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Gulf Region

Mitigating Bycatch of Southern Gulf of St. Lawrence Atlantic Cod (*Gadus morhua*) in NAFO Divisions 4T - 4Vn (November-April)

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Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The primary management measure proposed in the southern Gulf of St. Lawrence (sGSL) Atlantic Cod (*Gadus morhua*) rebuilding plan is to keep removals to the lowest level by introducing new and/or stricter management measures in all fisheries that intercept sGSL Atlantic Cod. In this study, we assessed spatial and temporal patterns of bycatch risk in four fisheries. Three of these fisheries, Atlantic Halibut (*Hippoglossus hippoglossus)*, Greenland Halibut (*Reinhardtius hippoglossoides)*, and Witch Flounder (*Glyptocephalus cynoglossus)* have been responsible for the majority of sGSL Atlantic Cod bycatch in recent years. The fourth fishery, Redfish (*Sebastes* spp.), was assessed because it was also noted for having relatively high bycatch levels, and because the commercial fishery reopened in 2024, potentially increasing bycatch impacts on Atlantic Cod.

To assess bycatch risk, we used both fisheries-independent and fisheries-dependent data in species distribution models, and we compared model predictions under different fishing scenarios to develop fishery-specific considerations for Fisheries and Harbour Management. Occurrence and density of Atlantic Cod in Northwest Atlantic Fisheries Organization (NAFO) 4T were associated with depth, making the adoption of depth-targeted strategies an important component of bycatch mitigation. In addition to depth, area-targeted mitigation strategies also offered solutions to lower bycatch rates. As noted elsewhere, winter distributions of Atlantic Cod in NAFO 4Vn may be more difficult to predict due to dense overwintering aggregation behaviour. In NAFO 4Vn, area closures may help mitigate bycatch in fisheries that operate there.

In addition to existing fisheries management practices, the best scenarios to minimize bycatch in each fishery include the following recommendations: (i) area- and depth-associated mitigation for the NAFO 4T Atlantic Halibut fishery, (ii) area-associated mitigation for the NAFO 4Vn Atlantic Halibut fishery, (iii) depth-associated mitigation for the NAFO 4T Witch Flounder fishery, (iv) depth-associated mitigation combined with a revised latitude limit for the NAFO 4T Greenland Halibut fishery, (v) area- and depth-associated mitigation for the NAFO 4T Redfish fishery, and (vi) either maintaining a winter closure of NAFO 4Vn to Redfish fishing, or applying area-associated mitigation combined with a latitude limit in the winter.

INTRODUCTION

The management unit for the southern Gulf of St. Lawrence (sGSL) Atlantic Cod (*Gadus morhua*) stock consists of the Northwest Atlantic Fisheries Organization (NAFO) Division 4T as well as subdivision 4Vn from November to April (hereafter sGSL Cod; Figure 1). This stock has been fished since the sixteenth century or earlier. Following the stock collapse in the 1990s, the fishery was closed from September 1993 to May 1998. An index fishery opened in 1999, but was closed in 2009. At the time of this study, a total allowable catch (TAC) of 300 t accounted for bycatch in commercial groundfish fisheries (152.2 t), scientific monitoring programs (75 t), recreational fisheries (50 t), Indigenous purposes (15 t), and French Reserve (7.8 t).

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the Laurentian South Designable Unit (DU) of Cod, which includes the sGSL Cod stock, as Endangered (COSEWIC 2010). This stock has been below its Limit Reference Point (LRP) since 1990 (Turcotte et al. 2024), placing it in the Critical Zone of the Precautionary Approach (PA) (DFO 2009). Under section 6.2 of the Fish Stocks Provisions (FSP) in the amended *Fisheries Act (2019)* and amended *Fishery General Regulations*, a rebuilding plan must be developed and implemented for a prescribed major fish stock. The rebuilding plan must be developed within 24 months from the time a stock has declined to or below its LRP, and for stocks already at or below their LRP. This timeline begins the day the stock is prescribed in regulation (April 4, 2022 for sGSL Cod).

As outlined in the PA framework (DFO 2009), the primary objective of a rebuilding plan is to promote stock growth above the LRP by ensuring that removals from all fishing sources are kept to the lowest possible level until the stock has cleared the Critical Zone, and there should be “no tolerance for preventable declines”. Rebuilding plans must also include additional restriction on catches. The primary management measure proposed in the sGSL Cod rebuilding plan is to keep removals to the lowest possible level by introducing new and/or stricter management measures in all fisheries that intercept sGSL Atlantic Cod.

This study aims to contribute to the rebuilding plan by addressing three objectives: (i) assess the extent of spatiotemporal overlap between sGSL Cod and commercially harvested species in which the majority of bycatch occurs; (ii) assess spatiotemporal patterns of bycatch from commercial and other catch data; and (iii) provide advice to Fisheries and Harbour Management on strategies to mitigate bycatch, especially pertaining to ‘bycatch hotspots’, i.e., areas of particularly high or persistent bycatch risk, where mitigation efforts could be focused.

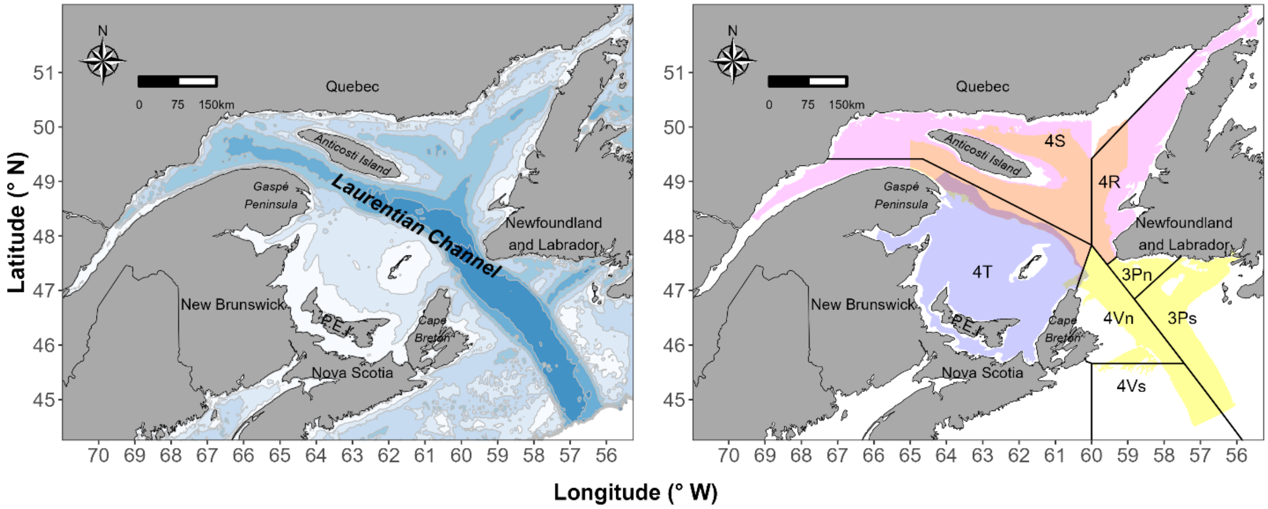

Figure 1: Maps of the NAFO 4TVn study area and surrounding regions. Left: Bathymetry, with depth intervals at 50 m, 100 m, and then every 100 m (light to dark blue shading indicates a transition from shallow to deep). Right: Thick black lines show NAFO divisions. The shaded blue area shows the southern Gulf of St. Lawrence autumn research vessel survey strata. The shaded pink area shows the northern Gulf of St. Lawrence summer research vessel survey area. The shaded yellow area shows the winter research vessel survey area. All maps that display coordinates in latitude and longitude show data projected with the coordinate reference system EPSG 4326 (datum WGS84). All other maps display data projected with coordinate reference system EPSG 32620 (datum WGS84; UTM zone 20N).

MATERIALS AND METHODS

STUDY SYSTEM

Since 2009, the average annual bycatch of sGSL Cod has been 110 t (Swain et al. 2019). In recent years, most of the bycatch has occurred in the Atlantic Halibut fishery (*Hippoglossus hippoglossus*; average 82% of Atlantic Cod bycatch from 2013 to 2017), with notable proportions in fisheries targeting Witch Flounder (*Glyptocephalus cynoglossus;* 11%), Greenland Halibut (*Reinhardtius hippoglossoides*; 4%), and Redfish (*Sebastes* spp.; 3%) (Swain et al. 2019).

Atlantic Halibut fishery

The commercial fishery directing for the NAFO Division 4RST Atlantic Halibut stock is carried out by longlines under a competitive management regime, or by individual transferable quota (ITQ). Since the 1960s, the stock has been exploited by 12 fleets in Quebec and the Maritime provinces (DFO 2023a). In NAFO Division 4T, the fishery is prosecuted both nearshore along the provincial coastlines, and in the Laurentian Channel. The fishery occurs throughout the year, however this varies by fleet. Summer and autumn are when nearly all fleets are active in the fishery. Landings have increased from a low of 91 t in 1982, and are now around 1,500 t, the highest level recorded in the past 60 years (DFO 2023a).

Witch Flounder fishery

The commercial fishery directing for the NAFO Division 4RST Witch Flounder stock is almost exclusively a mobile gear fishery using seines and trawls (Ricard 2022). The fishery predominately uses Danish seines, and occurs largely between May and September. From 2000 to 2011, the TAC was 1,000 t. As landings began to decline in 2008, falling to a low in

2010, the TAC was decreased to 500 t in 2012, and further reduced to 300 t from 2013 to 2016. Following the 2017 stock assessment, which showed an increasing trend in Witch Flounder biomass, the TAC was increased to 500 t in 2017, where it has remained to present (Ricard 2022). Since 2013, the TAC has been allocated equally to the 4R and the 4T fleets with fewer than ten fish harvesters targeting Witch Flounder. From 2013 to 2018, the TAC was almost entirely landed, however, since 2019 the 4T fleet has only landed a portion of the quota (Ricard 2022).

Greenland Halibut fishery

A directed gillnet fishery for the NAFO Division 4RST Greenland Halibut stock began in 1977, and fishing effort occurs in three main areas, including in the Western Gulf. Since 1994, fixed gear is the only gear allowed in the directed Greenland Halibut fishery, which generally occurs from mid-May through October. In the Western Gulf, landings reached highs near 3,000 t in 2015, and declined to the lowest levels in 2022 (DFO 2023b). Only fixed gear groundfish fishing fleets from the Gaspé Peninsula and the Quebec North Shore participate in the directed commercial fishery for Greenland Halibut in 4T. The directed fishery for Greenland Halibut is permitted to operate at depths of 180 m to 360 m, and for the Western Gulf, occurs along the slopes of the Laurentian Channel into the Estuary to a point off of the Gaspe Peninsula. In NAFO Division 4T, the area south of Cap Gaspé is permanently closed on the eastern side of the Peninsula (Figure 18 in DFO 2021a).

Redfish fishery

Two Redfish management units, Unit 1 and 2, overlap with sGSL Cod (DFO 2018a). Management Unit 1 includes NAFO 4T year-round and NAFO 4Vn seasonally from January through May, while Unit 2 includes NAFO 4Vn from June through December (DFO 2022). The commercial fishery for Unit 1 was under moratorium from 1995 to 2024 (Brassard et al. 2017; McAllister et al. 2021; Senay et al. 2023), however, an index fishery was established in 1998, and an experimental fishery was added in 2018. From 2018 to 2021, the combined index and experimental TACs for Unit 1 ranged from 4,500 t to 7,463 t (Senay et al. 2023). Over this period, total landings averaged < 20% of these TACs, due to limited fishing effort. Strong Unit 1 recruitment in the 2011 to 2013 year-classes led to a large increase in biomass (DFO 2022), resulting in reopening of the commercial fishery in 2024.

Most Redfish-directed fishing is done with seines or trawls. Conservation harvesting measures for Management Unit 1, which has the most overlap with sGSL Cod, typically include (i) time-area closures intended to protect spawning fish and concentration of juveniles, (ii) depth and area restrictions (at least 100 fathoms (182.9 m), between longitudes 59° and 65° (W) to avoid incidental catch of Greenland Halibut), and (iii) species-specific bycatch quotas (Brassard et al. 2017; DFO 2018b). However, additional area closures near the Gaspé Peninsula constrain the western limit further to 62.28°W (Figure 2 in Senay et al. 2023).

DATA SOURCES

Fisheries-independent surveys

Southern Gulf of St. Lawrence research vessel survey

DFO Gulf Region conducts an annual scientific bottom-trawl survey in the southern Gulf of St. Lawrence (hereafter sGSL Autumn RV survey). The multi-species, standardized survey follows a stratified random sampling design that spans the majority of the sGSL, and is conducted each autumn, usually in September (Hurlbut and Clay 1990; Benoît 2006). We obtained species catch densities (kg/tow per species) for survey years 2003 to 2021, using data that were standardized to a *CCGS Teleost* day tow with a Western IIA trawl and a tow distance of 1.75 nautical miles (Benoît 2006) (Figure 2). The approximate surface area covered by each standardized tow was 0.041 km^2. We obtained catch density along with spatial coordinates (degrees latitude and longitude) and depth (m) for 2,923 complete tows. The number of tows per year ranged from 83 (2003) to 244 (2005), with a mean of 154. Tow depths ranged from 15.0 m to 382.5 m. Atlantic Cod were recorded in 72.7% of tows, Atlantic Halibut 16.0%, Witch Flounder in 20.0%, Greenland Halibut in 25.4%, and Redfish in 24.8%.

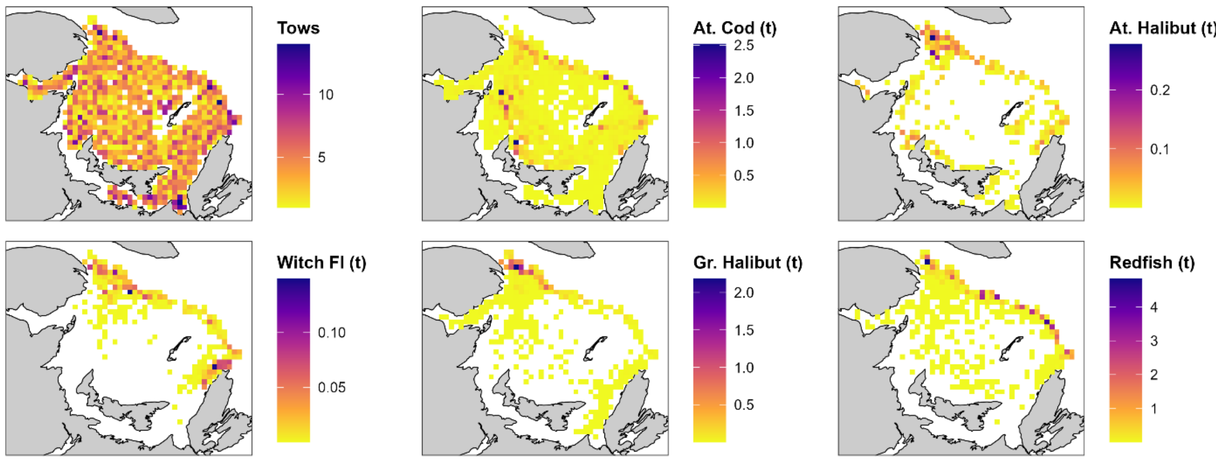

Figure 2: sGSL Autumn RV survey tows. Number of tows (top left), summed weight of Atlantic Cod (top middle), summed weight of Atlantic Halibut (top right), summed weight of Witch Flounder (bottom left), summed weight of Greenland Halibut (bottom middle), and summed weight of Redfish (bottom right). Each grid cell is 10 x 10 km.

Northern Gulf of St. Lawrence research vessel survey

DFO Quebec region conducts an annual scientific bottom-trawl survey in the northern Gulf of St. Lawrence, usually in August (hereafter nGSL Summer RV survey). The multi-species, survey follows a standardized, stratified random design, which covers the waters of the Laurentian Channel and areas north of the Channel, including NAFO Divisions 4R, 4S, and the northern part of 4T in the St. Lawrence Estuary (Bourdages and Savard 2007; Bourdages et al. 2022). We obtained catch density (kg/tow per species) for survey years 2003 to 2021 in the NAFO 4T region only, using data that were standardized to a *CCGS Teleost* tow with a four-sided Campelen 1800 shrimp trawl equipped with a Rockhopper footgear (Mccallum and Walsh 2002), and a tow distance of 0.75 nautical miles (Bourdages et al. 2022). The approximate surface area covered by each standardized tow was 0.023 km^2. We obtained catch density along with spatial coordinates (degrees latitude and longitude) and depth (m) for 879 complete tows (Figure 3). The number of tows per year in NAFO 4T ranged from 33 (2019 and 2020) to 84 (2005), with a mean of 46. Tow depths ranged from 48 m to 516 m. Atlantic Cod were recorded in 32.4% of tows, Atlantic Halibut in 22.9%, Witch Flounder in 86.3%, Greenland Halibut in 93.1%, and Redfish in 93.6%.

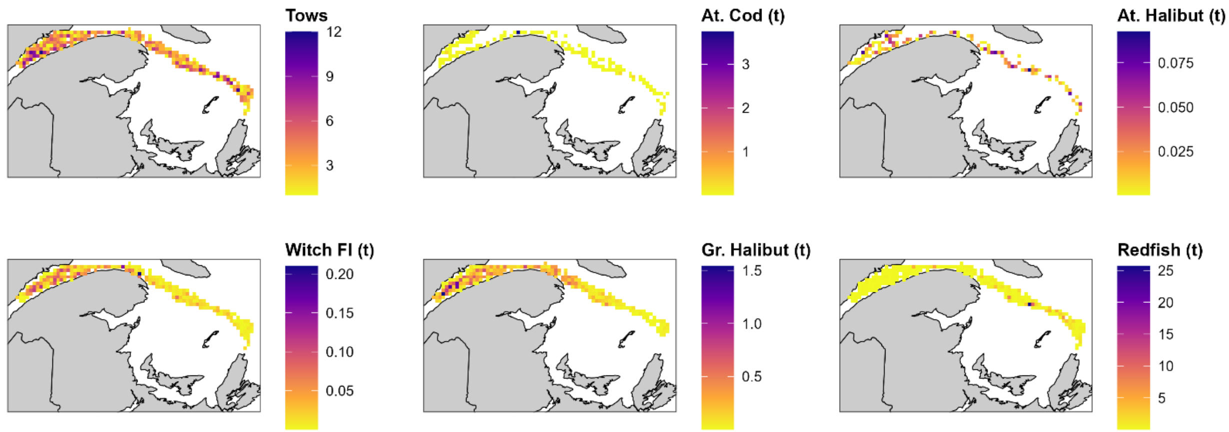

Figure 3: nGSL Research Vessel Survey tows. Number of tows (top left), summed weight of Atlantic Cod (top middle), summed weight of Atlantic Halibut (top right), summed weight of Witch Flounder (bottom left), summed weight of Greenland Halibut (bottom middle), and summed weight of Redfish (bottom right). Each grid cell is 10 x 10 km.

Winter research vessel survey

During the winters of 2022 and 2023, DFO conducted multi-species research vessel bottom-trawl surveys in January and February (hereafter Winter RV survey) within NAFO divisions 3Pn4RSTVn. *The Mersey Venture*, the sister ship to the *CCGS Teleost* (DFO 2020), was used each year. This survey followed a systematic unaligned sampling design. Trawls were conducted with the Campelen 1800 shrimp trawl used in the nGSL summer RV survey. We acquired data for 58 complete tows (30 in 2022, 28 in 2023) with a standardized tow of 15 minutes (approximate tow distance 0.75 nautical miles and a swept area of 0.0684 km^2) within NAFO 4TVn. We obtained catch density (kg/tow per species) along with spatial coordinates (degrees latitude and longitude) and depth (m) for 58 complete tows (Figure 4). All Winter RV survey data were considered preliminary at the time of study. Tow depths ranged from 169 m to 526 m. Atlantic Cod were recorded in 51.7% of tows, Atlantic Halibut in 27.6%, Witch Flounder in 86.2%, Greenland Halibut in 72.4%, and Redfish in 98.3%.

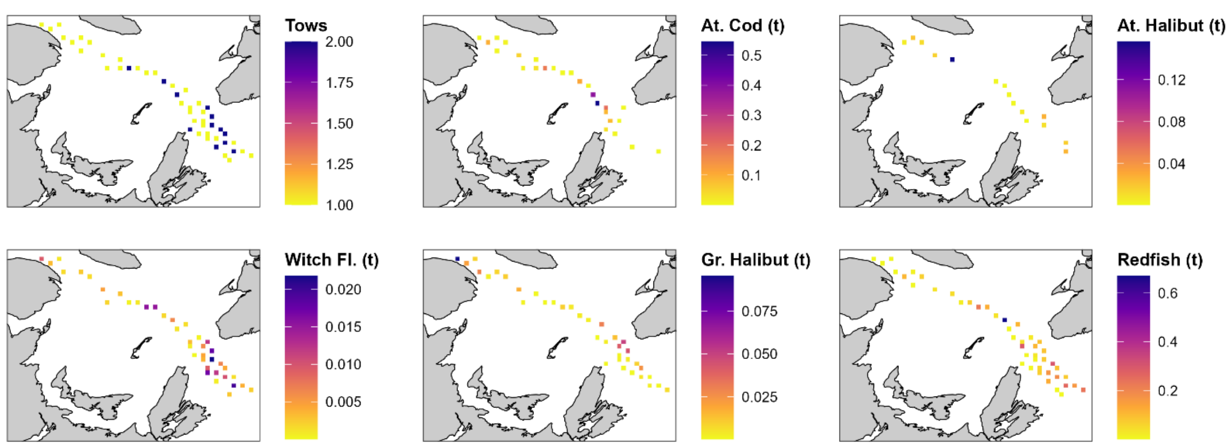

Figure 4: GSL Winter Research Vessel tows. Number of tows (top left), summed weight of Atlantic Cod (top middle), summed weight of Atlantic Halibut (top right), summed weight of Witch Flounder (bottom left), summed weight of Greenland Halibut (bottom middle), and summed weight of Redfish (bottom right). Each grid cell is 10 x 10 km.

Fisheries-dependent landings

Fisheries-dependent landings data (hereafter Landings) are collected each year by DFO regional offices, and maintained by the Statistical Services Unit. These data are organized by species groups (e.g., species caught), rather than by fishing event. Each record includes the landed weight of a species along with associated metadata that typically include the commercial fishing vessel identification number, main species sought, date caught, date landed, gear used, and geographic coordinates. However, individual records may have missing information. Prior to incorporating these data into scientific analyses, Science staff perform quality control processing that can include verification, correction, or omission/deletion of erroneous or incomplete records.

We used the **read.ziff** function from the **gulf** package (Vergara et al. 2023) in **R** (R Core Team 2022) to access Landings records. We initially accessed Landings records for years 1985 to 2021 and NAFO divisions 3PnPs4RSTVnVs. We obtained records reported to be within and adjacent to our target area (4TVn) so that we could independently assign NAFO designations based on reported geographic coordinates. As geographic coordinates were required for subsequent spatial analysis, we discarded records that lacked coordinates, which removed all records prior to 1990. We then assigned a NAFO division to each record, and removed records outside of the 4TVn boundaries.

Landings records include fields for both “date caught” and “date landed”, however, the former is less often reported. For records that did not report date caught, we inferred it to be the same as the date landed. If the date caught was reported as occurring after the date landed, the date landed was inferred to be the true date caught. In remaining cases, if the year caught did not match the year landed, the year landed was inferred to be the true year caught (only for months other than December and January).

After correcting the date information, we filtered data to retain records for the specific years and fisheries of interest (“main species sought”), as well as by time of year in NAFO 4Vn (i.e., only retaining months November through April). For fisheries other than Redfish, we retained years 2003 to 2021. For Redfish, we retained years 1990 to 1994, when there was a commercial Redfish fishery, and years 1998 to 2021, when there was an index and/or experimental Redfish fishery.

Next, we used the geographic coordinates provided in each retained record to estimate the water depth (m) at each location, by applying the function **depth** from the **gulf** package. The **depth** function returns a linearly interpolated estimate of water depth for a given set of coordinates based on a reference bathymetry map. After estimating the depth for each pair of coordinates, we removed records that appeared on land (removing records with depth ≥ 0 m), and converted depth estimates to absolute values.

Finally, we created a “fishing event identification (ID)” for each record so that we could compare weights (kg) of different species caught together. We created the fishing event ID by concatenating the following fields: commercial fishing vessel number, date, main species sought, gear class, gear alpha, gear amount, port landed, geographic coordinates, assigned depth, and assigned NAFO division.

Atlantic Halibut fishery

Prior to fitting models, we removed fishing events that occurred in water shallower than 5 m, as well as records that had zero catch of both Atlantic Halibut and Atlantic Cod. For NAFO 4T, we also removed events that occurred in March and November, due to low sample sizes. For our models, we retained 16,531 NAFO 4T fishing events, and 1,539 NAFO 4Vn fishing events (Table 1).

In NAFO 4T, Atlantic Cod were recorded in 49.4% of all events, while Atlantic Halibut were recorded in 97.0% (Table 2). The mean proportion of Atlantic Cod in the combined catch of both species (i.e., bycatch) was 12.8% (minimum = 0, maximum = 100, median = 0). Months July to September comprised 78.6% of all fishing events (Table 3). Longlines were used in 99.4% of all fishing events (Table 4). Fishing depths ranged from 5.8 m to 505.3 m (mean = 168.1, median = 170.2), however, the distribution of depths was bimodal, with concentrations either shallower or deeper than 100 m. This bimodal pattern is likely attributable to distributions of GSL Atlantic Halibut, which typically avoid the cold water intermediate layer between 50 to 100 m (DFO 2023a; Galbraith et al. 2023). The mean bycatch in water shallower than 100 m was 10.4%, while the mean bycatch in deeper water was 20.7%. There were seasonal shifts in effort across depth and space, with the majority of fishing events occurring in deeper (>100 m) offshore water from April through June, before concentrating in more shallow, inshore water from July through October. This shift reflects the fishing seasons of the different fleets in NAFO 4T. Over years 2003 to 2021, 23.0% of fishing events were in waters at or deeper than 100 m, catching 41.1% of the landed weight of Atlantic Halibut and 76.1% of the landed weight of Atlantic Cod. Patterns remained similar in the most recent five years, when 19.0% of events occurred in waters at or deeper than 100 m, capturing 39.2% of landed Atlantic Halibut and 69.8% of landed Atlantic Cod. The majority of landed Cod was caught east of the Gaspé Peninsula (Figure 5).

In NAFO 4Vn, Atlantic Cod were recorded in 51.5% of events, while Atlantic Halibut were recorded in 99.9%. The mean bycatch was 8.0% (minimum = 0, maximum = 100, median = 0.6). Longlines were used in 99.6% of fishing events. Months April, November, and December together comprised 78.9% fishing events (Table 3). NAFO 4Vn depths ranged from 5.0 m to 496.0 m (mean= 60.0, median= 28.0). Fishing depths were generally shallower in November and December compared to other months. The majority of landed Cod was caught in the northwest corner of 4Vn (Figure 6).

Table 1: Sample sizes of fishing events used in the species distribution models, shown by fishery, NAFO division, and year.

Year	Atlantic halibut directed events, NAFO 4T	Atlantic halibut directed events, NAFO 4Vn	Witch flounder directed events, NAFO 4T	Greenland halibut directed events, NAFO 4T	Redfish directed events, NAFO 4T	Redfish directed events, NAFO 4Vn
1990	-	-	-	-	-	109
1991	-	-	-	-	251	287
1992	-	-	-	-	235	445
1993	-	-	-	-	169	235
1994	-	-	-	-	472	294
1998	-	-	-	-	59	44
1999	-	-	-	-	263	6
2000	-	-	-	-	170	1
2001	-	-	-	-	238	30
2002	-	-	-	-	251	11
2003	376	1	213	727	208	13
2004	495	-	152	1,805	64	1
2005	382	8	199	1,697	168	10
2006	220	-	328	1,212	263	13
2007	253	7	243	735	46	6
2008	298	-	216	870	304	9

Year	Atlantic halibut directed events, NAFO 4T	Atlantic halibut directed events, NAFO 4Vn	Witch flounder directed events, NAFO 4T	Greenland halibut directed events, NAFO 4T	Redfish directed events, NAFO 4T	Redfish directed events, NAFO 4Vn
2009	396	1	128	1,004	399	4
2010	605	25	59	760	379	11
2011	828	55	55	467	414	7
2012	776	93	63	614	294	-
2013	748	162	70	643	168	-
2014	886	85	70	787	158	13
2015	1,087	86	60	568	211	-
2016	1,270	275	48	646	171	1
2017	1,529	139	46	647	166	-
2018	1,438	80	35	591	136	-
2019	1,443	69	34	690	138	12
2020	1,662	66	-	702	110	47
2021	1,839	387	7	409	183	18
TOTAL	**16,531**	**1,539**	**2,026**	**15,574**	**6,088**	**1,627**

Table 2: Total number of fishing events included in the species distribution models, along with the number of events that caught Atlantic Cod and the number of events that caught the fishery target.

NAFO	Presence	Atlantic halibut directed events	Witch flounder directed events	Greenland halibut directed events	Redfish directed events
4T	Total events	16,531	2,026	15,574	6,088
	Caught Atlantic Cod	8,159	1,839	1,346	1,022
	Caught Target	16,041	1,992	15,573	6,062
4Vn	Total events	1,539	-	-	1,627
	Caught Atlantic Cod	792	-	-	623
	Caught Target	1,538	-	-	1,621

Table 3: Sample sizes of fishing events used in the species distribution models, shown by NAFO division, fishery, and month.

