



Bycatch in the West Greenland lumpfish fishery, with particular focus on the common eider population

Flemming Ravn Merkel^{1,2,*}, Søren Post¹, Morten Frederiksen², Zita Bak-Jensen³, Julius Nielsen¹, Rasmus Berg Hedeholm³

¹Greenland Institute of Natural Resources, Kivioq 2, PO Box 570, 3900 Nuuk, Greenland

²Department of Ecoscience, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark

³Sustainable Fisheries Greenland, Jens Kreutzmann Aqq. 3, PO Box 73, 3900 Nuuk, Greenland

ABSTRACT: Incidental bycatch is a well-known challenge in gillnet fisheries throughout the world, and the fishery for North Atlantic lumpfish *Cyclopterus lumpus* roe is no exception. In Greenland, the fishery was Marine Stewardship Council-certified in 2015 but has pending conditions related to bycatch quantification, enforcement and mitigation strategies. To improve this situation and to assess the potential impact of bycatch, we collected independent on-board observer data on non-target fish and seabirds over 2 seasons (2019 and 2021). We recorded 6 fish species, but the only species constituting >1% of the lumpfish landings was the spotted wolffish *Anarhichas minor*. The bycatch of fish likely had little impact on the involved fish stocks. We recorded 4 seabird species, of which common eider *Somateria mollissima* was most common. When extrapolated to the entire West Greenland lumpfish fishery, the estimated bycatch of common eider was considerably higher in 2019 (19 938; 95% CI: 3486–59 661) than in 2021 (9802: 1260–29 940) due to a longer fishing season in 2019. On average, for 2019 and 2021, the bycatch was modelled to reduce the growth potential for the West Greenland winter population by 51%. In comparison, the current hunting level (16 538 birds yr⁻¹) reduced the growth potential by 30%. The larger impact of bycatch was mainly due to a larger proportion of adults and females being targeted. The common eider bycatch impacts mainly the breeding population in Canada and Southwest Greenland and less so in Northwest Greenland. As mitigation, we recommend temporal closures of the fishery unless modified gillnets, which markedly reduce bycatch, become available.

KEY WORDS: Seabird bycatch · Common eider · *Somateria mollissima* · Lumpfish fishery · *Cyclopterus lumpus* · Non-target fish · Greenland

1. INTRODUCTION

The incidental bycatch of seabirds is a well-known challenge in gillnet fisheries in all parts of the world, as even moderate harvesting pressures can have significant effects on bird populations (Österblom et al. 2002, Michael et al. 2017, Dias et al. 2019). Because species taken as bycatch are often migratory, the effects of bycatch are not limited to local populations

but extend beyond national borders and specific fisheries (Dias et al. 2019). Globally, at least 400 000 birds are estimated to die annually due to gillnet fisheries (Žydelis et al. 2013).

The gillnet fisheries in the North Atlantic for roe of lumpfish *Cyclopterus lumpus* are no exception to this problem, with significant bycatch being reported from all the major fishery regions in Iceland, Norway and Greenland (Fangel et al. 2015, MFRI 2018,

*Corresponding author: frm@ecos.au.dk

Christensen-Dalsgaard et al. 2019). Besides the biological consequences for non-target species, the unintentional bycatch has potential economic ramifications, as lumpfish fishers and companies must maintain the standards of the Marine Stewardship Council (MSC) in order to retain certification. An example is the world's largest lumpfish fishery in Iceland, where bycatch-related issues resulted in the withdrawal of the MSC certificate in 2019 (Lassen et al. 2021b).

The West Greenland lumpfish fishery was MSC-certified in 2015, but continues to have pending conditions relating to bycatch quantification, enforcement and strategy (Lassen et al. 2021a). Without accurate data on bycatch, it is challenging for scientists and managers to assess the impact on non-target species and problematic for the industry to maintain any sustainability accreditation. Therefore, obtaining accurate information on bycatch levels in the West Greenland lumpfish fishery is in the interest of all stakeholders, including non-governmental organizations (NGOs), the fishing industry, managers and individual fishers, especially as bycatch is presumed to be underreported (Lassen et al. 2021a).

The fishery takes place in April to June (during lumpfish spawning) in West Greenland coastal waters, employing large-meshed gill nets (260 mm). The nets are set in shallow water (<20 m), during a relatively short season (4–8 wk), where the fishery overlaps both in time and space with several overwintering populations of North Atlantic seabirds, most notably common eider *Somateria mollissima*, king eider *S. spectabilis*, long-tailed duck *Clangula hyemalis* and black guillemot *Cephus grylle* (Merkel et al. 2019). All of these avian species can potentially get entangled in fishing nets during feeding dives (Žydelis et al. 2013). The foraging habits of common eiders make them particularly vulnerable, as their preferred diving depth and local habitat overlap substantially with the lumpfish gillnets (Merkel & Mosbech 2008, Merkel et al. 2019). The long-tailed duck is also distributed in the coastal area (Merkel et al. 2019), but tends to forage in deeper waters (up to 66 m) than the common eider (up to 42 m) (Guillemette et al. 1993, Robertson & Savard 2020), and is therefore less likely to be caught. This is also the case for the king eider and black guillemot, because they are mainly distributed further offshore in Southwest Greenland during winter (Merkel et al. 2019). Although bycatch of birds appears to be underreported (Merkel 2011), the relative contribution of these species to the bycatch is confirmed by official reporting (Piniarneq 2019).

Northwest Greenland is the most important common eider breeding area in Greenland (Merkel 2004a). This breeding population winters in Southwest Greenland and has increased in size over the past 2 decades (Merkel 2010, F. Merkel unpubl.). However, recent surveys indicate that this is not the case for the sedentary breeding population in Southwest Greenland, which has shown only small fluctuations over the past decade (Rasmussen 2021). Local hunting also contributes substantially to the annual mortality of common eiders in Southwest Greenland (Piniarneq 2019), and there is a need to disentangle the impact of hunting and bycatch on the population trend. To do this, quantitative data on hunting and bycatch need to be supplemented with detailed information on demography, because adult birds, and in particular females, are most important for the growth potential of the population (e.g. Gruebler et al. 2008). Information on age and sex is not part of the obligatory reporting system in Greenland and can currently only be obtained by *in situ* observations of the bycatch.

To improve the management of the lumpfish fishery and assess its impact on other species, we quantified the bycatch in the West Greenland lumpfish fishery through *in situ* observations in the most important fishing area in 2019 and 2021. No observations were done in 2020 due to issues related to the SARS-CoV-2 (Covid-19) global pandemic. We provide data on all species taken as bycatch, using detailed data on common eider to estimate the relative impact of the bycatch on the common eider growth potential, and compare this to the effects of hunting. The results address specific MSC conditions for the lumpfish fishery, and provide managers with the knowledge needed to implement measures that ensure the sustainability of the fishery for lumpfish roe.

2. MATERIALS AND METHODS

2.1. Study area and fishery

All observations were done in the Nuuk area in West Greenland (Fig. 1). This area is centrally located in the Greenland lumpfish fishing area, extending from 60 to 70° N in West Greenland. The sampling area was between 63.83 and 64.34° N, which includes field codes JA024 to JH024 based on the field code grid applied to Greenlandic fisheries for reporting and geographical reference.

