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Greenland shark bycatch data in NAFO Subareas 0+1.

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ABSTRACT

Greenland shark (*Somniosus microcephalus*) are caught as bycatch in commercial fisheries in NAFO Subareas (SAs) 0+1. Records of Greenland Shark bycatch between 1980 and 2020 were compiled from Canadian at-sea observer data in SA 0, German at-sea observed data in SA 1 and Greenland logbooks in SA 1. Generalized linear models were used to assess relationships between the number and total weight of Greenland shark caught as bycatch and mean fishing depth, ordinal date, year and NAFO Division. By number, Greenland shark bycatch per fishing set was higher at depths between 950 and 1200 m, during July to September, and in 2011 and 2012 compared to other years; higher numbers were also recorded in SA 0 but numbers were generally not reported in SA 1 logbooks. Total weight of Greenland shark bycatch was higher at depths of 950 -1400 m, during November and December, and in 2015 compared to other years; total weight was higher in SA 0 compared to SA 1, but this difference could be affected by lower or less accurate reporting in logbooks. It is important to note that several countries are fishing in the Greenland EEZ and only Greenland and Germany have reported Greenland shark bycatch. Inverse distance wiegted interpolation was used to examine spatial patterns in Greenland shark bycatch. Locations with higher bycatch numbers and total weights were identified, particularly in Northern Baffin Bay and coastal waters in southern Baffin Bay and Davis Strait. Overall, the results suggest that while Greenland shark are caught as bycatch throughout NAFO SAs 0+1 and throughout the duration of fishing seasons, higher levels of bycatch occur at certain locations and times.

INTRODUCTION

Greenland shark (Somniosus microcephalus) are caught as bycatch in commercial fisheries in Canadian and Greenlandic Economic Exclusive Zones of Northwest Atlantic Fisheries Organization (NAFO) Subareas (SA) 0+1 (Simpson et al., 2021) (Figure 1). NAFO Fisheries Commision (FC) requested, in 2019, that SC identify areas and times where bycatch and discards of Greenland shark have a higher rate of occurrence. While SAs 0+1 are outside the NAFO Regulatory Area (NRA), patterns in Greenland shark bycatch in these northern areas provide a broader context to the bycatch in the Northwest Atlantic. To examine spatial and temporal patterns and statistical relationships in Greenland shark bycatch in SAs 0+1, data were compiled from logbooks from Greenland and German fleets fishing in SA 1 and at-sea observer (ASO) data from Canadian fleets in SA 0 (Table 1).

Generalized linear models (GLMs) were used to assess relationships between the number and total weight of Greenland shark caught in commercial fishing sets and fishing depth, ordinal day, latitude and longitude, year and NAFO Division. As a spatial analysis, Greenland shark bycatch numbers and total weights reported in logbooks or by ASOs were analyzed using Inverse Distance Weighted (IDW) interpolation to assess and visualize spatial structure in Greenland shark catches.

METHODS

At-sea observer data from Canadian offshore fleets fishing at depths of 200-1500 m in SA 0 were compiled from 1980 – 2020. Records included both fishing sets with and without Greenland shark bycatch and reported the fishing gear used, set coordinates, set date and time, duration, mean fishing depth and the number and total weight of Greenland sharks caught. Observer coverage differs among Divisions and fishing fleets. All fleets in Division 0A using mobile (trawl) or fixed (gillnet or longline) fishing gear have had 100% coverage since the fishery began in the late 1990s. Vessels in Division 0B using mobile fishing gear have also had 100% coverage since the mid to late 1990s; vessels using fixed gear have had 100% coverage between January 1 and April 30 since 2003, and 20% coverage between May 1 and December 31 since the mid to late 1990s.

For SA 1, data from 2000 to 2020 were compiled from logbooks provided by the Greenland Office of Fisheries Licenses (GFLK) and ASO data provided by the Federal Ministry of Food and Agriculture, Germany (since 2008). Logbooks and ASOs generally recorded the fishing gear used, set coordinates, set year and month, mean fishing depth and the total weight of Greenland shark caught. Logbook data from Greenland included inshore (Division 1A) and offshore (Divisions 1A-F) fisheries using trawls, longline and gillnet, at depths of 100 to 2000 m. ASO data from Germany included both the number and total weight of Greenland shark caught as well as the general list of data fields above. To improve bycatch reporting, Greenland developed a reporting protocol that was presented to the NAFO STACTIC Intersessional Meeting (STACTIC WP 19-36) in May 2019. The protocol is recommended for use by all NAFO Contracting Parties and includes the reporting of numbers, length and sex, which will improve the weight estimates.