NAFO	Month	Atlantic halibut directed events	Witch flounder directed events	Greenland halibut directed events	Redfish directed events
4T	Apr	718	24	670	-
	May	732	474	2,535	54
	Jun	1,132	387	3,760	1,839
	Jul	5,793	70	3,862	2,953
	Aug	4,485	227	2,801	995
	Sep	2,709	449	1,460	183
	Oct	962	392	486	64
	Nov	-	3	-	-

NAFO	Month	Atlantic halibut directed events	Witch flounder directed events	Greenland halibut directed events	Redfish directed events
	TOTAL	**16,531**	**2,026**	**15,574**	**6,088**
4Vn	Nov	314	-	-	208
	Dec	271	-	-	198
	Jan	76	-	-	291
	Feb	79	-	-	208
	Mar	169	-	-	216
	Apr	630	-	-	506
	TOTAL	**1,539**	**-**	**-**	**1,627**

Table 4: Sample sizes of fishing events used in the species distribution models, shown by NAFO division, fishery, and gear class. Values indicate final sample sizes, and likely underestimate the true number of fishing events.

NAFO	Gear class	Atlantic halibut directed events	Witch flounder directed events	Greenland halibut directed events	Redfish directed events
4T	Gillnet	24	-	15,574	21
	Handline	18	-	-	-
	Longline	16,430	-	-	21
	Seine	2	1,773	-	2,283
	Trawl	22	253	-	3,763
	Unspecified	35	-	-	-
	TOTAL	**16,531**	**2,026**	**15,574**	**6,088**
4Vn	Gillnet	2	-	-	-
	Handline	2	-	-	-
	Longline	1,533	-	-	-
	Seine	0	-	-	7
	Trawl	1	-	-	1,620
	Unspecified	1	-	-	-
	TOTAL	**1,539**	**-**	**-**	**1,627**

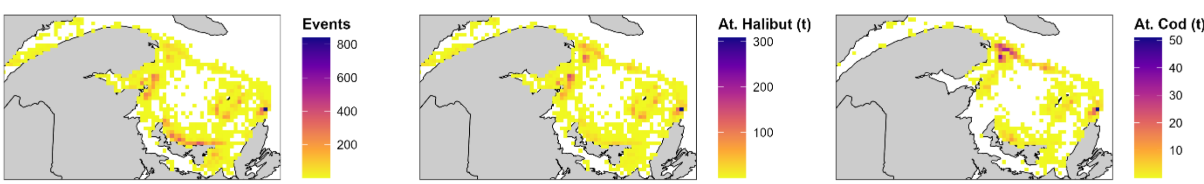

Figure 5: NAFO 4T Atlantic Halibut-directed fishing events. Number of fishing events (left), summed weight of Atlantic Halibut (middle) and summed weight of Atlantic Cod (right). Each grid cell is 10 x 10 km. Values do not represent total logbook Landings.

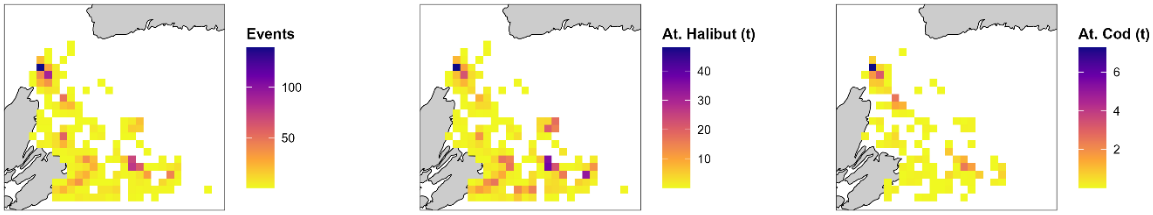

Figure 6: NAFO 4Vn Atlantic Halibut-directed fishing events. Number of fishing events (left), summed weight of Atlantic Halibut (middle) and summed weight of Atlantic Cod (right). Each grid cell is 10 x 10 km. Values do not represent total logbook Landings.

Witch flounder fishery

Prior to fitting models, we removed fishing events that occurred in water shallower than 100 m, based on Witch Flounder biology (Powles and Kohler 1970; Ricard 2022), as well as records that had zero catch of both Witch Flounder and Atlantic Cod. We retained 2,026 fishing events from NAFO 4T (Table 1). There were only 134 fishing events remaining in NAFO 4Vn, all from the month of November, of which 7 landed Cod. Thus we omitted NAFO 4Vn Witch Flounder-directed events from further analysis.

Atlantic Cod were recorded in 90.8% of events, while Witch Flounder were recorded in 98.3% (Table 2). The mean bycatch was 12.4% (minimum = 0, maximum = 100, median = 5.4). May and June together comprised 42.3% fishing events, while September and October accounted for 41.5% (Table 3). Seines were used in 87.5% of fishing events, followed by trawls (Table 4). Depths ranged from 100.0 m to 507.0 m (mean= 153.1, median= 160.2). Fishing depths were generally shallower in November and December compared to other months. The vast majority of events were clustered on the northwest side of Cape Breton (Figure 7).

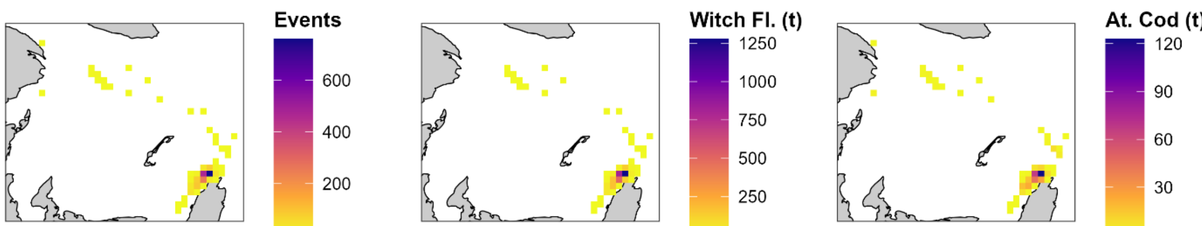

Figure 7: NAFO 4T Witch Flounder-directed fishing events. Number of fishing events (left), summed weight of Witch Flounder (middle) and summed weight of Atlantic Cod (right). Each grid cell is 10 x 10 km. Values do not represent total logbook Landings.

Greenland Halibut fishery

Prior to fitting models, we removed fishing events that occurred in water shallower than 130 m, based on Greenland Halibut biology (DFO 2021a, 2023b; Gauthier et al. 2021), as well as records that had zero catch of both Greenland Halibut and Atlantic Cod. We also removed any records that listed the type of gear used as anything other than gillnet. At this point there were no remaining records within NAFO division 4Vn. Finally, we removed events that occurred in November, due to a low sample size. We retained 15,574 Greenland Halibut fishing events for modelling (Table 1).

Atlantic Cod were recorded in 8.6% of fishing events, while Greenland Halibut were recorded in > 99.9% (Table 2). Months May through August comprised 83.2% of fishing events (Table 3). The mean bycatch was 0.3% (minimum = 0, maximum = 100, median = 0). Depths ranged from

130.3 m to 390.8 m (mean= 287.0, median= 288.8). The majority of bycatch occurred off the Gaspé Peninsula, east of L'Anse-à-Valleau, QC (Figure 8).

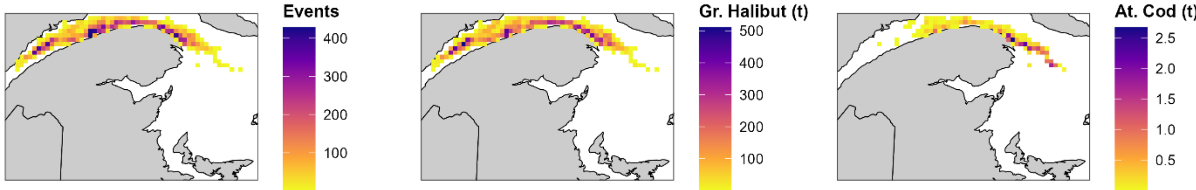

Figure 8: NAFO 4T Greenland Halibut-directed fishing events. Number of fishing events (left), summed weight of Witch Flounder (middle) and summed weight of Atlantic Cod (right). Each grid cell is 10 x 10 km. Values do not represent total logbook Landings.

Redfish fishery

For the Redfish fishery, we summarize the results and recommendations made by Sutton et al. (2024). Prior to fitting models, Sutton et al. (2024) removed fishing events that were shallower than 100 m, as well as records that had zero catch of both Redfish and Atlantic Cod. Months January, April, November and December were also omitted in NAFO 4T, due to low sample sizes (February and March had zero fishing events in NAFO 4T). For their models, they retained 6,088 NAFO 4T fishing events, and 1,627 NAFO 4Vn fishing events (Table 1).

In NAFO 4T, Atlantic Cod were recorded in 16.8% of events, while Redfish were recorded in 99.6% (Table 2). Months June through August comprised 95.1% of fishing events (Table 3). Trawls were used in 61.8% of events, followed by seines (37.5%), with gillnets and longlines each comprising 0.34% of events (Table 4). The mean bycatch was 2.1% (minimum = 0, maximum = 100, median = 0). NAFO 4T depths ranged from 100.5 m to 512.3 m (mean= 302.4, median= 298.8). The majority of bycatch occurred along the southern slopes of the Laurentian Channel (Figure 9).

In NAFO 4Vn, Atlantic Cod were recorded in 38.3% of events, while Redfish were recorded in 99.6% (Table 2). April accounted for 31.1% of events, with remaining months each accounting for between 12.8 to 17.9% of events (Table 3). Trawls were used in 99.6% of events, with seines were used in those remaining (Table 4). The mean bycatch was 2.7% (minimum = 0, maximum = 100, median = 0). NAFO 4Vn depths ranged from 105.0 m to 526.9 m (mean= 439.3, median= 450.9). Across all years, the majority of bycatch occurred in the northwest corner of the grid, corresponding to the area where most fishing events were concentrated (Figure 10).

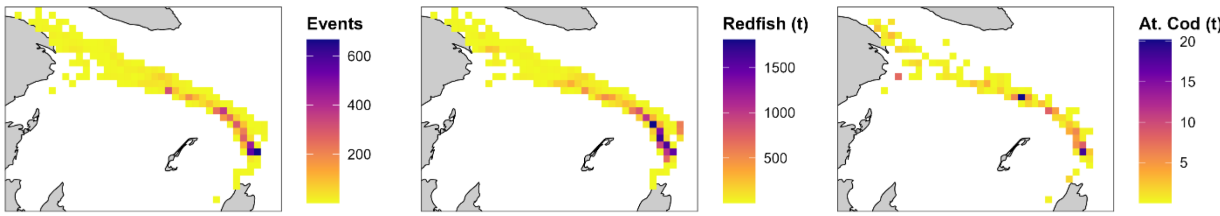

Figure 9: NAFO 4T Redfish-directed fishing events. Number of fishing events (left), summed weight of redfish (middle) and summed weight of Atlantic Cod (right). Each grid cell is 10 x 10 km. Values do not represent total logbook Landings.

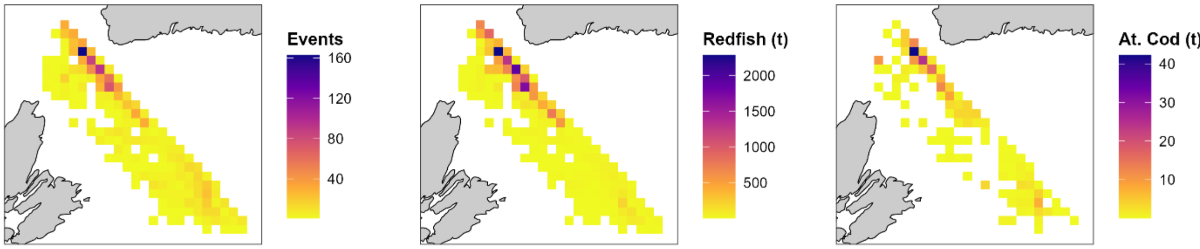

Figure 10: NAFO 4Vn Redfish-directed fishing events. Number of fishing events (left), summed weight of Redfish (middle) and summed weight of Atlantic Cod (right). Each grid cell is 10 x 10 km. Values do not represent total logbook Landings.

SPECIES DISTRIBUTION MODELS

Model fitting

We followed methods described in Sutton et al. (2024). To fit Generalized Linear Mixed-Effects (GLMM) SDMs to survey-based and Landings catch data, we used the **R** package, **sdmTMB** version 0.3.0 and later (Anderson et al. 2022). To construct each model's triangulated mesh, which is used to model the spatial components as random fields, we converted spatial coordinates to Universal Transverse Mercator (UTM) zone 20N, and applied the functions **make_mesh** and **add_barrier_mesh**, the latter of which defines coastline barriers. When specifying cut-offs to define the minimum allowed distance between mesh vertices, we used values that ensured fewer vertices than datapoints (5 km for nGSL Summer surveys, 5 to 10 km for sGSL Autumn RV surveys; 25 km for Winter RV surveys; 2 to 8 km for Landings models (Atlantic Halibut, NAFO 4T = 8 km, Atlantic Halibut NAFO 4Vn = 5 km, Witch Flounder = 2 km, Greenland Halibut = 4 km, both Redfish models = 5 km)).

The general formulation of these models is:

$$g(\mu_{s,t}) = X_{s,t}\beta + \omega_s + \epsilon_{s,t} \quad 1$$

Where $g()$ represents a link function; $\mu_{s,t}$ expected value (mean) of y a response variable at s a location (i.e., vector of coordinates) and t a time; $X_{s,t}$ is a matrix of main effect covariates; β represents a vector of fixed-effect coefficients; ω_s is the mean spatial random component at location s (constant through time), and; $\epsilon_{s,t}$ represents the spatiotemporal random field deviation which may be independent for each time slice, or modeled with $\delta_{s,t}$ a parameter defining deviations from one time step to the next (Anderson et al. 2022).

Model comparison

We used AIC, log-likelihood, and predictive accuracy estimated from three-fold cross-validation to choose the best model for each dataset. During initial model comparison, we sometimes applied different mesh sizes than during final model fitting, in order to improve computational speed. We used function **sdmTMB_cv** for cross-validation, arranging folds randomly, and estimated area under the curve (AUC) using the withheld data and function **auc** from package, **Metrics** version 0.1.4 (Hamner & Frasco 2018). Because the cross-validation folds did not contain equal numbers of observations, we collected the predicted values from all three folds and estimated AUC from the full dataset (e.g., Thompson et al. 2023). We did not perform model comparisons for models that did not converge (we used the function **sanity** from **sdmTMB** to assess model convergence).

Before fitting models, we centered and scaled depth by its standard deviation and we included comparisons of models in which the scaled depth was specified as a quadratic, to allow for non-linear relationships (e.g., Commander et al. 2022). When we tested year or month as predictors, we specified these as factors in order to calculate annual mean effects. Where appropriate, we additionally tested one-part and two-part models fitted with different error distributions (details in next section).

Fisheries-independent surveys model specification

We fit individual species-specific SDMs to catch data from the RV surveys. We specified predictors of catch density for each species in separate models (Table 5). To account for the presence of many zeros combined with positive continuous density estimates, we either used two-part models (i.e., hurdle) (Pennington 1983; Mullahy 1986), or one-part models with an error distribution that could support zero-inflated data (i.e., Tweedie) (Dunn and Smyth 2005). For hurdle models, we used a logit link to specify the binomial component and a log link to specify the positive-catch gamma component. For the one-part models, we specified the Tweedie distribution with a log link.

Fisheries-dependent landings model specification

Due to differences among vessels, gear, effort, and reporting, we were did not compare catch weights across fishing events in the Landings data. As per Sutton et al. (2024), we therefore calculated the proportion of Atlantic Cod in the combined weight of Atlantic Cod and the target species for each fishing event, and used this proportion as the response variable in SDMs (Table 5). Values of the proportion of Atlantic Cod were zero-inflated.

To fit SDMs to Landings data, we used beta regression models (Kieschnick and Mccullough 2003; Ferrari and Cribari-Neto 2004) implemented in a hurdle model structure. Beta regression can account for heteroskedasticity when the response variable consists of continuous data bounded by 0 and 1 (Geissinger et al. 2022). Because our zero-inflated data had few records with bycatch proportions of 1, and because **sdmTMB** did not implement zero-one-inflated beta models at the time of this study, we chose to transform the data rather than exclude any from our analysis. To transform our bycatch proportions, we multiplied them by 0.99999, which maintained our values of zero for the binomial component of our hurdle models, and constrained our positive catch values (i.e., those > 0) to less than 1 for the beta component. We specified both the binomial component and the beta component with a logit link. Due to spatial differences in fishing effort and in the distribution of sGSL Atlantic Cod throughout the year, we analysed data from NAFO 4T and 4Vn in separate models.

Table 5: Summary of data sets and variables used in our spatiotemporal and spatial-only models, along with measures of fit (area under the curve (AUC), and correlation coefficients between observed and predicted values (cor)). Fisheries-independent surveys include the southern Gulf of St. Lawrence (sGSL) research vessel (RV) survey, northern Gulf of St. Lawrence (nGSL) RV survey, and the winter RV survey. Sample size, n, indicates the number of tows for survey models, and the number of fishing events for fisheries models.

Data source	Predictors	Spatio-temporal	Time	Response	Years	Months	n	AUC	cor
Model: sGSL Autumn RV, Atlantic Cod*									
survey	poly(depth_scaled, 2) + fyear	ar1	year	presence	2003-2021	Aug-Oct	2,923	0.918	-
				density (kg/tow)	2003-2021	Aug-Oct	2,126	-	0.765
Model: sGSL Autumn RV, Atlantic Halibut									
survey	poly(depth_scaled, 2)	iid	year	presence	2003-2021	Aug-Oct	2,923	0.943	-
				density (kg/tow)	2003-2021	Aug-Oct	469	-	0.497
Model: sGSL Autumn RV, Witch Flounder									
survey	poly(depth_scaled, 2)	ar1	year	presence	2003-2021	Aug-Oct	2,923	0.983	-
				density (kg/tow)	2003-2021	Aug-Oct	585	-	0.843
Model: sGSL Autumn RV, Greenland Halibut									
survey	poly(depth_scaled, 2)	iid	year	density (kg/tow)	2003-2021	Aug-Oct	2,923	-	0.978
Model: sGSL Autumn RV, Redfish*									
survey	poly(depth_scaled, 2) + fyear	ar1	year	presence	2003-2021	Aug-Oct	2,923	0.935	-
				density (kg/tow)	2003-2021	Aug-Oct	726	-	0.682
Model: nGSL Summer RV, Atlantic Cod									
survey	depth_scaled + fyear	ar1	year	presence	2003-2021	Jul-Sep	879	0.915	-
				density (kg/tow)	2003-2021	Jul-Sep	285	-	0.949
Model: nGSL Summer RV, Atlantic Halibut									
survey	poly(depth_scaled, 2) + fyear	n/a	n/a	density (kg/tow)	2003-2021	Jul-Sep	879	-	0.416
Model: nGSL Summer RV, Witch Flounder									
survey	poly(depth_scaled, 2) + fyear	n/a	n/a	presence	2003-2021	Jul-Sep	879	0.995	-
		n/a	n/a	density (kg/tow)	2003-2021	Jul-Sep	759	-	0.761
Model: nGSL Summer RV, Greenland Halibut									
survey	depth_scaled + fyear	iid	year	density (kg/tow)	2003-2021	Jul-Sep	879	-	0.917
Model: nGSL Summer RV, Redfish									
survey	depth_scaled + fyear	n/a	n/a	density (kg/tow)	2003-2021	Jul-Sep	879	-	0.589

Data source	Predictors	Spatio-temporal	Time	Response	Years	Months	n	AUC	cor
Model: GSL Winter RV, Atlantic Cod*									
survey	poly(depth_scaled, 2)	n/a	n/a	density (kg/tow)	2022-2023	Jan-Feb	58	-	0.837
Model: GSL Winter RV, Atlantic Halibut									
survey	intercept-only	n/a	n/a	presence	2022-2023	Jan-Feb	58	0.882	-
				density (kg/tow)	2022-2023	Jan-Feb	16	-	0.973
Model: GSL Winter RV, Witch Flounder									
survey	poly(depth_scaled, 2	n/a	n/a	density (kg/tow)	2022-2023	Jan-Feb	58	-	0.742
Model: GSL Winter RV, Greenland Halibut									
survey	depth_scaled	n/a	n/a	density (kg/tow)	2022-2023	Jan-Feb	58	-	0.713
Model: GSL Winter RV, Redfish*									
survey	depth_scaled	n/a	n/a	density (kg/tow)	2022-2023	Jan-Feb	57	-	0.725
Model: Landings, Atlantic Halibut-directed, NAFO 4T									
fisheries	poly(depth_scaled, 2) + month + fyear + (1 | cfvn)	iid	year	bycatch presence	2003-2021	Apr-Oct	16,531	0.931	-
				bycatch proportion	2003-2021	Apr-Oct	8,159	-	0.619
Model: Landings, Atlantic Halibut-directed, NAFO 4Vn									
fisheries	fmonth + (1 | cfvn)	iid	year	bycatch presence	2003, 2005, 2007, 2009-2021	Nov-Apr	1,539	0.945	-
				bycatch proportion	2005, 2007, 2010-2021	Nov-Apr	792	-	0.772
Model: Landings, Witch Flounder-directed, NAFO 4T									
fisheries	(1 | cfvn)	n/a	n/a	bycatch presence	2003-2019, 2021	Apr-Nov	2,026	0.810	-
				bycatch proportion	2003-2019, 2021	Apr-Nov	1,839	-	0.540
Model: Landings, Greenland Halibut-directed, NAFO 4T									
fisheries	poly(depth_scaled, 2) + fyear + (1 | cfvn)	iid	year	bycatch presence	2003-2021	Apr-Oct	15,574	0.958	-

Data source	Predictors	Spatio-temporal	Time	Response	Years	Months	n	AUC	cor
				bycatch proportion	2003-2021	Apr-Oct	1,346	-	0.819
Model: Landings, Redfish-directed, NAFO 4T*									
fisheries	depth_scaled + fmonth + fyear + (1 | cfvn)	iid	year	bycatch presence	1991-1994, 1998-2021	May-Oct	6,088	0.854	-
				bycatch proportion	1991-1994, 1998-2021	May-Oct	1,022	-	0.872
Model: Landings, Redfish-directed, NAFO 4Vn*									
fisheries	depth_scaled + fmonth + (1 | cfvn)	iid	month	bycatch presence	1990-1994, 1998-2011, 2014, 2016, 2019-2021	Nov-Apr	1,627	0.933	-
				bycatch proportion	1990-1994, 1998-1999, 2001-2003, 2005-2011, 2014, 2019, 2020	Nov-Apr	623	-	0.867

* *From Sutton et al. (2024)*

Model diagnostics

We used the function **sanity** from **sdmTMB** to assess model convergence. We used randomized quantile residuals normal Q-Q plots and histograms to assess normality, and we mapped residuals to test for spatial autocorrelation (Figures A1-A21). Model coefficients are available in Tables A1-A17.

Model predictions

To make model predictions, we first constructed a 2 x 2 km grid spanning NAFO 4TVn. We then cropped this grid as needed to make predictions associated with each model (i.e., spanning geographic areas covered by DFO surveys, or pertaining to specific fisheries, see below). After constructing prediction grids, we used the function **predict** to make predictions about densities of each species (Research Vessel SDMs) or bycatch proportions (Landings SDMs). To estimate uncertainty in the predictions, we used 100 draws from the joint precision matrix of each model to calculate coefficients of variation (Figures A22-A30). For models that included depth as a predictor, we used the functions **visreg** from the **visreg** package, version 2.7.0 (Breheny and Burchett 2017), and **visreg_delta** from **sdmTMB** to visualize the relationship between depth and our response variables, by plotting the model fitted values in the univariate case (i.e., holding other predictor variables constant). To assess conditional effects, we only considered the most recent year of data due to model complexity and computational speed.

Details for model-specific prediction grids:

- sGSL Autumn RV (NAFO 4T): Spatial extent of 45.6825°N, 49.1600°N, 60.0995°W, 65.9306°W. Excludes survey stratum 402.
- nGSL Summer RV (NAFO 4T): Spatial extent of 45.6668°N, 49.4167°N, 57.487°W, 49.4167°W.
- Winter RV (NAFO 4TVn): Spatial extent of 45.6668°N, 49.4167°N, 57.4870°W, 64.9951°W.
- Atlantic Halibut fishery (NAFO 4T): Spatial extent of 45.7626°N, 49.4157°N, 60.1595°W, 69.7030°W. Excludes eight restricted areas (Eastern Honguedo Strait Coral and Sponge Conservation Area, North of Bennett Bank Coral Conservation Area, Western Honguedo Strait Coral Conservation Area, Slope of Magdalen Shallows Coral Conservation Area, Eastern Gulf of St. Lawrence Coral Conservation Area, Banc-des-Américains Marine Protected Area zone 1, the Miscou Bank region permanently closed to the Atlantic Halibut fishery, and the Miscou Bank region seasonally closed to the Atlantic Halibut fishery (only excluded from January through June). Depths restricted to at least 5 m. Depths range from 5.00 to 505.91 m.
- Atlantic Halibut fishery (NAFO 4Vn): Spatial extent of 47.8111°N, 45.6667°N, 57.487°W, 60.4077°W. Excludes St. Anne's Bank Marine Protected Area zone 1. Depths restricted to at least 5 m. Depths range from 5.66 to 530.76 m.
- Witch Flounder fishery (NAFO 4T): Spatial extent of 46.6037°N, 49.0203°N, 60.1275°W, 64.3057°W. Excludes five restricted areas (Eastern Honguedo Strait Coral and Sponge Conservation Area, North of Bennett Bank Coral Conservation Area, Slope of Magdalen Shallows Coral Conservation Area, Eastern Gulf of St. Lawrence Coral Conservation Area, and Banc-des-Américains Marine Protected Area). Also excludes disconnected grid squares. Depths restricted to at least 100 m. Depths range from 100.01 to 510.51 m.
- Greenland Halibut fishery (NAFO 4T): Spatial extent of 48.2330°N, 49.4165°N, 62.3878°W, 69.4050°W. Excludes east of the estuary that is south of Cap Gaspé (48.7500°N), as well as

three restricted areas (Eastern Honguedo Strait Coral and Sponge Conservation Area, Western Honguedo Strait Coral Conservation Area, Banc-des-Américains Marine Protected Area). Depths restricted to at least 130 m. Depths range from 130.10 to 366.31 m.

- Redfish fishery (NAFO 4T): From Sutton et al. (2024). Spatial extent of 47.1907°N, 48.6048°N, 62.2800°W, 60.0156°W. Excludes the Slope of Magdalen Shallows Coral Conservation Area and the Eastern Gulf of St. Lawrence Coral Conservation Area. Depths restricted to at least 182.9 m (100 fathoms). Depths range from 182.9 to 514.9 m.
- Redfish fishery (NAFO 4Vn): From Sutton et al. (2024). Spatial extent of 45.6744°N, 47.8119°N, 59.0004°W, 60.3157°W. Depths restricted to at least 182.9 m (100 fathoms). Depths range from 182.9 to 532.3 m.

BYCATCH RISK AND MANAGEMENT CONSIDERATIONS

To provide considerations about bycatch risk of sGSL Atlantic Cod in the Atlantic Halibut fishery, we use predictions from a SDM fitted to commercial Landings data. We did not use models fitted to DFO RV trawl survey data, as adult Atlantic Halibut (> 80 cm) may have low catchability in these surveys (Boudreau et al. 2017; Shackell et al. 2022).

To provide considerations about bycatch risk of sGSL Atlantic Cod in the Witch Flounder fishery, we used SDMs fitted to data from DFO sGSL RV trawl surveys. We did not use models fitted to commercial Landings data due to extremely limited geographic variation in recent years. Both DFO surveys overlap with areas that are open to the Witch Flounder fishery. We used sGSL models rather than nGSL, because the sGSL data had the greatest overlap with the Landings data.

To provide considerations about bycatch risk Atlantic Cod in the Greenland Halibut fishery, we used SDMs fitted to commercial Landings data and SDMs fitted to nGSL Summer RV survey data. The nGSL RV survey overlaps with the geographic area open to commercial fishing.

To provide considerations about bycatch risk Atlantic Cod in the Redfish fishery, we summarize the findings of Sutton et al. (2024), which used SDMs fitted to commercial Landings data and to DFO sGSL Autumn and GSL Winter RV trawl surveys. Here, we additionally compared SDMs fitted to nGSL Summer trawl survey data. All three DFO surveys overlap with areas and times that are of interest to the newly re-opened commercial Redfish fishery.

Atlantic Halibut fishery

We used predictions made on the fishery grid to estimate amounts of Atlantic Cod bycatch under scenarios with different Atlantic Halibut TACs and different fishing restrictions. The grid assumed equal fishing effort across space. For each grid cell, we averaged model predicted bycatch proportions by month across most recent years of data beginning with year 2017. We estimated the total tonnes of Atlantic Cod bycatch in each cell as:

$$a \; x \; b \; x \; TAC[i] \qquad 2$$

, where *a* is the model predicted proportion of bycatch, *b* is the expected proportion of TAC caught per month, calculated by dividing the total Landings of Atlantic Halibut per month divided by the total Landings of Atlantic Halibut, and *TAC[i]* is a given annual TAC allowance. We then summed the results across grid cells.