Approximately 20–25% of Greenland's annual total lumpfish landings are caught by Nuuk-based

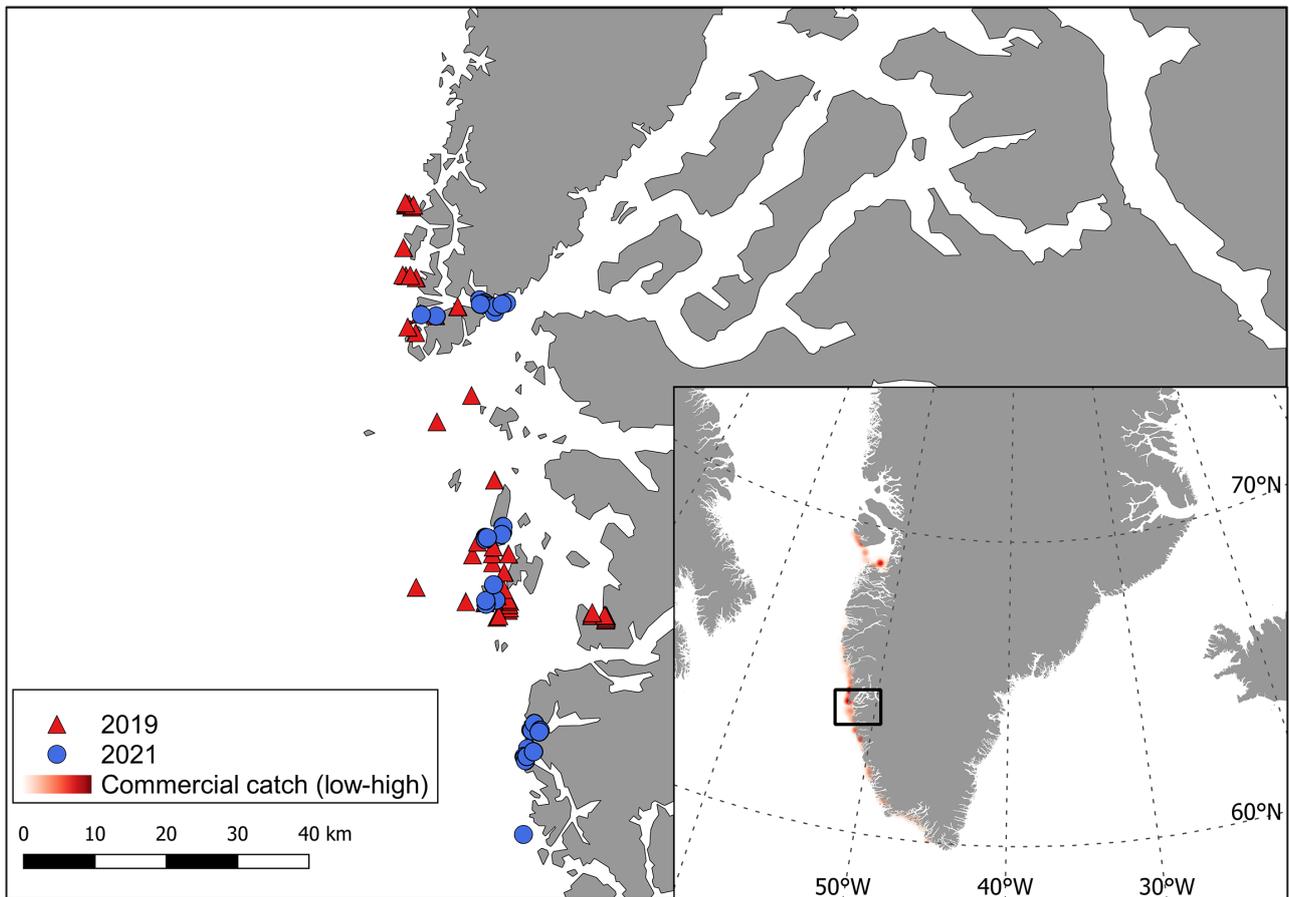


Fig. 1. *In situ* sampling sites in West Greenland in 2019 and 2021. The intensity of the commercial lumpfish fishery is shown in the inset as a heatmap based on combined 2019 and 2021 data on lumpfish landings

fishers fishing in the study area investigated here (GS 2021). The fishing fleet consists of small open boats (Fig. 2), typically between 6 and 8 m, that land their catch daily to local buyers. Normally, only the roe is landed, and the carcasses are discarded at sea. In 2019 and 2021, there were, on average, 632 active lumpfish fishing boats (each manned by 1–2 persons) in all of Greenland, of which 88 were active in the study area.

The lumpfish fishery is managed according to a management plan that defines 7 management areas (Ministry of Fisheries and Hunting 2021). The fishing season is defined locally, but it starts on 1 April at the earliest, with the exact date being determined by weather conditions and presumed fish density. The season is limited to no more than 60 d, but typically lasts for less than half of that due to constraints on the total allowable catch (TAC) (Ministry of Fisheries and Hunting 2021). There is a region-specific TAC, but no individual TAC. Thus, the fishery is essentially an Olympic fishery ('first come, first served'). It starts when female lumpfish arrive at the coastline, which

varies slightly from year to year. The onset of the fishery is also linked to latitude, normally being early April in South Greenland and late May in the northern part of the fishing area. In Nuuk, the season typically starts in early to mid-April. Each fisher sets between 5 and 100 nets, each 60 m in length. The nets are typically combined in rows of 5–6 nets anchored at both ends and set at 5–25 m depth. Less frequently, one end of the net row is tethered to shore.

The nets are typically set at the start of the fishing season and moved as little as possible. The average soak time is 2–3 d. The small vessels are exempt from keeping logbooks, but all catch, including bycatch, must be reported in weight at the landing site.

2.2. Bycatch sampling

Initially, we contacted the Greenland Hunters and Fishers Association (Kalaallit Nunaanni Aalisartut Piniartullu Kattuffiat, KNAPK) to inform them about the project. KNAPK notified local fishers of the pro-



Fig. 2. Bycatch and net retrieval from typical lumpfish fishing boat in Southwest Greenland, 2022. Picture taken from the authors' boat positioned adjacent to the fishing vessel. On the left, a common eider entangled in the net; on the right, a lumpfish being removed from the net. Photos: Julius Nielsen

ject, and flyers were distributed before the fishing season at landing sites, the local port and local KNAPK headquarters. No fishermen were contacted directly in advance. On a sampling day, we approached the fishers in the morning when they refueled and asked to accompany them to the fishing grounds on that day. All participation by fishers was voluntary, and all except 1 fisher approached were willing to assist with sampling. The fishers were chosen semi-haphazardly each day, as we preferred to follow fishers with a large number of nets (>20 nets). This approach was chosen to maximize the sampling coverage, while at the same time sampling different areas within the study area (see Fig. 1). Hence, on most days when weather allowed, we accompanied a fisher to the fishing grounds in our boat (a 6.5 m open boat powered by a 250 hp outboard engine) and approximately 1% of the landing catches (in biomass) in the study area was sampled.

At the fishing grounds, the fishers emptied their nets as they would normally do. We positioned our boat so that it was possible to count all lumpfish entering the boat. All bycatch was disentangled and transferred to our boat after the nets had been emp-

tied. Each specimen taken as bycatch was photographed and returned to the fisher after processing (to avoid influencing the subsequent use of the bycatch, e.g. own consumption). Before returning, the bycatch was identified to species level, and for fish, the length was measured (total length, TL, measured to nearest cm). The sex and age (juvenile/adult) of birds were also determined using external examination (Baker 1993). In both 2019 and 2021, we measured the length of a subsample of the female lumpfish on 8 different occasions spanning the entire fishing season. The sub-sample included 20–50% of the lumpfish caught in a given net. The soak time, position and number of nets were registered at each sampling location.

2.3. Bycatch estimation

Greenland's Fisheries License Control Authority (Grønlands Fiskerilicenskontrol, GFLK) maintains records of all individual landings (by roe quantity) in the sampling area. Based on these records, we divided the seasons into 2 periods; Early and Late.

The Early period was defined as the period it took to catch approximately 50% of the catches in the sampling area that year, and the Late period was the remaining part of the season. In 2019, the periods were 10 April to 7 May and 8–27 May, and in 2021 they were 11–25 April and 26 April to 7 May. The reason for dividing the season into periods was the expected spring migration of overwintering birds out of the study area (see Section 4), which might result in seasonally dependent bycatch rates. To balance the sampling effort in the Early and Late periods in 2021, the cut-off date was shifted slightly, causing the landed amount to be 43% and 57% in the 2 periods.

For each sampling event, we calculated the female lumpfish catch per unit effort (CPUE):

$$\text{CPUE}_{\text{female lumpfish}} = \frac{K \times \text{no. females}}{(\text{soak time (h)} \times \text{net length (m)})} \quad (1)$$

where K is a season-specific constant indicating the amount of roe in an average female that season. K was calculated based on the length measurements and the relationship between length and roe amount described by Hedeholm et al. (2014). K equaled 0.435 kg female⁻¹ in 2019 and 0.530 kg female⁻¹ in 2021 (see Section 3 for average lengths). The CPUE was then calculated for the Early and Late periods as the average of all sampling events ($\text{CPUE}_{\text{female lumpfish, period}}$).

