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Mitigating Bycatch of Southern Gulf of St. Lawrence NAFO Division 4T White Hake (*Urophycis tenuis*)

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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

Key management measures proposed in the southern Gulf of St. Lawrence White Hake (*Urophycis tenuis)* rebuilding plan include keeping removals from all sources at the lowest possible level, monitoring sources of fishing mortality, and enforcing compliance of management measures. In this study, we assessed spatial and temporal patterns of bycatch risk in four fisheries responsible for the majority of White Hake bycatch from 2013 to 2022.

To assess bycatch risk, we used fisheries-independent and/or 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 White Hake were associated with depth, making depth-specific mitigation an important component of bycatch mitigation strategies for the Redfish fishery and possibly the Greenland Halibut and Witch Flounder fisheries. For the Greenland Halibut and Atlantic Halibut fisheries, locations and/or months of high bycatch risk were identified in which mitigation efforts could be focused. The vast majority of surveys and fishing activities occurred from May to October, however, a reopened commercial Redfish fishery operating between January and May is likely to overlap with the overwintering habitat of White Hake and other groundfish. During winter months, stricter depth-associated mitigation strategies may be warranted.

INTRODUCTION

The designatable unit (DU) for southern Gulf of St. Lawrence (sGSL) White Hake (*Urophycis tenuis*) occurs primarily within the Northwest Atlantic Fisheries Organization (NAFO) Division 4T (Figure 1). Although it is unclear whether White Hake in the St. Lawrence Estuary belong to the sGSL stock, this location is currently included within the stock management area (Turcotte et al. 2025). Historically a commercially important groundfish in the sGSL, the directed fishery was closed in 1995 due to low abundance, and has remained under moratorium to present day. The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the status of sGSL White Hake as Endangered in 2013 (COSEWIC 2013). A total allowable catch (TAC) of 30 tonnes (t) remains to account for bycatch in other groundfish fisheries, catch in a limited recreational fishery, catch for scientific purposes, and Indigenous food, social and ceremonial fisheries.

This stock has been below its Limit Reference Point (LRP) since 1992 (Turcotte et al. 2025), 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 also for stocks already at or below its LRP. This timeline begins the day the stock is prescribed in regulation (April 4, 2022 for sGSL White Hake).

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 often include additional restriction on catches. For sGSL White Hake, the rebuilding plan notes that new management measures and/or adjustments to existing management measures already in place in other commercial groundfish fisheries may be introduced to further reduce interactions and keep White Hake bycatch under established limits. The rebuilding plan also notes that target depth ranges in specific fisheries or fishing areas, and spatial-temporal closures are examples of measures that could be implemented.

This study aims to contribute to the rebuilding plan by: (i) assessing the extent of spatiotemporal overlap between sGSL White Hake and commercially harvested species in which the majority of bycatch occurs; (ii) assessing the spatiotemporal patterns of bycatch from fishery and/or other catch data; and (iii) providing 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, where mitigation efforts could be focused.

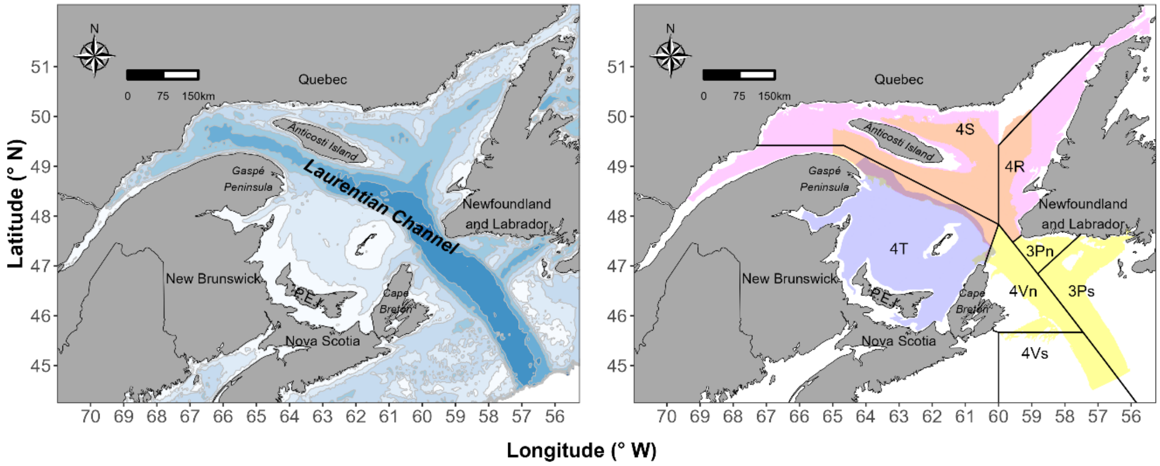

Figure 1. Maps of the NAFO 4T study area and surrounding regions. Left: Bathymetry showing depth intervals at 50 m, 100 m, and then every 100 m (light to dark blue shading indicates a transition from shallow to deep). Right: Thick black lines show NAFO divisions. The shaded pink area shows the nGSL DFO Research Vessel survey area. The shaded blue area shows the sGSL DFO Research Vessel regular survey area. The shaded yellow area shows the GSL winter Research Vessel survey area.

MATERIALS AND METHODS

STUDY SYSTEM

From 2013 to 2022, the average annual reported landings of sGSL White Hake was approximately 17 t (Turcotte et al. 2025). After adjusting for discards, most bycatch was attributed to fisheries targeting Greenland Halibut (*Reinhardtius hippoglossoides*; 46%), Redfish (*Sebastes* spp.; 31%), Atlantic Halibut (*Hippoglossus hippoglossus*; 13%), and Witch Flounder (*Glyptocephalus cynoglossus;* 10%).

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. The soak time limit is 72 hours. In the Western Gulf, landings reached highs near 3,000 t in 2015 and have since declined to the lowest levels in 2022 (DFO 2023a). 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 NAFO 4T. The directed fishery for Greenland Halibut operates at depths of 180 m to 360 m, and for the Western Gulf, occurs along the slopes of the Laurentian Channel into the Estuary off the Gaspe Peninsula. In NAFO Division 4T, the area south of Cap Gaspé is permanently closed on the eastern side of the Peninsula (DFO 2021).

Redfish fishery

The commercial fishery for Redfish Management Unit 1 was under moratorium from 1995 until 2024, however, an index fishery and an experimental fishery operated from 1998 to 2023 and from 2018 to 2023 respectively (Brassard et al. 2017; McAllister et al. 2021; DFO 2022; Senay et al. 2023). During these periods, most Redfish-directed fishing used seines or trawls. Strong recruitment events for the 2011 to 2013 year classes led to a large increase in biomass

(DFO 2022), resulting in the reopening of the commercial fishery in 2024. The 2024 TAC was set for 60,000 t.

Conservation harvesting measures for 2024 authorized fishing within NAFO Division 4RST between longitudes 59° and 65° W from June 15 to December 31, and within NAFO sub-divisions 3Pn and 4Vn between January 1 and March 31. From June 15 to October 31, fishing activities must be carried out at depths of at least 300 m (164 fathoms). From November 1 to March 31, fishing activities must be carried out at depths of at least 183 m (100 fathoms). Species-specific bycatch quotas are also described in harvesting plans, as well as details of area closures.