For the first scenario, we estimated Cod bycatch over the entire fishing grid for months April through October, which reflected the spatial area and seasons of the raw Landings data. For additional scenarios, we proposed fishing area closures and/or depth restrictions associated with high bycatch risk. In each scenario, we assumed equal fishing effort across space.

Witch Flounder fishery

We used the sGSL Autumn RV models for Atlantic Cod and Witch Flounder to make predictions of the catch density of each species over the fishing grid. Then we calculated the relative proportion of Atlantic Cod in the combined predictions of both species, and inferred these proportions to be a survey-based proxy of bycatch risk. For each grid cell, we averaged predictions by month for years 2017 onward, and we used these values to estimate expected amounts of Cod bycatch under scenarios with different Witch Flounder TACs and different fishing restrictions. We estimated the expected amounts of Atlantic Cod bycatch by using equation 2. In each scenario, we assumed equal fishing effort across space.

Greenland Halibut fishery

We used the nGSL Summer RV models for Atlantic Cod and Greenland Halibut to make predictions of the catch density of each species over the fishing grid. Then we calculated the relative proportion of Atlantic Cod in the combined predictions of both species, and inferred these proportions to be a survey-based proxy of bycatch risk. For each grid cell, we averaged predictions by month for years 2017 onward. We compared these RV-based bycatch estimates to the Landings model estimates made over the same grid, averaged over the same years. We estimated the expected amounts of Atlantic Cod bycatch by using equation 2. In each scenario, we assumed equal fishing effort across space.

Redfish fishery

We summarize the results and considerations for Fisheries and Harbour Management made in Sutton et al. (2024). For each grid cell, predictions were averaged by month across all years of data (1990 to 2021), to preserve years when there was an existing commercial Redfish fishery. Estimates of the total tonnes of Atlantic Cod bycatch were made with a modification of equation 2, which excluded *b*, the expected proportion of TAC caught per month (i.e., because details were not yet available for the re-opening of the commercial fishery, it was assumed that the full annual TAC could be restricted to any individual month). Each scenario assumed equal fishing effort across space.

RESULTS

MODEL PREDICTIONS AND DEPTH EFFECTS

Fisheries-independent surveys

sGSL Autumn RV

Predictions from the sGSL Autumn RV Atlantic Cod model demonstrated a long-term distribution shift from shallow (inshore) to deeper (offshore) water (Figure 11), which has been previously documented (Swain et al. 2019; Sutton et al. 2024). Over time, there was a shift northward from the SW Magdalen Shallows toward the Gaspé Peninsula and along the southern slope of the Laurentian Channel. In contrast to Cod, there was little change in spatial distribution over time of the other species. For Atlantic Halibut, the greatest predicted densities occurred east of the Gaspé Peninsula, along the southern slope of the Laurentian Channel, into the Cape Breton Trough, and finally the east side of the Magdalen Islands. However, this distribution may not be a good reflection of adult Atlantic Halibut, due to the above noted poor catchability in the RV trawl surveys. Witch Flounder were predicted to occur almost exclusively in deeper water northeast of the Gaspé Peninsula, along the Laurentian Channel, and into the Cape Breton Trough. Greenland Halibut and Redfish were similarly distributed in deeper waters of the Laurentian Channel, however, Greenland Halibut were most concentrated near the western boundary of the prediction grid.

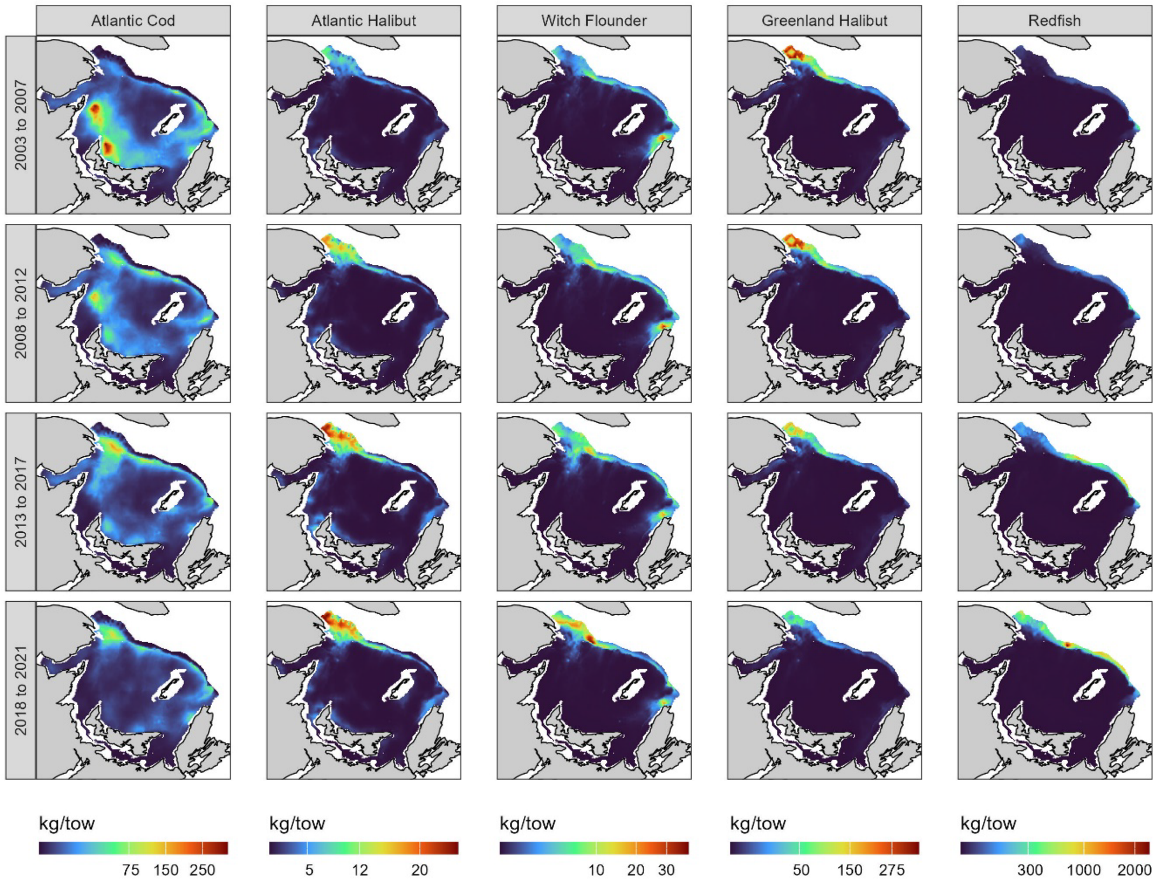

Figure 11: From left to right, distribution of Atlantic Cod, Atlantic Halibut, Witch Flounder, Greenland Halibut, and Redfish over time, based on southern Gulf of St. Lawrence Autumn research vessel models.

Plots of the conditional effect of depth on species probability of occurrence and catch densities indicated overlap in depth-use profiles of all species (Figure 12). The greatest overlaps with Atlantic Cod occurred with Atlantic Halibut. Witch Flounder, Greenland Halibut, and Redfish were generally more associated with deeper water.

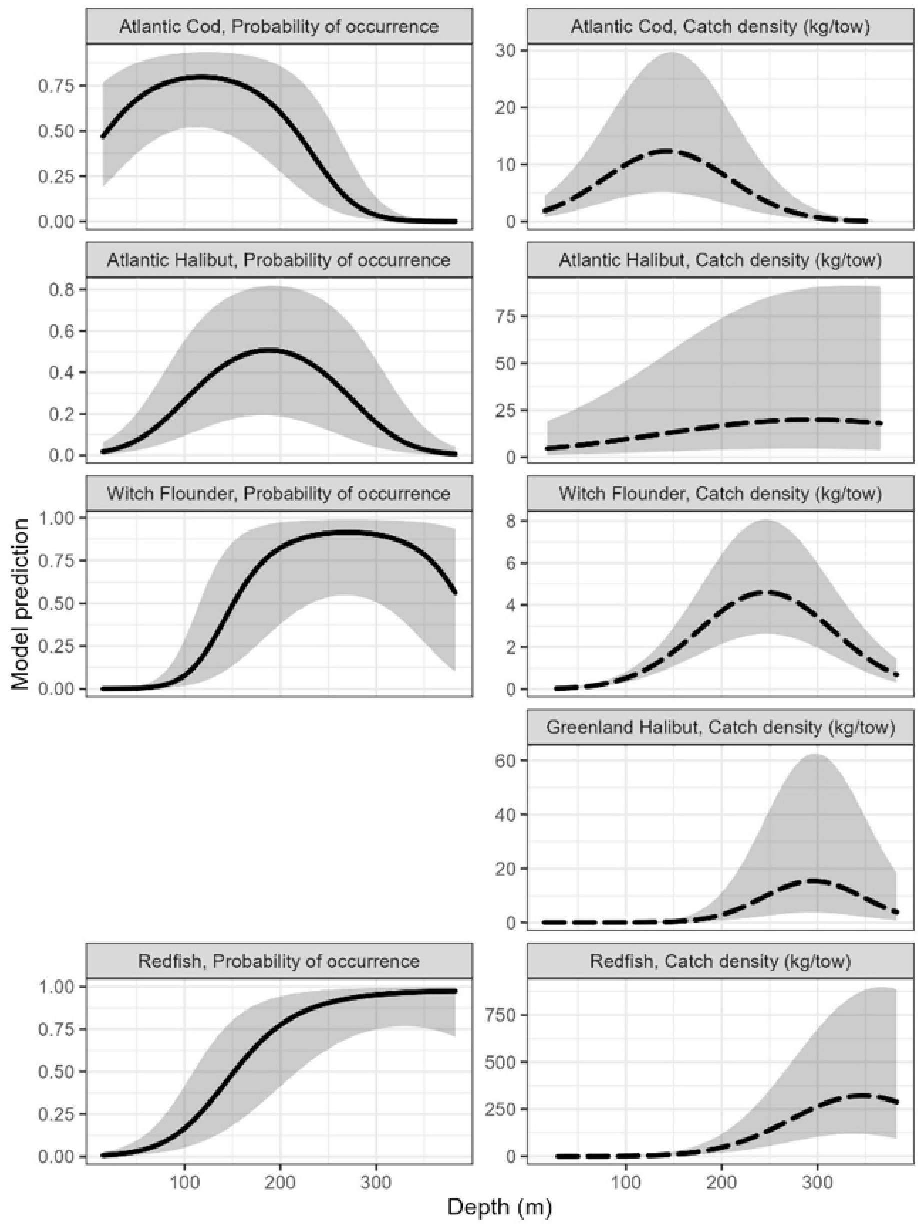

Figure 12: Conditional effect of depth on Atlantic Cod (top row), Atlantic Halibut (second row), Witch Flounder (third row), Greenland Halibut (fourth row), and Redfish (bottom row), based on southern Gulf of St. Lawrence Autumn research vessel models. Left-hand panels indicate probability of occurrence; right-hand columns indicate catch density. Empty panels indicate models that did not include a binomial component.

nGSL Summer RV

Over the time series, there were no shifts in the spatial distribution of species over the nGSL Summer RV spatial grid, although there were changes in overall densities of some species (Figure 13). Predicted Cod densities were greatest in the shallower areas, which included areas east of the Gaspé Peninsula and north of the Cape Breton Trough. Atlantic Halibut predicted densities were concentrated along the southern slope of the Laurentian Channel, around the Gaspé Peninsula, and into the estuary. Witch Flounder and Greenland Halibut predicted densities increased from east to west. Redfish predicted densities were greatest in the centre and eastern portions of the Laurentian Channel.

Plots of the conditional effect of depth on species probability of occurrence and catch densities indicated overlap in depth-use profiles of all species (Figure 14). As with the sGSL Autumn RV models, Atlantic Cod appeared to decrease in probability of occurrence and in catch density at deeper depths, and Atlantic Halibut showed the greatest overlap with Cod.

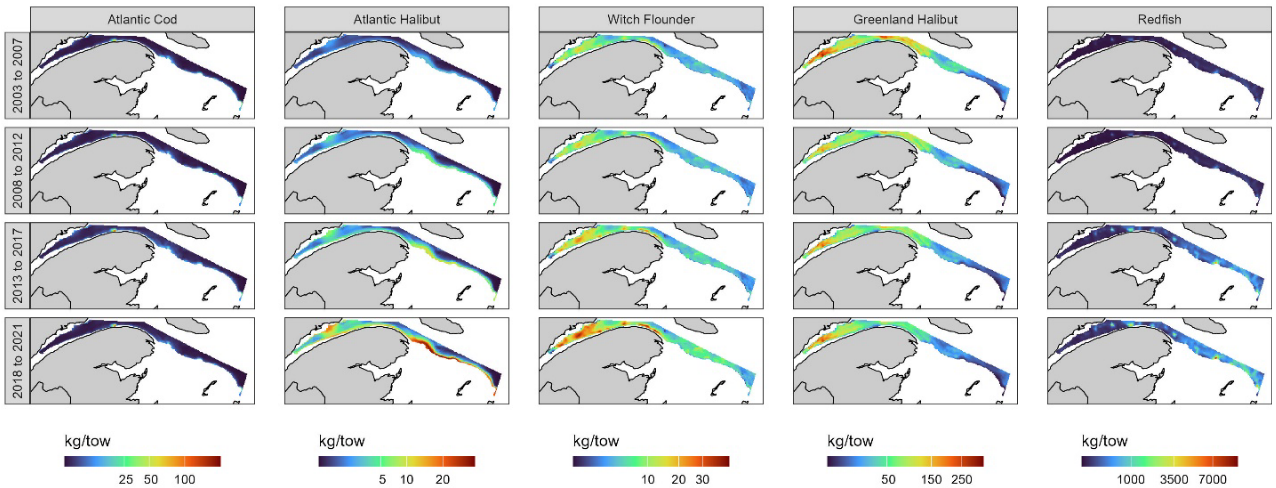

Figure 13: From left to right, distribution of Atlantic Cod, Atlantic Halibut, Witch Flounder, Greenland Halibut, and Redfish over time based on northern Gulf of St. Lawrence Summer research vessel models.

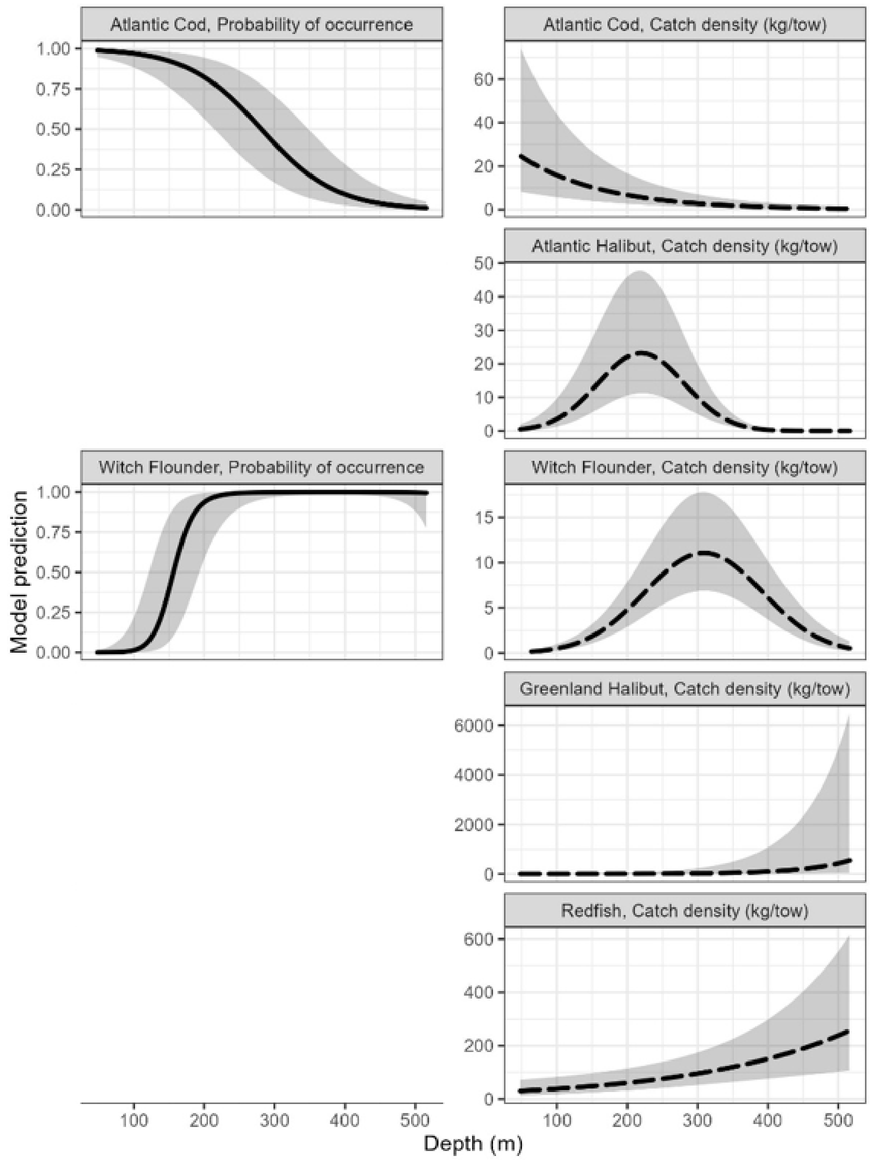

Figure 14: Conditional effect of depth on Atlantic Cod (top row), Atlantic Halibut (second row), Witch Flounder (third row), Greenland Halibut (fourth row), and Redfish (bottom row), based on northern Gulf of St. Lawrence Summer research vessel models. Left-hand panels indicate probability of occurrence; right-hand panels indicate catch density. Empty panels indicate models that did not include a binomial component.

Winter RV

Winter RV model predicted Atlantic Cod densities were greatest near the northwest tip of Cape Breton Island and along the southern slopes of the Laurentian Channel toward the Magdalen Islands (Figure 15). The patchy predicted distribution of Atlantic Halibut reflected the low catchability of this species in the RV surveys. Witch flounder predicted densities were greater in deeper water compared to Atlantic Cod, and were more evenly distributed throughout 4TVn. Greenland Halibut predicted densities were greatest northeast of the Gaspé Peninsula and in discontinuous pockets across the grid. Redfish predicted densities were concentrated in deeper waters of the Laurentian Channel, particularly in the eastern portion of NAFO 4T and into NAFO 4Vn.

Plots of the conditional effect of depth on species catch densities indicated some overlap in depth-use profiles of all species (Figure 16). As with the sGSL Autumn RV and nGSL Summer RV models, Atlantic Cod catch densities were low at deeper depths.

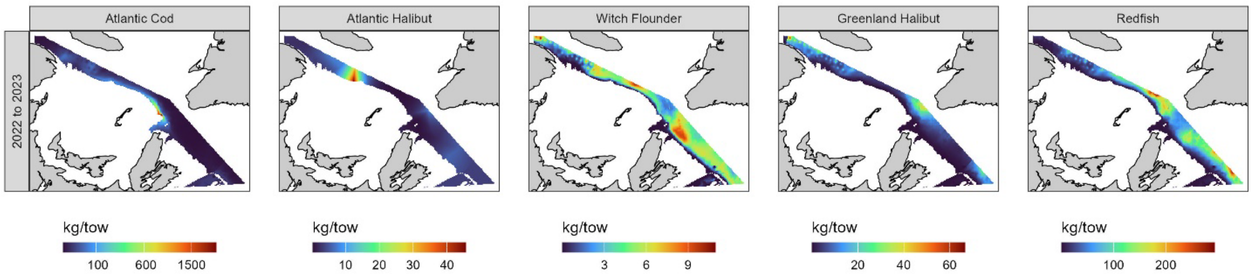

Figure 15: Distribution of Atlantic Cod, Atlantic Halibut, Witch Flounder, Greenland Halibut, and Redfish over time based on Gulf of St. Lawrence Winter research vessel models.

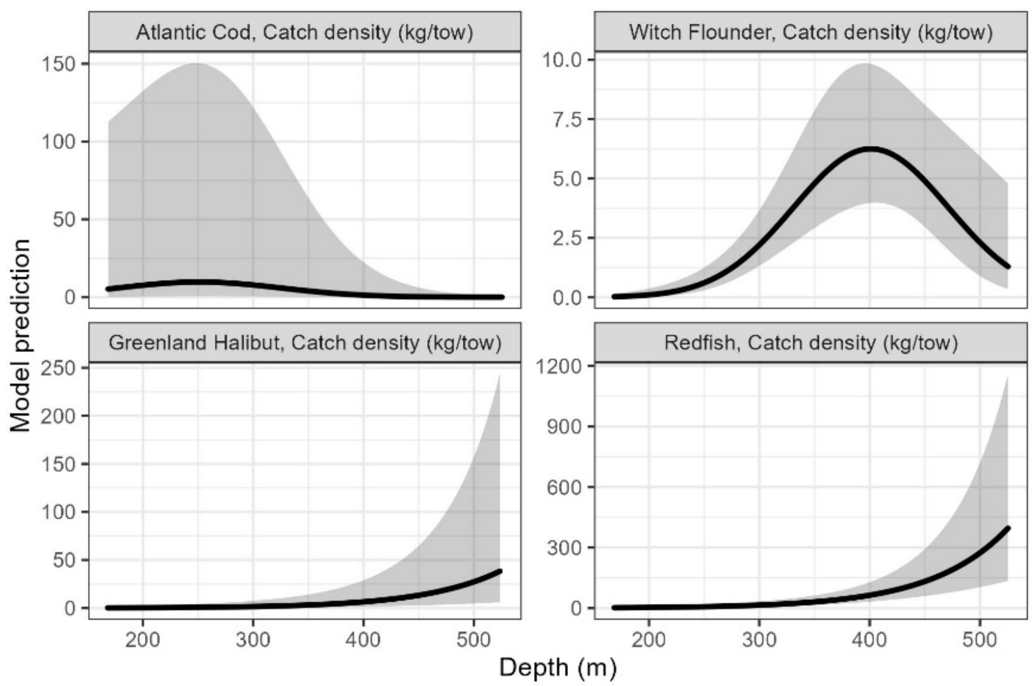

Figure 16: Conditional effect of depth on catch densities of Atlantic Cod (top left), Witch Flounder (top right), Greenland Halibut (bottom left), and Redfish (bottom right) based on Gulf of St. Lawrence Winter research vessel models. Atlantic Halibut is absent from the plot because depth was not a fixed factor in the model. Winter RV models did not include a binomial component.

Fisheries-dependent landings

Atlantic Halibut fishery

Averaging over years 2017 onward, areas associated with higher predicted bycatch in the Atlantic Halibut fishery occurred east of the Gaspé Peninsula, in the northeast region of the Cape Breton Trough, immediately east of the Magdalen Islands, north of central PEI, and in pockets along the southern slope of the Cape Breton Trough as well as north of the Gaspé

Peninsula (Figure 17). These locations corresponded with areas of high Cod densities (Figure 11). Averaging across months, the probability of Cod bycatch in year 2021 peaked (i.e., at least 90% of its maximum probability) at depths approximately greater than 202 m (Figure 18). The proportion of Cod bycatch was greatest (i.e., above the mean) between depths of approximately 53 m and 343 m (Figure 18). Greater risk of Cod bycatch in the Atlantic Halibut NAFO 4Vn fishery occurred in an area in the western region of 4Vn (Figure 19).

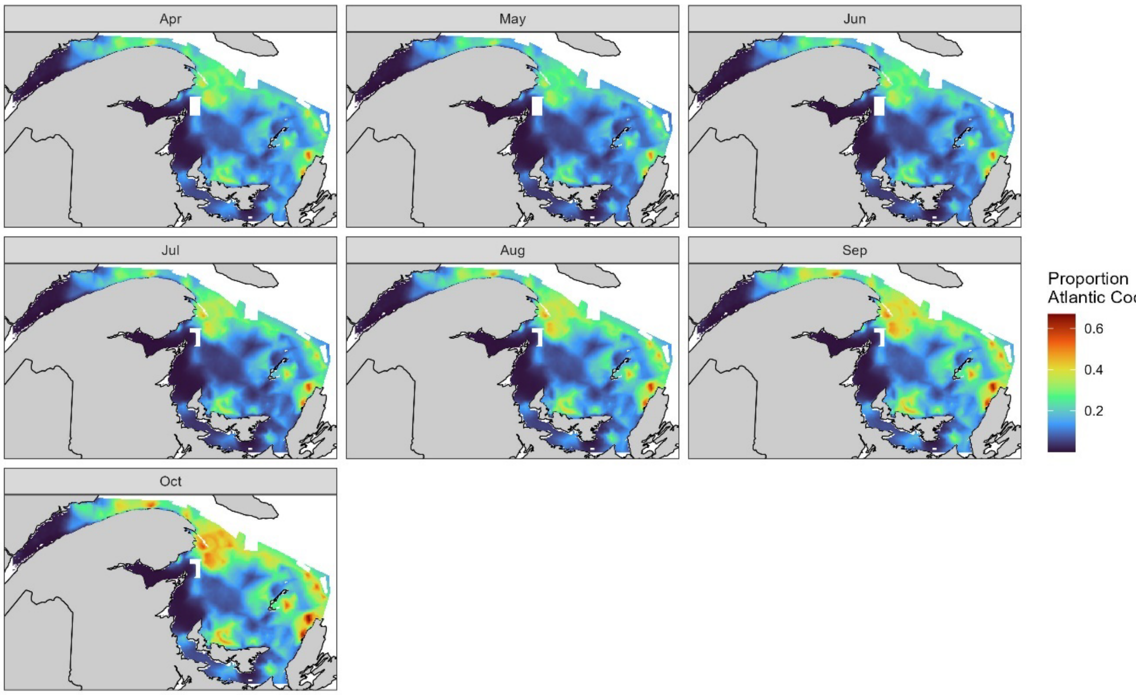

Figure 17: Landings model predicted bycatch of Atlantic Cod in a NAFO 4T Atlantic Halibut fishery. Predictions were made over a spatial grid where Atlantic Halibut-directed fishing is assumed to be permitted. Predictions were averaged from years 2017 onward.

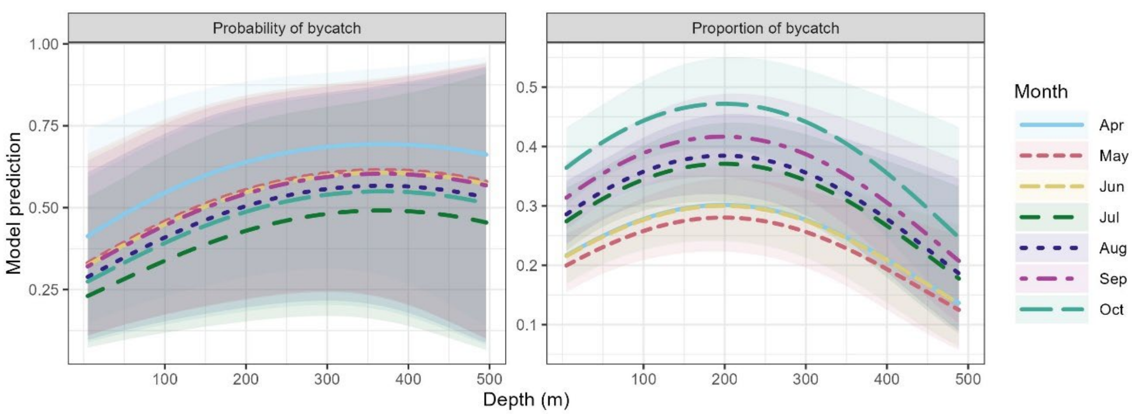

Figure 18: Conditional effect of depth on the probability (left) and proportion (right) of Atlantic Cod bycatch in the Atlantic Halibut NAFO 4T fishery, based on a Landings model.

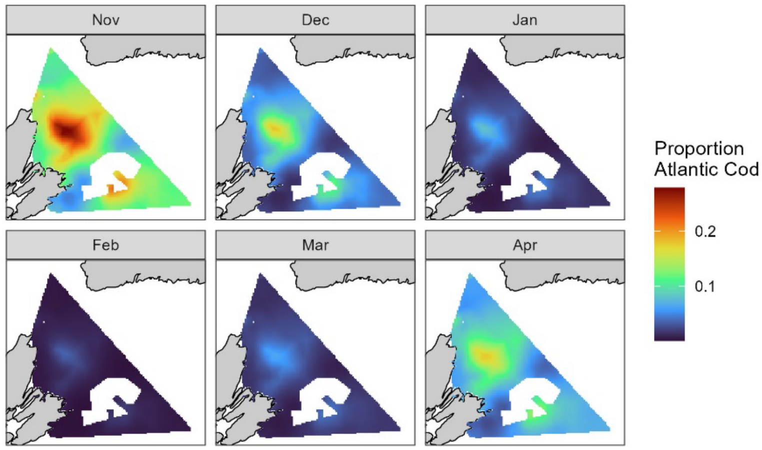

Figure 19: Landings model predicted bycatch of Atlantic Cod in a NAFO 4Vn Atlantic Halibut fishery. Predictions were made over a spatial grid where Atlantic Halibut-directed fishing is assumed to be permitted. Predictions were averaged from years 2017 onward.