Using $\text{CPUE}_{\text{female lumpfish, period}}$ we calculated the total effort (net hours) needed to catch the amount of lumpfish roe in that period:

$$\frac{\text{Total net hours}_{\text{period}}}{\text{Total landings}_{\text{period}} / \text{CPUE}_{\text{female lumpfish, period}}} \quad (2)$$

where $\text{Total landings}_{\text{period}}$ (for the study area) were derived from the GFLK data: 107 t in 2019_{early}, 103 t in 2019_{late}, 116 t in 2021_{early}, 153 t in 2021_{late}.

For each bycatch species, we estimated a sample-specific CPUE as:

$$\text{CPUE}_{\text{species, sample}} = \frac{\text{no. caught}_{\text{sample}}}{(\text{soak time (h)}_{\text{sample}} \times \text{net length (m)}_{\text{sample}})} \quad (3)$$

To provide an uncertainty measure of the bycatch estimates, we calculated 95% confidence intervals (CIs) around the mean CPUE for each species and period. This was done by bootstrapping, where we randomly drew (with replacement) 10 000 new data sets of observations for the individual CPUE observations. Mean and CIs (2.5 and 97.5% quantiles) were estimated from the distribution of the bootstrapped CPUE data. The estimated bycatch for each species in a given period was calculated as:

$$\text{Bycatch estimate}_{\text{species, period}} = \text{CPUE}_{\text{species, period}} \times \text{Total net hours}_{\text{period}} \quad (4)$$

and repeated for the upper and lower CPUE confidence limits.

These calculations applied only to the study area. To provide estimates of the bycatch for the entire Greenland fishery, all estimates were extrapolated by multiplying by a factor determined by the year-specific proportion of the fishery taking place in the study area. In 2019, this factor was 5.52, and in 2021 it was 4.29. This was done for all species that were caught in both years and both periods, as well as for Atlantic halibut *Hippoglossus hippoglossus* that was caught less frequently. The uncertainty was too large for other species and hence the data from these did not allow for meaningful conclusions. The fish species taken as bycatch were not weighed during sampling, but using the average lengths, the fish bycatch estimates were converted to weight using published conversion factors (Froese & Pauly 2020).

2.4. Common eider impact assessment model

The bycatch data and supporting information from other studies allowed for a detailed population impact assessment for common eider, but not for other species. The impact was assessed for the total winter population in Greenland, which was estimated to be 442 676 eiders (95% CI: 405 090–487 542) in March 2017 (Merkel et al. 2019). This constitutes a shared winter population of birds breeding in Canada and West Greenland, belonging to the northern common eider subspecies *Somateria mollissima borealis* (Lyngs 2003, Mosbech et al. 2006, Goudie et al. 2020). Because the proportional mixture of these breeding populations in the wintering area is unknown and likely to change over the lumpfish season, it was not possible to allocate the potential impact of bycatch on specific breeding populations.

We included hunting in the model for 2 purposes: to illustrate the relative impact of bycatch and hunting, and to account for the hunting effect on the age composition of the winter population before the bycatch period. For the model, we used the average number of common eiders reported shot for Southwest Greenland for the period 2012–2017 (Piniarneq 2019, Table 1). Birds hunted outside Southwest Greenland, i.e. north of the district of Ilulissat and in East Greenland, comprise 20% of the total hunt (Piniarneq 2019) and were not included in the model. No recent information about the age and sex distri-

Table 1. Initial values for common eider population size, hunting and bycatch levels, and the age and sex composition of birds from hunting and bycatch in Southwest Greenland

Parameter	Value	Year(s)	Source
Winter population size (95% CI)	442676 (405090–487542)	2017	Merkel et al. (2019)
Hunting, mean (range) no. of birds	16538 (12331–23662)	2012–17	Piniarneq (2019)
Hunting, proportion of juvenile/older	0.65/0.35	2000–01	Merkel (2004b)
Hunting, proportion of female/male	0.46/0.54	2000–01	Merkel (2004b)
Total bycatch (95% CI)	19938 (3486–59661)	2019	This study, Table 4
Total bycatch (95% CI)	9802 (1260–29940)	2021	This study, Table 4
Bycatch, proportion of juvenile/older	0.24/0.76	2019, 2021	This study, Table 4
Bycatch, proportion of female/male	0.60/0.40	2019, 2021	This study, Table 4

bution of the hunted birds was available, so we had to rely on previous studies from the local market in Nuuk, where commercial hunters sell their harvest (Merkel 2004b, Table 1).

The impact on the common eider population was modelled separately for 2019 and 2021, but the age and sex composition of the bycatch were averaged across the 2 years due to sample size considerations. The model was constructed as a deterministic female-only matrix population model with 4 age classes and a pre-breeding census (Caswell 2001). It was programmed in R version 3.5.2 (R Core Team 2018), and the 'popbio' package was used for demographic modelling (Stubben & Milligan 2007). We used the same values used by Gilliland et al. (2009) for most demographic parameters, including a combination of parameter values known from existing field data specific to the northern common eider. Also, values extracted from published literature on other sub-species of common eiders (Table 2) were used. For clutch size, we used a slightly higher value than Gilliland et al. (2009), based on more recent data from West Greenland (Merkel 2010).

We partitioned the annual cycle into 3 equal periods of 4 mo, referred to as summer, fall and winter, and partitioned annual survival rates (Table 2) among these 3 periods. As a starting point, we assumed that the population was below carrying capacity and that there were no stresses on the population, i.e. no periodic catastrophic events, stochasticity in demographic parameters, hunting or bycatch mortality. Under these conditions, it was assumed that annual adult survival rates would be near the maximum reported for common eiders (~95%; Swennen 1991). This scenario predicted an intrinsic population growth rate (λ) of 1.074, similar to the population growth rate observed during a period of expansion of a non-hunted common eider population in the Dutch Wadden Sea (1.07; Swennen 1991). The stable age distribution of this projection had 24.8% of the population ≤ 2 yr old just before the breeding season. Hunting in Southwest Greenland occurs in the fall and during winter, while bycatch takes place in late winter. In the model, both hunting and bycatch were removed at the end of the winter, i.e. allowing natural fall and winter mortality to act on the popula-

Table 2. Age-specific demographic parameter values used by Gilliland et al. (2009) were also used in our eider impact assessment model to simulate the shared (Greenland/Canada) northern common eider population wintering in Southwest Greenland. Clutch size has been updated (from 3.6 eggs) with newer information from West Greenland

Parameter	Age class (yr)				Source
	1	2	3	≥ 4	
Proportion breeding (pb)	0	0.26	0.42	1.00	Baillie & Milne (1982)
Clutch size (cs)	0	3.7	3.7	3.7	Merkel (2010)
Nest success (ns)	0	0.9	0.9	0.9	Nyegaard (2004), Gilliland et al. (2009)
Hatch success (hs)	0	0.9	0.9	0.9	Nyegaard (2004), Gilliland et al. (2009)
Duckling survival (S_d)	0	0.3	0.3	0.3	Swennen (1991)
Overall fecundity ^a (F)	0	0.23	0.38	0.90	
Annual survival (S_a)	0.5 ^b	0.69	0.95	0.95	Non-harvested population: Swennen (1991)

^aOverall fecundity: $F = pb \times cs \times ns \times hs \times S_d$
^bNot including the duckling survival (S_d)

tion first. Thus, we assumed that hunting and bycatch mortality was additive to natural mortality. Hunting was removed first and subsequently bycatch, and the age distribution was recalculated in between these transitions. Population projections were run over 10 yr.

3. RESULTS

3.1. Lumpfish

The lumpfish fishery differed substantially between 2019 and 2021. The catch of roe in the study area was similar (2019: 209 t; 2021: 269 t), but the 2019 season was longer (2019: 47 d; 2021: 26 d), although both seasons started at the same time. This was caused by a difference in CPUE. In our samples, the average CPUE (females per 1000 m net per hour) differed 160% between years: 1.79 (95% CI: 0.37–5.32) and 4.66 (0.90–13.22) in 2019 and 2021, respectively. In addition to dissimilar CPUEs, the difference between years was augmented by smaller females in 2019 (mean \pm SD; 2019: 36.1 \pm 2.9 cm, N = 758; 2021: 38.0 \pm 3.0 cm, N = 452).