Atlantic Halibut fishery

The commercial fishery directing for the NAFO Division 4RST Atlantic Halibut stock is carried out using longlines under a competitive management regime, or by individual transferable quota (ITQ). The soak time limit is 72 hours. Since the 1960s, the stock has been exploited by 12 fleets in Quebec, Newfoundland and Labrador, and the three Maritime provinces (DFO 2023b). In NAFO Division 4T, the fishery is active 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 2023b).

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). Since 2003, the fishery has been predominately done using Danish seines, and occurs largely between May and September. From 2000 to 2011, the TAC was set to 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 NAFO 4R and the NAFO 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).

At-Sea Observer Program

The At-Sea Observer Program (ASO) collects detailed information on fishing activities at sea, including data on the target species, bycatch, and discards. The targeted minimum coverage for commercial groundfish fisheries ranges from 5% to 20% of all fishing trips, and depends on the fishery and fleet. From 2013 to 2022, ASO data indicated that discarding of White Hake at sea occurred in the Greenland Halibut, Redfish, and Atlantic Halibut fisheries (Turcotte et al. 2025), despite discarding having been prohibited since 1993 (Benoît et al. 2010). Discard rates estimated from ASO data were 51.2%, 11.3%, and 1.8% of the total weight of White Hake caught in each fishery respectively. By extrapolating ASO results to the reported commercial bycatch of White Hake, it was estimated that total removals of White Hake may be underestimated by an average of 30% (7% to 53% across the years studied).

DATA SOURCES

Fisheries-independent surveys

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 RV survey). The multi-speciessurvey 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 estuary of the St. Lawrence River (Bourdages and Savard 2007; Bourdages et al. 2022). We obtained species catch densities (kg/tow per species) for survey years 2013 to 2022 in NAFO 4T (Figure 2), 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 409 complete tows. The number of tows per year in NAFO 4T ranged from 32 (2020) to 49 (2013). White Hake were recorded in 64.8% of tows, Redfish in 96.6%, Greenland Halibut in 92.9%, Atlantic Halibut in 26.2% and Witch Flounder in 82.2%. Tow depths ranged from 48 m to 516 m.

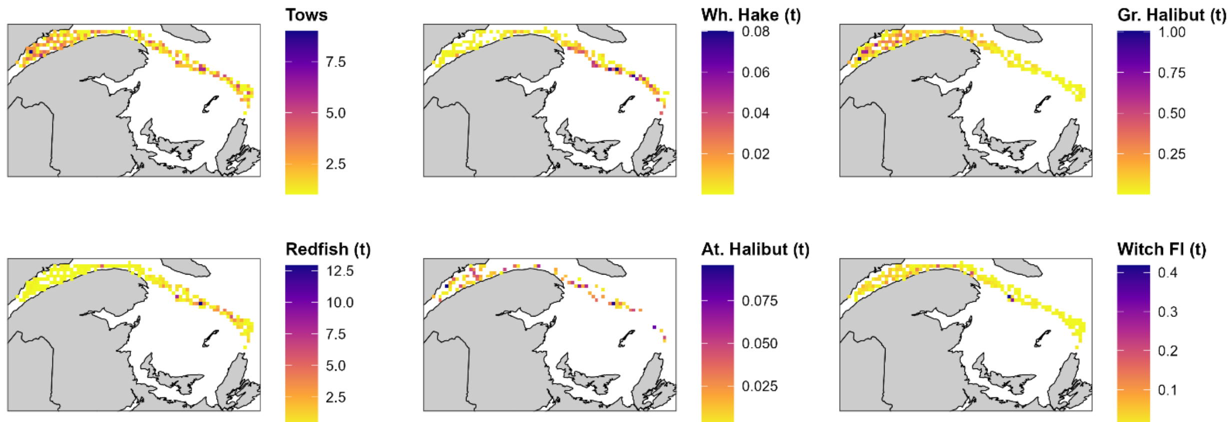

Figure 2. Number of nGSL RV tows (top left), total weight of White Hake (top centre), total weight of Greenland Halibut (top right), total weight of Redfish bottom left), total weight of Atlantic Halibut (bottom centre), total weight of Witch Flounder (bottom right). Weights are in tonnes. Grid cells are 10 x 10 km.

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 RV survey). The multi-species 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 for survey years 2013 to 2023 and survey strata 415 to 439 (Figure 3), 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 and Swain 2003a; Benoît 2006; Benoît and Yin 2023).The approximate surface area covered by each standardized tow was 0.041 km^2. We obtained catch density data along with spatial coordinates (degrees latitude and longitude) and depth (m) for 1,371 complete tows. The number of tows per year ranged from 86 (2020) to 161 (2015). White

Hake were recorded in 20.9% of tows, Greenland Halibut in 29.4%, Redfish in 34.2%, Atlantic Halibut in 20.4%, and Witch Flounder in 23.4%. Tow depths ranged from 19 m to 386 m.

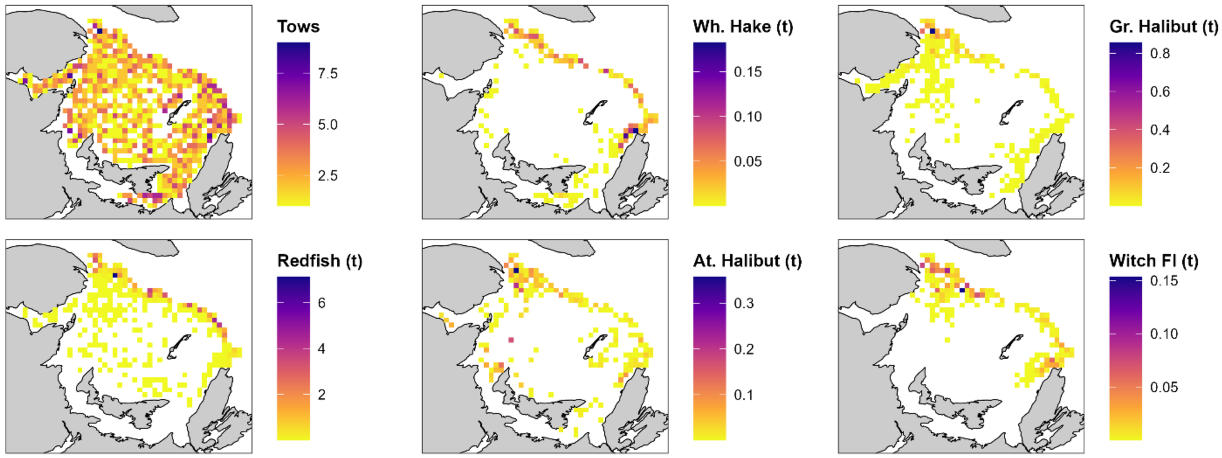

Figure 3. Number of sGSL RV tows (top left), total weight of White Hake (top centre), total weight of Greenland Halibut (top right), total weight of Redfish (bottom left), total weight of Atlantic Halibut (bottom centre), total weight of Witch Flounder (bottom right). Weights are in tonnes. Grid cells are 10 x 10 km.