Witch Flounder fishery

The Witch Flounder NAFO 4T Landings model performed poorly at predicting across the spatial area associated with the fishing grid, probably due to the very limited spatial area included in the raw data (Figure 20). We therefore did not include this model in developing future management considerations. For comparison, we calculated the relative proportion of Atlantic Cod in the combined predictions of Atlantic Cod and Witch Flounder from the sGSL RV and GSL RV models. Both RV models suggested that Atlantic Cod generally occurred at higher densities relative to Witch Flounder along the southern slope of the Laurentian Channel. Immediately northwest of Cape Breton, where commercial fishing is concentrated, predicted densities of each species were more similar, resulting in intermediate bycatch proportions.

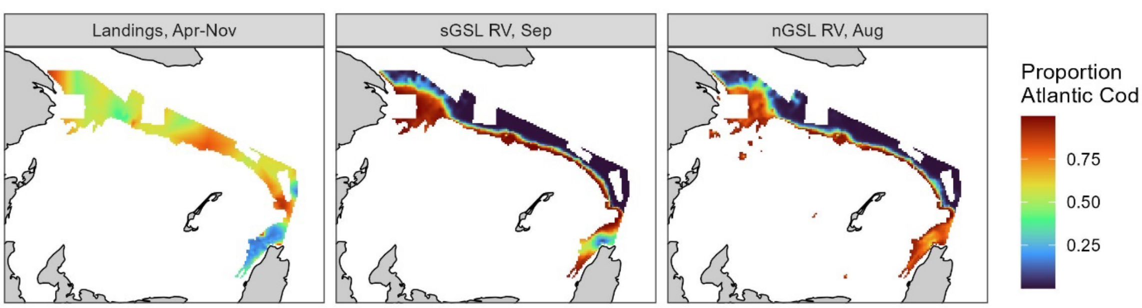

Figure 20: Landings and RV model predicted bycatch of Atlantic Cod in a NAFO 4T Witch Flounder fishery. Predictions were made over a spatial grid where Witch Flounder-directed fishing is assumed to be permitted. sGSL RV and nGSL RV predictions were averaged over years 2017 onward.

Greenland Halibut fishery

The Greenland Halibut NAFO 4T Landings model indicated that greatest risk of Atlantic Cod bycatch occurred east of Cap Gaspé, and in the shallow water immediately north of the peninsula (Figure 21). Year 2021 probability of Cod bycatch peaked at depths shallower than 134 m (Figure 22), however, it should be noted that that the minimum depth for data used in the model was 130 m. The proportion of Atlantic Cod bycatch was greatest at depths shallower than approximately 199 m.

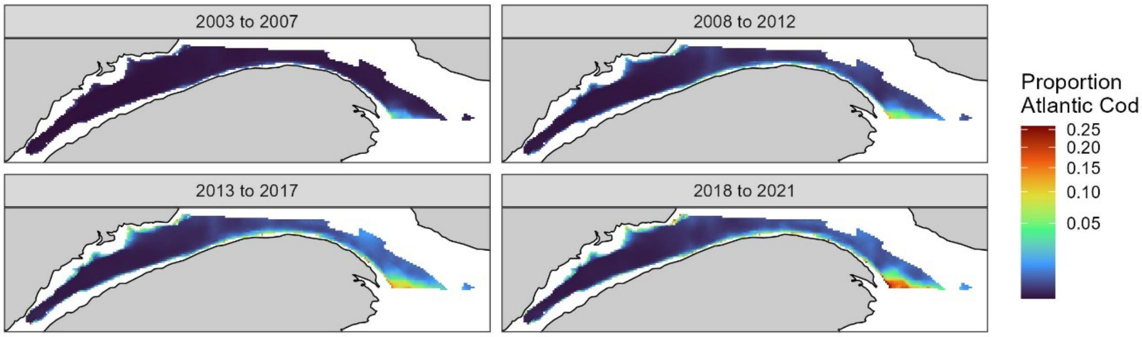

Figure 21: Landings model predicted bycatch of Atlantic Cod in a NAFO 4T Greenland Halibut fishery. Predictions were made over a spatial grid where Greenland Halibut-directed fishing is assumed to be permitted. Predictions were averaged over the years indicated.

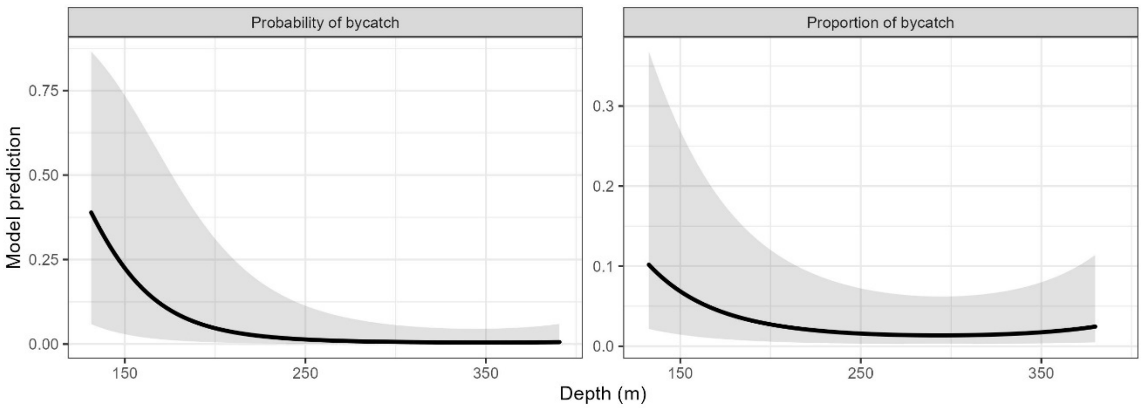

Figure 22: Conditional effect of depth on the probability (left) and proportion (right) of Atlantic Cod bycatch in the Greenland Halibut NAFO 4T fishery, based on a Landings model.

Redfish fishery

Within NAFO 4T, Landings model predictions indicated that greatest risk of Atlantic Cod bycatch was along the southern slope of the Laurentian Channel (Figure 23). Within NAFO 4Vn landing model predictions indicated that Atlantic Cod bycatch tended to occur in more shallow areas of the fishing grid, especially near the southwest corner (Figure 23). However, there were occasional hotspots in deeper water, which corresponded to large bycatch events in the raw data.

Averaging across months, year 2021 probability of Atlantic Cod bycatch in NAFO 4T peaked at depths shallower than approximately 142 m (Figure 24). The proportion of Atlantic Cod bycatch in NAFO 4T was greatest at depths shallower than approximately 295 m. Averaging across months, year 2021 probability of Atlantic Cod bycatch in NAFO 4Vn peaked between approximate depths 140 m to 400 m. The proportion of Atlantic Cod bycatch in NAFO 4Vn was greatest at depths shallower than approximately 316 m.

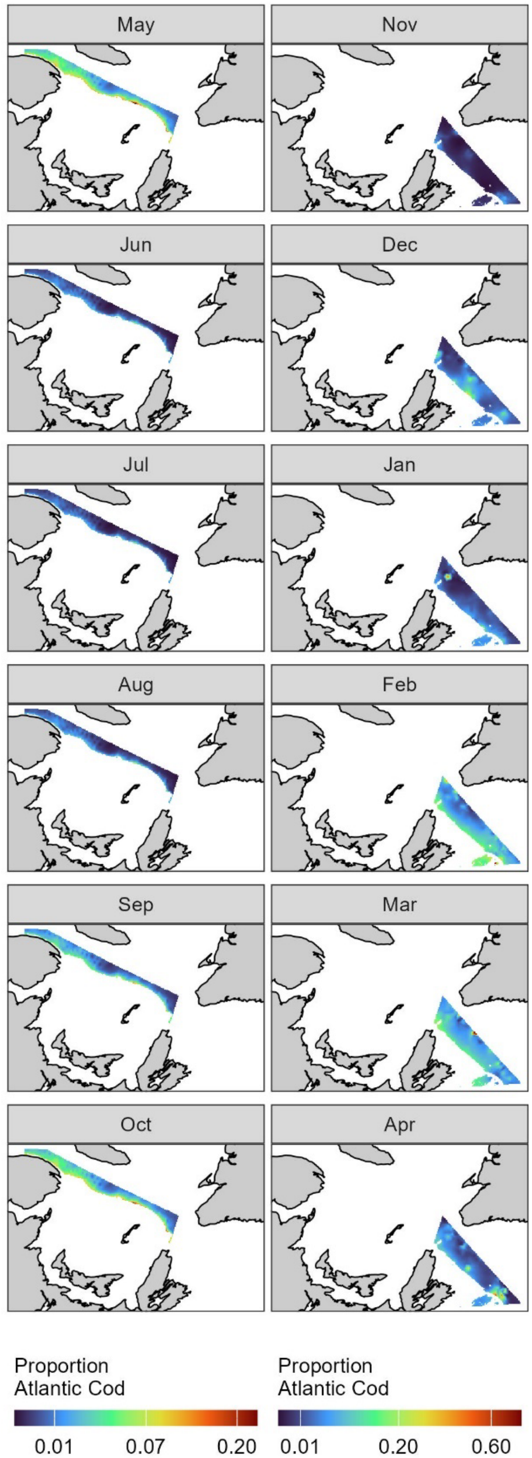

Figure 23: Landings model predicted bycatch of Atlantic Cod in NAFO 4T (left) and NAFO 4Vn (right) Redfish fisheries. Predictions were made over a spatial grid where Redfish-directed occurred historically. Predictions were averaged over all years, to include years in which commercial fishing occurred.

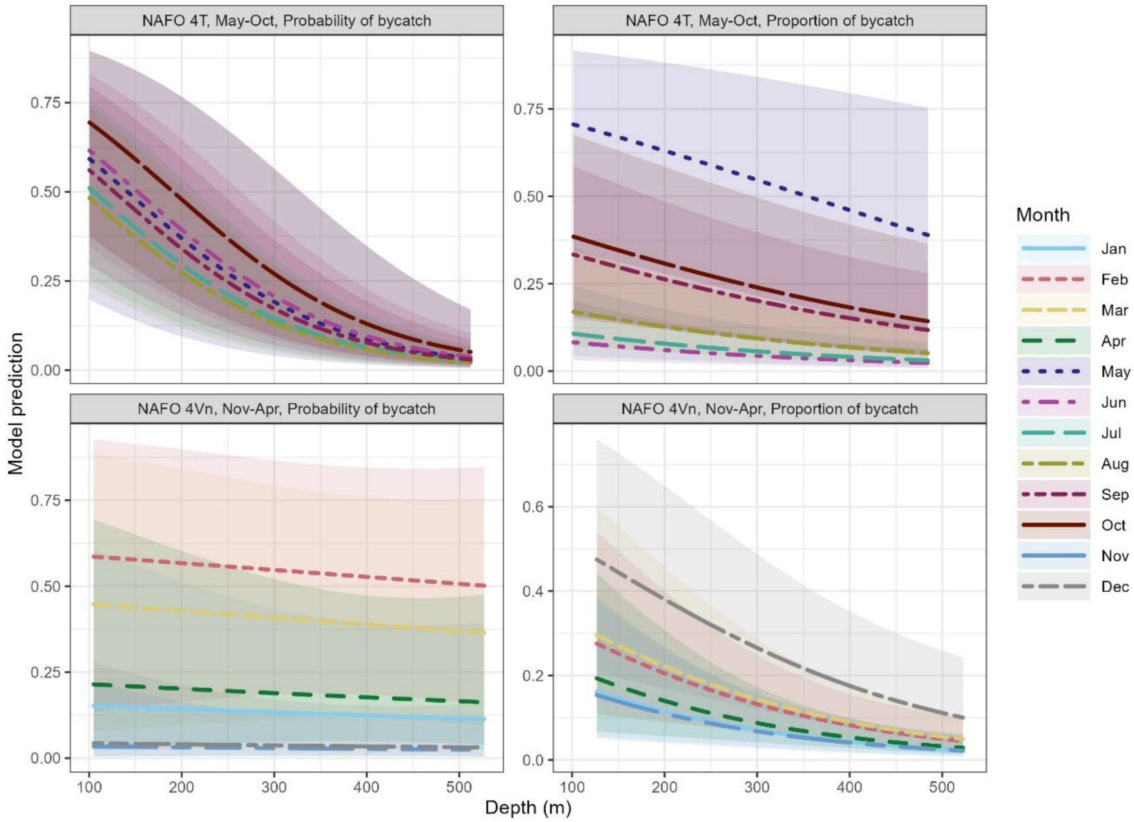

Figure 24: Conditional effect of depth on the probability (left) and proportion (right) of Atlantic Cod bycatch in the Redfish NAFO 4T (top) and Redfish NAFO 4Vn (bottom) fisheries, based on Landings models.

BYCATCH RISK AND MANAGEMENT CONSIDERATIONS

Atlantic Halibut fishery

Atlantic Halibut, NAFO 4T

Based on the spatial bycatch patterns described above, we implemented scenarios with area- and depth-specific strategies to mitigate Atlantic Cod bycatch in the Atlantic Halibut NAFO 4T fishery (Table 6 and Figure 25). Our scenarios included area closures (Banc-des-Américains Marine Protected Area zones 2a and 2b and eight additional closures), and a seasonal depth restriction (between 100 to 280 m for September and October). For each scenario, we considered TACs of 500 t, 1,000 t, and 1,500 t. All predictions were based on the Landings model.

Compared to the current fishing grid, the scenario with permanent area closures and a seasonal depth closure reduced predicted bycatch by an average of 17.5% per month. Compared to the current fishing grid, the scenario with only permanent area closures reduced predicted bycatch by an average of 14.8%. Compared to the current fishing grid, the scenario with only a seasonal depth closure reduced predicted bycatch by an average of 13.2%.

Table 6: Expected tonnes (t) of southern Gulf of St. Lawrence (sGSL) Atlantic Cod bycatch with different Atlantic Halibut NAFO 4T TACs and minimum fishing depths. Predictions were made from the model, "Landings, Atlantic Halibut, NAFO 4T". Predictions were averaged over years 2017 onward.

Month	Exp. Prop. TAC	TAC: 750	TAC: 1,000	TAC: 1,500	Percent change from current
Scenario: Current					
Apr	0.07	9	12	18	-
May	0.06	6	8	13	-
Jun	0.14	17	23	35	-
Jul	0.35	46	61	91	-
Aug	0.21	32	43	64	-
Sep	0.12	22	30	45	-
Oct	0.06	11	15	23	-
	Total	**144**	**192**	**289**	-
Scenario: Area closures only					
Apr	0.07	8	11	16	12.8
May	0.06	5	7	11	14.2
Jun	0.14	15	20	30	14.3
Jul	0.35	38	51	76	16.6
Aug	0.21	27	36	54	15.3
Sep	0.12	19	26	38	14.8
Oct	0.06	10	13	19	16.0
	Total	**122**	**163**	**244**	**Average: 14.8**
Scenario: Seasonal depth closure (100 – 280 m) only					
Apr	0.07	9	12	18	-
May	0.06	6	8	13	-
Jun	0.14	17	23	35	-
Jul	0.35	46	61	91	-
Aug	0.21	32	43	64	-
Sep	0.12	20	26	39	12.5
Oct	0.06	10	13	20	13.8
	Total	**140**	**187**	**280**	**Average: 13.2**
Scenario: Area closures and seasonal depth closure (100 – 280 m)					
Apr	0.07	8	11	16	12.8
May	0.06	5	7	11	14.2
Jun	0.14	15	20	30	14.3
Jul	0.35	38	51	76	16.6
Aug	0.21	27	36	54	15.3
Sep	0.12	17	23	34	23.7
Oct	0.06	8	11	17	25.7
	Total	**119**	**159**	**238**	**Average: 17.5**

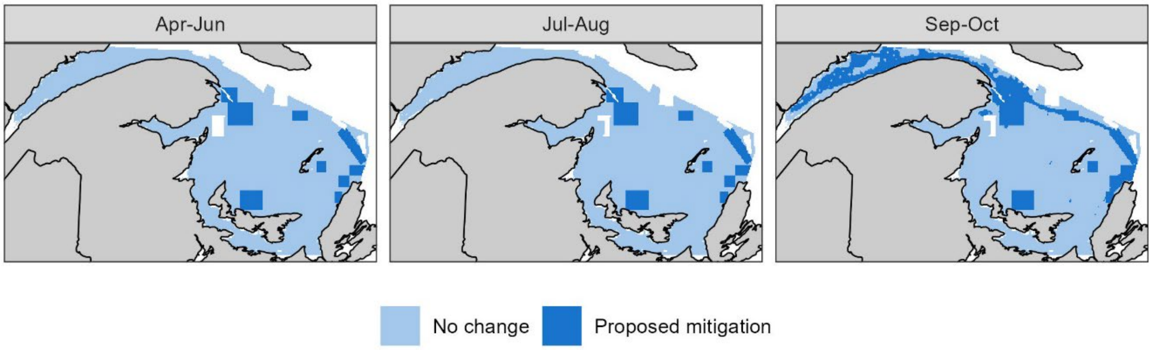

Figure 25: Map of the Atlantic Halibut NAFO 4T fishing grid, indicating, indicating locations considered in the bycatch scenarios.

Atlantic Halibut, NAFO 4Vn

Based on the spatial bycatch patterns described above, we implemented a scenario with one area-specific closure to mitigate Atlantic Cod bycatch in the Atlantic Halibut NAFO 4Vn fishery (Table 7 and Figure 26). We considered TACs of 750 t, 1,000 t, and 1,500 t. All predictions were based on the Landings model. Compared to the current fishing grid, the proposed area closure reduced bycatch by an average of 13.8% per month.

Table 7: Expected tonnes (t) of southern Gulf of St. Lawrence (sGSL) Atlantic Cod bycatch with different Atlantic Halibut NAFO 4Vn TACs and minimum fishing depths. Predictions were made from the model, "Landings, Atlantic Halibut, NAFO 4Vn". Predictions were averaged over years 2017 onward.

Scenario	Month	TAC: 750	TAC: 1,000	TAC: 1,500	Percent change from current
Current	Nov	17.1	22.7	34.1	-
	Dec	9.4	12.6	18.9	-
	Jan	0.7	1.0	1.5	-
	Feb	0.2	0.3	0.4	-
	Mar	3.7	4.9	7.4	-
	Apr	26.4	35.2	52.7	-
	Total	**57.5**	**76.6**	**114.9**	-
Area closure	Nov	15.3	20.4	30.7	10.1
	Dec	8.0	10.7	16.0	15.3
	Jan	0.6	0.8	1.2	16.4
	Feb	0.2	0.2	0.3	17.9
	Mar	3.2	4.3	6.4	12.8
	Apr	23.7	31.6	47.4	10.1
	Total	**51.0**	**68.0**	**102.0**	**Average 13.8**

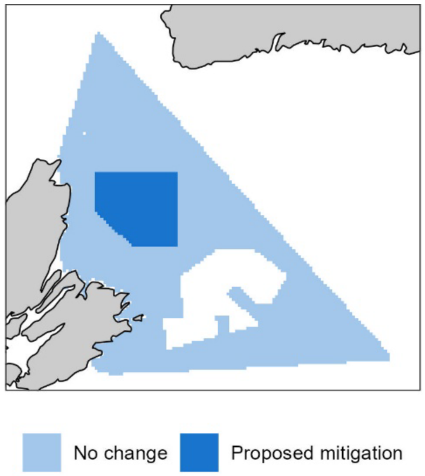

Figure 26: Map of the Atlantic Halibut NAFO 4Vn fishing grid indicating the location considered in the bycatch scenario.

Witch Flounder fishery

Based on the spatial bycatch patterns described above, we implemented scenarios with minimum fishing depths of 100 m, 180 m, 200 m, and 220 m, and Witch Flounder TACs of 250 t, 500 t, and 1,000 t (Table 8 and Figure 27). For each scenario, we derived the expected bycatch of Atlantic Cod from the sGSL RV Atlantic Cod and sGSL RV Witch Flounder model predictions. Assuming equal effort across the fishing grid, the inclusion of the most shallow depths resulted in greater predicted tonnage of Atlantic Cod than Witch Flounder. By comparison, the scenarios with deeper minimum fishing depths resulted in 95 to 99% reductions in expected tonnes of Cod bycatch.

Table 8: Expected tonnes (t) of southern Gulf of St. Lawrence (sGSL) Atlantic Cod bycatch with different Witch Flounder NAFO 4T TACs and minimum fishing depths. Predictions were made from the models, "sGSL Autumn RV, Atlantic Cod" and "sGSL Autumn RV, Witch Flounder". Predictions were averaged over years 2017 onward.

Scenario	TAC: 250	TAC: 500	TAC: 1,000	Percent change from current
Min. depth 100 m (current)	3,115	6,230	12,459	-
Min. depth 180 m	147	294	588	95.3
Min. depth 200 m	78	156	312	97.5
Min. depth 220 m	44	88	175	98.6

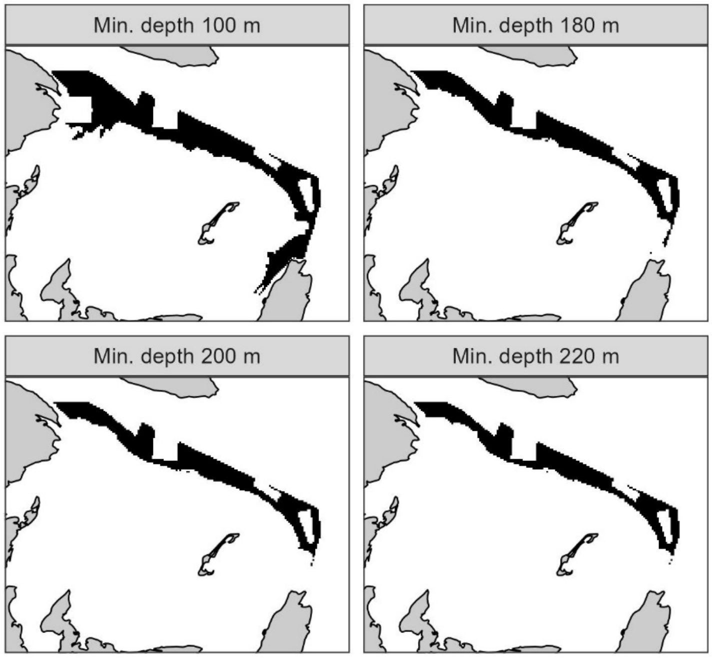

Figure 27: Map of the Witch Flounder fishing grid indicating depths considered in the bycatch scenarios.

Greenland Halibut fishery

Based on the spatial bycatch patterns described above, we implemented scenarios with an area closure and minimum fishing depths of 180 m and 200 m for Greenland Halibut TACs of 750 t, 1,000 t, and 1,500 t (Table 9 and Figure 28). The area closure was assigned by shifting the eastern latitude limit from Cap Gaspé to Les Trois-Ruisseaux (48.9164°N). For each scenario, we derived the expected bycatch of Atlantic Cod from the Landings model as well as from the nGSL Summer RV Atlantic Cod and Greenland Halibut models (Figure 29). Assuming equal effort across the fishing grid, the scenario with the area closure and a minimum fishing depth of 200 m resulted in 81% to 84% reductions in expected tonnes of Atlantic Cod bycatch. In practice, the proposed area closure combined with a minimum fishing depth of 200 m is likely to impact only a small proportion of Greenland Halibut harvesters, as the majority of fishing events between 2017 to 2021 occurred in locations and depths where no changes to current bycatch mitigation practices are proposed (Figure 28).

Table 9: Expected tonnes (t) of southern Gulf of St. Lawrence (sGSL) Atlantic Cod bycatch with different Greenland Halibut NAFO 4T TACs scenarios. Predictions were made from the models, “Landings, Greenland Halibut”, “nGSL Summer RV, Atlantic Cod” and “nGSL Summer RV, Greenland Halibut”. Predictions were averaged over years 2017 onward.

Model	Scenario	TAC: 750	TAC: 1,000	TAC: 1,500	Percent change from current
Landings	Current	9	12	18	-
	Area closure	5	7	11	40.4
	Area closure and min. depth 180	2	3	4	76.1
	Area closure and min. depth 200	2	2	3	81.3
nGSL RV	Current	92	123	184	-
	Area closure	80	106	160	13.1
	Area closure and min. depth 180	39	53	79	57.2
	Area closure and min. depth 200	15	20	29	84.0

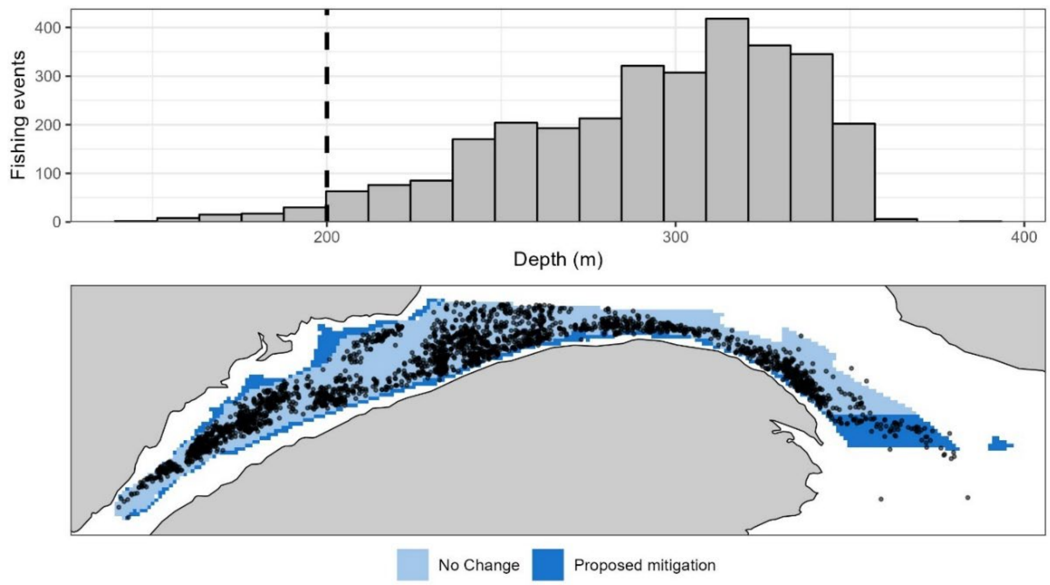

Figure 28: Histogram of Greenland Halibut fishing events by depth from 2017 to 2021, with a vertical line indicating the proposed minimum fishing depth of 200 m (top), and map of the Greenland Halibut fishing grid indicating a bycatch mitigation scenario with an area closure and a minimum fishing depth of 200 m (bottom). The bottom panel also shows the locations of fishing events from 2017 to 2021.

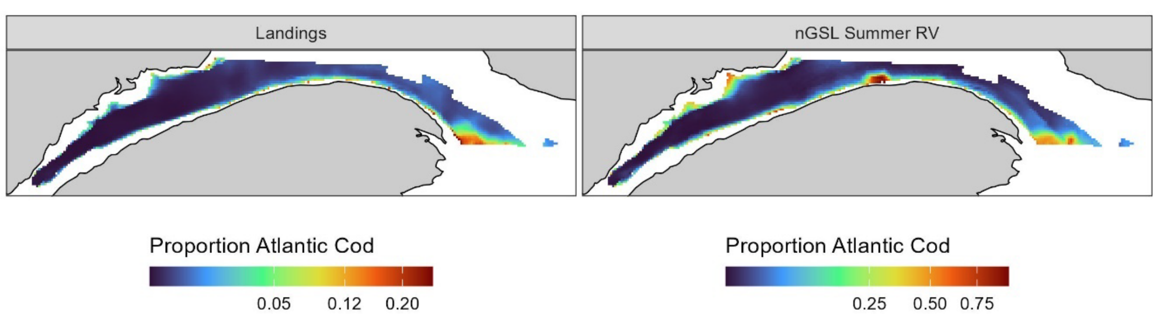

Figure 29: Model-predicted proportion of Atlantic Cod based on Landings and nGSL Summer RV models. Predictions were averaged from years 2017 onward.

Redfish fishery

Redfish, NAFO 4T

Sutton et al. (2024) implemented a current bycatch scenario using the area and season open to the Redfish Unit 1 index and experimental fishery (Figure 30), and a proposed bycatch scenario that limited fishing to months June through August, and which included both an area closure and a minimum fishing depth of 300 m (Table 10 and Figure 31). For each scenario, they derived the expected bycatch of Atlantic Cod from Landings and RV models. Model predicted bycatch in the proposed scenario was reduced by at least 56% compared to historical fishing and at least 46% compared to current scenario (estimates derived from the Landings model predictions, averaged over all months considered). As commercial harvesting plans were not available at the time of their study, Sutton et al. (2024) assumed that each TAC could be set for any individual month.