Male CPUEs were approximately 5 times lower than female CPUEs. In 2019, the male CPUEs were highest early in the season but dropped drastically from 9 May and onwards. For the remainder of the season, male bycatch was virtually absent. In 2021, such a period of low CPUEs was not observed, as the season ended much earlier, although on 29 April, the CPUE was very low.

3.2. Bycatch

Ten bycatch species were recorded (4 birds and 6 fishes, Table 3). Marine mammals were not observed. The most common bycatch was common eider, which was present in both years and all periods. The same was true for 3 fish species (Atlantic cod *Gadus morhua*, Greenland cod *G. macrocephalus* and spotted wolffish *Anarhichas minor*), but in smaller numbers. Bycatch was present in 48% of the sampling events in 2019 (N = 52) and 59% in 2021 (N = 41). However, the number of species was generally low, and only 10% of the sampling events included 5 specimens or more. The samples with a large bycatch were all connected to common eider and 2021, with 4 notable events with 7, 8, 10 and 16 common eiders caught in a single row of nets, although the mean net length (row of nets) in these 4 events was longer than the overall mean length of observed nets (1005 m versus 288 m, respectively). The mean soak time was the same as the overall mean (60 h). In 2019, the highest number of common eiders in a single sample was 5 (net length = 300 m, soak time = 144 h). In both years, the common eiders were mainly older birds (adults or subadults), whereas only 6% (2019) and 30% (2021) were young birds (<1 yr). Females were more common as bycatch, constituting 69% of the common eiders in 2019 and 57% in 2021.

For commonly caught species, the CPUEs were high, but due to large variation also relatively uncertain (Fig. 3), because large bycatches are sporadic events. For common eider, the CPUEs were similar in 2019 and 2021, and in both years, the CPUE declined

Table 3. All species taken as bycatch in 2019 and 2021 divided into Early and Late periods (N). The average fish length is total length. Conservation status according to the global IUCN Red List (IUCN 2022) and the national Greenland Red List (Boertmann & Bay 2018) is also shown (LC: Least Concern; NT: Near Threatened; VU: Vulnerable)

Species	— 2019 —		— 2021 —		Average length (cm)	Red List status national/global
	Early period	Late period	Early period	Late period		
Birds						
Common eider <i>Somateria mollissima</i>	11	5	48	11	–	LC/NT
Long-tailed duck <i>Clangula hyemalis</i>	0	2	0	0	–	LC/VU
Black guillemot <i>Cepphus grylle</i>	1	0	0	0	–	LC/LC
Great northern diver <i>Gavia immer</i>	0	0	1	0	–	NT/LC
Fish						
Atlantic cod <i>Gadus morhua</i>	3	7	2	10	49	–/VU
Spotted wolffish <i>Anarhichas minor</i>	2	5	2	5	114	–
Greenland cod <i>Gadus macrocephalus</i>	3	2	2	2	51	–
Atlantic halibut <i>Hippoglossus hippoglossus</i>	0	1	6	4	57	–/EN
American plaice <i>Hippoglossoides platessoides</i>	0	1	0	0	40	–
Shorthorn sculpin <i>Myoxocephalus scorpius</i>	0	1	0	1	25	–

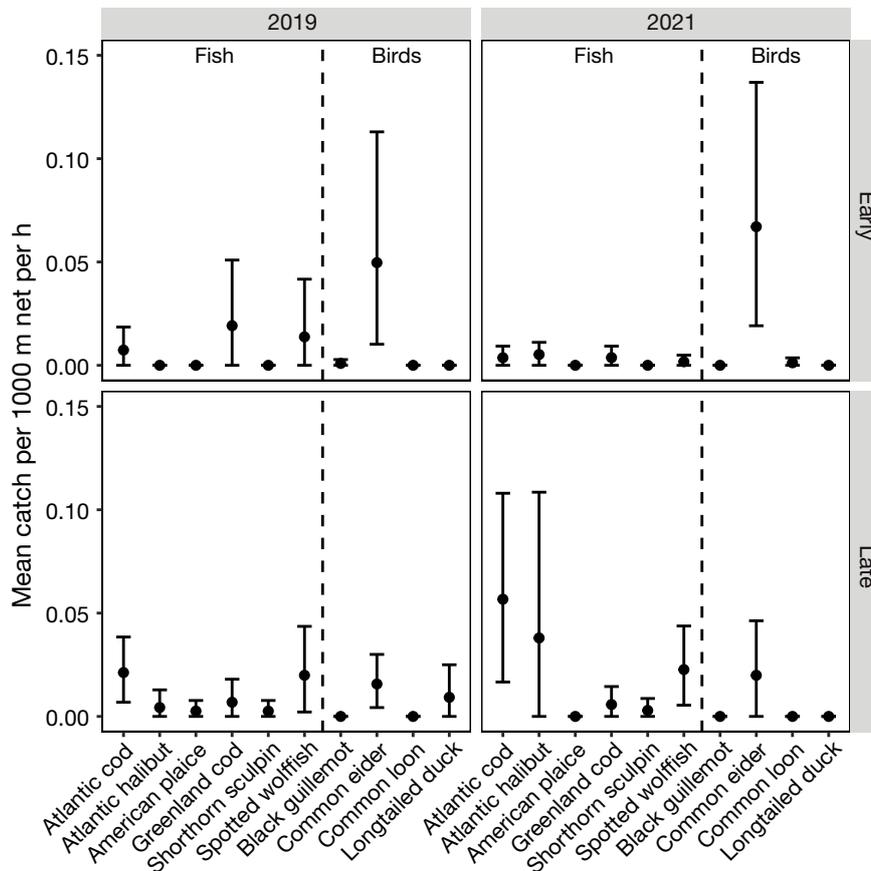


Fig. 3. Species-specific catch per unit effort (CPUE) values (mean \pm 95% confidence intervals) in 2019 and 2021 divided into an Early and Late period of the fishing season

late in the season. For fishes, CPUEs were generally low, although there was an increase at the end of the season in 2021, when Atlantic cod and Atlantic halibut became more common. For Atlantic halibut, this change was primarily caused by a single sample including 3 specimens, and only 1 additional specimen was caught in all remaining samples. For Atlantic cod, the change was caused by few specimens (1–2) in several samples.

Despite the difference in the duration of the fishing season and the uncertainty associated with the CPUEs, the bycatch estimates for most species were similar between years (Table 4). The exceptions were species only caught in either 2019 (black guillemot, long-tailed duck, American plaice *Hippoglossoides platessoides*) or 2021 (great northern diver [common loon] *Gavia immer*).

For common eider, the estimated bycatch in the study area was 3612 (95% CI: 631–10799) in 2019 and 2285 (293–6361) in 2021. When extrapolated to the entire West Greenland lumpfish fishery, the estimated bycatch was considerably higher in 2019 (19938 [3486–59661]) than in 2021 (9802 [1260–29940]). Most bycatch occurred in the Early period and declined to less than half in the Late period in both

years. The opposite was estimated for fish bycatch, which increased for all species from the Early to the Late period (except 2019 for Greenland cod) (Table 4). The bycatch 95% CIs overlapped between years for all species, and therefore no differences were significant.

The total estimated weight (extrapolated to the entire fishery) of the most common fish taken as bycatch in 2019 and 2021, respectively, were: spotted wolffish: 190 and 65 t; Atlantic halibut: 3 and 12 t; Atlantic cod: 10 and 10 t; Greenland cod: 12 and 2 t.