Winter research vessel survey

During the winters of 2022 to 2024, 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 (described above). We obtained species catch densities 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 (Figure 4). For each tow, we retained spatial coordinates (degrees latitude and longitude) and depth (m). White Hake were recorded in 94.8% of tows, Redfish in 98.3%, Greenland Halibut in 72.4%, Atlantic Halibut in 27.6% and Witch Flounder in 86.2%. Tow depths ranged from 102 m to 525 m. All Winter RV survey data and analyses should be considered preliminary at this time, as data validation has not yet taken place. Data from 2024 were not available.

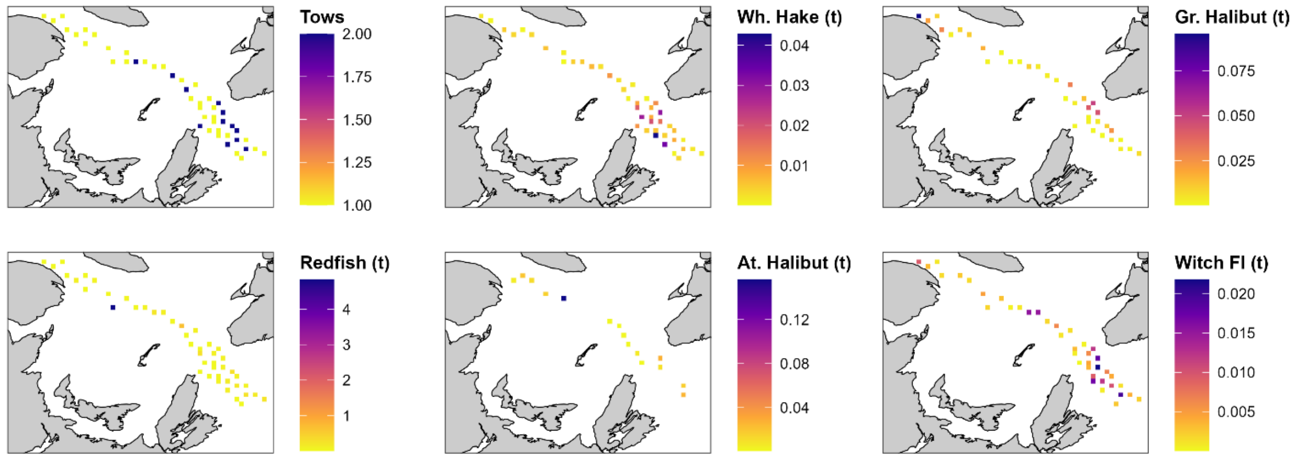

Figure 4. Number of Winter RV tows (top left), total weight of White Hake (top centre), total weight of Greenland Halibut (top right), total weight of Redfish (bottom left), total weight of Atlantic Halibut (bottom centre), total weight of Witch Flounder (bottom right). Weights are in tonnes. Grid cells are 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 meta-data that typically includes 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 in-house **gulf** package (Vergara et al. 2023) in **R** (R Core Team 2022) to access landings records. We initially accessed landings records for years 2013 to 2022 and NAFO divisions 3Pns4RSTVns. We obtained records reported to be within and adjacent to our target area (4T) 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 (hence, estimates of weights caught in the subsequent analysis do not indicate total landings). We then assigned a NAFO division to each record, and removed records outside of the 4T 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).

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 (“[GEBCO 2023]”). After estimating the depth for each pair of coordinates, we removed records with depth ≥ 0 m, and converted depth estimates to absolute values.

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. Next, we separated data by fishery (“main.species.sought”), and applied fishery-specific filters as appropriate prior to model development.

Greenland Halibut fishery

We removed fishing events that occurred in water shallower than 130 m, based on Greenland Halibut biology (DFO 2021, 2023a; Gauthier et al. 2021), as well as records that had zero catch of both Greenland Halibut and White Hake. We also removed any events using gears other than gillnet. Of the remaining 6,479 fishing events (Figure 5), White Hake were recorded in 17.04% of events, while Greenland Halibut were recorded in 99.97%. The mean bycatch (i.e., weight of White Hake divided by the combined weight of White Hake and Greenland Halibut) , was 0.54% (minimum = 0, maximum = 100%, median = 0). Depths ranged from 133 m to 391 m (mean = 291, median = 296). Fishing occurred from months April through October, with the majority of events (86.1%) occurring from May through August.

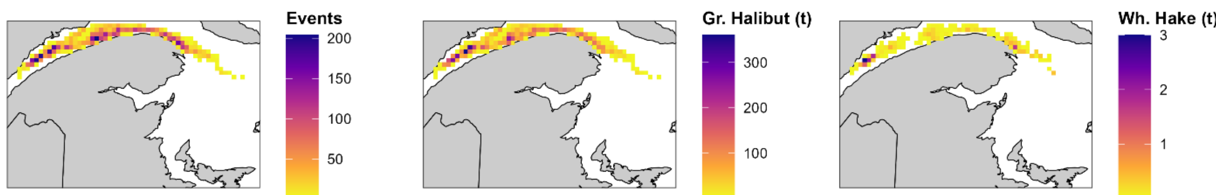

Figure 5. Number of Greenland Halibut-targeted fishing events (left), total weight of Greenland Halibut (centre), and total weight of White Hake (right). Weights are in tonnes. Grid cells are 10 x 10 km.

As White Hake discard rates are notably high in the Greenland Halibut fishery (Turcotte et al. 2025), landing data may underestimate true bycatch levels. Therefore, we also examined ASO data from Turcotte et al. (2025). White Hake occurred in 39.2% of 1,245 ASO fishing events, while Greenland Halibut occurred in 100%. The mean bycatch was 0.84% (minimum = 0, maximum = 50%, median = 0). Depths ranged from 152 m to 374 m (mean = 286, median = 290). Fishing occurred from months April through October, with the majority of events (74.5%) occurring from June through August.

Redfish fishery

We removed Redfish-targeted fishing events that had zero catch of both Redfish and White Hake, and those using gear other than trawls or seines. We also removed events that occurred in water shallower than 100 m, based on Redfish biology (DFO 2022), and months with few fishing events. Within the retained 1,544 fishing events, months included were June through October, however, September and October together only encompassed 9% of fishing events. Seines were the dominant gears used (86.0%). Depths ranged from 114 m to 484 m (mean = 299, median = 296). Fishing effort in terms of number of events was concentrated over the eastern portion of the southern slopes of the Laurentian Channel (Figure 6). Total weights of Redfish and of White Hake reflected this effort. White Hake were recorded in 44.6% of events, while Redfish were recorded in 99.7%. The mean bycatch was 6.38% (minimum = 0, maximum = 100, median = 0).