It is important to note that Greenland shark are typically not weighed using a scale when caught as bycatch given the time and effort required. Weights are estimated visually or by comparing a measurement of shark length with an established length-weight key. Weight records are therefore subject to observer bias and accuracy.

Greenland shark bycatch data from the different countries were combined into a single dataset, following which data exploration was undertaken to identify outliers and assess homogeneity, normality, zero inflation, collinearity, relationships among variables, interactions and independence in the response variable (Zuur et al. 2010), and to visualize the raw data. Latitude, longitude and NAFO Division showed strong collinearity; latitude and longitude were excluded from furtherer analyses. Similarly, fishing gear type and data source (ASO vs. logbook) were also excluded from the analyses because of collinearity with NAFO Division. The number of Greenland sharks caught was not available in the Greenlandic logbooks, and weight was not always reliable until 2016, since some records have very low weights (e.g. 1 to 30 kg). Missing count data were imputed as a minimum of 1 shark for each set with a reported catch weight. All analyses were conducted using R v. 4.0.4.

GLMs were developed to examine relationships between the number or total weight of Greenland sharks caught per fishing set and mean fishing depth, ordinal day, year, and NAFO Division. For number of Greenland shark caught, the GLM was fit using a negative binomial distribution using the MASS (version 7.3-53) package (Ripley et al., 2021) following data exploration and statistical comparisons with the poisson and negative binomial distributions using the distplot function in the vcd (version 1.4-8) package (Meyer et al., 2020). The GLM for total Greenland shark weight was fit using a lognormal distribution with lme4 (version 1.1-26) package

(Bates et al., 2020); the suitability of a gamma distribution was assessed but the lognormal distribution provided significantly better fit.

To visualize spatial patterns in Greenland shark bycatch in NAFO SAs 0+1 IDW analyses were conducted using the gstat (v. 2.0-7) package (Pebesma and Graeler, 2021). IDW was conducted with raw count and weight data, not log transformed data. Four smoothing parameter values were used for each of the IDW analyses (2, 5, 10, 30); the smoothing parameter affects the weighting of data points with distance during the interpolation, with larger parameter values resulting in greater influence of more distant points. The catch data were projected onto a grid of 5 km wide cells to balance spatial resolution with computing time. The data available included records of fishing sets with Greenland shark bycatch, but data were not available for spatial patterns in overall fishing effort, therefore the IDW results could not incorporate catch rate into the analysis, only actual catches.

RESULTS AND DISCUSSION

Most of the observed or reported bycatch occurred in the NAFO SA 0+1 Greenland halibut fishery. Sorting grids are mandatory in shrimp fisheries in the area and most Greenland sharks should escape through the window. A notable decrease in Greenland shark bycatch in the Canadian shrimp fishery was observed immediately following implementation of the Nordmore grate in 1996 (see Siferd 2010 for general changes in bycatch in the Canadian shrimp fishery).

It is important to keep in mind that only vessels with ASOs in Canadian waters have reported data, and not all vessels in Greenlandic waters have been fully reporting bycatch of Greenland shark. Until 2017, the Greenlandic logbooks included a column to provide the weight (in kg) but some fisheries in Greenland reported the weight in kg caught and others reported the number of individuals, which makes it difficult to estimate total bycatch numbers or weight. These recognized but unquantified amounts of Greenland shark bycatch mean that any analyses could miss locations, times or conditions that have been associated with higher amounts of Greenland shark bycatch. It is also important to recall that Greenland shark are typically not weighed when caught as bycatch and reported weights are therefore subject to observer accuracy and bias.

