Hanamseth et al., 2018; Field et al., 2019), and temporal and spatial local-scale fishery closures (Melvin et al., 1999). To reduce bycatch, there is an increased reliance on spatiotemporal measures such as periodic closures of the fishery or gear-switching (Žydelis et al., 2013), which may be met with resistance by the fishing industry. However, there are demonstrable cases where local-scale fishery closures have reduced bycatch without impacting target fish catch negatively (Melvin et al., 1999), and closures during the pre-breeding period around important seabird colonies have previously been proposed as a bycatch reduction measure for the Canadian lumpsucker fishery (Benjamins et al., 2008). Closures in shallower depths may also help to reduce bycatch (Carretta and Chivers, 2004), and this was suggested for the Icelandic lumpsucker fishery, where birds are more likely to get caught in shallower set nets (Marine and Freshwater Institute, 2018). Careful consideration of target and bycatch species ecology may allow for designing well-functioning closures that reduce bycatch while minimising economic impact.

Of the four seabird species that constituted the bulk of the bycatch in the lumpsucker fishery, only the common eider is currently recognized as near threatened on the global list of threatened species (IUCN, 2018). At the national level however, only the great cormorant is of least concern across areas with lumpsucker fisheries, whereas the three others (black guillemot, common guillemot and common eider) are listed as vulnerable in at least one country with the black guillemot rated as endangered in Iceland (cf. Table 3). Although our results are subjected to different sources of bias discussed above, they strongly indicate that the lumpsucker fishery alone may be a potential "high-risk" fishery for all these species, at least in some countries and regions.

Bycatch of seabirds in lumpsucker nets is not only of conservation concern but has other consequences as well. As the first of the three largest lumpsucker fleets, the Icelandic fishery was certified as sustainable by the Marine Stewardship Council in 2014. This certification was suspended in 2018 due to high bycatch of harbour seals (*Phoca vitulina*), grey seals (*Halichoerus grypus*), and black guillemots (Gascoigne et al., 2017). Both the Norwegian and Greenlandic fisheries are now committed through conditions of MSC certification to assess and address bycatch (Lassen et al., 2015; Gaudian et al., 2017). Certification may be a pre-requisite to market access in some cases (Potts et al., 2016), so addressing bycatch as part of this process may also become an economic concern as well as a biological one. It is, however, worrying that fisheries, such as that with gillnets set for lumpsucker, can be certified as sustainable with limited information on seabird bycatch. Fortunately, the MSC is in the process of reviewing its standard, with the requirements for endangered, threatened and protected species identified as a key topic (MSC, 2019). Improving the data requirements for the extent of bycatch of such species should be a starting point, as other authors have pointed out (Crespo and Crawford, 2019).

It is important to bear in mind that fishers do not set out to capture birds intentionally. Though there are undoubtedly challenges to overcome in tackling gillnet bycatch, particularly in the local or small-scale fisheries that often favour this gear type, reducing the capture of seabirds should evidently be a win-win for fishers and conservationists. Efforts and resources invested to find solutions should match the scale of the issue, which is clearly substantive.

Declaration of Competing Interest

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