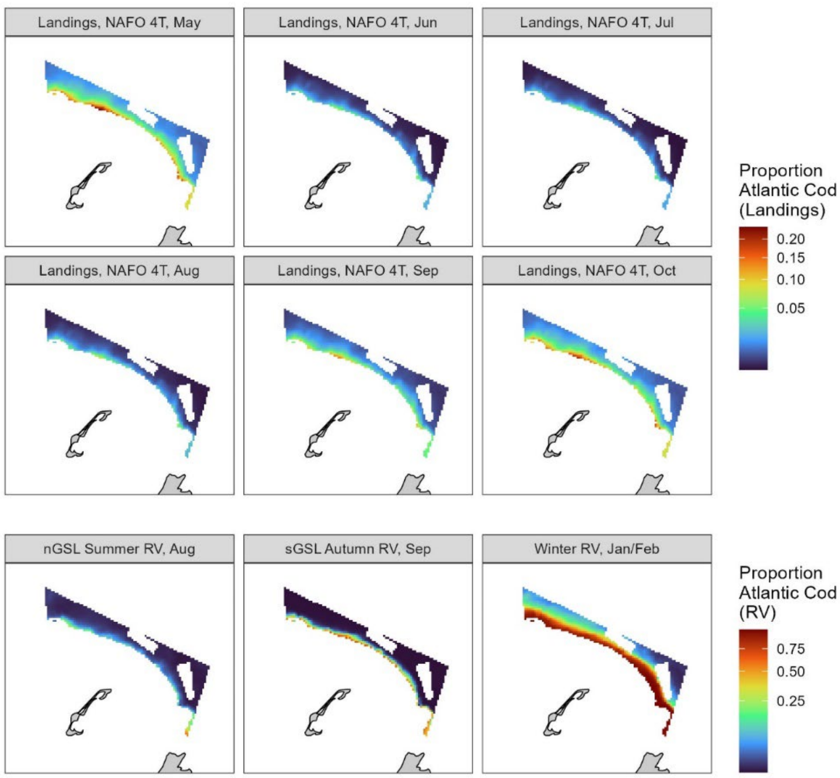

Figure 30: Model predicted proportion of Atlantic Cod over the current NAFO 4T Redfish fishing grid, based on Landings and RV models. Predictions were averaged over all years.

Table 10: From Sutton et al. (2024). Expected tonnes (t) of southern Gulf of St. Lawrence (sGSL) Atlantic Cod bycatch with different Redfish NAFO 4T TACs scenarios. Predictions were made from the models, "Landings, Redfish, NAFO 4T", "sGSL Autumn RV, Atlantic Cod" and "sGSL Autumn RV, Redfish".

Model	Month	Scenario	TAC 5,000	TAC 10,000	TAC 20,000	Percent change from historical to proposed	Percent change from current to proposed
sGSL RV	Sep	1. Historical	**696**	**1,392**	**2,784**	**-**	**-**
		2. Proposed	0	0	0	100	100
		Current	**528**	**1,057**	**2,113**	-	-
Landings	May	1. Historical	**194**	**388**	**777**	**-**	**-**
		2. Proposed	0	0	0	100	-
		Current	0	0	0	-	-
	Jun	1. Historical	35	70	140	**-**	**-**
		2. Proposed	31	61	123	11.4	8.8
		Current	34	68	136	-	-
	Jul	1. Historical	30	60	121	**-**	**-**
		2. Proposed	27	54	107	10.0	10.0
		Current	30	59	119	-	-
	Aug	1. Historical	41	81	**162**	**-**	**-**
		2. Proposed	36	72	144	12.2	10.0
		Current	40	80	**159**	-	-
	Sep	1. Historical	93	**185**	**371**	**-**	**-**
		2. Proposed	0	0	0	100	100
		Current	90	**180**	**361**	-	-
	Oct	1. Historical	**171**	**342**	**683**	**-**	**-**
		2. Proposed	0	0	0	100	100
		Current	**163**	**326**	**652**	-	-

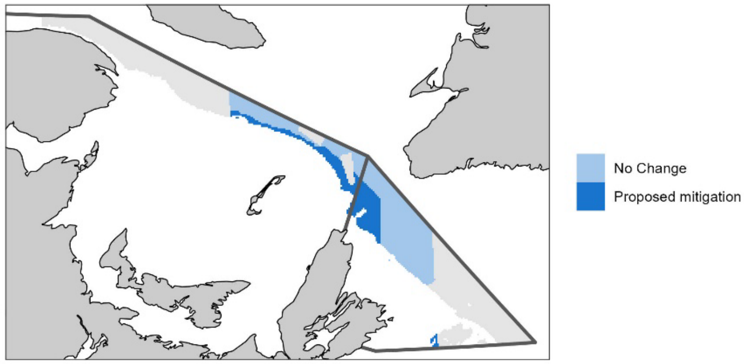

Figure 31: Bycatch mitigation scenario to minimize bycatch of Atlantic Cod in a NAFO 4TVn Redfish fishery. The gray shaded region indicates the historical fishing area based on Landings records. The light blue region indicates the area open to the index and experimental fishery. The dark blue region indicates the proposed closure areas. Proposed closures include one area closure that overlaps part of NAFO 4T and part of NAFO 4Vn north of Cape Breton, along with a 300 m minimum fishing depth in NAFO 4T. Thick solid lines indicate NAFO division boundaries.

Redfish, NAFO 4Vn

Sutton et al. (2024) proposed closing NAFO 4Vn during winter months (November through April). However, in the case of a winter 4Vn commercial fishery, we propose closing the area adjacent to the northwest tip of Cape Breton, as well as the area below latitude 45.9000°N (Figures 31 and 32). Compared to the assumed current scenario, the proposed area closure reduced predicted bycatch by at least 29% (estimate derived from the Landings model predictions, averaged over all months considered; Table 11).

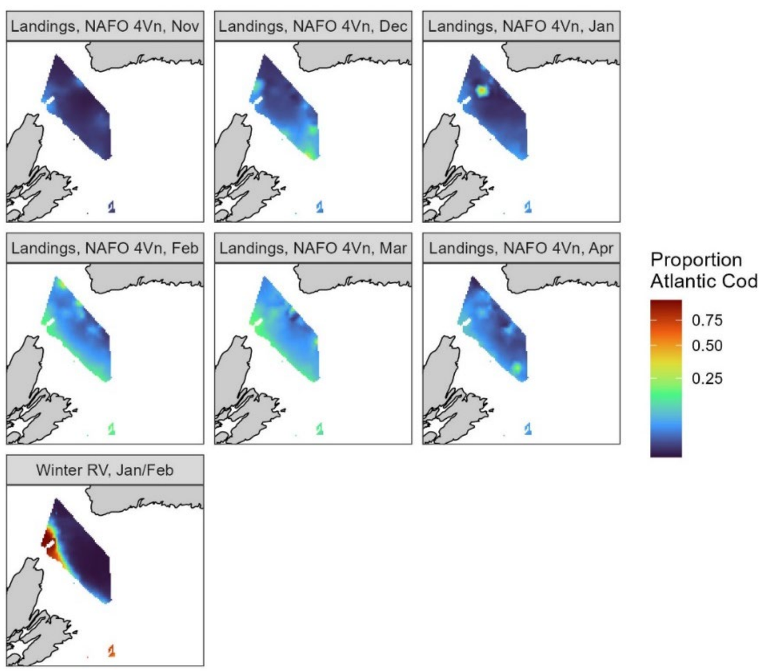

Figure 32: Model predicted proportion of Atlantic Cod over the current NAFO 4Vn Redfish fishing grid, assuming a winter fishery, based on Landings and RV models. Predictions were averaged over all years.

Table 11: NAFO 4Vn predicted tonnes (t) of sGSL Atlantic Cod bycatch with monthly Redfish TACs of 5,000 t, 10,000 t, and 20,000 t under current and proposed fishing areas. Bold values indicate bycatch weights that exceed the current annual quota of 152.2 t of Atlantic Cod bycatch across all commercial groundfish fisheries. In each scenario, tonnes of Atlantic Cod were estimated assuming the full Redfish TAC was caught in a single month, and that the Redfish TAC was evenly distributed across the available spatial area. Data from Sutton et al. 2024.*

Model	Month	Scenario	TAC 5,000	TAC 10,000	TAC 20,000	Percent change from current to proposed
Winter RV	Jan/Feb	Current	**5,214**	**10,429**	**20,858**	**-**
		Proposed	9	19	37	99.8
Landings 4Vn	Nov	Current	32	64	129	-
		Proposed	20	40	80	37.5
	Dec	Current	**178**	**357**	**714**	**-**
		Proposed	146	**291**	**583**	18.0
	Jan	Current	101	**201**	**402**	**-**
		Proposed	65	129	**259**	35.6
	Feb	Current	**326**	**652**	**1,305**	**-**
		Proposed	**236**	**472**	**943**	27.6
	Mar	Current	**382**	**764**	**1,529**	**-**
		Proposed	**275**	**549**	**1,098**	28.0
	Apr	Current	**177**	**353**	**707**	**-**
		Proposed	131	**262**	**524**	26.0

*In this scenario, NAFO 4Vn is assumed to be open to a winter fishery despite being closed in recent harvesting plans.

DISCUSSION

Despite the implementation of a commercial fishing moratorium since 2009, the sGSL Atlantic Cod stock is predicted to become functionally extinct by mid-century (Swain et al. 2019). Predation by Grey Seals (*Halichoerus grypus*) is considered the primary factor preventing stock recovery (Neuenhoff et al. 2019; Swain et al. 2019), and even with no fishing, the stock is projected to continue to decline (Swain et al. 2019), making rebuilding unlikely. Nevertheless, in compliance with the PA framework, the rebuilding plan aims to *preserve the stock such that should the prevailing conditions limiting the stock's recovery change, the stock retains the potential to rebuild (Moritz 2002; Hutchings 2015; Wolf et al. 2015).* At this time, the core management measure proposed in the rebuilding plan is to introduce new and/or stricter management measures in all fisheries that intercept sGSL Atlantic Cod. Even though fisheries are not the main factor currently preventing stock recovery, bycatch mitigation will continue to be important, because as biomass of sGSL Cod continues to decline, so will the stock's ability to sustain bycatch. This study aimed to develop recommendations to minimize bycatch of the depleted sGSL Cod stock, without proposing decreases in TACs for fisheries targeting other, healthier groundfish stocks. This was achieved by proposing seasonal, area, and/or depth restrictions that should limit catches of sGSL Cod, while simultaneously increasing selectivity for the healthier stocks. In this study, we used closures to estimate the amount of Cod that would be caught if there was zero bycatch in specific locations, depths, and/or time periods, however, other mitigation strategies could potentially be applied.

The Atlantic Halibut fishery maintains the largest spatial and depth overlap with sGSL Atlantic Cod, and thus unsurprisingly accounts for the vast majority of bycatch. In the case of the Atlantic Halibut NAFO 4T fishery, which has a bimodal depth pattern, a closure of intermediate depths, without any further restrictions, could lead to a noticeable reduction in bycatch. However, seasonal depth closures combined with area closures were better at lowering bycatch compared to permanent depth restrictions alone. In NAFO 4Vn, establishment of an area closure where bycatch risk was high resulted in a similar bycatch reduction. However, due to limited sample sizes that prevented us from include temporal information in the NAFO 4Vn model, we were unable to make inferences about seasonal risk. Because Atlantic Halibut may not be captured efficiently in RV surveys, Landings data may remain preferable for assessing bycatch in future analyses. However, note that the probability of occurrence in RV surveys (DFO 2021b) reflected the distribution of Atlantic Halibut in the Landings data used here. Future work could aim to model inshore/shallow and offshore/deep Landings data separately, or include fleet as a model variable, data permitting. If Landings data were either collected or maintained in a different format (e.g., by fishing event rather than by species caught), it could also be possible to include a metric for fishing effort in the models.

The Witch Flounder fishery was the smallest fishery considered, both in terms of spatial scale and annual Landings. Furthermore, in recent years there were very few fish harvesters targeting Witch Flounder. Nevertheless, this fishery accounts for the second largest amount of Cod bycatch. This fishery has high latent potential for bycatch of sGSL Cod, as the TAC has not been fully caught in recent years, and participation in the fishery has been low (Ricard 2022). If the biomass of Witch Flounder continues to increase, interest in this fishery could be renewed particularly if the TAC was to increase, and the number of harvesters could increase. Consequently, the potential for Cod bycatch could also increase substantially. Furthermore, it remains unknown whether the fishery would continue to operate over the restricted spatial scale currently observed, or whether fishing effort would be more widely distributed. As Witch Flounder is generally most abundant in the deeper waters of NAFO 4T one could mediate bycatch risk by depth restrictions. Minimum fishing depth restrictions are predicted to result in low Cod bycatch combined with large Witch Flounder Landings. If more harvesters become involved in the 4T fishery, this would likely increase the data available for a Witch Flounder Landings model, to improve model predictions outside the area where fishing is currently concentrated.

The Greenland Halibut fishery operates mainly within the St. Lawrence Estuary and western portion of the Gulf off northern Gaspé, and accounts for the third largest amount of Cod bycatch. Although, bycatch predictions obtained from the nGSL Summer RV models were substantially larger than those from the Landings model, differences in gear and fishing behaviour are expected to contribute to differences in predictions made from models fitted to different data sets (i.e. Landings vs survey data). The Landings data set would not have captured Cod potentially discarded at sea, or Cod that may have decayed in gillnets depending on the gear soak times (e.g., Chamberland and Benoît 2024). As Atlantic Cod is a round fish as opposed to a flatfish like Greenland Halibut, it is possible that Atlantic Cod decay at a faster rate than Greenland Halibut, meaning that with longer soak times a portion of the bycatch/mortality could go undetected, resulting in lower proportions of Cod relative to Greenland Halibut.

The Unit 1 commercial Redfish fishery was under a moratorium from 1995 to 2024. With the reopening of the commercial fishery, there is concern about additional bycatch pressure on sGSL Cod. Sutton et al. (2024) examined spatial and temporal patterns of overlap between these stocks by combining Landings and RV survey model predictions. At the time of their study, the parameters under which the new commercial fishery would operate were unknown. Sutton et al. (2024) provided several recommendations for the management of the Redfish fishery, which we continue to support. In addition, we considered the possibility that a commercial Redfish fishery might operate in NAFO 4Vn during the winter months, and so propose an area closure within NAFO 4Vn. With the reopening of the commercial fishery, data used in future Landings models may not need to include the earlier years examined in Sutton et al. (2024) and here. In practice, bycatch rates in the future Redfish fishery may be lower than predicted for various reasons, including improvement in the fishing technology, fishing timing, location of the fishing grounds, and depth restrictions. As the Redfish fishery develops, it will be necessary to closely monitor sGSL Cod bycatch.

Cod distribution overlaps with that of several groundfish species and fisheries in the sGSL. However, there are some differences in these species' spatial use and depth use profiles, along with associated patterns of bycatch risk. These patterns may offer solutions to mitigate cCod bycatch without reducing target fishery TACs. Most of the data we examined were collected from NAFO division 4T during spring to fall (April to October). As described elsewhere, this is the period when sGSL Cod is most dispersed (Swain et al. 1998, 2019). Cod and other species overwinter in the deeper waters of the Laurentian Channel and, for Cod, in NAFO division 4Vn. During the overwintering period, dense schooling behaviour may result in sporadic, large bycatch events. Furthermore, the Laurentian Channel also represents overwintering habitat for multiple other species already at low abundances including White Hake (*Urophycis tenuis*), American Plaice (*Hippoglossoides platessoides*), and Atlantic Herring (*Clupea harengus*), thus, we reiterate cautions made elsewhere about operating a fishery on overwintering grounds (Rolland et al. 2022; Sutton et al. 2024). Finally, we recommend revisiting these spatiotemporal analyses on regular basis, to account for possible distribution changes.

SUMMARY OF RECOMMENDATIONS

Fishery	Recommendations	Rationale
Atlantic Halibut, NAFO 4T, April to October	• Close Banc-des-Américains Marine Protected Area zones 2a and 2b. • Eight new permanent area closures. • Seasonal fishing depth closure between 100 to 280 m for September and October.	Model predicted bycatch reduced by 17.5%
Atlantic Halibut, NAFO 4Vn, November to April.	One new permanent area closure.	Model predicted bycatch reduced by 13.8%
Witch Flounder, NAFO 4T, April to November	Minimum fishing depth of 200 m.	Model predicted bycatch reduced by 97.5%.
Greenland Halibut, NAFO 4T, April to October	• Minium fishing depth of 200 m. • Shift the latitude limit from Cap Gaspé to Les Trois-Ruisseaux (48.9164°N).	Model predicted bycatch reduced by 81.3% to 84.0%.

Fishery	Recommendations	Rationale
Redfish, NAFO 4T, May to October	From Sutton et al (2024): • One new area closure • Minimum fishing depth of 300 m • Restricting fishing season to months June through August	Model predicted bycatch reduced by 45.8%
Redfish, NAFO 4Vn, November to April	From Sutton et al (2024): • Closure of NAFO 4Vn during months November to April. Alternative solution proposed here: • One new permanent area closure • No fishing below latitude 45.9000°N	Model predicted bycatch reduced by 28.8%

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APPENDIX 1

SUPPORTING TABLES

Table A1: Fixed effects coefficients from the Atlantic Cod sGSL autumn RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	1.3680	0.6858	0.0239	2.7121
poly(depth_scaled, 2)1	-53.0531	7.7484	-68.2397	-37.8666
poly(depth_scaled, 2)2	-48.8517	6.4737	-61.5399	-36.1634
fyear2004	0.1880	0.4870	-0.7665	1.1425
fyear2005	0.7489	0.5564	-0.3416	1.8393
fyear2006	0.0684	0.6027	-1.1129	1.2497
fyear2007	0.4855	0.6468	-0.7821	1.7531
fyear2008	0.2265	0.6641	-1.0750	1.5281
fyear2009	0.1137	0.6899	-1.2384	1.4658
fyear2010	0.4206	0.7133	-0.9774	1.8187
fyear2011	0.1148	0.7268	-1.3097	1.5393
fyear2012	0.6660	0.7447	-0.7935	2.1256
fyear2013	0.3812	0.7583	-1.1051	1.8675
fyear2014	-0.3722	0.7469	-1.8361	1.0917
fyear2015	-0.2887	0.7548	-1.7682	1.1908
fyear2016	-1.0050	0.7579	-2.4904	0.4804
fyear2017	-2.0996	0.7663	-3.6015	-0.5978
fyear2018	0.2949	0.7932	-1.2597	1.8495
fyear2019	-1.9195	0.7766	-3.4416	-0.3975
fyear2020	-1.1337	0.7987	-2.6991	0.4318
fyear2021	-0.9013	0.7779	-2.4259	0.6233
Response: catch density				
(Intercept)	1.3578	0.4276	0.5197	2.1959
poly(depth_scaled, 2)1	-20.8624	6.4694	-33.5422	-8.1826
poly(depth_scaled, 2)2	-39.9724	4.4430	-48.6805	-31.2643
fyear2004	0.2970	0.2946	-0.2805	0.8745
fyear2005	0.0111	0.3386	-0.6526	0.6748
fyear2006	0.1118	0.3729	-0.6191	0.8428
fyear2007	0.0290	0.3950	-0.7453	0.8033
fyear2008	-0.1527	0.4105	-0.9573	0.6519
fyear2009	-0.3858	0.4291	-1.2267	0.4551
fyear2010	-0.4130	0.4362	-1.2679	0.4418
fyear2011	-0.6849	0.4459	-1.5587	0.1890
fyear2012	-0.4491	0.4497	-1.3305	0.4323
fyear2013	0.2481	0.4590	-0.6515	1.1478
fyear2014	0.0977	0.4642	-0.8121	1.0075
fyear2015	-0.0032	0.4632	-0.9111	0.9047
fyear2016	-0.2816	0.4742	-1.2110	0.6477
fyear2017	-1.1423	0.4920	-2.1065	-0.1780

Term	Estimate	SE	95Lower	95Upper
fyear2018	-1.1949	0.4817	-2.1390	-0.2508
fyear2019	-0.9781	0.4984	-1.9549	-0.0014
fyear2020	-0.5096	0.4988	-1.4872	0.4679
fyear2021	0.1366	0.4843	-0.8127	1.0859

Table A2: Fixed effects coefficients from the Atlantic Halibut sGSL autumn RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-2.1786	0.5906	-3.3361	-1.0210
poly(depth_scaled, 2)1	23.3859	10.6518	2.5087	44.2630
poly(depth_scaled, 2)2	-46.8685	7.8256	-62.2064	-31.5305
Response: catch density				
(Intercept)	2.0211	0.7310	0.5883	3.4539
poly(depth_scaled, 2)1	19.3914	4.7700	10.0424	28.7403
poly(depth_scaled, 2)2	-6.7194	3.3799	-13.3438	-0.0949

Table A3: Fixed effects coefficients from the Witch Flounder sGSL autumn RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-4.3681	0.7596	-5.8568	-2.8794
poly(depth_scaled, 2)1	135.6343	16.8042	102.6987	168.5700
poly(depth_scaled, 2)2	-57.6215	9.4691	-76.1806	-39.0623
Response: catch density				
(Intercept)	-1.7128	0.2435	-2.1901	-1.2355
poly(depth_scaled, 2)1	63.5201	6.0077	51.7452	75.2949
poly(depth_scaled, 2)2	-35.0337	3.8319	-42.5441	-27.5233

Table A4: Fixed effects coefficients from the Greenland Halibut sGSL autumn RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: catch density				
(Intercept)	-5.9101	0.6916	-7.2656	-4.5546
poly(depth_scaled, 2)1	184.5318	8.8042	167.2758	201.7878
poly(depth_scaled, 2)2	-62.9842	4.3613	-71.5323	-54.4362
fyear2004	-0.0733	0.4667	-0.9880	0.8414
fyear2005	0.2558	0.4582	-0.6422	1.1538
fyear2006	-0.0149	0.4674	-0.9309	0.9011
fyear2007	0.8800	0.4601	-0.0217	1.7818
fyear2008	0.6736	0.4535	-0.2153	1.5624
fyear2009	-0.0730	0.4729	-0.9998	0.8538
fyear2010	0.1302	0.4743	-0.7994	1.0598
fyear2011	0.5938	0.4683	-0.3241	1.5116
fyear2012	0.3385	0.4673	-0.5774	1.2545

Term	Estimate	SE	95Lower	95Upper
fyear2013	0.1906	0.4734	-0.7373	1.1185
fyear2014	-0.1627	0.4699	-1.0836	0.7583
fyear2015	-0.1284	0.4645	-1.0387	0.7820
fyear2016	0.4051	0.4644	-0.5051	1.3152
fyear2017	0.2288	0.4804	-0.7129	1.1704
fyear2018	-0.7226	0.4957	-1.6942	0.2490
fyear2019	-0.3994	0.4887	-1.3572	0.5584
fyear2020	-0.3968	0.4909	-1.3589	0.5652
fyear2021	-0.5840	0.4717	-1.5085	0.3406

Table A5: Fixed effects coefficients from the Redfish sGSL autumn RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-2.6355	0.7060	-4.0192	-1.2518
poly(depth_scaled, 2)1	104.0310	12.7162	79.1078	128.9542
poly(depth_scaled, 2)2	-18.7940	8.5008	-35.4552	-2.1327
fyear2004	-0.7336	0.6230	-1.9547	0.4875
fyear2005	0.3914	0.5923	-0.7695	1.5523
fyear2006	0.5575	0.6239	-0.6654	1.7804
fyear2007	0.2410	0.6484	-1.0298	1.5117
fyear2008	0.2782	0.6478	-0.9915	1.5478
fyear2009	0.7045	0.6556	-0.5804	1.9894
fyear2010	1.5428	0.6518	0.2653	2.8203
fyear2011	0.2299	0.6904	-1.1232	1.5831
fyear2012	1.1530	0.6626	-0.1458	2.4517
fyear2013	2.3524	0.6655	1.0480	3.6568
fyear2014	1.7970	0.6582	0.5070	3.0870
fyear2015	1.4483	0.6646	0.1458	2.7508
fyear2016	1.2382	0.6717	-0.0783	2.5547
fyear2017	1.0044	0.6960	-0.3598	2.3685
fyear2018	1.1367	0.7114	-0.2576	2.5310
fyear2019	0.7358	0.7102	-0.6561	2.1277
fyear2020	0.1897	0.7496	-1.2795	1.6590
fyear2021	0.1392	0.7052	-1.2430	1.5213
Response: catch density				
(Intercept)	-2.2501	0.6294	-3.4837	-1.0164
poly(depth_scaled, 2)1	125.4551	5.4147	114.8425	136.0678
poly(depth_scaled, 2)2	-30.6137	3.8899	-38.2377	-22.9896
fyear2004	-0.9397	0.6706	-2.2541	0.3747
fyear2005	-1.6402	0.6426	-2.8998	-0.3807
fyear2006	-0.6024	0.6708	-1.9171	0.7124
fyear2007	-1.4792	0.6951	-2.8416	-0.1169
fyear2008	-0.7671	0.6948	-2.1289	0.5947
fyear2009	-1.2998	0.6993	-2.6703	0.0708
fyear2010	-1.0025	0.6940	-2.3626	0.3576

Term	Estimate	SE	95Lower	95Upper
fyear2011	-0.2608	0.7438	-1.7187	1.1970
fyear2012	-0.4831	0.7035	-1.8619	0.8956
fyear2013	-0.4289	0.6928	-1.7867	0.9290
fyear2014	-0.1330	0.6969	-1.4990	1.2330
fyear2015	0.1951	0.7024	-1.1815	1.5717
fyear2016	0.8748	0.7104	-0.5175	2.2672
fyear2017	0.5589	0.7349	-0.8815	1.9993
fyear2018	0.3437	0.7371	-1.1011	1.7885
fyear2019	0.8161	0.7460	-0.6461	2.2782
fyear2020	1.1371	0.7789	-0.3895	2.6637
fyear2021	1.3453	0.7680	-0.1598	2.8505

Table A5: Fixed effects coefficients from the Atlantic Cod nGSL summer RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-2.3802	0.8003	-3.9488	-0.8116
depth_scaled	-1.8457	0.1870	-2.2122	-1.4793
fyear2004	1.1739	0.8135	-0.4205	2.7683
fyear2005	0.5572	0.7750	-0.9618	2.0763
fyear2006	0.6149	0.8499	-1.0509	2.2807
fyear2007	0.9658	0.8278	-0.6567	2.5882
fyear2008	1.2177	0.8079	-0.3658	2.8012
fyear2009	1.3600	0.8172	-0.2416	2.9617
fyear2010	1.1956	0.8475	-0.4656	2.8567
fyear2011	1.3288	0.8156	-0.2698	2.9273
fyear2012	2.0541	0.8313	0.4247	3.6835
fyear2013	2.3001	0.8301	0.6730	3.9271
fyear2014	2.4528	0.8545	0.7779	4.1276
fyear2015	2.8680	0.8442	1.2135	4.5225
fyear2016	3.4401	0.8704	1.7341	5.1461
fyear2017	1.8753	0.8678	0.1744	3.5763
fyear2018	1.5489	0.8771	-0.1702	3.2681
fyear2019	0.8497	0.9079	-0.9298	2.6291
fyear2020	0.9091	0.9249	-0.9036	2.7218
fyear2021	2.3330	0.8730	0.6220	4.0441
Response: catch density				
(Intercept)	2.5874	1.0162	0.5957	4.5791
depth_scaled	-0.8388	0.1514	-1.1355	-0.5420
fyear2004	-1.3836	1.1835	-3.7031	0.9360
fyear2005	-1.8255	1.1706	-4.1198	0.4688
fyear2006	-1.7381	1.2307	-4.1503	0.6740
fyear2007	-1.1125	1.2039	-3.4721	1.2471
fyear2008	-0.7698	1.1114	-2.9480	1.4084
fyear2009	-1.9316	1.0965	-4.0806	0.2175
fyear2010	-2.1333	1.1244	-4.3370	0.0704

Term	Estimate	SE	95Lower	95Upper
fyear2011	-2.0046	1.1119	-4.1839	0.1748
fyear2012	-1.7006	1.0945	-3.8457	0.4446
fyear2013	-1.5744	1.0764	-3.6842	0.5353
fyear2014	-1.3751	1.0904	-3.5123	0.7621
fyear2015	-1.1639	1.0754	-3.2716	0.9438
fyear2016	-1.9673	1.0802	-4.0845	0.1500
fyear2017	-1.6872	1.1063	-3.8556	0.4811
fyear2018	-1.8199	1.1592	-4.0919	0.4520
fyear2019	-1.8982	1.1705	-4.1923	0.3959
fyear2020	-1.9930	1.1912	-4.3276	0.3416
fyear2021	-1.4065	1.1028	-3.5678	0.7549

Table A6: Fixed effects coefficients from the Atlantic Halibut nGSL summer RV model. Values are on the link scale. Temporary model.