Collection of data has been improving in Greenland since 2017, when it became mandatory to report all Greenland sharks, although only vessels larger than 30ft are required to submit logbooks. When sharks are alive they must be released, but under all circumstances, they must be recorded in the logbook as bycatch. Since 2019, GLFK inspectors and occasionally fishermen have been collecting length distribution and sex data of Greenland sharks; these data will allow accurate estimates of Greenland shark weights.

A negative binomial GLM examining relationships between the number of Greenland shark caught as bycatch and mean fishing depth, ordinal day, year and NAFO Division found significant effects of all explanatory variables (Appendix 1). All interaction terms were removed during model fitting. The number of Greenland shark caught per fishing set was higher at depths between 950 and 1200 m. Higher numbers were caught in 2011 and 2012 compared to other years and catch numbers were higher during July to September. The number of Greenland shark caught per fishing set was higher in SA 0, but this pattern was likely affected by the need to impute catch numbers from total catch weight in SA 1.

A lognormal GLM examining relationships between the total weight of Greenland shark caught as bycatch in individual fishing sets and mean fishing depth, ordinal day and NAFO Division, with Year as a random effect, found significant effects of all explanatory variables (Appendix 2). The total weight of Greenland shark per fishing set was higher at depths between 950 and 1400 m. Comparing depth ranges with higher bycatch amounts by number and weight, catches with higher numbers of Greenland shark extend to 1200 m deep while large catches by weight extend to 1400 m, suggesting that large catchs between 1200 and 1400 m are composed of larger-bodied sharks. Total Greenland shark weight was highest in 2015 and highest in November and December across years. Similar to catch numbers, total weight was higher in SA 0 compared to SA 1, probably due to misreporting of the fleets fishing in Greenlandic waters. It is important to note that several countries are fishing in the Greenland EEZ and only Greenland and Germany have reported Greenland shark bycatch.

IDW analyses identified a few locations that had higher levels of Greenland shark bycatch by number or total weight (Figures 2 and 3). Higher Greenland shark bycatch, by number of sharks in individual fishing sets, were identified in central and northern Baffin Bay (red areas in Figure 2A at ~71N, 62W; 73N, 72W; and 74N, 57W). As the smoothing parameter increased to 5, 10 and 30, these areas of higher bycatch numbers became more dispersed, except the area at ~71N, 62W which became more pronounced with a parameter of 30, and additional coastal areas with higher bycatch numbers emerged (e.g. ~66N, 62W). The IDW analyses with total Greenland shark weight per fishing set showed similar areas of high bycatch at ~73N, 72W and 74N, 57W with a smoothing parameter of 2, but the high catch numbers observed at ~71N, 62W did not coincide with an area of high total weight. As the smoothing parameter increased the two areas of high total weight became more dispersed and an area of high total weight emerged at ~71N, 62W, where high bycatch numbers were also observed. When locations with higher bycatch become more dispersed with higher smoothing parameter values, the results suggest that the high catches are highly concentrated in space. Conversely, locations with higher bycatch that become more pronounced as the smoothing parameter increases are more dispersed in space.

The current IDW analyses suggest that concentrated areas with high bycatch exist in northern Baffin Bay, while areas with high bycatch are more dispersed in southern Baffin Bay and Davis Strait. Comparing the IDW results with the overall distribution of reported Greenland shark bycatch (Figure 1), the locations in Baffin Bay with higher and more concentrated bycatch amounts are near the northern extent of the data and are more separated from other data points (particularly in northwestern Greenland), therefore the apparent higher level of concentration could be an artefact of sampling bias.

The analyses conducted here have identified areas, times and conditions with higher bycatch amounts within the data available, but given recent improvements in the consistency of data collection regarding Greenland shark bycatch, similar analyses should be conducted again after additional data have been collected (i.e. in 3 to 5 years). Subsequent analyses would benefit from including ASO or logbook data from all fishing sets regardless of whether Greenland shark bycatch was reported. Inclusion of sets without Greenland shark bycatch would allow consideration of conditions in areas that have no Greenland shark bycatch and application of other modeling approaches, such as the approach proposed by Yan et a. (2021).