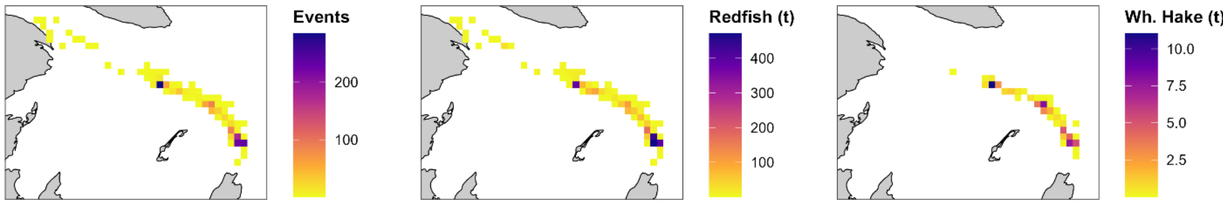

Figure 6. Number of Redfish-targeted fishing events (left), total weight of Redfish (centre), and total weight of White Hake (right). Weights are in tonnes. Grid cells are 10 x 10 km.

Atlantic Halibut fishery

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 White Hake. For computational speed and to improve model fit, we removed data from vessels associated with only a single fishing event, as well as fishing events with White Hake proportions > 0.65 (21 fishing events; models that included these data points failed to converge). The vast majority of these high proportion White Hake fishing events were located either north of PEI (n = 11) in depths shallower than 40 m, or north of Cape Breton (n = 7) in depths between 175 m and 265 m (Figure A1). The remaining high proportion White Hake events were located along the west coast of Cape Breton, or along the northeast coast of the Gaspé Peninsula.

Finally, we removed fishing events that occurred in March or November, due to low sample sizes. Of the remaining 12,009 fishing events (Figure 7), White Hake were recorded in 5.67% of events, while Atlantic Halibut were recorded in 100%. The mean bycatch was 0.44% (minimum = 0, maximum = 50%, median = 0). Months July through August comprised 74% of fishing events. Longlines were used in 100% of events. Depths ranged from 5 m to 492 m (mean = 63, median = 31), and displayed a bimodal distribution. The mean bycatch for fishing events shallower than 100 m (n = 9,060) was 0.09%, while the mean bycatch at greater depths was 1.5%.

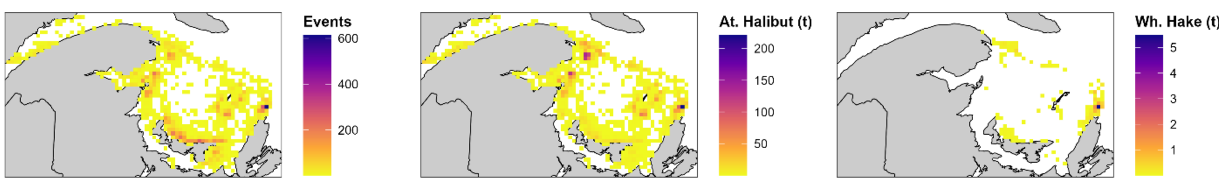

Figure 7. Number of Atlantic Halibut-targeted fishing events (left), total weight of Atlantic Halibut (centre), and total weight of White Hake (right). Weights are in tonnes. Grid cells are 10 x 10 km.

Witch Flounder fishery

We removed fishing events that occurred in water shallower than 100 m, based on species biology (Powles and Kohler 1970; Ricard 2022), as well as records that had zero catch of both Witch Flounder and White Hake. Of the remaining 375 fishing events (Figure 8), White Hake were recorded in 272 (72.5%), while Witch Flounder were recorded in 99.5%. The mean bycatch was 4.5% (minimum = 0, maximum = 100%, median = 1.1%). Depths ranged from 101 m to 196 m (mean = 152, median = 157). Months May and June comprised 87% of fishing events. Seines were used in 97% of events, with the trawls making up the remainder. Due to limited spatial variation in landings data, we only fit models to DFO Research Vessel data.

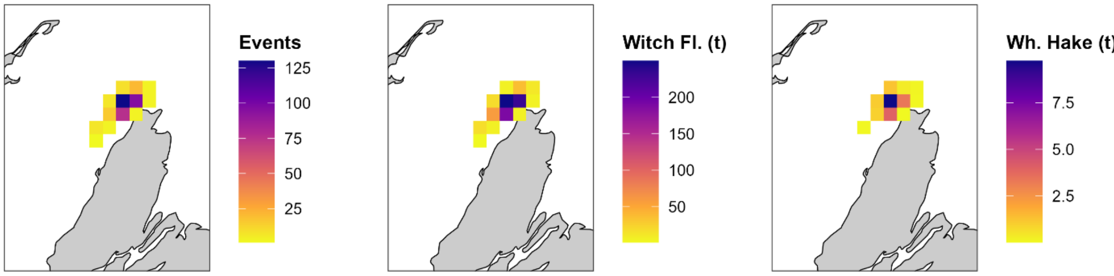

Figure 8. Number of Witch Flounder-targeted fishing events (left), total weight of Witch Flounder (centre), and total weight of White Hake (right). Weights are in tonnes. Grid cells are 10 x 10 km.

SPATIAL MODELLING

Assessing bycatch risk

To provide considerations about bycatch risk of White Hake in the Greenland Halibut fishery, we developed Species Distribution Models (SDMs) for commercial landings data, for ASO data, and for DFO nGSL RV trawl surveys. The ASO data represent a subset of the commercial landings data that include information on discards. The northern Gulf of St. Lawrence research vessel trawl survey overlaps with the geographic area open to commercial fishing.

To provide considerations to Fisheries and Harbour Management about bycatch risk of White Hake in the Redfish fishery, we developed SDMs for landings data, and for DFO nGSL, sGSL, and winter RV trawl surveys. All three DFO surveys overlap with areas and times that are of interest to the newly re-opened commercial Redfish fishery.

To provide considerations about bycatch risk of White Hake in the Atlantic Halibut fishery, we developed a SDM for commercial landings data. We did not develop models for 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 White Hake in the Witch Flounder fishery, we developed SDMs for data from DFO nGSL and sGSL RV trawl surveys. We did not use 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.

Fitting models

To fit Generalized Linear Mixed-Effects (GLMM) SDMs to survey-based and commercial catch data, we used the **R** package, **sdmTMB** version 0.4.2 (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 was used to define coastline barriers. When specifying cut-offs to define the minimum allowed distance between mesh vertices, we used values that resulted in fewer vertices than datapoints.

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 comparisons

We used AIC, log-likelihood, and predictive accuracy estimated from three-fold cross-validation to choose the best model for each dataset (e.g., Sutton et al. 2024). During cross-validation, we used function **sdmTMB_cv**, 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 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 mean effects. Where appropriate, we evaluated spatial-only models (spatial random fields constant over time) against spatiotemporal models (spatial random fields estimated for each year). For spatiotemporal models, we initially specified independent and identically distributed (iid) temporal autocorrelation, before evaluating first order autoregressive (ar1) or random walk (rw) alongside each top model's parameters.

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. 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 error distribution that could support zero-inflated data (i.e., Tweedie) (Dunn and Smyth 2005). For hurdle models, we used a logit link function 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 in vessels, gear, effort, and reporting, we were unable to compare catch weights across fishing events in the landings data. As per Sutton et al. (2024), we therefore calculated the proportion of White Hake in the combined weight of White Hake and the target species for each fishing event, and used this proportion as the response variable in SDMs. Values of the proportion of White Hake (henceforth bycatch) were typically zero-inflated.