Term	Estimate	SE	95Lower	95Upper
Response: catch density				
(Intercept)	-2.4127	0.7648	-3.9117	-0.9136
poly(depth_scaled, 2)1	-35.6273	4.3297	-44.1133	-27.1413
poly(depth_scaled, 2)2	-51.9177	5.5295	-62.7553	-41.0800
fyear2004	1.3644	0.8675	-0.3360	3.0647
fyear2005	1.4099	0.8062	-0.1701	2.9900
fyear2006	0.8801	0.9063	-0.8963	2.6565
fyear2007	1.1129	0.8851	-0.6218	2.8477
fyear2008	1.9769	0.8087	0.3918	3.5619
fyear2009	2.1083	0.8085	0.5237	3.6929
fyear2010	2.3359	0.8136	0.7412	3.9306
fyear2011	1.6792	0.8284	0.0555	3.3029
fyear2012	1.9291	0.8239	0.3143	3.5438
fyear2013	1.9003	0.8265	0.2804	3.5203
fyear2014	3.3745	0.7819	1.8420	4.9070
fyear2015	2.7843	0.7903	1.2353	4.3332
fyear2016	1.8167	0.8532	0.1445	3.4889
fyear2017	1.8818	0.8695	0.1777	3.5860
fyear2018	3.5919	0.7829	2.0575	5.1263
fyear2019	3.1425	0.7990	1.5764	4.7085
fyear2020	3.4472	0.8020	1.8754	5.0190
fyear2021	3.7707	0.7768	2.2481	5.2933

Table A7: Fixed effects coefficients from the Witch Flounder nGSL summer RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	3.2739	1.0727	1.1714	5.3765
poly(depth_scaled, 2)1	101.5665	21.2606	59.8965	143.2366
poly(depth_scaled, 2)2	-58.4192	16.3519	-90.4683	-26.3701
fyear2004	2.5219	1.6958	-0.8019	5.8456
fyear2005	1.5718	1.2740	-0.9252	4.0688
fyear2006	3.0550	1.6801	-0.2379	6.3478
fyear2007	3.1241	1.8113	-0.4260	6.6743
fyear2008	11.7628	3.7212	4.4694	19.0562
fyear2009	4.4428	1.6749	1.1600	7.7256
fyear2010	6.5461	2.1441	2.3438	10.7485
fyear2011	4.4528	1.6916	1.1373	7.7683
fyear2012	5.2313	1.9193	1.4696	8.9930
fyear2013	1.8858	1.3210	-0.7033	4.4750
fyear2014	0.8195	1.2193	-1.5703	3.2093
fyear2015	0.9542	1.2784	-1.5514	3.4597
fyear2016	5.5330	2.0617	1.4920	9.5739
fyear2017	2.8454	1.9066	-0.8914	6.5823
fyear2018	4.1883	1.7777	0.7042	7.6725
fyear2019	1.3106	1.4349	-1.5016	4.1229
fyear2020	1.2049	1.4046	-1.5480	3.9578
fyear2021	1.5578	1.2979	-0.9859	4.1016
Response: catch density				
(Intercept)	1.5780	0.2312	1.1248	2.0313
poly(depth_scaled, 2)1	17.2798	2.7374	11.9145	22.6451
poly(depth_scaled, 2)2	-28.0706	2.9718	-33.8953	-22.2460
fyear2004	-0.6521	0.2314	-1.1057	-0.1985
fyear2005	-0.6232	0.1997	-1.0146	-0.2317
fyear2006	-0.7435	0.2147	-1.1644	-0.3226
fyear2007	-0.6256	0.2150	-1.0468	-0.2043
fyear2008	-0.6643	0.2069	-1.0698	-0.2587
fyear2009	-0.8050	0.2120	-1.2205	-0.3895
fyear2010	-0.1811	0.2210	-0.6143	0.2522
fyear2011	-0.4318	0.2118	-0.8470	-0.0166
fyear2012	-0.2148	0.2092	-0.6249	0.1953
fyear2013	0.2339	0.2175	-0.1924	0.6603
fyear2014	-0.2401	0.2212	-0.6736	0.1934
fyear2015	-0.3505	0.2191	-0.7798	0.0789
fyear2016	-0.2251	0.2222	-0.6607	0.2105
fyear2017	-0.2684	0.2278	-0.7148	0.1781
fyear2018	-0.1175	0.2294	-0.5672	0.3322
fyear2019	0.7476	0.2418	0.2737	1.2215
fyear2020	-0.0630	0.2341	-0.5219	0.3959

Term	Estimate	SE	95Lower	95Upper
fyear2021	0.1091	0.2338	-0.3492	0.5674

Table A8: Fixed effects coefficients from the Greenland Halibut nGSL summer RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: catch density				
(Intercept)	3.5617	1.2297	1.1516	5.9718
depth_scaled	1.4739	0.0726	1.3315	1.6163
fyear2004	-0.2420	0.2012	-0.6363	0.1524
fyear2005	-0.3139	0.1909	-0.6881	0.0604
fyear2006	-0.3455	0.1968	-0.7312	0.0402
fyear2007	-0.3819	0.1982	-0.7702	0.0065
fyear2008	-0.3637	0.1997	-0.7550	0.0277
fyear2009	-0.9563	0.2035	-1.3551	-0.5575
fyear2010	-0.5480	0.2058	-0.9514	-0.1447
fyear2011	-0.5524	0.1992	-0.9427	-0.1621
fyear2012	-0.7317	0.1996	-1.1229	-0.3406
fyear2013	-0.8595	0.2060	-1.2631	-0.4558
fyear2014	-0.5197	0.2017	-0.9151	-0.1243
fyear2015	-0.5999	0.2007	-0.9932	-0.2066
fyear2016	-0.6803	0.2082	-1.0884	-0.2721
fyear2017	-1.0080	0.2093	-1.4183	-0.5977
fyear2018	-0.9198	0.2096	-1.3307	-0.5090
fyear2019	-1.0497	0.2208	-1.4824	-0.6170
fyear2020	-0.9814	0.2147	-1.4023	-0.5606
fyear2021	-0.7676	0.2122	-1.1835	-0.3516

Table A9: Fixed effects coefficients from the Redfish nGSL summer RV model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: catch density				
(Intercept)	2.5282	0.3492	1.8437	3.2126
depth_scaled	0.4455	0.1343	0.1823	0.7087
fyear2004	-0.5508	0.3347	-1.2068	0.1052
fyear2005	-0.6024	0.2898	-1.1704	-0.0343
fyear2006	-0.3671	0.3166	-0.9875	0.2534
fyear2007	-0.6893	0.3214	-1.3193	-0.0593
fyear2008	-0.1494	0.3092	-0.7555	0.4566
fyear2009	-1.1600	0.3163	-1.7800	-0.5401
fyear2010	-1.3036	0.3299	-1.9501	-0.6571
fyear2011	-0.6706	0.3080	-1.2742	-0.0670
fyear2012	-0.6489	0.3093	-1.2552	-0.0426
fyear2013	0.2604	0.2977	-0.3231	0.8438
fyear2014	0.4400	0.3072	-0.1621	1.0422
fyear2015	1.2228	0.2932	0.6481	1.7975
fyear2016	2.3673	0.2962	1.7868	2.9477
fyear2017	2.4900	0.2908	1.9200	3.0600
fyear2018	2.3735	0.2881	1.8089	2.9381
fyear2019	2.7545	0.2951	2.1760	3.3330
fyear2020	2.1160	0.3035	1.5210	2.7109
fyear2021	1.9566	0.2887	1.3908	2.5225

Table A10: Fixed effects coefficients from the Atlantic Cod, Atlantic Halibut, Witch Flounder, Greenland Halibut and Redfish winter RV models. Values are on the link scale.

Species	Term	Estimate	SE	95Lower	95Upper
Atlantic Cod	**Response: catch density**				
	(Intercept)	0.3784	1.4099	-2.3850	3.1418
	poly(depth_scaled, 2)1	-11.8243	3.7611	-19.1959	-4.4528
	poly(depth_scaled, 2)2	-5.9634	2.4182	-10.7029	-1.2238
Atlantic Halibut	**Response: presence**				
	(Intercept)	-1.1089	0.5067	-2.1020	-0.1159
	Response: catch density				
	(Intercept)	2.6603	0.6367	1.4123	3.9082
Witch Flounder	**Response: catch density**				
	(Intercept)	0.7519	0.2151	0.3302	1.1736
	poly(depth_scaled, 2)1	8.7840	1.6567	5.5369	12.0312
	poly(depth_scaled, 2)2	-6.6681	1.6928	-9.9859	-3.3503
Greenland Halibut	**Response: catch density**				
	(Intercept)	1.2974	0.7596	-0.1913	2.7861
	depth_scaled	1.3687	0.3630	0.6573	2.0801
Redfish	**Response: catch density**				
	(Intercept)	3.6148	0.3537	2.9215	4.3081
	depth_scaled	1.3711	0.2731	0.8358	1.9064

Table A11: Fixed effects coefficients from the Landings Atlantic Halibut 4T model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response variable: presence				
(Intercept)	-0.0772	0.6025	-1.2580	1.1035
poly(depth_scaled, 2)1	37.1913	18.0797	1.7557	72.6270
poly(depth_scaled, 2)2	-5.9470	6.7285	-19.1346	7.2407
May	-0.3526	0.2082	-0.7607	0.0554
June	-0.3834	0.2026	-0.7805	0.0138
July	-0.8540	0.2343	-1.3132	-0.3947
August	-0.5499	0.2361	-1.0126	-0.0873
September	-0.3993	0.2414	-0.8724	0.0738
October	-0.6202	0.2548	-1.1195	-0.1208
2004	0.5321	0.5137	-0.4747	1.5389
2005	-0.4864	0.5312	-1.5275	0.5546
2006	-0.3708	0.5484	-1.4457	0.7040
2007	-0.4652	0.5493	-1.5419	0.6115
2008	-0.9664	0.5343	-2.0136	0.0808
2009	-1.1674	0.5229	-2.1923	-0.1425
2010	-0.5189	0.5168	-1.5318	0.4941
2011	-0.8781	0.5092	-1.8761	0.1200
2012	-0.3385	0.4938	-1.3063	0.6293
2013	-0.8383	0.5011	-1.8204	0.1439
2014	-0.9990	0.4946	-1.9683	-0.0297
2015	-0.7007	0.4872	-1.6557	0.2542
2016	-0.5546	0.4841	-1.5034	0.3942
2017	-0.6883	0.4809	-1.6309	0.2543
2018	-1.1355	0.4823	-2.0807	-0.1902
2019	-1.0443	0.4807	-1.9865	-0.1021
2020	-1.3051	0.4837	-2.2531	-0.3571
2021	-1.0462	0.4773	-1.9817	-0.1107
Response variable: proportion				
(Intercept)	-0.1139	0.1993	-0.5046	0.2768
poly(depth_scaled, 2)1	16.6717	6.1748	4.5694	28.7741
poly(depth_scaled, 2)2	-7.9570	2.7202	-13.2885	-2.6255
May	-0.1030	0.0825	-0.2647	0.0588
June	-0.0067	0.0795	-0.1625	0.1490
July	0.3114	0.0934	0.1283	0.4946
August	0.3694	0.0942	0.1847	0.5541
September	0.5030	0.0996	0.3078	0.6982
October	0.7279	0.1181	0.4963	0.9594
2004	-0.0299	0.2101	-0.4416	0.3819
2005	-0.1292	0.2355	-0.5908	0.3324
2006	-0.0969	0.2391	-0.5656	0.3717
2007	-0.9090	0.2362	-1.3720	-0.4460
2008	-0.7667	0.2346	-1.2265	-0.3069
2009	-1.1850	0.2317	-1.6392	-0.7309

Term	Estimate	SE	95Lower	95Upper
2010	-0.7282	0.2167	-1.1530	-0.3033
2011	-0.5944	0.2127	-1.0113	-0.1775
2012	-0.6220	0.2066	-1.0270	-0.2170
2013	-1.1512	0.2137	-1.5701	-0.7322
2014	-0.8224	0.2086	-1.2312	-0.4136
2015	-1.0571	0.2029	-1.4549	-0.6594
2016	-1.0307	0.2026	-1.4279	-0.6336
2017	-0.8592	0.1998	-1.2507	-0.4676
2018	-1.1271	0.2051	-1.5291	-0.7252
2019	-0.9677	0.2026	-1.3649	-0.5706
2020	-1.0203	0.2055	-1.4229	-0.6176
2021	-1.0021	0.2000	-1.3942	-0.6100

Table A12: Fixed effects coefficients from the Landings Atlantic Halibut 4Vn model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-1.4543	0.6864	-2.7997	-0.1090
fmonth2	-0.3888	0.5805	-1.5267	0.7490
fmonth3	1.1035	0.5117	0.1006	2.1065
fmonth4	1.9312	0.5228	0.9064	2.9559
fmonth11	1.9537	0.5403	0.8948	3.0127
fmonth12	0.3094	0.5260	-0.7216	1.3403
Response: proportion				
(Intercept)	-2.5983	0.3186	-3.2228	-1.9738
fmonth2	-0.7433	0.3225	-1.3753	-0.1113
fmonth3	-0.5601	0.2755	-1.1001	-0.0201
fmonth4	0.5115	0.2770	-0.0315	1.0545
fmonth11	1.1328	0.2796	0.5848	1.6808
fmonth12	0.8836	0.3040	0.2878	1.4793

Table A13: Fixed effects coefficients from the Landings Witch Flounder model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	2.4885	0.2993	1.9019	3.0751
Response: proportion				
(Intercept)	0.4054	0.4251	-0.4278	1.2386

Table A14: Fixed effects coefficients from the Landings Greenland Halibut model. Values are on the link scale.

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-5.8320	0.8520	-7.5019	-4.1622
poly(depth_scaled, 2)1	-75.5121	12.4786	-99.9698	-51.0545

Term	Estimate	SE	95Lower	95Upper
poly(depth_scaled, 2)2	28.7412	7.3870	14.2630	43.2194
fyear2004	-0.2183	0.8655	-1.9147	1.4781
fyear2005	-1.1118	0.8828	-2.8419	0.6184
fyear2006	-0.5766	0.9151	-2.3701	1.2170
fyear2007	0.1155	0.9034	-1.6551	1.8861
fyear2008	0.0017	0.9190	-1.7996	1.8030
fyear2009	0.7483	0.8716	-0.9600	2.4567
fyear2010	1.3825	0.8669	-0.3167	3.0816
fyear2011	1.3349	0.8800	-0.3898	3.0596
fyear2012	3.3954	0.8501	1.7292	5.0616
fyear2013	4.1406	0.8364	2.5014	5.7799
fyear2014	3.0752	0.8470	1.4151	4.7353
fyear2015	3.1785	0.8598	1.4933	4.8637
fyear2016	2.9322	0.8637	1.2394	4.6249
fyear2017	3.0262	0.8552	1.3500	4.7023
fyear2018	3.5419	0.8481	1.8796	5.2042
fyear2019	2.3392	0.8773	0.6198	4.0587
fyear2020	1.7763	0.8796	0.0523	3.5004
fyear2021	0.5144	1.1235	-1.6876	2.7164
Response: proportion				
(Intercept)	-4.0542	0.4340	-4.9049	-3.2035
poly(depth_scaled, 2)1	-12.0071	8.4491	-28.5670	4.5527
poly(depth_scaled, 2)2	23.1710	4.7746	13.8131	32.5290
fyear2004	0.4263	0.5355	-0.6233	1.4759
fyear2005	-0.0836	0.5752	-1.2110	1.0438
fyear2006	0.0220	0.6137	-1.1808	1.2248
fyear2007	-0.2570	0.6140	-1.4604	0.9464
fyear2008	0.1801	0.5361	-0.8708	1.2309
fyear2009	0.5683	0.5357	-0.4816	1.6182
fyear2010	0.6316	0.5077	-0.3635	1.6267
fyear2011	0.5312	0.5192	-0.4864	1.5488
fyear2012	0.3678	0.4608	-0.5354	1.2710
fyear2013	0.6197	0.4571	-0.2761	1.5155
fyear2014	0.2359	0.4594	-0.6644	1.1362
fyear2015	0.2064	0.4667	-0.7083	1.1210
fyear2016	0.2726	0.4719	-0.6524	1.1976
fyear2017	0.8001	0.4675	-0.1162	1.7165
fyear2018	1.5317	0.4598	0.6306	2.4329
fyear2019	1.6299	0.5148	0.6209	2.6389
fyear2020	0.3776	0.4982	-0.5989	1.3541
fyear2021	-0.0864	0.8986	-1.8477	1.6749

Table A15: Fixed effects coefficients from the Landings Redfish 4T model. Values are on the link scale. Reproduced from Sutton et al. (2024).

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-3.8508	0.8320	-5.4814	-2.2201
depth_scaled	-0.6116	0.0782	-0.7649	-0.4583
fmonth6	0.0990	0.7148	-1.3020	1.5000
fmonth7	-0.3325	0.7140	-1.7320	1.0670
fmonth8	-0.4418	0.7184	-1.8498	0.9663
fmonth9	-0.1301	0.7533	-1.6064	1.3463
fmonth10	0.4464	0.8044	-1.1302	2.0231
fyear1992	0.6543	0.5710	-0.4649	1.7735
fyear1993	1.5636	0.6109	0.3663	2.7609
fyear1994	1.5395	0.5635	0.4351	2.6440
fyear1998	4.2454	0.6600	2.9518	5.5390
fyear1999	2.9861	0.6150	1.7808	4.1914
fyear2000	0.5463	0.7404	-0.9048	1.9975
fyear2001	1.7139	0.6718	0.3973	3.0306
fyear2002	3.0597	0.6194	1.8457	4.2737
fyear2003	2.5992	0.6247	1.3749	3.8235
fyear2004	3.4812	0.6822	2.1442	4.8182
fyear2005	2.8397	0.6493	1.5671	4.1123
fyear2006	2.6166	0.6277	1.3863	3.8468
fyear2007	0.6558	1.0820	-1.4648	2.7764
fyear2008	1.4593	0.6871	0.1127	2.8059
fyear2009	1.8408	0.6226	0.6206	3.0610
fyear2010	1.7668	0.6334	0.5253	3.0082
fyear2011	1.5276	0.6526	0.2485	2.8067
fyear2012	1.9699	0.6535	0.6891	3.2507
fyear2013	1.4813	0.6983	0.1126	2.8500
fyear2014	3.0729	0.7065	1.6883	4.4576
fyear2015	2.3627	0.6760	1.0378	3.6876
fyear2016	1.4042	0.6758	0.0798	2.7287
fyear2017	0.2086	0.7914	-1.3424	1.7597
fyear2018	-0.3210	0.8293	-1.9464	1.3045
fyear2019	0.8471	0.7359	-0.5952	2.2894
fyear2020	1.3556	0.7350	-0.0851	2.7962
fyear2021	1.4310	0.6942	0.0703	2.7916
Response: proportion				
(Intercept)	0.7972	0.6506	-0.4779	2.0724
depth_scaled	-0.2329	0.0781	-0.3860	-0.0798
fmonth6	-3.2778	0.6041	-4.4617	-2.0938
fmonth7	-2.9945	0.6010	-4.1724	-1.8165
fmonth8	-2.4589	0.6006	-3.6361	-1.2816
fmonth9	-1.5654	0.6304	-2.8010	-0.3298
fmonth10	-1.3430	0.6822	-2.6801	-0.0059

Term	Estimate	SE	95Lower	95Upper
fyear1992	-0.6356	0.5850	-1.7822	0.5110
fyear1993	-0.7139	0.6350	-1.9585	0.5307
fyear1994	-0.2128	0.5444	-1.2798	0.8542
fyear1998	-0.7372	0.5927	-1.8989	0.4244
fyear1999	0.4716	0.5150	-0.5378	1.4810
fyear2000	0.0401	0.7701	-1.4693	1.5494
fyear2001	0.1479	0.6005	-1.0291	1.3249
fyear2002	1.2683	0.5306	0.2284	2.3082
fyear2003	0.7781	0.5712	-0.3414	1.8975
fyear2004	1.2080	0.5784	0.0743	2.3416
fyear2005	0.9532	0.5881	-0.1994	2.1058
fyear2006	0.4927	0.5647	-0.6142	1.5996
fyear2007	2.1350	0.9349	0.3025	3.9674
fyear2008	1.1140	0.5565	0.0233	2.2048
fyear2009	0.5700	0.5120	-0.4335	1.5734
fyear2010	0.4264	0.5232	-0.5991	1.4519
fyear2011	0.2721	0.5392	-0.7847	1.3289
fyear2012	0.2040	0.5411	-0.8565	1.2645
fyear2013	-0.2373	0.6474	-1.5061	1.0315
fyear2014	-0.1154	0.5954	-1.2825	1.0516
fyear2015	-0.7815	0.5582	-1.8756	0.3126
fyear2016	-0.5975	0.5734	-1.7214	0.5264
fyear2017	-0.4642	0.7916	-2.0158	1.0873
fyear2018	-0.3330	0.8596	-2.0178	1.3517
fyear2019	-1.2728	0.6253	-2.4983	-0.0473
fyear2020	-1.4704	0.6895	-2.8218	-0.1190
fyear2021	-0.6185	0.6028	-1.8000	0.5630

Table A16: Fixed effects coefficients from the Landings Redfish 4Vn model. Values are on the link scale. Reproduced from Sutton et al. (2024).

Term	Estimate	SE	95Lower	95Upper
Response: presence				
(Intercept)	-2.1660	0.7426	-3.6216	-0.7104
depth_scaled	-0.0555	0.1772	-0.4027	0.2918
fmonth2	2.0616	0.9486	0.2024	3.9208
fmonth3	1.5033	0.9542	-0.3670	3.3735
fmonth4	0.4157	0.8992	-1.3467	2.1782
fmonth11	-1.6338	0.9314	-3.4594	0.1917
fmonth12	-1.3829	0.9748	-3.2936	0.5277
Response: proportion				
(Intercept)	-3.2993	0.4141	-4.1109	-2.4877
depth_scaled	-0.3628	0.1174	-0.5929	-0.1327
fmonth2	0.6784	0.4575	-0.2182	1.5750
fmonth3	0.7772	0.4755	-0.1547	1.7092
fmonth4	0.2154	0.4545	-0.6754	1.1062
fmonth11	-0.0617	0.5762	-1.1911	1.0677
fmonth12	1.5440	0.5557	0.4549	2.6330

SUPPORTING FIGURES

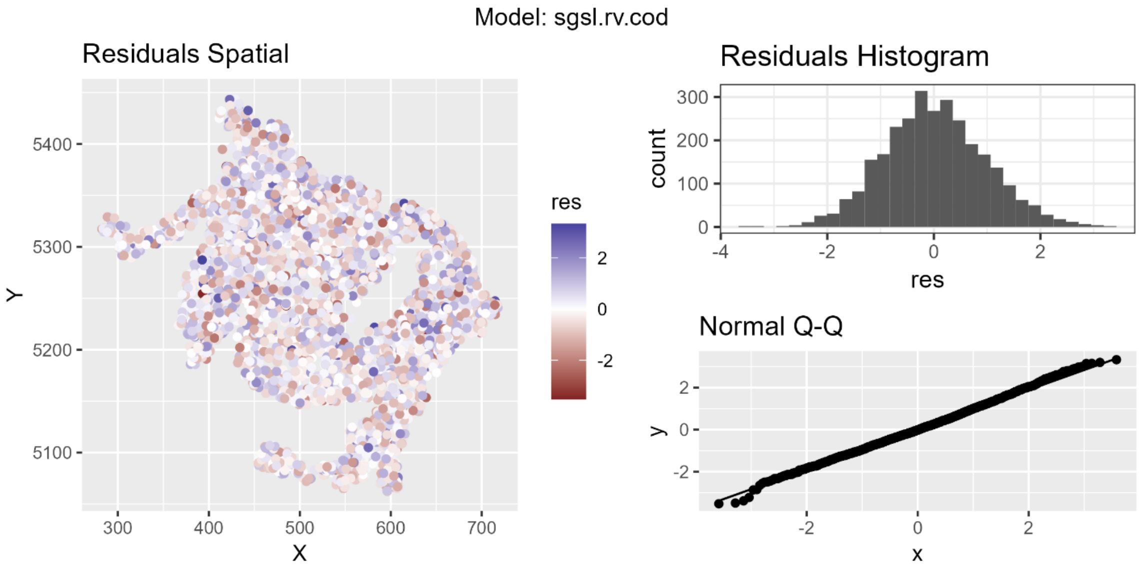

Figure A1: Model diagnostics for the Atlantic Cod sGSL Autumn RV Survey model.

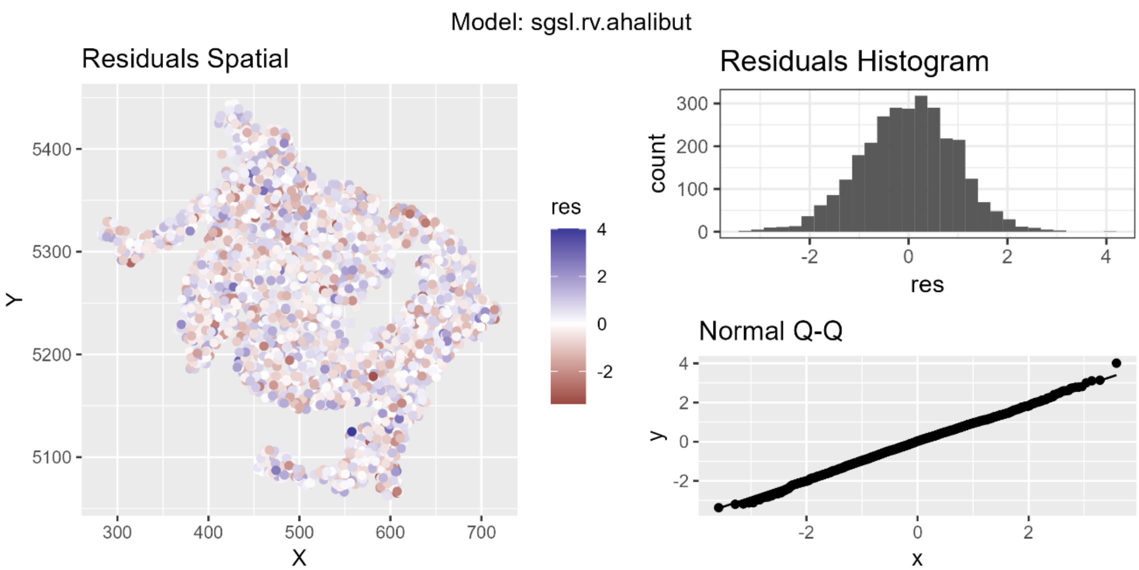

Figure A2: Model diagnostics for the Atlantic Halibut sGSL Autumn RV Survey model.

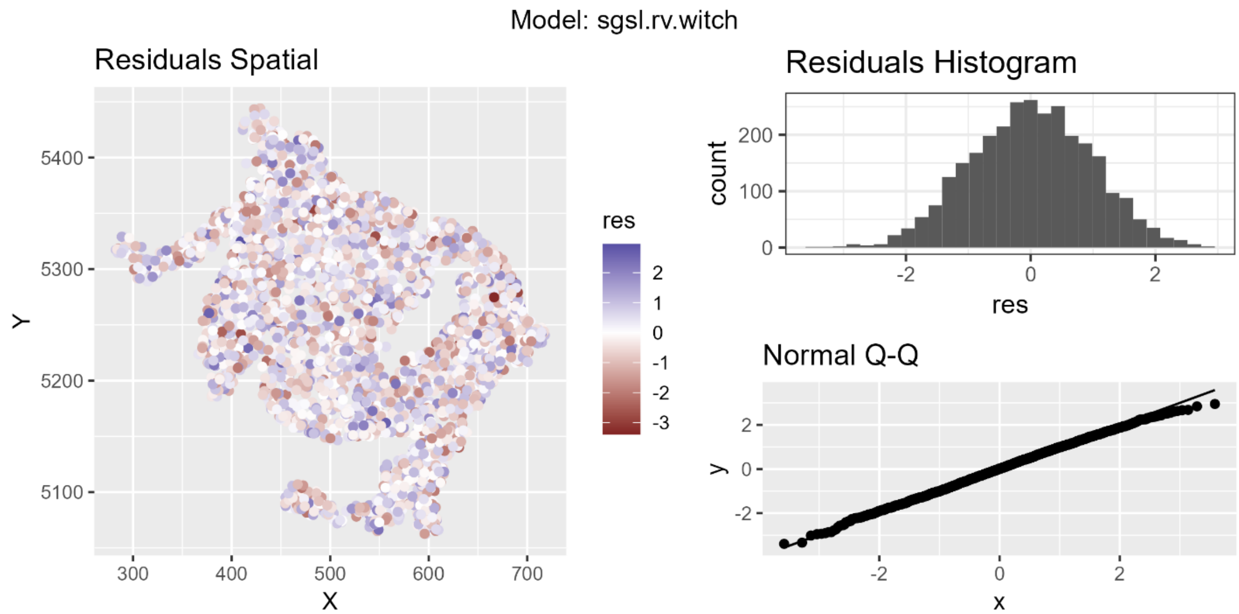

Figure A3: Model diagnostics for the Witch Flounder sGSL Autumn RV Survey model.

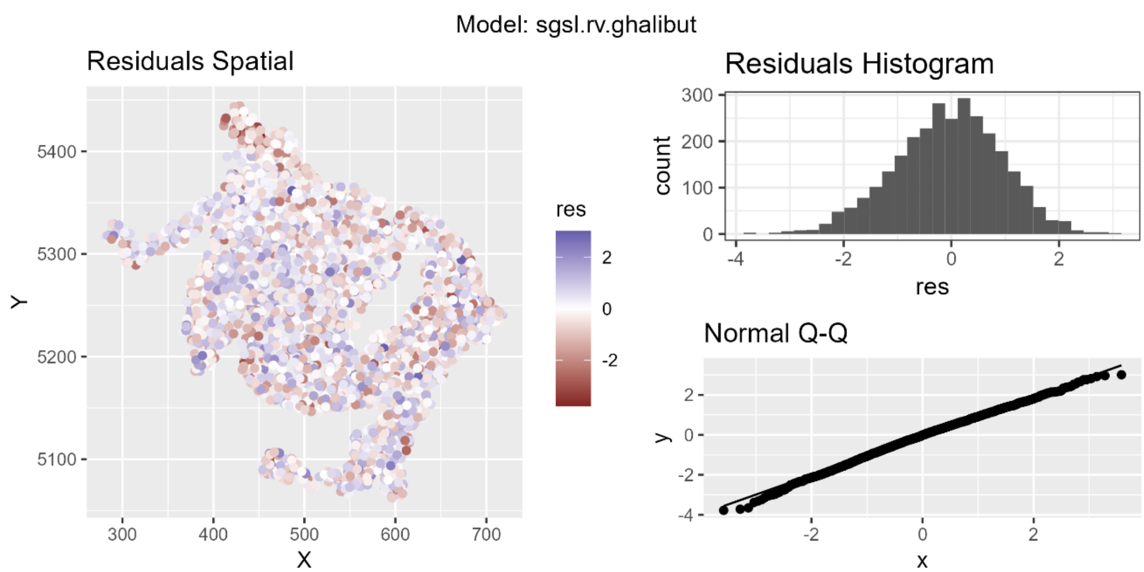

Figure A4: Model diagnostics for the Greenland Halibut sGSL Autumn RV Survey model.