ACKNOWLEDGEMENTS

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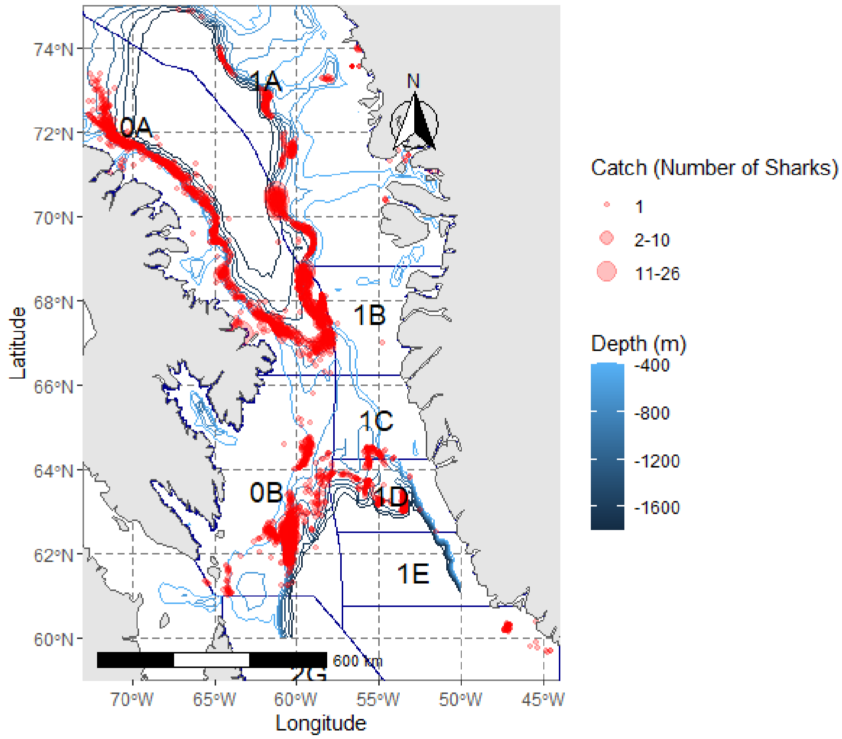

Figure 1. Locations of Greenland shark bycatch by commercial fishing fleets from Canada, Germany and Greenland in NAFO SAs 0+1. Bycatch data were compiled from vessel logbooks in SA 1 (2000-2020) and at-sea observers in SA 0 (1980 and 2020).