To fit SDMs to fisheries-dependent 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 sometimes included 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 that contained bycatch proportions of 1 rather than exclude them 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 hurdle models, and constrained 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 function.

Model diagnostics

We used the function **sanity** from **sdmTMB** to assess model convergence. We mapped randomized quantile residuals to test for spatial autocorrelation, and in most cases we used Q-Q plots and histograms to assess normality of these residuals (Figures A2-A14). We did not use normality tests for models fit with beta error distributions (i.e. positive catch components of the landings models), as deriving diagnostics for beta regression is still an area of active research (e.g., Cribari-Neto and Zeileis 2010; Espinheira et al. 2017; Pereira 2019). Coefficients from final models used in downstream analysis are available in Tables A1-A4.

MODEL PREDICTIONS

To make model predictions we first constructed a 4 x 4 km grid spanning NAFO 4T. We then cropped this grid as needed to make predictions associated with each fishery, maintaining spatial, depth, and/or seasonal restrictions outlined in recent harvesting plans (Table 1). We used the function **predict** to make predictions about densities of each species (Research Vessel SDMs) or bycatch proportions (Landings SDMs). To obtain survey-based proxies for bycatch risk from the Research Vessel SDMs, we calculated the proportion of White Hake in the combined predictions of White Hake and each other species of interest in comparable models (e.g., sGSL RV models).

To estimate the total tonnes of White Hake likely to be caught in the Greenland Halibut and Atlantic Halibut fisheries, we included proxies of effort. The first proxy, per month effort, was calculated by dividing the total monthly weight of the target species summed over the most recent five years (2018 to 2022) by the total weight of the target species captured over the same time period (summed across months). The second proxy, per grid cell effort, was calculated from the total weight of the target species captured within each grid cell over the most recent five years divided by the total weight of the target species captured over the same time period. All weights used for these calculations originated from the raw landings data described above. We estimated the total tonnes of White Hake bycatch as the sum of:

$$a \; x \; b \; x \; c \; x \; TAC \qquad 2$$

where *a* is the model-predicted proportion of White Hake in each grid cell, *b* is the expected proportion of the annual TAC caught per month, *c* is the expected proportion of TAC caught in each grid and *TAC* is an annual TAC for the relevant fishery.

We did not include proxies of effort in the Redfish or Witch Flounder fisheries. Our rationale was the absence of commercial fishing data for the Redfish fishery, and extremely spatially limited effort in the Witch Flounder fishery during the time period covered. For these fisheries, we estimated the total tonnes of White Hake using a subset of equation 2:

$$a \; x \; TAC \qquad 3$$

Uncertainty and conditional effects

To estimate uncertainty in individual model predictions, we used 100 draws from the joint precision matrix of each model to calculate coefficients of variation. 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). We held year at 2022 to assess conditional effects, as this was the most recent year available across all data sets.

Table 1. Details of fishery-specific 4x4 km prediction grids in NAFO Division 4T.

Fishery	Grid specifications
Greenland Halibut	Between longitudes 62.38°W and 69.41°W, and latitudes 48.23°N and 49.42°N. Excludes east of the estuary that is south of Cap Gaspé (48.75°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). Minimum fishing depths of at least 130 m (71 fathoms).
Redfish	Longitude limit of 65°W. Excludes the 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, and Eastern Gulf of St. Lawrence Coral Conservation Area. Minimum fishing depths of at least 183 m (100 fathoms) and 300 m (164 fathoms) were considered.
Atlantic Halibut	Longitude limit of 69.59°W. Excludes the 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). Minimum fishing depths of at least 5 m (3 fathoms).
Witch Flounder	Between longitudes 60°W and 65°W. Excludes the 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, and Banc-des-Américains Marine Protected Area. Minimum fishing depths of at least 100 m (55 fathoms), 200 m (109 fathoms), and 300 m (164 fathoms) were considered.

RESULTS

TOP MODELS

Each of the 13 top models included depth as a predictor, while 8 models also included year (Table 2). Two of the three Landings models included month as a predictor of bycatch. The top ASO model for the Greenland Halibut fishery included soak time (i.e. hours fished) as a predictor of bycatch. Soak time is often missing from commercial landings data, and hence could only included in the ASO model, however, soak times in fixed gear fisheries may be relevant to bycatch studies (e.g., Turcotte et al. 2025). In terms of model fit, all but one AUC estimates were > 0.90. The AUC for the Redfish Landings model was 0.78. Correlation coefficients between observed and predicted values were generally between 0.64 and 0.96, but were lower for the Greenland Halibut and Atlantic Halibut Landings models. However, estimated bycatch in terms of expected tonnes of White Hake were similar between the Greenland Halibut Landings and ASO models, despite differences in correlation coefficients (see below).

DISTRIBUTION OF WHITE HAKE IN THE RV SURVEYS

The three RV surveys showed that White Hake were concentrated along the southern slopes of the Laurentian Channel, from the northwest of Cape Breton to northeast of the Gaspé Peninsula (Figure 9). Concentrations decreased substantially in more shallow water, and within the central and western portions of the St. Lawrence Estuary. Preliminary data from the Winter RV survey suggested that White Hake shift into deeper water to the eastern portion of NAFO 4T, and likely into 4Vn, during January and February.

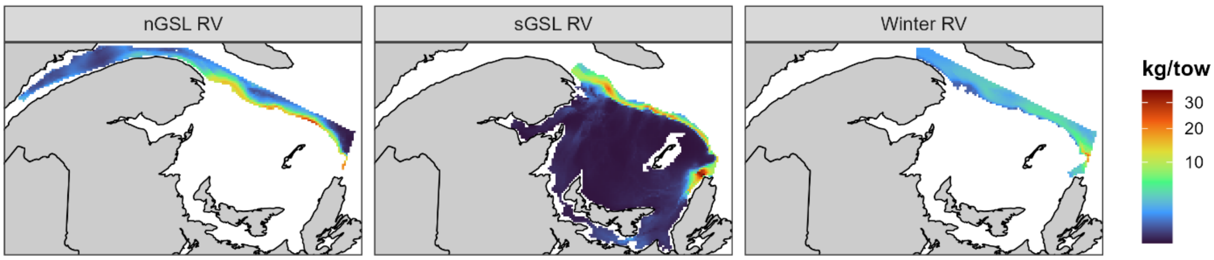

Figure 9. Model-predicted catch densities (kg/tow) of White Hake from Research Vessel (RV) models, over the spatial areas associated with each survey. Predictions were averaged across years. The legend is square root transformed. Left to Left to right: nGSL RV model (August), sGSL RV model (September), and Winter RV model (January and February).

Table 2. Model parameters and measures of fit (area under the curve (AUC), and correlation coefficients (cor) between observed and predicted values). Sample size, N, indicates the number of tows for survey models, and the number of fishing events for fisheries models.