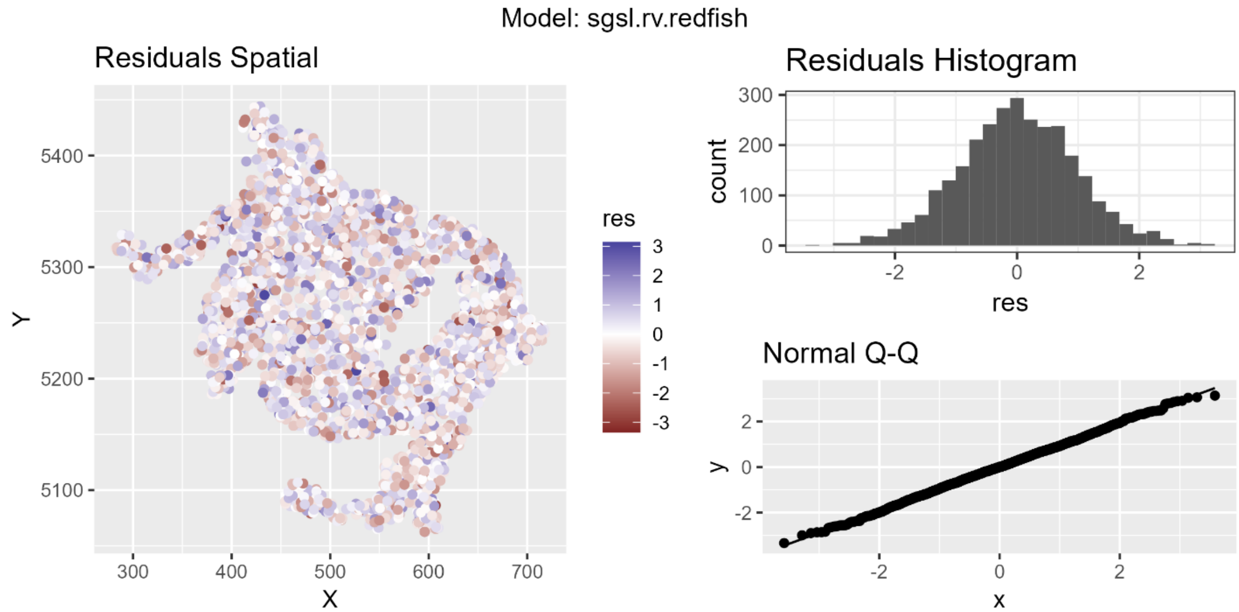

Figure A5: Model diagnostics for the Redfish sGSL Autumn RV Survey model.

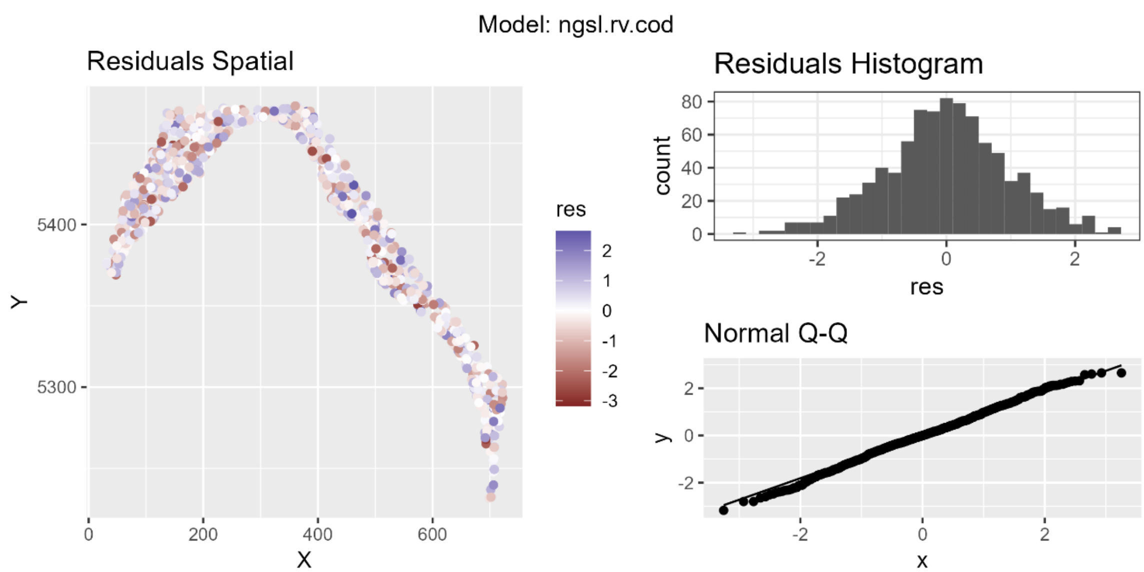

Figure A6: Model diagnostics for the Atlantic Cod nGSL Summer RV Survey model.

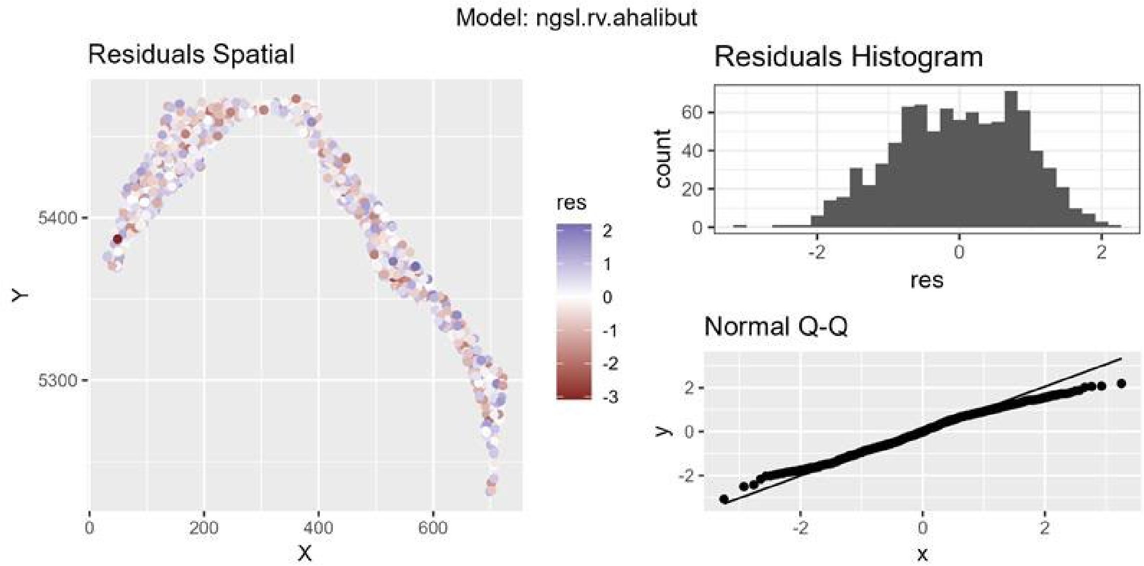

Figure A7: Model diagnostics for the Atlantic Halibut nGSL Summer RV Survey model.

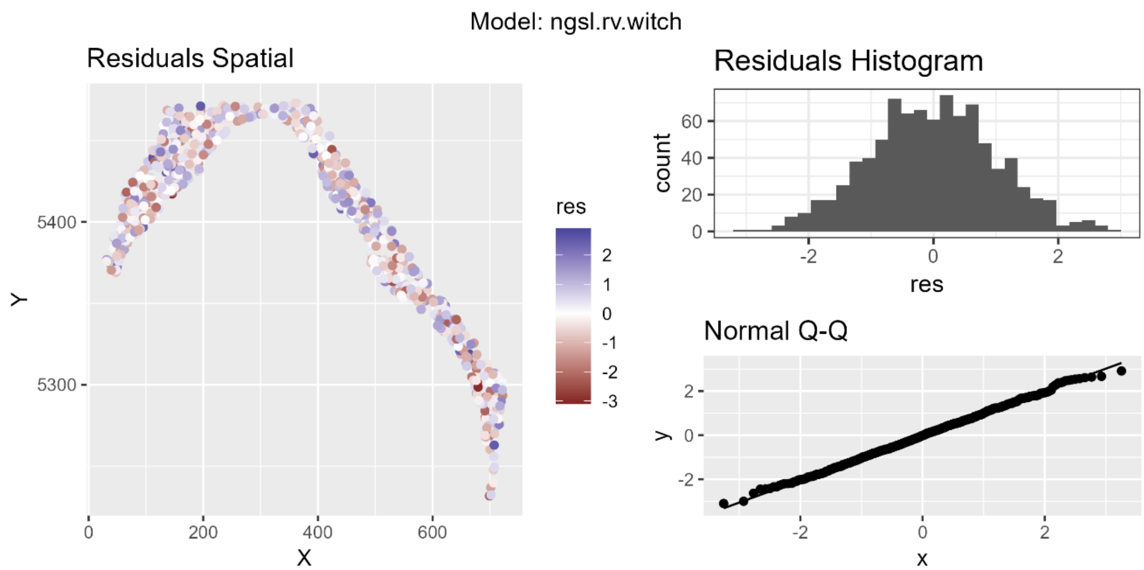

Figure A8: Model diagnostics for the Witch Flounder nGSL Summer RV Survey model.

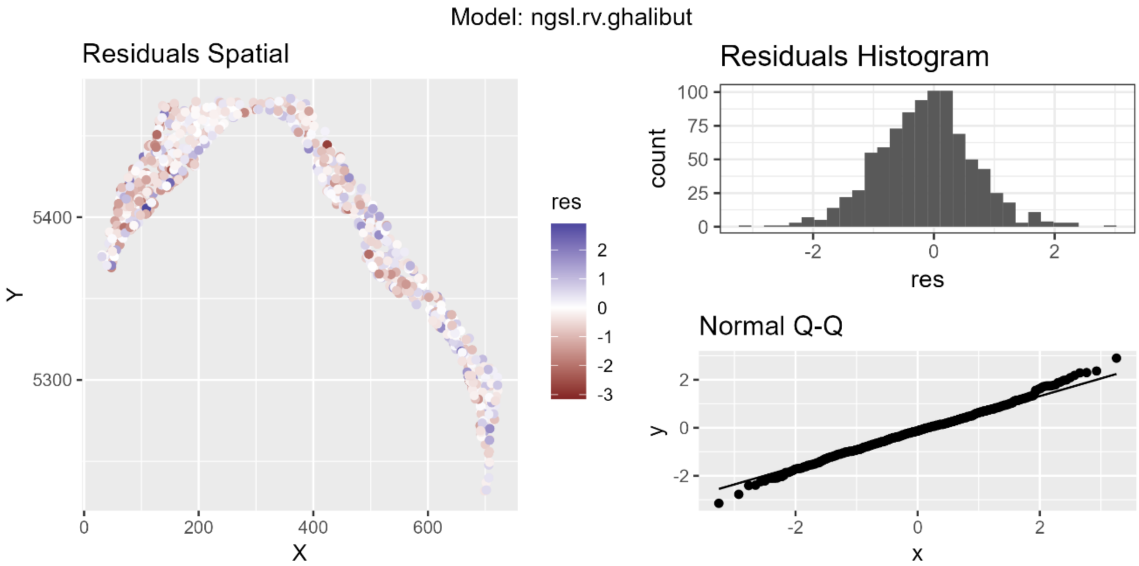

Figure A9: Model diagnostics for the Greenland Halibut nGSL Summer RV Survey model.

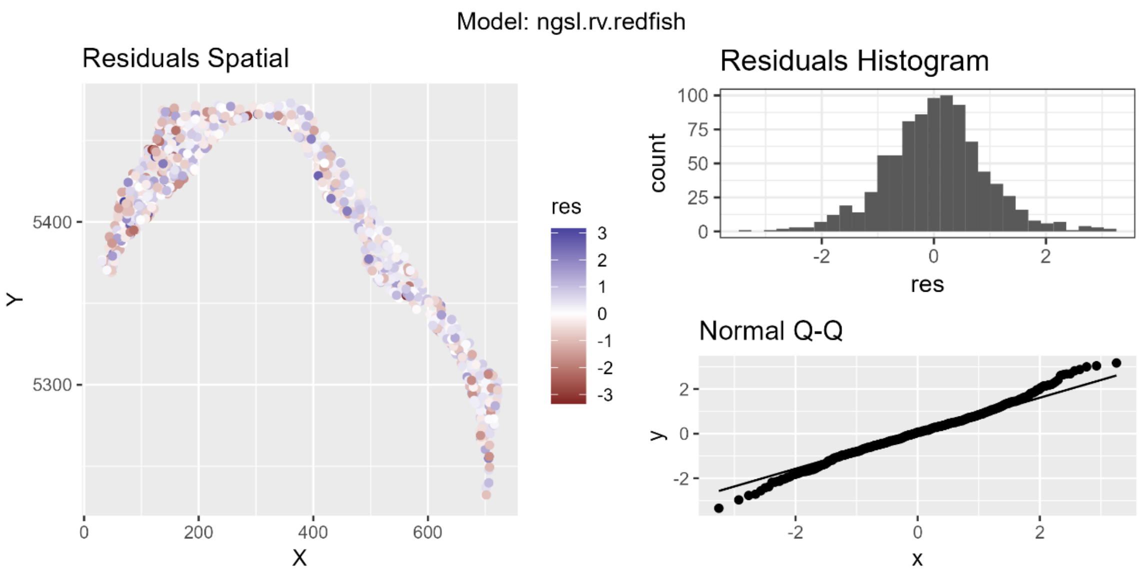

Figure A10: Model diagnostics for the Redfish nGSL Summer RV Survey model.

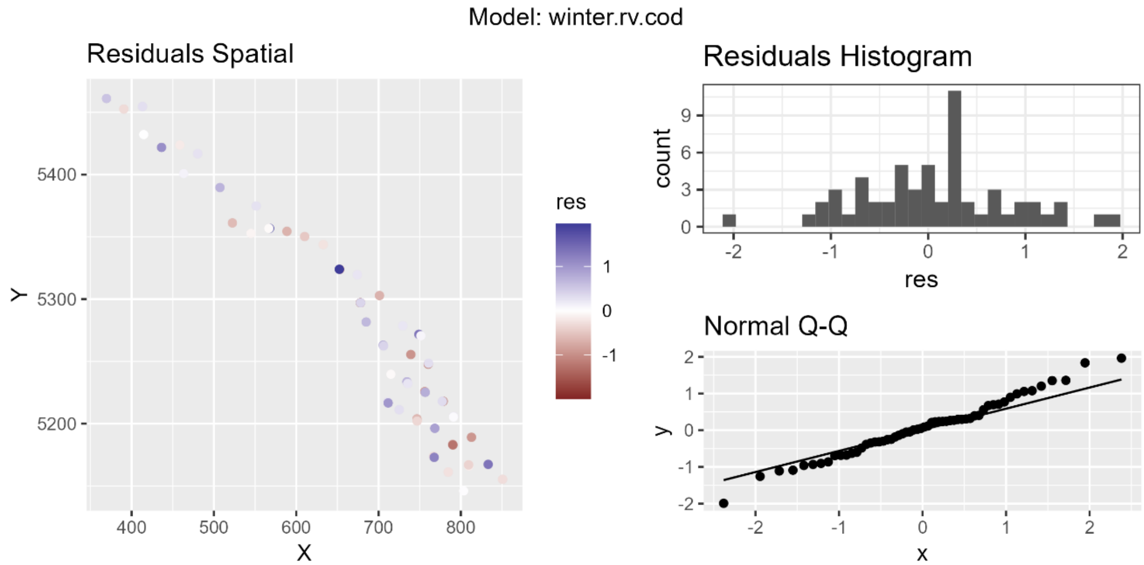

Figure A11: Model diagnostics for the Atlantic Cod Winter RV Survey model.

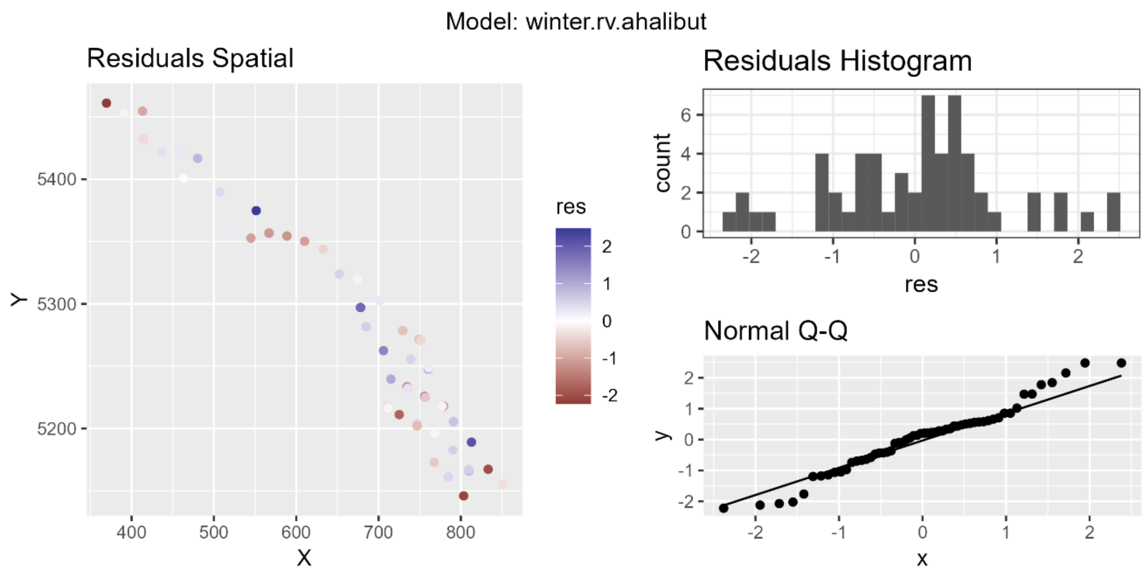

Figure A12: Model diagnostics for the Atlantic Halibut Winter RV Survey model.

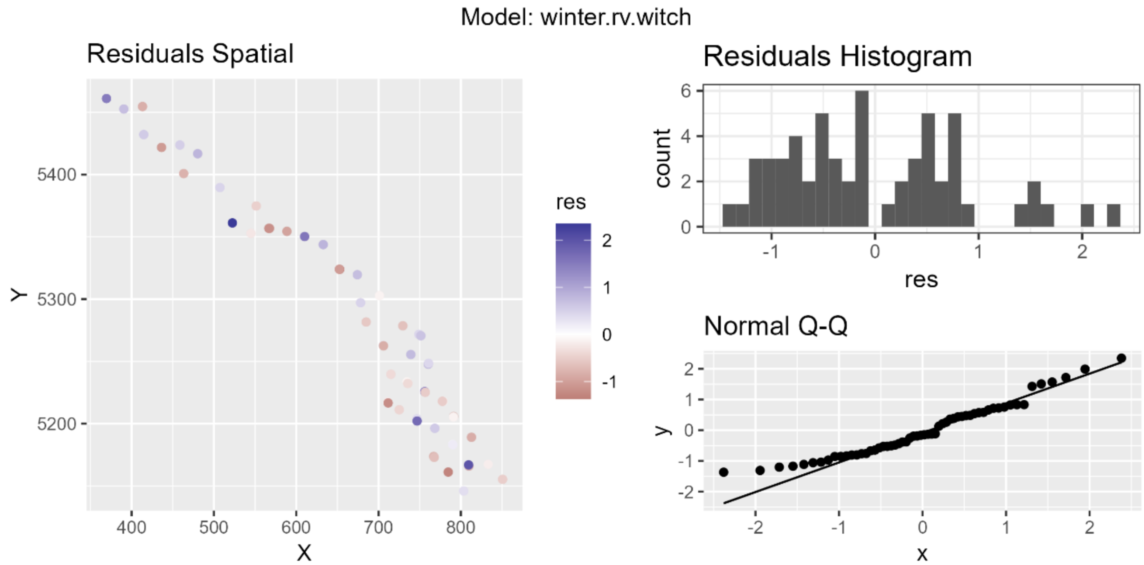

Figure A13: Model diagnostics for the Witch Flounder Winter RV Survey model.

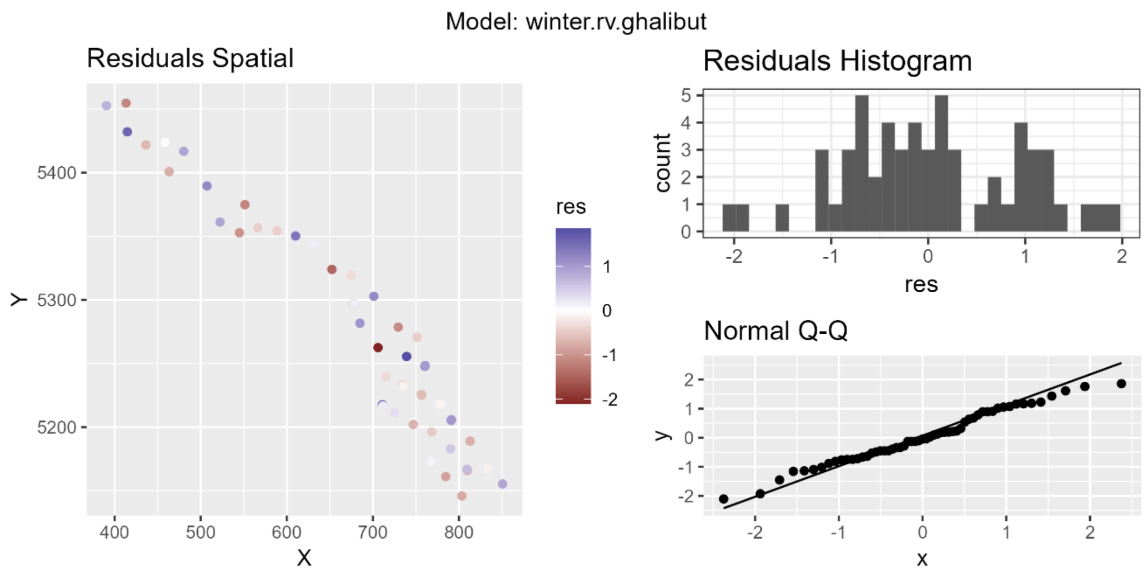

Figure A14: Model diagnostics for the Greenland Halibut Winter RV Survey model.

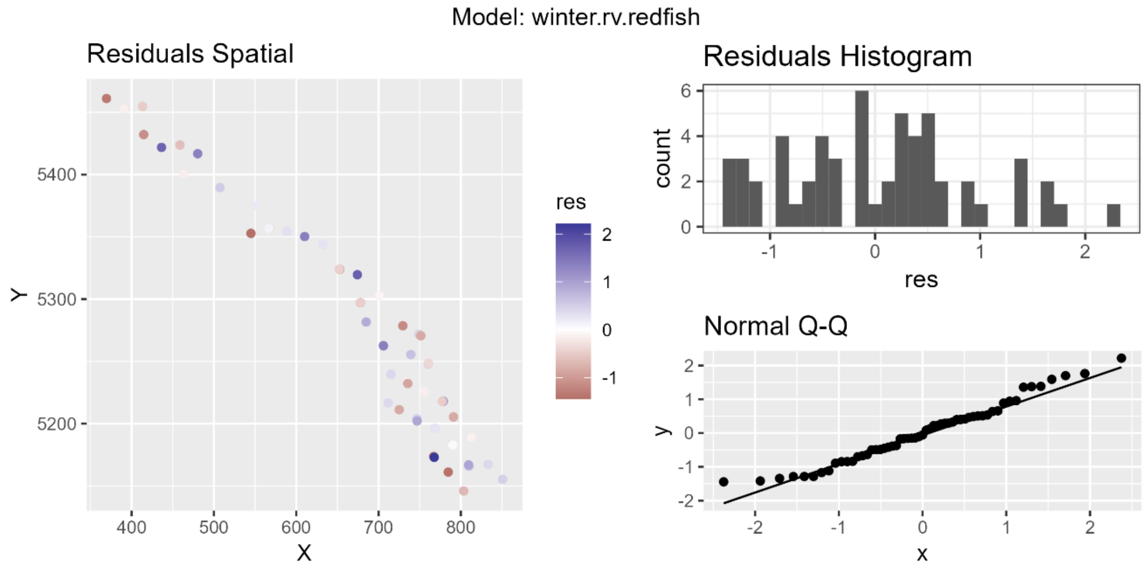

Figure A15: Model diagnostics for the Redfish Winter RV Survey model.

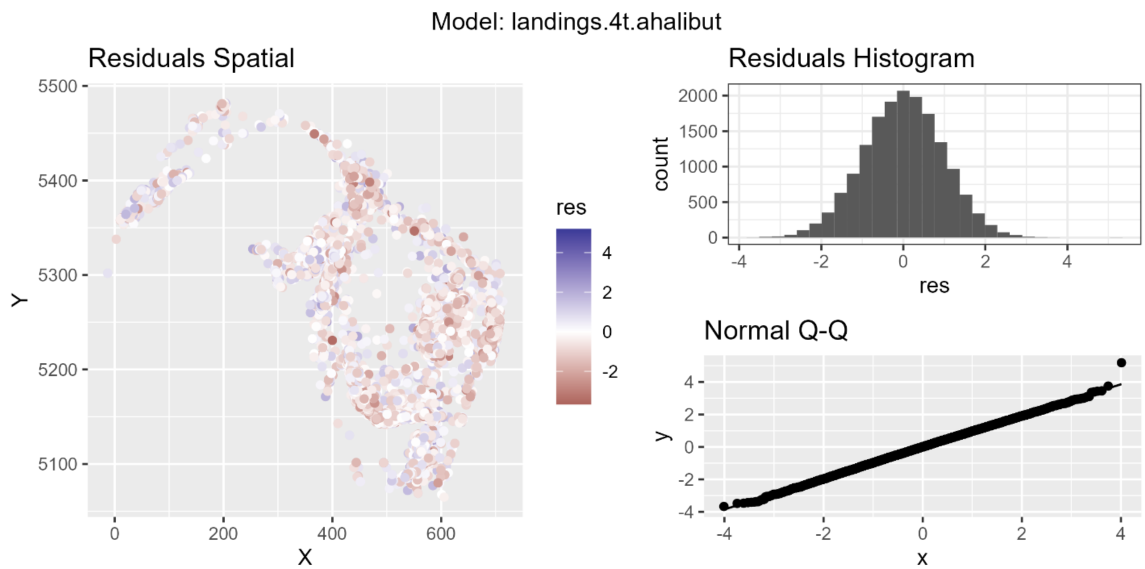

Figure A16: Model diagnostics for the Landings NAFO 4T Atlantic Halibut-directed fishery model.

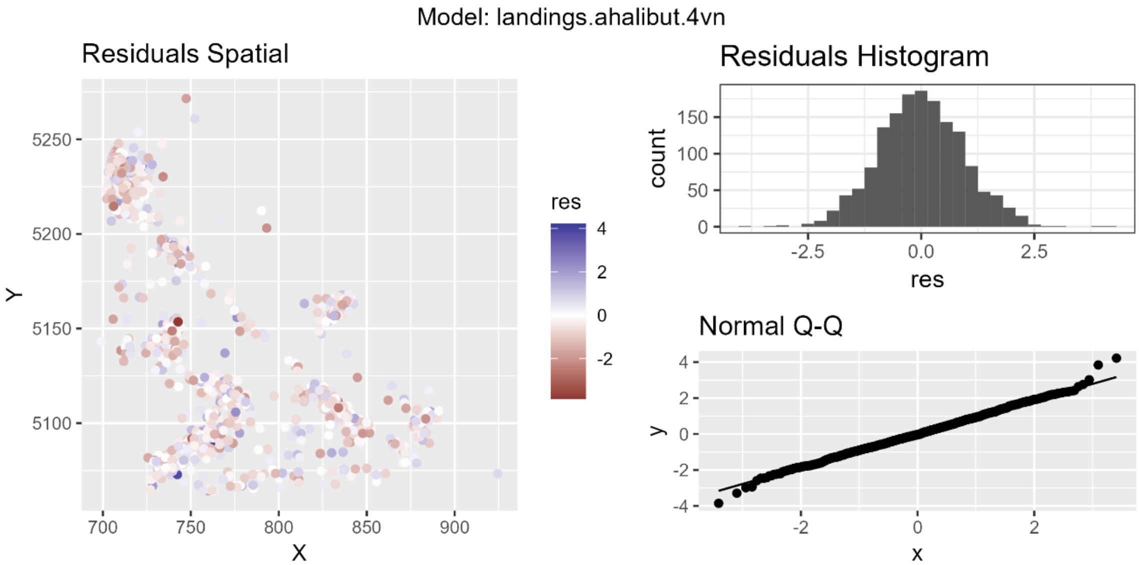

Figure A17: Model diagnostics for the Landings NAFO 4Vn Atlantic Halibut-directed fishery model.