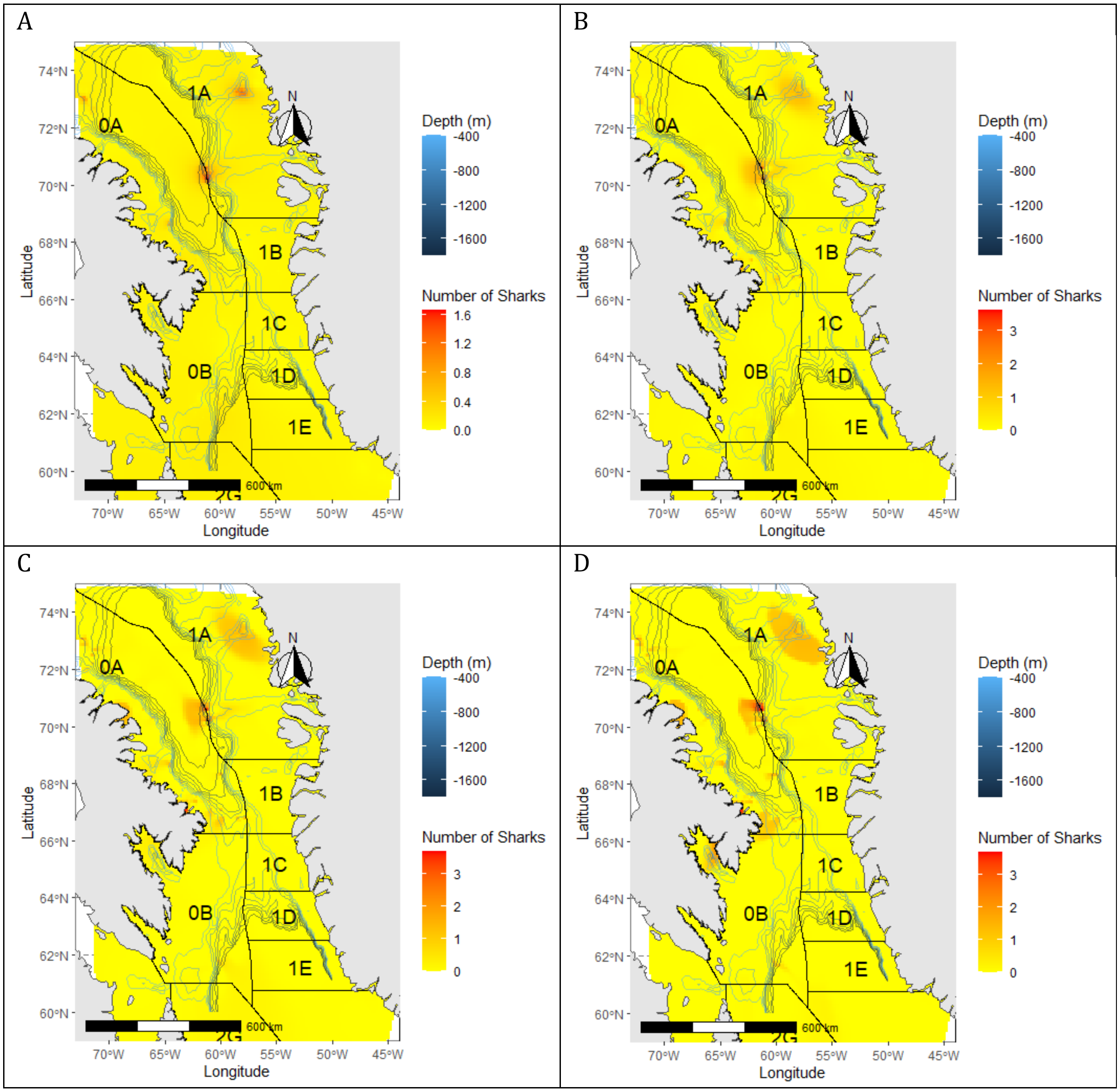

Figure 2. Inverse distance weighing (IDW) analyses of number of Greenland shark caught as bycatch in commercial fishing sets and reported in logbooks or by at-sea observers. IDW was conducted with 4 difference smoothing parameter values: A) 2, B) 5, C) 10, D) 30.