3.3. Common eider impact assessment

The basic model scenario showed an asymptotic annual growth rate λ of 1.074 in the absence of hunting and bycatch, corresponding to a 7.4% increase per year (Table 5). For 2019, the impact of bycatch was roughly 3 times higher than the impact of hunting (Table 5), because more birds were estimated to be killed by bycatch and because bycatch involved a larger proportion of females and adult birds (Table 1). In 2019, the average realised growth potential after 10 yr was

Table 4. Species-specific bycatch estimates in numbers for birds and in weight (t) for fishes for the study area by period and in total. The estimated total commercial fishing effort (million net hours) is given for each period. For some species, the total bycatch is also extrapolated to the entire fishery (see Section 2)

Species	2019				2021			
	Early period	Late period	Total (95% CI) Study area	Total (95% CI) Entire fishery	Early period	Late period	Total (95% CI) Study area	Total (95% CI) Entire fishery
Effort (million net hours)	51.8	66.3	118.1 (93.9–156.7)	–	22.8	37.8	60.6 (46.3–83.1)	–
Birds (n)								
Common eider <i>Somateria mollissima</i>	2567	1044	3612 (631–10799)	19938 (3486–59661)	1526	759	2285 (293–6961)	9802 (1260–29940)
Long-tailed duck <i>Clangula hyemalis</i>	0	607	607 (0–2039)	–	0	0	0 (0–0)	–
Black guillemot <i>Cephus grylle</i>	48	0	48 (0–208)	–	0	0	0 (0–0)	–
Great northern diver <i>Gavia immer</i>	0	0	0 (0–0)	–	28	0	28 (0–126)	–
Fish (t)								
Atlantic cod <i>Gadus morhua</i>	0.39	1.46	1.85 (0.39–4.66)	10.21 (2.16–25.74)	0.09	2.23	2.32 (0.50–5.76)	9.99 (2.17–24.79)
Spotted wolffish <i>Anarhichas minor</i>	12.18	22.21	34.38 (18.87–112.51)	189.96 (104.25–621.60)	0.67	14.42	15.09 (2.78–38.28)	64.92 (11.97–164.65)
Greenland cod <i>Gadus macrocephalus</i>	1.55	0.70	2.25 (0–8.30)	12.42 (0–45.86)	0.13	0.34	0.47 (0–1.58)	2.02 (0–6.82)
Atlantic halibut <i>Hippoglossus hippoglossus</i>	0	0.52	0.52 (0–1.93)	2.89 (0–10.67)	0.22	2.63	2.85 (0–9.92)	12.26 (0–42.68)
American plaice <i>Hippoglossoides platessoides</i>	0	0.10	0.10 (0–0.38)	–	0.00	0.00	0 (0–0)	–
Shorthorn sculpin <i>Myoxocephalus scorpius</i>	0	0.04	0.04 (0–0.14)	–	0.00	0.02	0.02 (0–0.9)	–

Table 5. Growth rate (λ) for the common eider population in Southwest Greenland under different model scenarios and the size of the reduction caused by hunting and bycatch. See Tables 1 & 2 for input parameter values

Model scenario	Added mortality	λ	Contribution from hunting	Contribution from bycatch
1: Base model (BM)	None	1.074		
2: BM + 2019 harvest	+Hunting +Bycatch	0.981	–0.022	–0.071
3: BM + 2021 harvest	+Hunting +Bycatch	1.030	–0.022	–0.022
4: BM + mean harvest (2019, 2021)	+Hunting +Bycatch	1.014	–0.022	–0.038

negative ($\lambda = 0.981$) when including both bycatch and hunting mortality. In contrast, bycatch and hunting had equal impacts in 2021 (-0.022 vs. -0.022 , Table 5), and the growth potential after 10 yr was 3.0% per year ($\lambda = 1.030$). Assuming that the mean bycatch in 2019 and 2021 represents a realistic mean bycatch level for the winter population, the growth potential would average 1.4% per year after 10 yr when including both bycatch and hunting mortality (model 4, Table 5).

4. DISCUSSION

4.1. Bycatch of common eider

Our results are in line with other reports on seabird bycatch from the North Atlantic lumpfish fishery (Christensen-Dalsgaard et al. 2019), namely that common eider is the most common species. The estimated mean size of the common eider bycatch for 2019 and 2021, when extrapolated to the whole fish-

ery in Southwest Greenland ($14\,870$ birds yr^{-1}), was roughly 3 times higher than the annual mean number reported to the Greenlandic national harvest regime (Piniarneq 2019). Such a difference was expected, since underreporting is a well-established phenomenon when comparing self-reported bycatch data to observed bycatch data (Northridge 1996, NMFS 2004, MFRI 2018, Christensen-Dalsgaard et al. 2019).

For the impact assessment on the common eider population, we extrapolated the bycatch estimate from our study area to the entire lumpfish fishing area to match the available estimate for the total winter population (see Section 2). Using the same CPUE for common eider bycatch outside our study area adds to the uncertainties, and further studies are needed to verify this assumption. Although the density of common eiders is fairly even in late winter throughout the coastal area of Southwest Greenland (Merkel et al. 2019), a lower bycatch rate north of our study area could be expected due to the later onset of the lumpfish fishery. In contrast, a higher bycatch rate could be expected south of our study area where the lumpfish fishery starts earlier. For now, we argue that the conservation perspectives of having a rough first estimate of the total common eider bycatch in Greenland outweighs the uncertainty about bycatch CPUE outside our study area.

The extrapolated bycatch for 2019 and 2021 for the entire lumpfish fishery was slightly smaller than the reported mean number of hunted birds ($14\,870$ vs. $16\,538$ birds, Table 1). However, according to the assessment model, the impact of the bycatch was considerably larger (Table 5). Hunting reduced the potential growth rate by 30%, whereas bycatch caused a reduction of 51% (Table 5, model scenario 4). The model illustrates that the common eider population wintering in Southwest Greenland is more vulnerable to bycatch mortality. This is mainly because the bycatch involves a larger proportion of females and adult birds (see also Genovart et al. 2017), while hunting primarily affects the younger segment of the population (Merkel 2004b). A contributing factor is that bycatch mortality occurs in late winter, when natural winter mortality and hunting mortality have already affected the population.

Although there is good support from the literature that our base model scenario (Table 5) represents an optimal growth situation for common eider ($\lambda = 1.074$), Merkel (2010) showed that the growth rate for the breeding population in Northwest Greenland during the 2000s was higher ($\lambda = 1.126$) than this theoretical optimum. It thus seems that the current

bycatch mortality is not a serious threat to the Northwest Greenland breeding population, probably because this breeding population tends to winter in the northern part of the wintering area ($64.2\text{--}69^\circ\text{N}$, Mosbech et al. 2006) where the lumpfish fishery is absent or less intensive (Fig. 1). In contrast, eiders breeding in eastern Canada tend to winter further south in Southwest Greenland ($60\text{--}64.5^\circ\text{N}$, Mosbech et al. 2006) and could be more heavily impacted by the bycatch. This is also the case for the sedentary breeding population in Southwest Greenland, which has been more or less stable over the past decade (Rasmussen 2020, 2021). Here, the combined impact from hunting and especially bycatch could be the main reason why this population is not increasing.

In both 2019 and 2021, there was a tendency that bycatch was lower in the second half of the fishing period (Table 4), which could be due to eiders migrating out of the wintering area at some point in late April or early May (Merkel et al. 2006, Mosbech et al. 2006). Such a decrease in the eider density would likely lead to lower total bycatch rates. However, this may not be the case for the local breeding population that remains in the study area throughout the fishing season (Merkel et al. 2006, Mosbech et al. 2006), making them more exposed to late-season bycatch. A more in-depth analysis of the bycatch impact on the different breeding populations in eastern Canada and western Greenland will require additional information about breeding population sizes and migration patterns. Alternatively, a method where the origin of the eiders can be determined by means of claw tissue sampling could perhaps be developed, similar to Steenweg et al. (2017) who used stable isotopes to infer overwintering locations of pre-breeding eiders in eastern Canada.

4.2. Bycatch of other seabirds

Bycatch studies in Iceland and Norway also report black guillemot as a common bycatch species (Christensen-Dalsgaard et al. 2019), but our study, as well as previous work (Merkel 2004b, 2011), indicates that black guillemot is a rare bycatch species in Greenland. This is likely because of a small overlap between the lumpfish fishery and the black guillemot distribution. Aerial surveys from Southwest Greenland showed that the main winter distribution of black guillemot occurs north of 67°N and usually in connection with dense pack ice at some distance from the coastal zone (Merkel et al. 2019). Long-tailed ducks have previously been reported as

bycatch in small numbers from Iceland and Greenland (Merkel 2011, Christensen-Dalsgaard et al. 2019), and this study also documents a few bycatch incidents (Table 3). Based on the fact that the Nuuk coastal area constitutes a key wintering area for long-tailed ducks in Southwest Greenland, with densities almost as high as for common eider (Merkel et al. 2019), the estimated total bycatch of 607 long-tailed ducks in 2019 (and the absence in 2021, Table 4) is smaller than what could be expected. However, the estimate of 607 birds is relatively high (50% of the common eider relative bycatch) considering that the total winter population of long-tailed duck in West Greenland is estimated to be only 41 500 birds (Merkel et al. 2019). Additional sampling is needed to verify the magnitude of the bycatch of long-tailed ducks in Greenland. Bycatch of great northern diver, which is listed as near threatened on the Greenland red list (Boertmann & Bay 2018), has not previously been reported for Greenland, and the single bird that was caught in our study also indicates that this is likely a rare occurrence.