Data	Model error family	Predictorsyuh7	Spatio-temporal	Mesh	Response	N	AUC	cor
White Hake								
nGSL RV	tweedie	depth	-	8	density (kg/tow)	409	-	0.871
sGSL RV	delta gamma	depth, year	iid	10	presence	1,371	0.974	-
					density (kg/tow)	286	-	0.640
Winter RV	tweedie	depth	-	25	density (kg/tow)	58	-	0.743
Greenland Halibut								
nGSL RV	tweedie	depth	rw	8	density (kg/tow)	409	-	0.925
Landings	delta beta	depth, year, vessel (random factor)	iid	16	bycatch presence	6,479	0.955	-
					bycatch proportion	1,104	-	0.336
ASO	delta beta	depth, soak time, year, month, vessel (random factor)	iid	10	bycatch presence	1,245	0.936	-
					bycatch proportion	488	-	0.858
Redfish								
nGSL RV	tweedie	depth, year	ar1	8	density (kg/tow)	409	-	0.958
sGSL RV	delta gamma	depth, year	iid	10	presence	1,371	0.919	-
					density (kg/tow)	469	-	0.765
Winter RV	tweedie	depth	-	25	density (kg/tow)	57	-	0.716
Landings	delta gamma	depth, month, year, vessel (random factor)	iid	5	bycatch presence	1,544	0.780	-
					bycatch proportion	689	-	0.706
Atlantic Halibut								
Landings	delta beta	depth, month, year, vessel (random factor)	-	10	bycatch presence	12,009	0.965	-
					bycatch proportion	681	-	0.348
Witch Flounder								
nGSL RV	delta gamma	depth, year	-	8	presence	409	0.995	-
					density (kg/tow)	336	-	0.707
sGSL RV	delta gamma	Depth	ar1	10	presence	1,371	0.987	-
					density (kg/tow)	321	-	0.908

WHITE HAKE AND GREENLAND HALIBUT

The nGSL RV models indicated low to moderate spatial overlap between Greenland Halibut and White Hake over the area open to the fishery (Figure 10). The greatest concentrations of White Hake occurred just east of the Gaspé Peninsula and along its northern coastline. In contrast, Greenland Halibut were most concentrated in the north and especially within the western portion of the Estuary. Uncertainty in Greenland Halibut model predictions was low and relatively uniform across the spatial grid (Figure A15). Uncertainty was higher for the less common White Hake, and was greater within the centre and western portions of the Estuary, where the lowest densities occurred. While depth use profiles overlapped, the largest densities of White Hake were generally associated with more shallow depths than those of Greenland Halibut, and overlap was minimal deeper than 350 m (Figure 10).

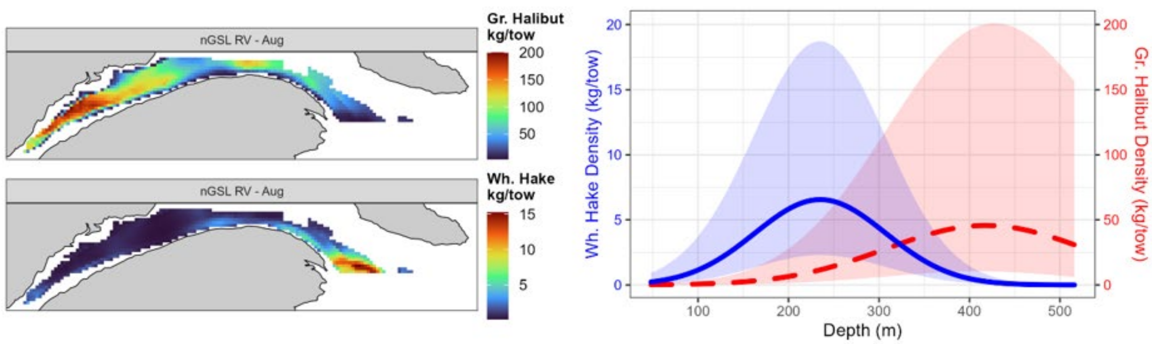

Figure 10. Left: Model-predicted catch densities (kg/tow) of Greenland Halibut (top) and White Hake (bottom) from nGSL Research Vessel (RV) models. Predictions were averaged across years. Right: Conditional effect of depth on Greenland Halibut and White Hake catch densities based on nGSL RV models.

Bycatch risk and management considerations

Although the nGSL RV models suggested greater magnitudes of bycatch risk compared to the Landings and ASO models, spatial patterns were similar across models (Figure 11). There was a consistent pattern of greater bycatch risk just east of the Gaspé Peninsula, extending along the coastline into the mouth of the Estuary. The central and westerns portions of the Estuary generally had lower bycatch risk, except where depths were more shallow (e.g., towards the coastlines and the extreme western portion of the grid. The ASO model predictions suggested lower bycatch risk from August through October, however, this pattern did not appear statistically significant (Table A4). There were no strong spatial patterns associated with uncertainty in model predictions Figure A16). Uncertainty was lower for the Landings model compared to the ASO model. For the ASO model, uncertainty appeared greater from August through October when compared to the previous months.

Both the probability and the proportion of White Hake bycatch declined with increasing depth (Figure 12). For the Landings model, both the mean probability of bycatch and the mean proportion of bycatch decreased below 5% near 300 m. For the ASO model, the mean proportion of bycatch was maintained below 5% across all depths considered.

The majority of fishing events were concentrated within the Estuary (Figures 5 and 11), in locations of lower bycatch risk (Figure 11). Fishing events occurred in the higher bycatch risk area east of the Gaspé Peninsula mainly during August followed by September (Figure 11). During August, 9.1%, 10.4%, and 60.7% of the monthly bycatch of White Hake (0.5 t, 1.8 t, 8.5 t) was associated with fishing in the high risk area, based on ASO, Landings, and nGSL RV models respectively. For comparison, total reported landings of Greenland Halibut averaged 655 t per year from 2018 to 2022. Reported average White Hake bycatch in the fishery was 6.8 t, but was estimated to be 12.7 t after adjusting for discarding (Turcotte et al. 2025).