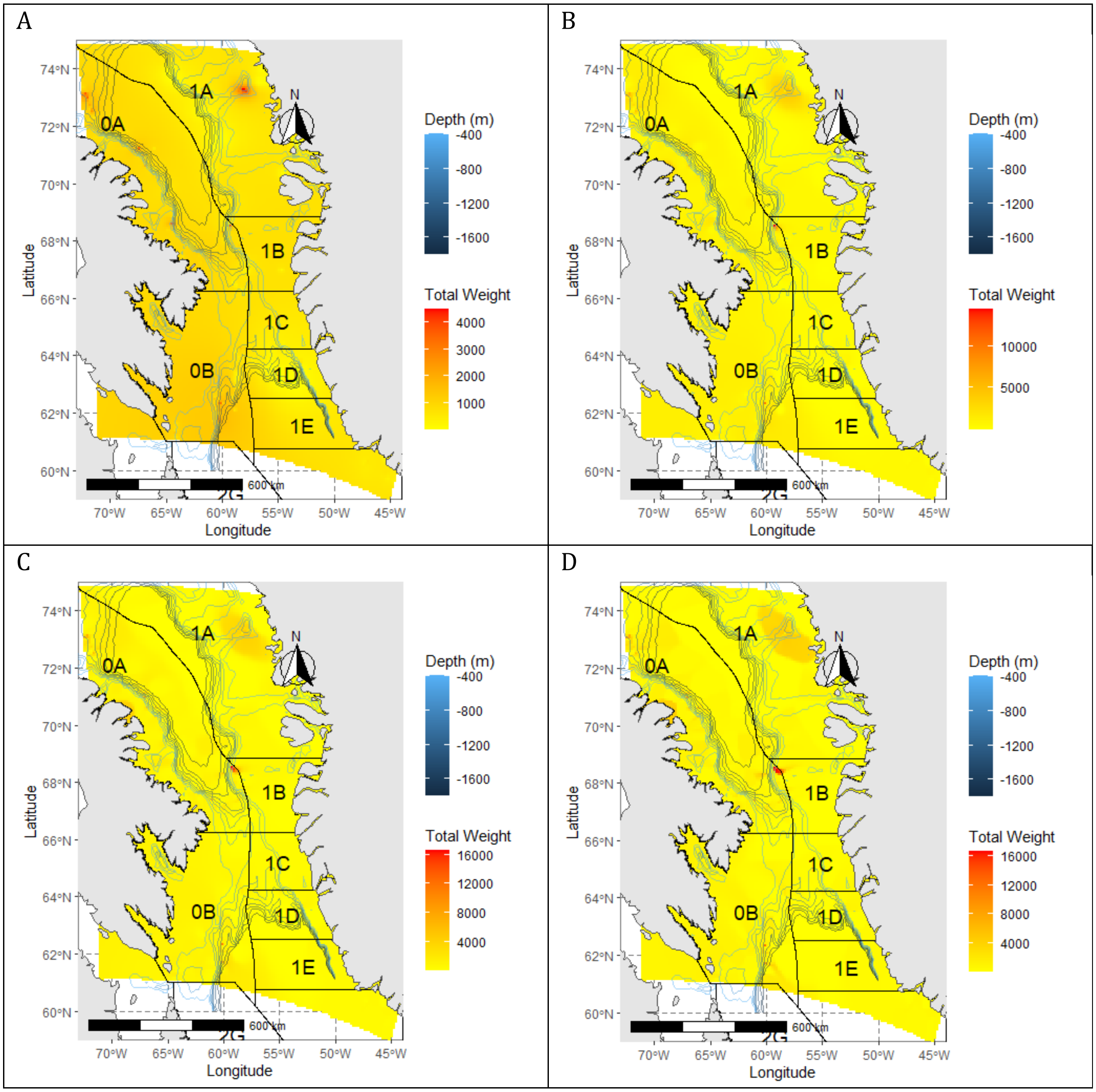

Figure 3. Inverse distance weighing (IDW) analyses of total weight of Greenland shark caught as bycatch in commercial fishing sets and reported in logbooks or by at-sea observers. IDW was conducted with 4 difference smoothing parameter values: A) 2, B) 5, C) 10, D) 30.

Table 1. Number of commercial fishing sets by year for which data from at-sea observers (Subarea 0) or logbooks (Subarea 1) were available and number of these sets that had Greenland shark bycatch. Data are shown for 2000-2020 but data from Canada used in the analyses also included 1980-1999.

	Subarea 0		Subarea 1	
Year	Number of sets observed	Number of observed sets with Greenland shark bycatch	Number of sets reported in logbooks	Number of reported sets with Greenland shark bycatch
2000	35044	115	41019	66
2001	36242	237	44159	40
2002	39139	286	59988	214
2003	31395	341	59276	274
2004	41033	265	51361	70
2005	32728	264	47376	0
2006	28634	284	40073	0
2007	28750	420	32630	0
2008	14603	284	36703	0
2009	14500	164	36540	0
2010	29920	146	34263	0
2011	22708	147	26185	2
2012	19717	166	26715	2
2013	21022	226	30067	0
2014	17350	150	27514	0
2015	15946	215	23827	45
2016	21216	197	18377	37
2017	25490	206	24068	100
2018	20075	89	23678	113
2019	10208	181	19361	79
2020*	121	115	20129	120

- Canadian ASO data were limited in 2020 because of travel and working restrictions as a result of the COVID-19 pandemic.

Appendix 1. GLM: Number of Greenland Sharks Caught

A generalized linear model was used to assess the relationships between the number of Greenland shark caught in commercial fishing sets and fishing depth, ordinal day, latitude and longitude.

glm.nb(formula = EST_NUM_CAUGHT ~ DEPTH + ORDINAL + YEAR + DIVISION,

data = northernbycatchlowhat, init.theta = 42.11377204, link = log)

Deviance Residuals:

Min	1Q	Median	3Q	Max
-0.6372	-0.2942	-0.2028	-0.0099	9.3963

Coefficients:

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-2.816e+01	3.127e+00	-9.004	< 2e-16 ***
DEPTH	2.594e-04	4.825e-05	5.376	7.60e-08 ***
ORDINAL	8.108e-04	1.399e-04	5.796	6.80e-09 ***
YEAR	1.391e-02	1.557e-03	8.938	< 2e-16 ***
DIVISION0B	9.476e-02	2.631e-02	3.601	0.000317 ***
DIVISION1A	-1.894e-01	4.582e-02	-4.134	3.57e-05 ***
DIVISION1B	-3.338e-01	2.933e-01	-1.138	0.255043
DIVISION1C	-2.318e-01	8.668e-02	-2.674	0.007485 **
DIVISION1D	-1.980e-01	5.379e-02	-3.682	0.000232 ***
DIVISION1F	-9.440e-02	1.560e-01	-0.605	0.545019

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
(Dispersion parameter for Negative Binomial (42.1138) family taken to be 1)
Null deviance: 2964.9 on 6709 degrees of freedom
Residual deviance: 2770.7 on 6700 degrees of freedom
AIC: 16952

Number of Fisher Scoring iterations: 1
Theta: 42.1
Std. Err.: 10.8
2 x log-likelihood: -16930.0

Single term deletions
Model:

EST_NUM_CAUGHT ~ DEPTH + ORDINAL + YEAR + DIVISION

	Df	Deviance	AIC	LRT	Pr(>Chi)
<none>		2770.7	16950		
DEPTH	1	2799.9	16977	29.232	6.422e-08 ***
ORDINAL	1	2804.8	16982	34.155	5.090e-09 ***
YEAR	1	2850.2	17028	79.529	< 2.2e-16 ***
DIVISION	6	2837.7	17005	67.059	1.637e-12 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Appendix 2. GLM: Weight of Greenland Shark Caught

A generalized linear model was used to assess the relationships between the total weight of Greenland shark caught in commercial fishing sets and fishing depth, ordinal day, year and NAFO Division.

Formula: log(CATCH_WEIGHT) ~ DEPTH + ORDINAL + DIVISION + (1 | YEAR)

Data: northernbycatch2

REML criterion at convergence: 14876.1

Scaled residuals:

Min	1Q	Median	3Q	Max
-4.1395	-0.5514	0.0032	0.6085	3.7026

Random effects:

Group Name	Variance	Std.Dev.
YEAR (Intercept)	0.5065	0.7117
Residual	1.7191	1.3111

Number of obs: 4363, groups: YEAR, 25

Fixed effects:

	Estimate	Std. Error	t value
(Intercept)	5.1960291	0.1952687	26.610
DEPTH	0.0003872	0.0001297	2.986
ORDINAL	0.0023700	0.0002584	9.171
DIVISION0B	0.7476620	0.0553459	13.509
DIVISION1A	-2.6377940	0.0773795	-34.089
DIVISION1B	-1.6752599	0.3447604	-4.859
DIVISION1C	-1.8425818	0.1231266	-14.965
DIVISION1D	-4.3491971	0.0948662	-45.846
DIVISION1F	-0.7781095	0.2201878	-3.534

Correlation of Fixed Effects:

	(Intr)	DEPTH	ORDINA	DIVISION0	DIVISION1A	DIVISION1B	DIVISION1C	DIVISION1D
DEPTH	-0.554							
ORDINAL	-0.267	-0.141						
DIVISION0B	-0.034	-0.245	0.207					
DIVISION1A	0.081	-0.203	-0.068	0.268				
DIVISION1B	0.052	-0.091	-0.029	0.060	0.089			
DIVISION1C	-0.022	-0.136	0.199	0.181	0.155	0.044		
DIVISION1D	0.086	-0.459	0.353	0.431	0.319	0.066	0.211	
DIVISION1F	-0.235	0.335	0.029	0.017	0.026	0.007	0.032	-0.069

Single term deletions

Model: log(CATCH_WEIGHT) ~ DEPTH + ORDINAL + DIVISION + (1 | YEAR)

	npar	AIC	LRT	Pr(Chi)
<none>		14850		
DEPTH	1	14857	8.81	0.003003 **
ORDINAL	1	14932	83.37	< 2.2e-16 ***
DIVISION	6	17819	2980.81	< 2.2e-16 ***

---Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1