One striking difference between this study and previous bycatch work in Greenland is the absence of king eiders. A local market survey in Nuuk in 2000/2001 found that 28% of the eider bycatch were king eiders (Merkel 2004b). The absence in 2019/2021 is perhaps related to a recent northerly shift in the king eider distribution. Aerial winter surveys conducted in 2017 showed that almost all king eiders were distributed north of Nuuk, while densities were higher and more evenly distributed in Southwest Greenland during similar surveys conducted in 1999 (Merkel et al. 2002, 2019). The absence of king eiders in the present bycatch study suggests that densities are still low in the Nuuk area.

4.3. Mitigation of seabird bycatch

Minimizing bycatch is in the interest of all stakeholders, including NGOs, the fishing industry and the individual fishers. This goal can be pursued by implementing spatial or temporal closures of the fishery to avoid using the areas or periods where bycatch mortality is highest (O'Keefe et al. 2014, 2021). In theory, both tools could potentially reduce the bycatch of eiders in the Greenland lumpfish fishery, and there are also documented cases where spatial and temporal closures have been used successfully to reduce the bycatch without negatively impacting target fish catch (Melvin et al. 1999). However, the spatial approach can be challenging since it relies on effective

enforcement of the closed areas and detailed knowledge on the distribution, and the interannual variation, of both the bycatch species and lumpfish (Gunnarsson & Tómasson 2011, O'Keefe et al. 2021). From a biological and enforcement point of view, temporal closures alone represent the simpler solution and are likely the more effective method to minimize bycatch. As previously mentioned, the observed lower bycatch level of eiders in the later part of the fishing period (Table 4) is likely linked to a gradual reduction in bird densities due to spring migration, which is expected to occur in the period from mid-April to mid-May (Mosbech et al. 2006). Since the cumulative lumpfish catch curve in April is less steep than later in the season (GINR 2021), the ideal trade-off might be to postpone the onset of the fishery until, for instance, 1 May in this study area. In 2019, 71% of the common eider bycatch was caught in the early period (before 7 May) and 54% in 2021 (before 25 April; Table 4). Thus, based on these 2 years and the current study area, a significant reduction of bycatch levels would be expected if the onset of the fishery is postponed until 1 May. For the fishery, the possible socioeconomic impact is mainly linked to logistical constraints, because the small boats involved in this fishery may not be able to increase the effort and catch the quota in a shorter time. Shifting the season also has a natural endpoint since the lumpfish depart the coastal areas in late May or early June, depending on the area (Kennedy et al. 2015). The fact that the arrival and departure of the lumpfish in Southwest Greenland follow a latitudinal gradient also complicates the temporal closure approach. Finally, it is important to recognise that temporal closures would only benefit the migrating part of the winter eider population, i.e. birds breeding in Northwest Greenland or Canada, not the local breeding population in Southwest Greenland. Although the latter makes up only a small proportion of the winter population, this breeding population appears to have the least favourable conservation status (Merkel 2010, Maftai et al. 2015, Rasmussen 2020, 2021).

Mitigation using modified nets that can drastically reduce bycatch while maintaining lumpfish catch rates would be an attractive alternative approach to minimize bycatch without the unwanted effects of spatial or temporal closures. Modified nets are easily manufactured, require little or no enforcement, and all fishers are affected equally. However, in contrast to longline and trawl fisheries (ACAP 2022), best-practice technical mitigation measures have proven difficult to develop for gillnet bycatch, despite some research attention (Martin & Crawford 2015, Hanam-

seth et al. 2018, Field et al. 2019, Cantlay et al. 2020, Rouxel et al. 2021). Inspired by Melvin et al. (1999), who had some success by increasing the contrast of drifting gillnets, modified lumpfish gillnets have been tested in Greenland in 2021 and 2022. The data are currently being analysed and will be published elsewhere.

4.4. Bycatch of fish

The large 260 mm mesh used in the lumpfish fishery naturally excludes most fish bycatch. Besides the large spotted wolffish, which are caught by the gills, all other fish bycatch is accidental entanglement of smaller species. This high selectivity for the target species generally means that fish bycatch in the lumpfish fishery is of minor importance, and only spotted wolffish constituted more than 1% of the lumpfish landings (4.3% in 2019 and 1.5% in 2021). Similar low fish bycatch rates were observed in both the Norwegian and Icelandic lumpfish fisheries (Dignan et al. 2020, Lassen et al. 2021b), although Atlantic cod was relatively common in the Icelandic fishery (5–11% of lumpfish landings). This is probably related to the much larger cod stock in Iceland, which includes larger individuals that are more easily caught in the gillnets (ICES 2021) or perhaps a larger species overlap in Iceland.

Spotted wolffish is not a common bycatch in numbers, but an average weight of almost 17 kg makes them the dominant bycatch in terms of weight. There is no directed commercial fishery for spotted wolffish in Greenland, but the total reported landings in all fisheries were 227 t in 2019 (2021 numbers not available), and the lumpfish fishery appears to be the primary source of fishery mortality for this species. There is no survey targeting spotted wolffish in the inshore area, but the stock distribution covers both in- and offshore West Greenland waters, and the annual fish survey in offshore waters indicates a 4-fold increase in spotted wolffish biomass over the past 15 yr (Nygaard & Nogueira 2021). Hence, spotted wolffish bycatch in the lumpfish fishery does not appear to hinder stock productivity, but there are no fishery reference points estimated for spotted wolffish, and these should be considered before concluding on the effect of the current catch (not limited to lumpfish fishery bycatch).

Atlantic halibut are listed on the global IUCN Red List as 'Endangered' (Sobel 1996), and fishers are by Greenlandic law obligated to release them alive whenever possible. The survival rate of released

Atlantic halibut in the gillnet fishery is unknown, but even with an assumed mortality rate of 100%, the estimated bycatch is less than 1% of lumpfish landings. There are no specific surveys to inform on the Atlantic halibut stock in West Greenland, but inshore gillnet surveys targeting Atlantic cod show a reduced Atlantic halibut abundance over the past decade (A. Retzel pers. comm.). However, considering the combination of low bycatch estimates and the specimens caught being juveniles (based on size), the lumpfish fishery likely has little impact on the Atlantic halibut stock.

In general, fish bycatch appears to be underreported. For instance, the total reported bycatch of the main fish species in 2021 were 0.8 t wolffish, 1.4 t Atlantic cod and 0.09 t Atlantic halibut, which is 1.2, 14 and 0.7% of the estimated bycatch in this study. The discrepancy may be different (higher or lower) considering the uncertainty in our study, but some level of underreporting seems highly likely. Although none of the bycatch species is severely impacted by the lumpfish fishery, an effort should be made to ensure correct reporting, as the industry otherwise risks losing the MSC certification as a consequence. Some of the bycatch can be landed at landing sites alongside the lumpfish, but often fishers only catch 1–2 fish per trip, and rather than landing the catch, these are kept for personal consumption and reporting is not considered 'worthwhile' by the fishers.