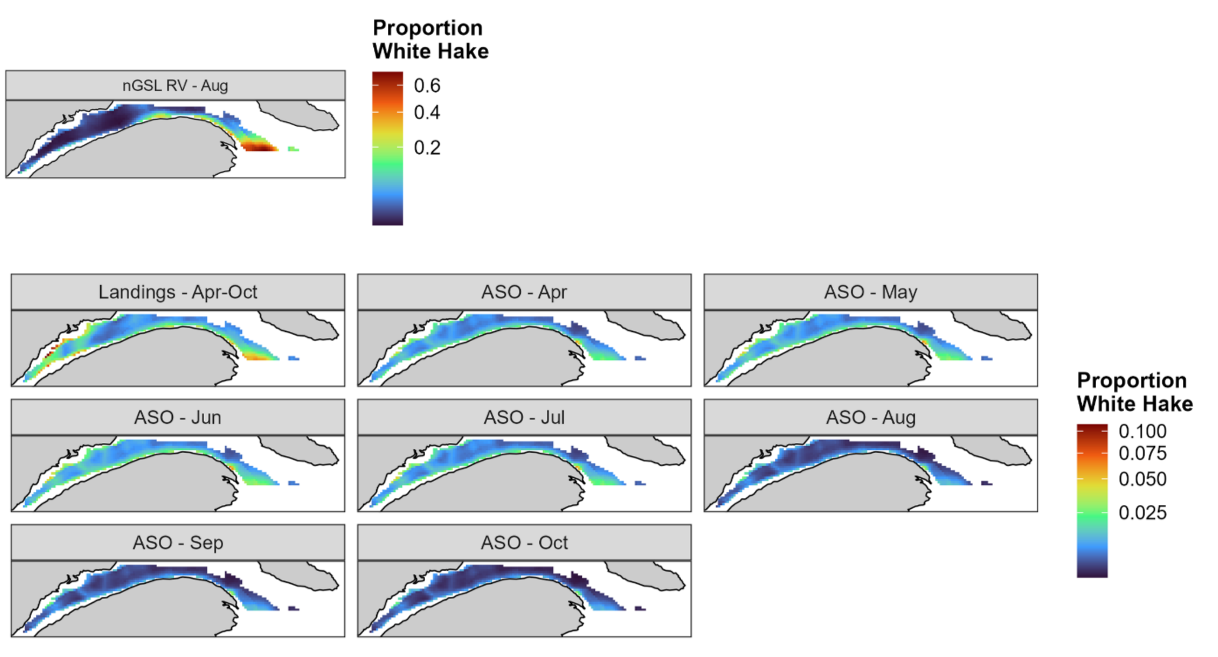

Figure 11. Model-predicted bycatch of White Hake in a Greenland Halibut fishery. Predictions were averaged across years. The minimum depth considered was 130 m. The legends are square-root transformed. Top row: predictions from the nGSL RV models (August). Second row, left to right: predictions from the Landings model (April - October), At Sea Observer model (ASO, April), ASO model (May). Bottom row: Predictions from the Landings model (September, October). Third row, left to right: predictions from the ASO model (June, July, August). Bottom row: Predictions from the ASO model (September, October).

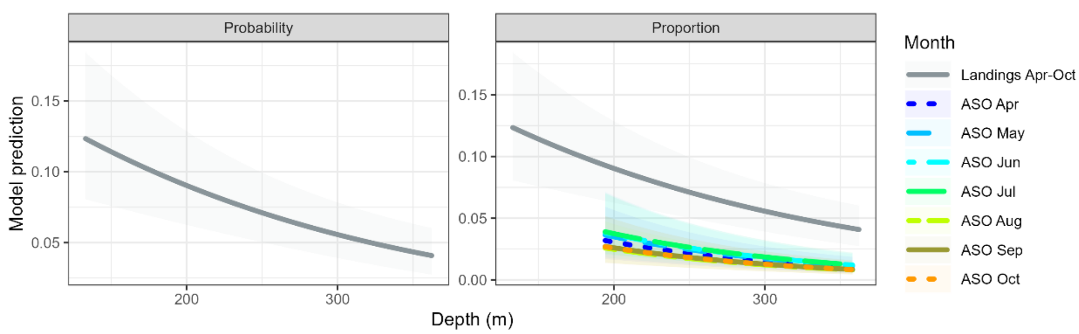

Figure 12. Conditional effect of depth on the probability (left) and proportion (right) of White Hake bycatch in a Greenland Halibut fishery. Estimates obtained from the Landings model and ASO models. Probability is not shown for the ASO model because depth was not a significant predictor of probability.

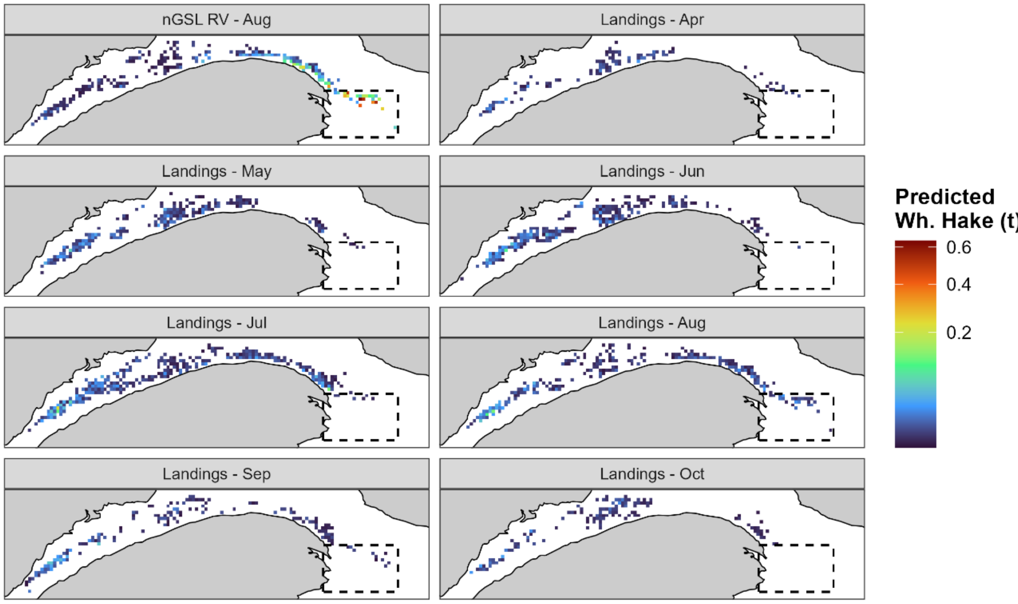

Figure 13. Predicted tonnes of White Hake bycatch in a Greenland Halibut fishery with a NAFO Division 4T TAC of 655 t. Predictions were made in grid cells where Greenland Halibut was caught in the commercial fishery in years 2018-2022. The polygon drawn just east of the Gaspé Peninsula indicates where fishing events have occurred in a high bycatch risk area south of Les Trois-Ruisseaux. Grid cells are 4 x 4 km. Top row, left to right: Predictions from nGSL RV models (August), and the Landings model (April). Patterns from At Sea Observer model are not shown, as these were generally similar to those of the Landings model (e.g., Table 3).

Table 3. Predicted tonnes of White Hake bycatch in a Greenland Halibut fishery by model and month, given an annual Greenland Halibut TAC of 655 t. The righthand column refers to the polygon shown in Figure 13.