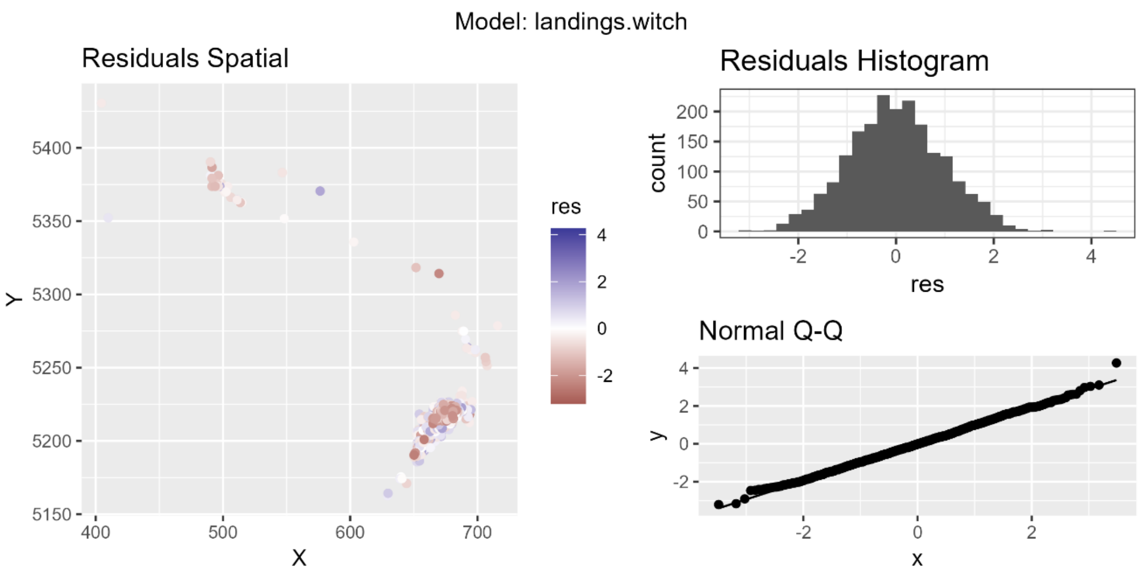

Figure A18: Model diagnostics for the Landings NAFO 4T Witch Flounder-directed fishery model.

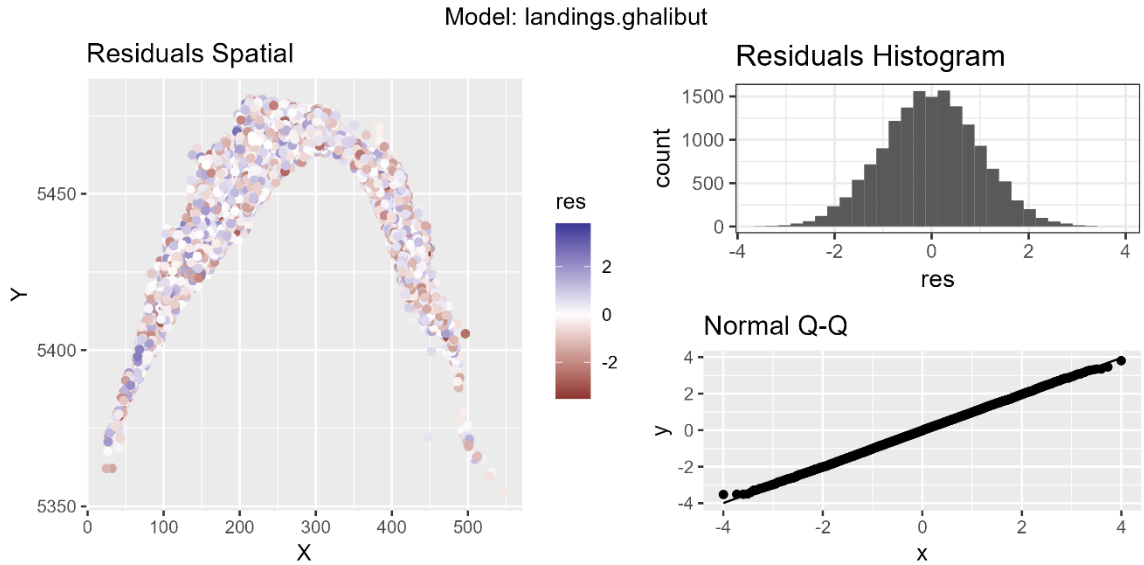

Figure A19: Model diagnostics for the Landings NAFO 4T Greenland Halibut-directed fishery model.

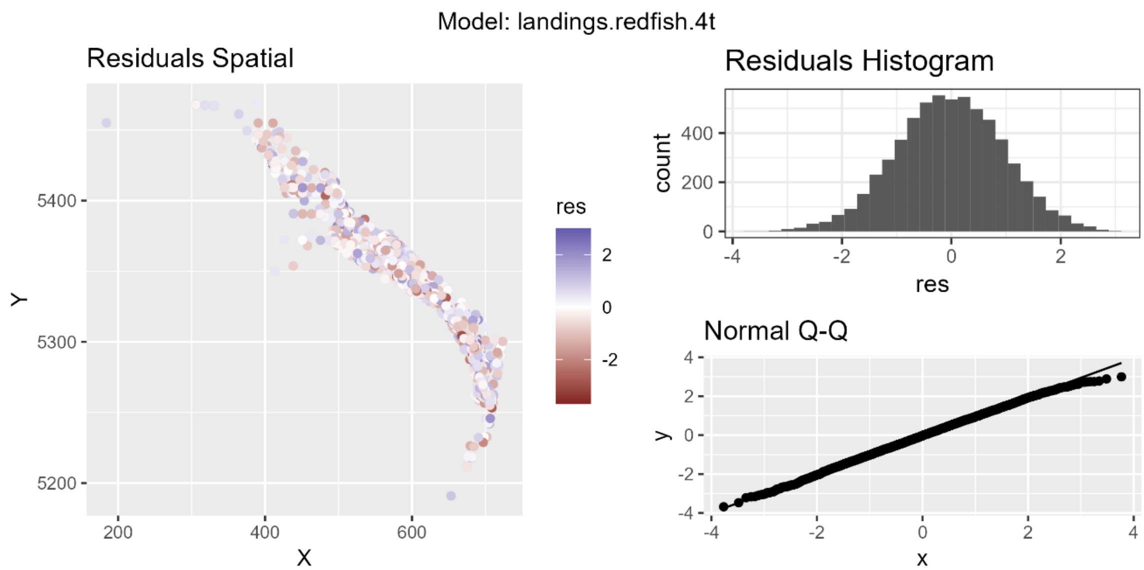

Figure A20: Model diagnostics for the Landings NAFO 4T Redfish-directed fishery model.

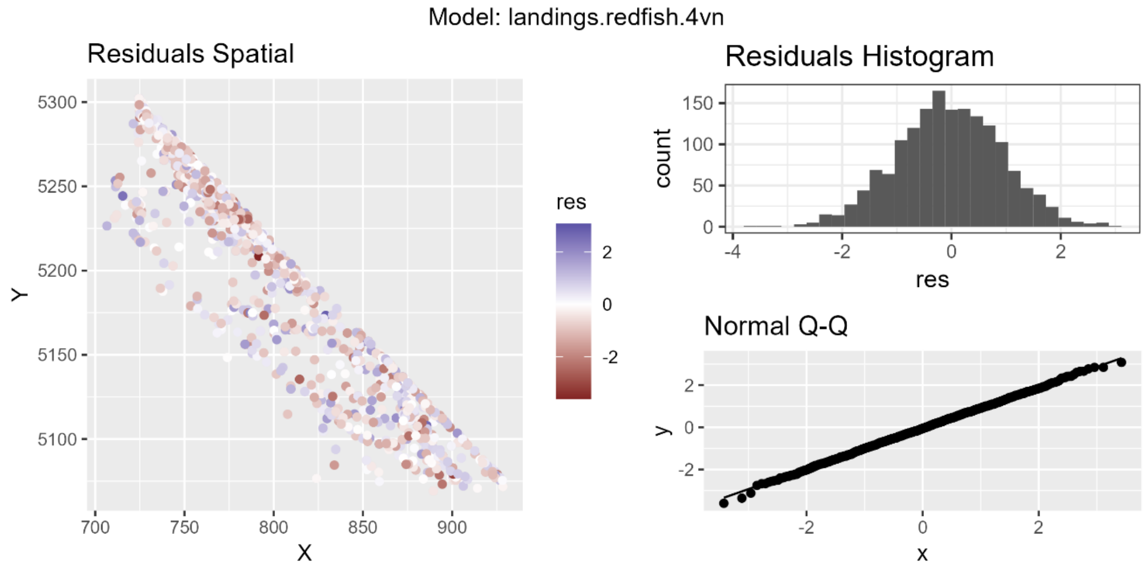

Figure A21: Model diagnostics for the Landings NAFO 4Vn Redfish-directed fishery model.

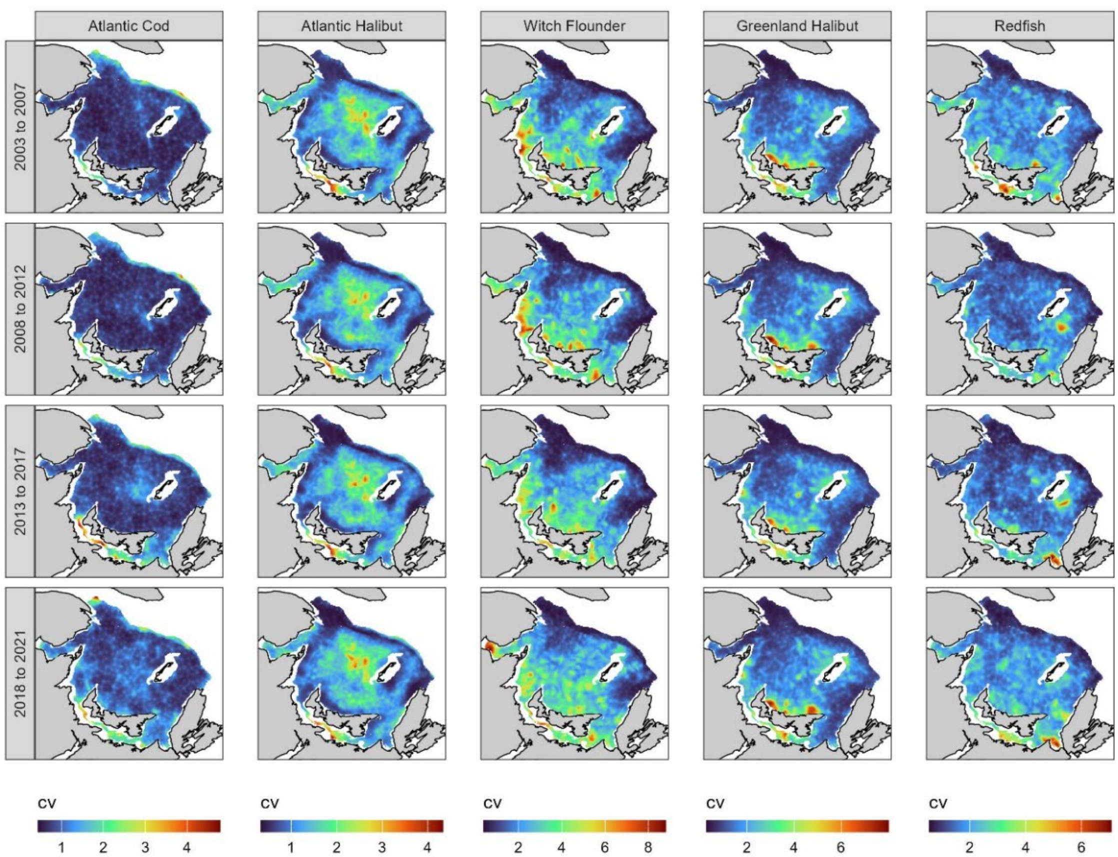

Figure A22: sGSL Autumn Survey uncertainty in model predictions (coefficient of variation). Legends are square-root transformed. Map colours represent means for the time periods indicated.

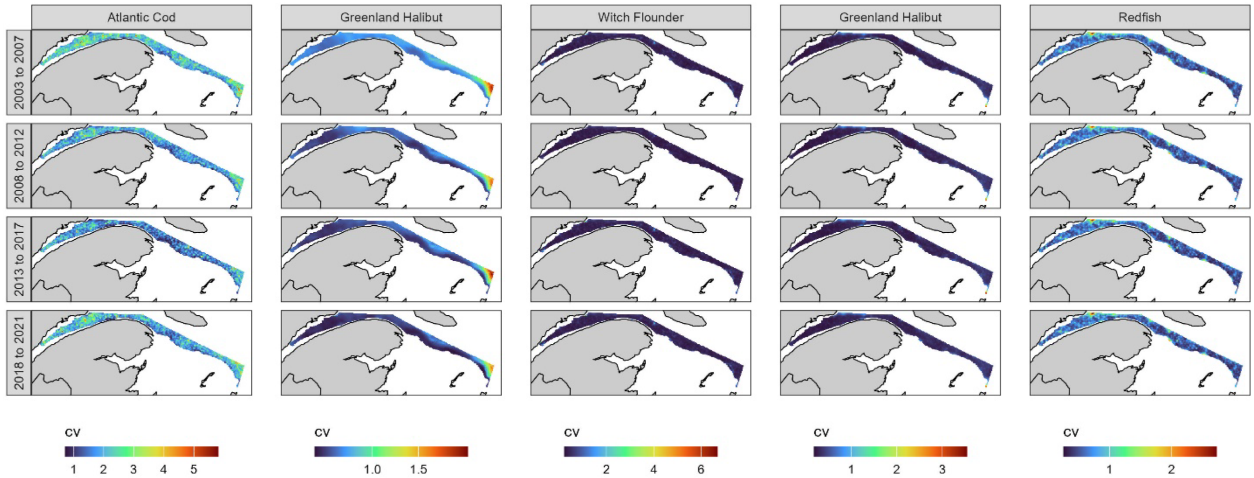

Figure A23: nGSL Summer Survey uncertainty in model predictions (coefficient of variation). Legends are square-root transformed. Map colours represent means for the time periods indicated.

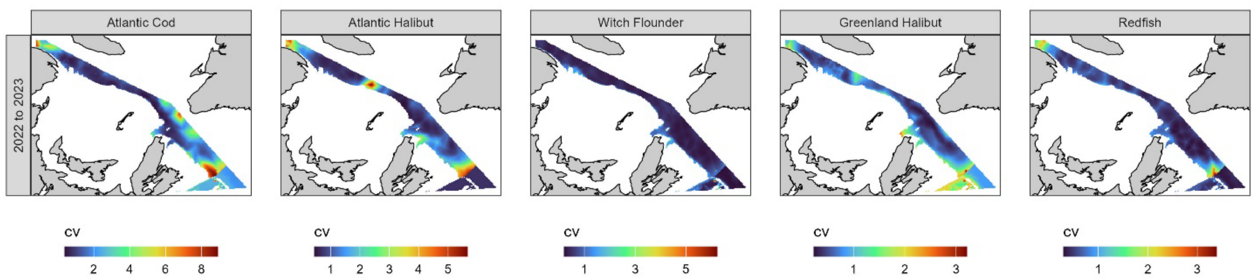

Figure A24: Winter Survey uncertainty in model predictions (coefficient of variation). Legends are square-root transformed. Map colours represent means for years 2022 and 2023.

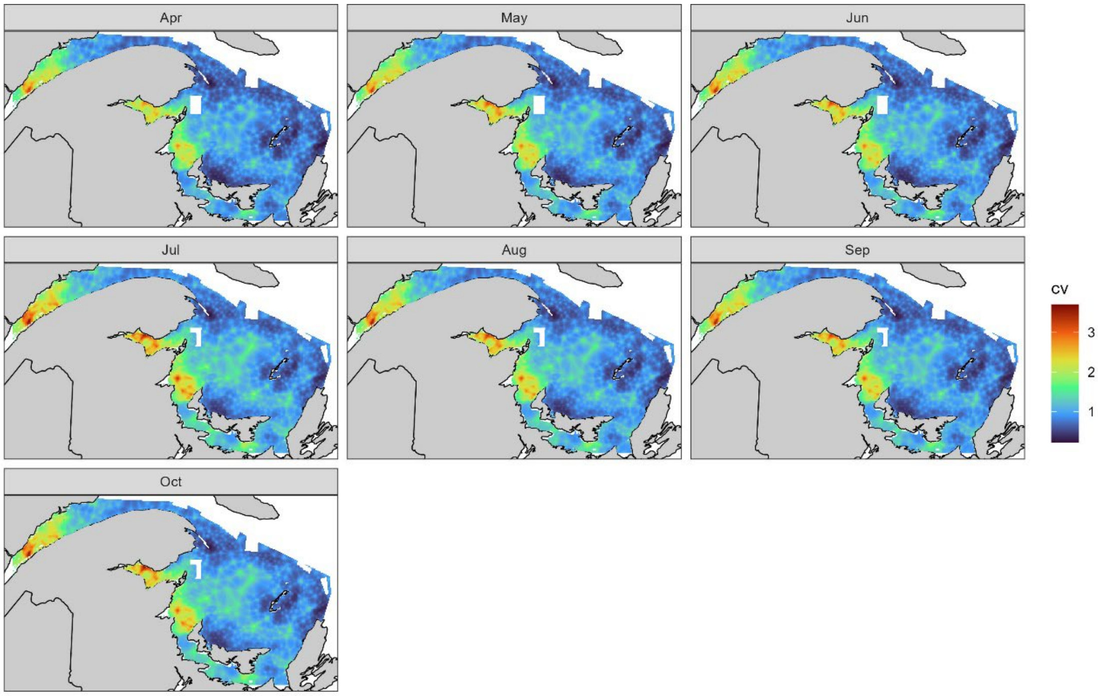

Figure A25: Uncertainty (coefficient of variation) in model predictions of Atlantic Cod in a NAFO 4T Atlantic Halibut fishery, based on the Landings model. Predictions were averaged over years 2017 onward.

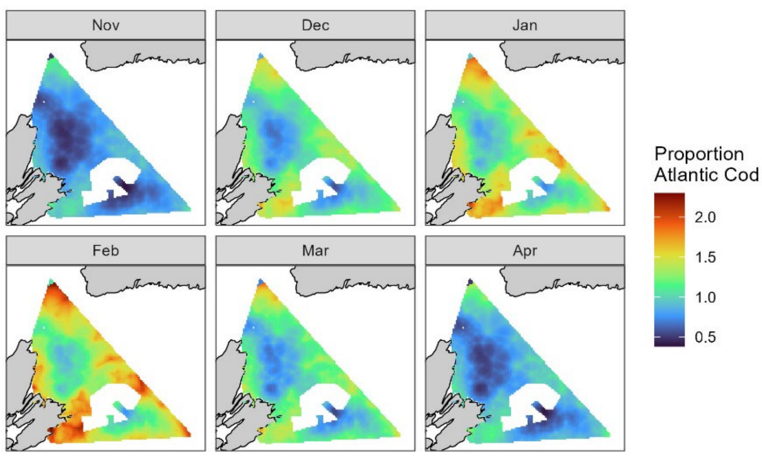

Figure A26: Uncertainty (coefficient of variation) in model predictions of Atlantic Cod in a NAFO 4Vn Atlantic Halibut fishery, based on the Landings model. Predictions were averaged from years 2017 onward.

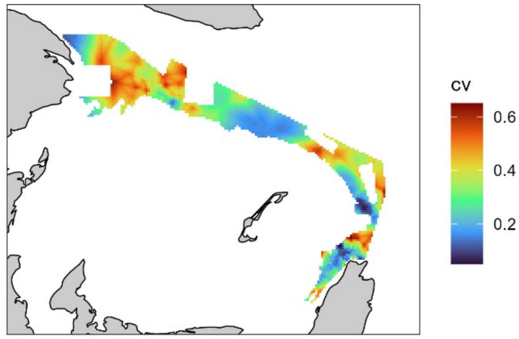

Figure A27: Uncertainty (coefficient of variation) in model predicted bycatch of Atlantic Cod in a NAFO 4T Witch Flounder fishery based on the Landings model, Predictions were made over a spatial grid where Witch Flounder-directed fishing is assumed to be permitted.

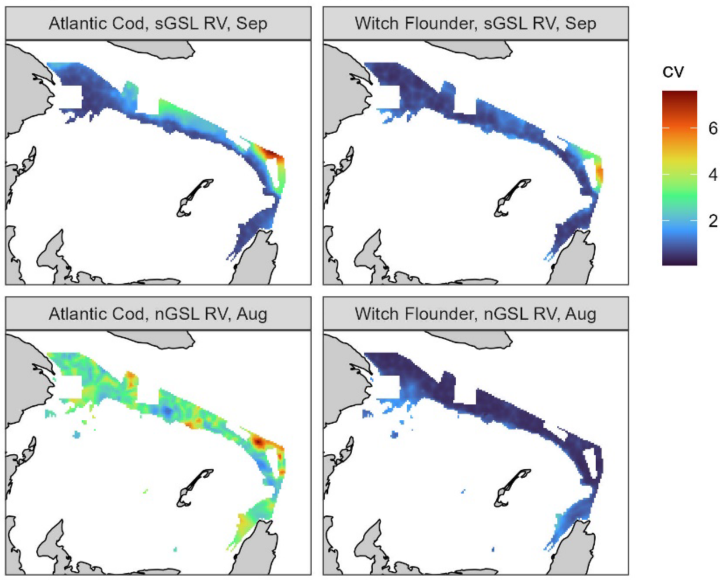

Figure A28: Uncertainty (coefficient of variation) in model predicted catch densities of Atlantic Cod (left) and Witch Flounder (right) based on sGSL RV (top) and nGSL RV (bottom) models. Predictions were made over a spatial grid where Witch Flounder-directed fishing is assumed to be permitted. Predictions were averaged over years 2017 onward.

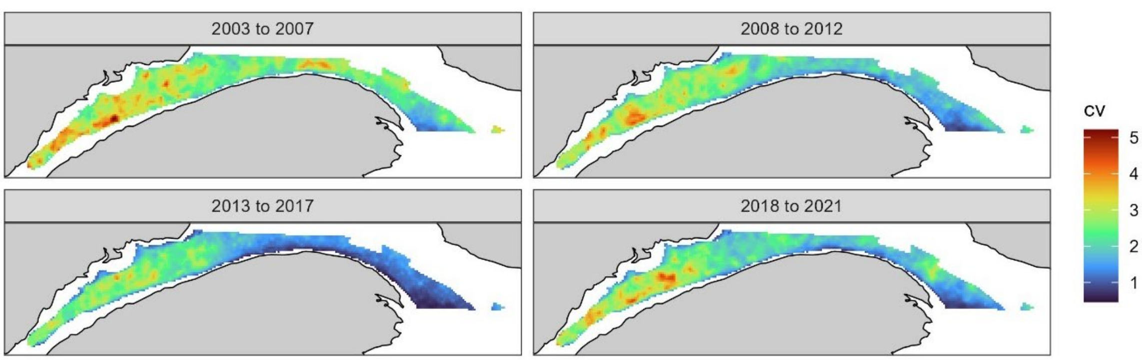

Figure A29: Uncertainty (coefficient of variation) in model predicted bycatch of Atlantic Cod in a NAFO 4T Greenland Halibut fishery based on the Landings model. Predictions were made over a spatial grid where Greenland Halibut-directed fishing is assumed to be permitted.

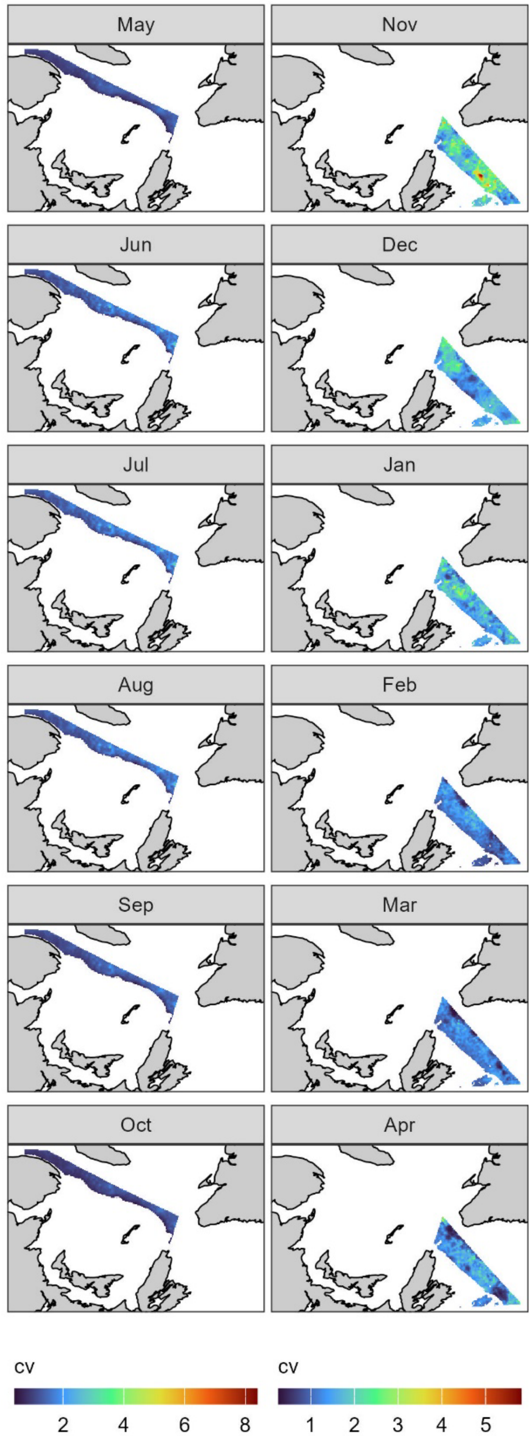

Figure A30: Uncertainty (coefficient of variation) in model predicted bycatch of Atlantic Cod in a NAFO 4T (left) and NAFO 4Vn (right) Redfish fishery based on the Landings models. Predictions were averaged over all years.

APPENDIX 2

Overview of the main revisions made since the February 2024 CSAS meeting

- Updated the model selection process
- Updated equation 2
- Updated bathymetry reference for Greenland Halibut Landings (details below) and revised the associated scientific advice in an erratum to the SAR

Revised bathymetry reference

During the February 2024 CSAS meeting for the rebuilding plan for 4TVn Atlantic Cod, it was identified that the bathymetry reference used by the **gulf** package was outdated (GEBCO_2014). Of particular concern were the depths assigned to the western portion of the St. Lawrence Estuary, which largely affected Greenland Halibut Landings data as well as the Greenland Halibut fishing area prediction grid (Figure A31).

To address these concerns, we applied an updated bathymetry reference (GEBCO_2023) to the Greenland Halibut Landings data and to the Greenland Halibut fishing area prediction grid. Using the updated Landings data, we repeated all associated analyses beginning with data quality control and model selection, and we made model predictions over the updated fishing grid. We also made predictions over the updated fishing grid using nGSL RV models for Greenland Halibut and Atlantic Cod. The preceding document has been updated to reflect these changes.

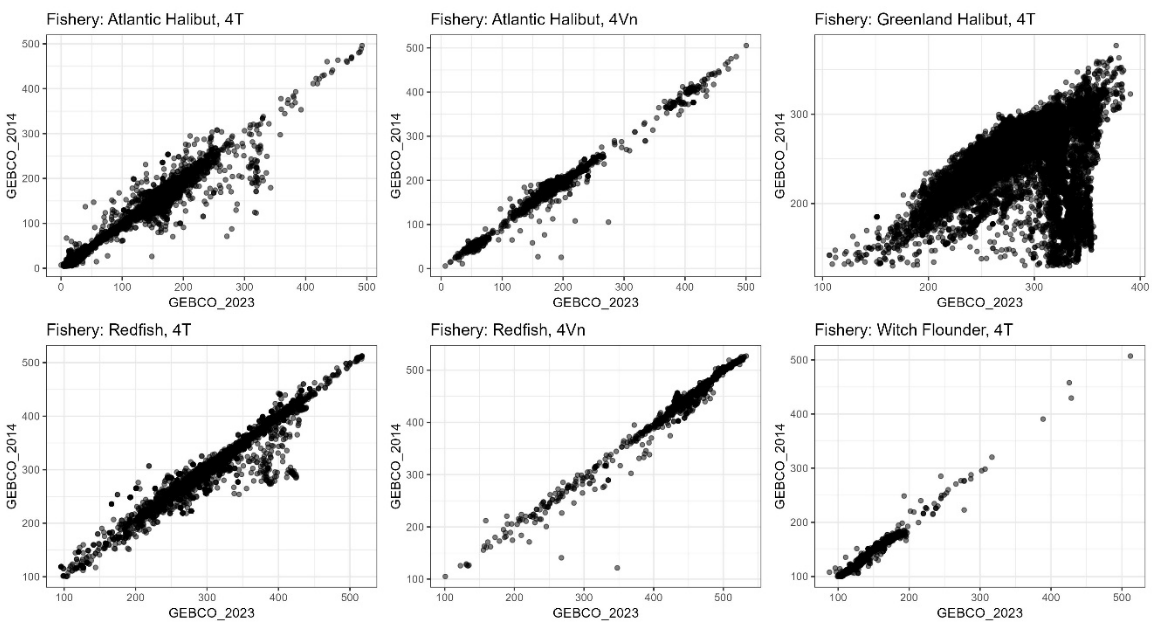

Figure A31: Depths assigned to Landings data coordinates using the GEBCO_2014 and GEBCO_2023 bathymetry references.