4.5. Conclusions and further work

In general, the confidence intervals of the bycatch estimates are wide, and the estimates should therefore be treated with caution. However, since high precision of bycatch rates is difficult to obtain due to the nature of the bycatch (relatively rare incidents and large variation in the numbers caught), some degree of uncertainty should also be accepted, at least in the early study phase. Despite the uncertainties, the present dataset represents a considerable improvement on the previous information available on seabird bycatch in the Greenland lumpfish fishery (Merkel 2004b, 2011). For the fish species, this is the first report on bycatch levels. Our results clearly show that bycatch in the Greenland lumpfish fishery is a concern for at least the common eider population, and we believe that the rough estimate of the total bycatch presented here is sufficient to act upon. It is unsustainable that the impact of bycatch on the common eider population appears to be roughly the same

as or larger than the impact of hunting. Hunting is an integrated part of the management strategy for eiders in Greenland and an important component of the ecosystem services that many Greenlanders rely on (Merkel & Tremblay 2018). It should be noted that hunting may be more extensive than reported here. The quality of the official hunting statistics has not been validated in recent time, but at least in the early 1990s there was indication of underreporting (Frich 1997). However, even with possible conservative estimates the harvest, the present study indicates that in some years, the combined impact of hunting and bycatch in Southwest Greenland during winter and spring is unsustainable for the local breeding population in Southwest Greenland and the Canadian breeding population. At this point, the most obvious solution to reduce this bycatch is by postponing the onset of the fishery until approximately 1 May. This may reduce the bycatch significantly but will undoubtedly compromise the fishery and make management more challenging. Over time, such temporal closures could be replaced or supplemented by other mitigation measures if new techniques, such as modified gillnets, become available.

Additional estimation of bycatch rates in Southwest Greenland is clearly still necessary. For bycatch species where we have extrapolated beyond our study area, there is a need to verify that bycatch CPUE is not markedly different outside our study area. As the most common bycatch species, this is especially important for common eider, but also for other species such as long-tailed duck and king eider. The apparent absence of king eider bycatch within the Nuuk study area may be due to a northern shift in winter distribution, which highlights the need for sampling north of the Nuuk study area. Finally, additional bycatch monitoring is vital to document whether mitigation measures or other management actions reduce the bycatch.

Having emphasized the importance of additional sampling, it should also be noted that this is not a simple task. Given the fleet composition with many active boats and a large latitudinal gradient (>1000 km) of the fishery, implementing an independent observer programme that will ensure proper bycatch estimates would require a sizeable dedicated sampling programme beyond the capabilities of the current Greenland management set-up (Babcock et al. 2003). One alternative option for achieving a sufficient sampling effort in this fishery is remote electronic monitoring (REM), which is increasingly used worldwide (van Helmond et al. 2020). The REM would provide unbiased data and

possibly motivate fishers to report. However, a REM system is challenged by the implementation and maintenance resources, the many active fishers and the resistance it may face from fishers (Mangi et al. 2015). However, it is a viable option especially if combined with detailed snapshot studies such as the present study.

Acknowledgements. This study was co-financed by the Ocean Stewardship Fund–Science and Research Fund (SRF), Sustainable Fisheries Greenland and the Greenland Institute of Natural Resources. We are indebted to all the fishers for their time, collaboration and for sharing insights about the fishery. We also thank Steffen Oppedal for providing input to the bycatch estimation procedure.

LITERATURE CITED

- ACAP (2022) Agreement on the conservation of albatrosses and petrels bycatch mitigation review and advice. <https://acap.aq/en/resources/bycatch-mitigation/mitigation-advice> (accessed 27 January 2022)
- Babcock EA, Pikitch EK, Hudson CG (2003) How much observer coverage is enough to adequately estimate bycatch? Pew Institute for Ocean Science, Miami, FL
- ✦ Baillie SR, Milne H (1982) The influence of female age on breeding in the eider *Somateria mollissima*. *Bird Study* 29:55–66
- Baker K (1993) Identification guide to European non-passerines. British Trust for Ornithology, Thetford
- Boertmann D, Bay C (2018) Grønlands rødliste 2018. Fortegnelse over grønlandske dyr og planter trusselstatus. Aarhus Universitet, Nationalt Center for Energi og Miljø (DCE) og Grønlands Naturinstitut. <https://natur.gl/raadgivning/roedliste/>
- ✦ Cantlay JC, Bond AL, Wells-Berlin AM, Crawford R and others (2020) Ineffectiveness of light emitting diodes as underwater deterrents for long-tailed ducks *Clangula hyemalis*. *Glob Ecol Conserv* 23:e011102
- Caswell H (2001) Matrix population models. Construction, analysis, and interpretation. Sinauer, Sunderland, MA
- ✦ Christensen-Dalsgaard S, Anker-Nilssen T, Crawford R, Bond A and others (2019) What's the catch with lump-suckers? A North Atlantic study of seabird bycatch in lump-sucker gillnet fisheries. *Biol Conserv* 240:108278
- ✦ Dias MP, Martin R, Pearmain EJ, Burfield IJ and others (2019) Threats to seabirds: a global assessment. *Biol Conserv* 237:525–537
- Dignan S, Scarcella G, Hønneland G (2020) ISF Iceland lumpfish. Public Certification Report. Marine Stewardship Council fisheries assessments, Initial Assessment MSC045/01. SAI Global Limited, London
- ✦ Fangel K, Aas Ø, Vølstad JH, Bærum KM and others (2015) Assessing incidental bycatch of seabirds in Norwegian coastal commercial fisheries: empirical and methodological lessons. *Glob Ecol Conserv* 4:127–136
- ✦ Field R, Crawford R, Enever R, Linkowski T and others (2019) High contrast panels and lights do not reduce bird bycatch in Baltic Sea gillnet fisheries. *Glob Ecol Conserv* 18:e00602
- Frich AS (1997) Lomviefangst i Grønland 1993. Greenland Institute of Natural Resources, Nuuk

- Froese R, Pauly D (2020) FishBase 2000: concepts, design and data sources. ICLARM, Los Baños
- Genovart M, Doak DF, Igual JM, Sponza S, Kralj J, Oro D (2017) Varying demographic impacts of different fisheries on three Mediterranean seabird species. *Glob Change Biol* 23:3012–3029
- Gilliland S, Gilchrist HG, Rockwell R, Robertson GJ, Savard JP, Merkel FR, Mosbech A (2009) Evaluating the sustainability of harvest among northern common eiders in Greenland and Canada. *Wildl Biol* 15:24–36
- GINR (Greenland Institute of Natural Resources) (2021) Assessment of lumpfish (*Cyclopterus lumpus*) in West Greenland based on commercial data 2010–2021. Tech Rep Greenland Institute of Natural Resources, Nuuk. <https://natur.gl/wp-content/uploads/2021/09/Assessment-of-lumpfish-Cyclopterus-lumpus-in-West-Greenland-2021.pdf>
- Goudie RI, Robertson GJ, Reed A (2020) Common eider (*Somateria mollissima*), version 1.0. In: Billerman SM (ed) *Birds of the world*. Cornell Lab of Ornithology, Ithaca, NY. <https://doi.org/10.2173/bow.comeid.01>
- Gruebler MU, Schuler H, Müller M, Spaar R, Horch P, Naef-Daenzer B (2008) Female biased mortality caused by anthropogenic nest loss contributes to population decline and adult sex ratio of a meadow bird. *Biol Conserv* 141: 3040–3049
- GS (Greenland Statistics) (2021) 2020 Fisheries. <https://stat.gl/dialog/main.asp?lang=da&version=202105&sc=FI&colcode=t>
- Guillemette M, Himmelman JH, Barette C, Reed A (1993) Habitat selection by common eiders in winter and its interaction with flock size. *Can J Zool* 71: 1259–1266
- Gunnarsson TG, Tómasson G (2011) Flexibility in spring arrival of migratory birds at northern latitudes under rapid temperature changes. *Bird Study* 58:1–12
- Hanamseth R, Barry Baker G, Sherwen S, Hindell M, Lea MA (2018) Assessing the importance of net colour as a seabird bycatch mitigation measure in gillnet fishing. *Aquat Conserv* 28:175–181
- Hedeholm R, Blicher ME, Grønkjær P (2014) First estimates of age and production of lumpsucker (*Cyclopterus lumpus*) in Greenland. *Fish Res* 149:1–4
- ICES (2021) Northwestern Working Group (NWWG). ICES Scientific Reports 3:52,
- IUCN (2022) Red List of Threatened Species. Version 2022-1. IUCN, www.iucnredlist.org.
- Kennedy J, Jónsson SP, Kasper JM, Ólafsson HG (2015) Movements of female lumpfish (*Cyclopterus lumpus*) around Iceland. *ICES J Mar Sci* 72:880–889
- Lassen H, Huntington T, Cappell R, Chaudhury S (2021a) Reassessment of the Greenland lumpfish fishery. Public Certification Report 2019-016, Rev. 4. DNV GL Business Assurance Norway AS. <https://fisheries.msc.org/en/fisheries/greenland-lumpfish/@assessments>
- Lassen HJ, Boström J, Chaudhury S (2021b) NFA Norway Ling & Tusk and NFA Norway lumpfish fisheries. NFA Norway Ling & Tusk and NFA Norway lumpfish fisheries. 3rd Surveillance Report. DNV Business Assurance Norway AS. <https://fisheries.msc.org/en/fisheries/nfa-norway-ling-tusk-and-nfa-norway-lumpfish/@assessments>.
- Lyngs P (2003) Migration and winter ranges of birds in Greenland—an analysis of ringing recoveries. *Dan Ornitol Foren Tidsskr* 97:1–167
- Maftei M, Davis SE, Mallory ML (2015) Assessing regional populations of ground-nesting marine birds in the Canadian High Arctic. *Polar Res* 34:25055
- Mangi SC, Dolder PJ, Catchpole TL, Rodmell D, de Rozarieux N (2015) Approaches to fully documented fisheries: practical issues and stakeholder perceptions. *Fish Fish* 16:426–452
- Martin GR, Crawford R (2015) Reducing bycatch in gillnets: a sensory ecology perspective. *Glob Ecol Conserv* 3: 28–50
- Melvin EF, Parrish JK, Conquest LL (1999) Novel tools to reduce seabird bycatch in coastal gillnet fisheries. *Conserv Biol* 13:1386–1397
- Merkel FR (2004a) Evidence of population decline in common eiders breeding in western Greenland. *Arctic* 57: 27–36
- Merkel FR (2004b) Impact of hunting and gillnet fishery on wintering eiders in Nuuk, Southwest Greenland. *Waterbirds* 27:469–479
- Merkel FR (2010) Evidence of recent population recovery in common eiders breeding in western Greenland. *J Wildl Manag* 74:1869–1874
- Merkel FR (2011) Gillnet bycatch of seabirds in Southwest Greenland, 2003–2008. Tech Rep 85. Pinngortitaleriffik, Greenland Institute of Natural Resources, Nuuk
- Merkel FR, Mosbech A (2008) Diurnal and nocturnal feeding strategies in common eiders. *Waterbirds* 31:580–586
- Merkel FR, Tremblay JE (2018) Living resources. In: Mosbech A, Lemay M, Simon M, Merkel F and others (eds) *Adaptation actions for a changing Arctic: perspectives from the Baffin Bay/Davis Strait Region*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, p 133–199
- Merkel FR, Mosbech A, Boertmann D, Grøndahl L (2002) Winter seabird distribution and abundance off southwestern Greenland, 1999. *Polar Res* 21:17–36
- Merkel FR, Mosbech A, Sonne C, Flagstad A, Falk K, Jamieson SE (2006) Local movements, home ranges and body condition of common eiders *Somateria mollissima* wintering in Greenland. *Ardea* 94:639–650
- Merkel FR, Johansen KL, Nielsen RD, Petersen IK, Sterup J, Mosbech A (2019) Wintering seabirds in south-west Greenland, 2017. *Polar Res* 38:3462
- MFRI (Marine and Freshwater Research Institute) (2018) Bycatch of seabirds and marine mammals in lumpsucker gillnets 2014–2017. Tech Rep. Marine and Freshwater Research Institute, Hafnarfjörður. <https://www.hafogvatn.is/static/files/skjol/techreport-bycatch-of-birds-and-marine-mammals-lumpsucker-en-final-draft.pdf>
- Michael PE, Thomson R, Barbraud C, Delord K and others (2017) Illegal fishing bycatch overshadows climate as a driver of albatross population decline. *Mar Ecol Prog Ser* 579:185–199
- Ministry of Fisheries and Hunting (2021) Management plan for female lumpfish in West Greenland. Ministry of Fisheries and Hunting, Government of Greenland, Nuuk
- Mosbech A, Gilchrist HG, Merkel FR, Sonne C, Flagstad A, Nyegaard H (2006) Year-round movements of northern common eiders *Somateria mollissima borealis* breeding in Arctic Canada and West Greenland followed by satellite telemetry. *Ardea* 94:651–665
- NMFS (National Marine Fisheries Service) (2004) Evaluating bycatch: a national approach to standardized bycatch monitoring programs. Tech Memo NMFS-F/SPO-66. National Marine Fisheries Service, NOAA, US

- Department of Commerce. <https://spo.nmfs.noaa.gov/sites/default/files/tm66.pdf>
- Northridge SP (1996) A review of marine mammal bycatch observer schemes with recommendations for best practice. JNCC Rep 219. Joint Nature Conservation Committee, Aberdeen
- Nyegaard H (2004) Reproductive success of the common eider *Somateria mollissima* in a colony in West Greenland. MSc thesis, University of Copenhagen
- Nygaard R, Nogueira A (2021) Biomass and abundance of demersal fish stocks off West and East Greenland estimated from the Greenland Institute of Natural Resources (GINR) Shrimp and Fish Survey (SFW), 1990–2020. Scientific Council meeting—June 2021. NAFO SCR Doc 21/014REV. <https://www.nafo.int/Portals/0/PDFs/sc/2021/scr21-014REV.pdf>
- ✦ O’Keefe CE, Cadrin SX, Stokesbury KDE (2014) Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. *ICES J Mar Sci* 71:1286–1297
- ✦ O’Keefe CE, Cadrin SX, Glemarec G, Rouxel Y (2021) Efficacy of time–area fishing restrictions and gear-switching as solutions for reducing seabird bycatch in gillnet fisheries. *Rev Fish Sci Aquacult*, <https://doi.org/10.1080/23308249.2021.1988051>
- ✦ Österblom H, Fransson T, Olsson O (2002) Bycatches of common guillemot (*Uria aalge*) in the Baltic Sea gillnet fishery. *Biol Conserv* 105:309–319
- Piniarneq (2019) Hunting statistics from Piniarneq/LULI, 9 Dec 2019. Department of Hunting, Fishing and Agriculture, Government of Greenland. Data available on request from apn@nanoq.gf (accessed 9 December 2019)
- R Core Team (2018) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- Rasmussen LM (2020) Ederfuglemonitoring ved Nuuk – feltrapport 2020. Pinngortitaleriffik, Greenland Institute of Natural Resources, Nuuk
- Rasmussen LM (2021) Ederfuglemonitoring ved Nuuk — feltrapport 2021. Pinngortitaleriffik, Greenland Institute of Natural Resources, Nuuk
- ✦ Robertson GJ, Savard JP (2020) Long-tailed duck (*Clangula hyemalis*). In: Billerman SM (ed) *Birds of the world*, version 10. Cornell Lab of Ornithology, Ithaca, NY. <https://doi.org/10.2173/bow.lotduc.01>
- ✦ Rouxel Y, Crawford R, Cleasby IR, Kibel P and others (2021) Buoys with looming eyes deter seaducks and could potentially reduce seabird bycatch in gillnets. *R Soc Open Sci* 8:210225
- ✦ Sobel J (1996) Atlantic halibut *Hippoglossus hippoglossus*. The IUCN Red List of Threatened Species 1996: e.T10097A3162182 <https://dx.doi.org/10.2305/IUCN.UK.1996.RLTS.T10097A3162182.en>
- ✦ Steenweg RJ, Crossin GT, Kyser TK, Merkel FR and others (2017) Stable isotopes can be used to infer the overwintering locations of prebreeding marine birds in the Canadian Arctic. *Ecol Evol* 7:8742–8752
- ✦ Stubben C, Milligan B (2007) Estimating and analyzing demographic models using the popbio package in R. *J Stat Softw* 22:1–23
- Swennen C (1991) Ecology and population dynamics of the common eider in the Dutch Wadden Sea. PhD dissertation, Rijksuniversiteit, Groningen
- ✦ van Helmond ATM, Mortensen LO, Plet-Hansen KS, Ulrich C and others (2020) Electronic monitoring in fisheries: lessons from global experiences and future opportunities. *Fish Fish* 21:162–189
- ✦ Żydelis R, Small C, French G (2013) The incidental catch of seabirds in gillnet fisheries: a global review. *Biol Conserv* 162:76–88

Editorial responsibility: Lisa Ballance,
Newport, Oregon, USA
Reviewed by: 3 anonymous referees

Submitted: May 30, 2022
Accepted: November 1, 2022
Proofs received from author(s): December 3, 2022