Model	Month	Greenland Halibut (t)	White Hake (t)	White Hake (t) in box	Percent White Hake in box
nGSL RV	Aug	100.2	8.5	5.144	60.7%
Landings	Apr	38.8	0.5	0.015	2.7%
	May	111.2	1.4	0.005	0.4%
	Jun	128.7	1.7	0.006	0.4%
	Jul	170.7	2.9	0.019	0.6%
	Aug	100.2	1.8	0.189	10.4%
	Sep	62.7	1.1	0.030	2.7%
	Oct	42.7	0.6	0.000	-
	Total	**655**	**10**	**0.264**	2.6%
ASO	Apr	38.8	0.4	0.009	2.3%
	May	111.2	1.2	0.003	0.3%
	Jun	128.7	1.6	0.005	0.3%
	Jul	170.7	1.9	0.011	0.5%
	Aug	100.2	0.5	0.049	9.1%
	Sep	62.7	0.3	0.008	2.6%
	Oct	42.7	0.2	0.000	-
	Total	**655**	**6.1**	**0.085**	**1.4%**

Science advice

Based on current information on the fishery and the bycatch scenarios described above, the, science advice to minimize bycatch of White Hake in the Greenland Halibut fishery is as follows:

- Shift the eastern latitude limit north from Cap Gaspé to Les Trois-Ruisseaux to avoid an area with high densities of White Hake and low densities of Greenland Halibut. 9% to 61% of August's predicted bycatch of White Hake (0.5 t to 8.5 t) was associated with fishing in the high risk area.
- Promote adherence to gear soak time regulations (i.e., maximum of 72 hours), as longer soak times likely lead to unaccounted fishing mortality (e.g., Chamberland and Benoît 2024), and thus undetected bycatch.

WHITE HAKE AND REDFISH

The RV models indicated spatial and depth overlaps between Redfish and White Hake, although peak Redfish densities extended into deeper water (Figures 14 and 15). The greatest concentrations of White Hake occurred along the southern slopes of the Laurentian Channel, particularly north and east of the Magdalen Islands (Figure 14). Predicted catch densities of Redfish were greater than those for White Hake. Concentrations of Redfish occurred north of the Magdalen Islands, and extended deeper into the Channel compared to White Hake. Uncertainty in model predictions was generally low and even over the spatial area (Figure A17). Exceptions for sGSL RV models occurred in the northeast and northwest corners, especially at the deepest depths. The northwest corner of the grid was also associated with a pocket of greater uncertainty of Redfish catch densities in the Winter RV model.

Models from both the nGSL and sGSL RV surveys, which primarily take place in August and September respectively, suggested sharp declines in White Hake deeper than ~300 m (Figure 15). Winter RV model estimates were lower overall than the other RV models, with concentrations occurring in deeper water, primarily in eastern portions of the grid (Figures 14 and 15).

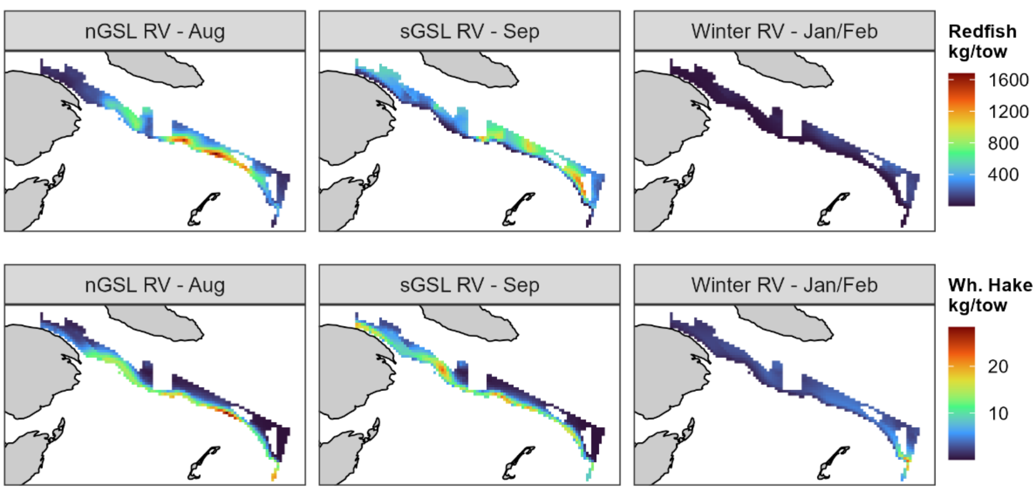

Figure 14. Model-predicted catch densities (kg/tow) of Redfish and White Hake from Research Vessel (RV) models. Predictions were averaged across years. The minimum depth considered was 183 m. Top row, left to right: Redfish predictions from the nGSL RV model (August), sGSL RV model (September), and Winter RV model (January and February). Bottom row, left to right: White Hake prediction from the nGSL RV models (August), sGSL RV model (September), and Winter RV model (January and February).

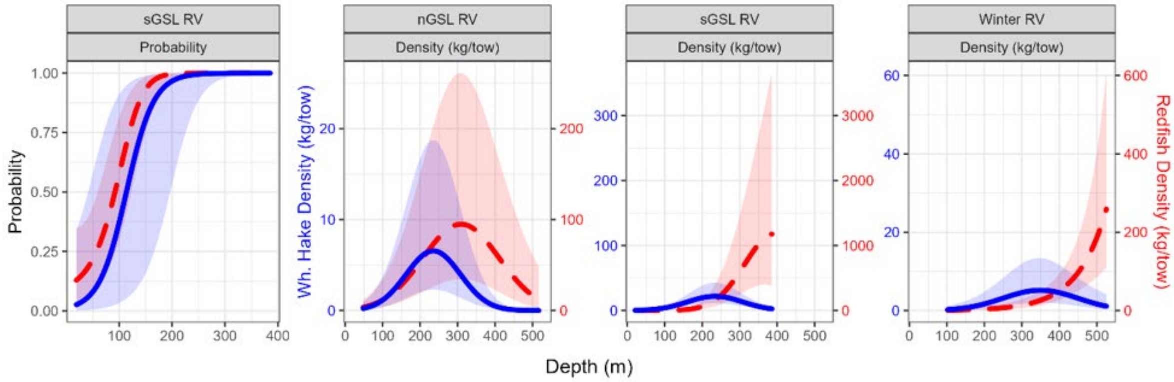

Figure 15. Conditional effect of depth on Redfish (dashed, red) and White Hake (solid, blue). From left to right: Probability of occurrence by depth of each species based on the sGSL RV models; Catch densities of each species based on nGSL RV models, sGSL RV models, and Winter RV models.

Bycatch risk and management considerations

There was a consistent pattern of greater bycatch risk along the southern slopes of the Laurentian Channel across all models and months considered (Figure 16). Bycatch risk and predicted tonnes of White Hake were greater based on RV models compared to equivalent months in the Landings model (Table 4, Figure 16). The greatest bycatch was associated with months October (Landings model) and January/February (Winter RV model). Uncertainty in the Landings model predictions was lowest along the southern slopes of the Laurentian Channel, especially north of the Magdalen Islands (Figure A18), coinciding with the greatest number of fishing events. Uncertainty was greatest in the northeast corner of the grid, and at deeper depths in the western portion of the grid, where data was more limited. Both the probability and the proportion of White Hake bycatch increased from shallow depths before declining again deeper than ~300 m (Figure 17). Depending on the month and model considered, the predicted tonnes of White Hake bycatch in a Redfish fishery was reduced by 27% to 80% by changing the minimum fishing depth from 183 m to 300 m (Table 4, Figure A21). For comparison, total reported landings of Redfish averaged 129 t per year from 2018 to 2022. Reported average White Hake bycatch in the fishery was 4.1 t, but was estimated to be 4.5 t after adjusting for discarding (Turcotte et al. 2025).

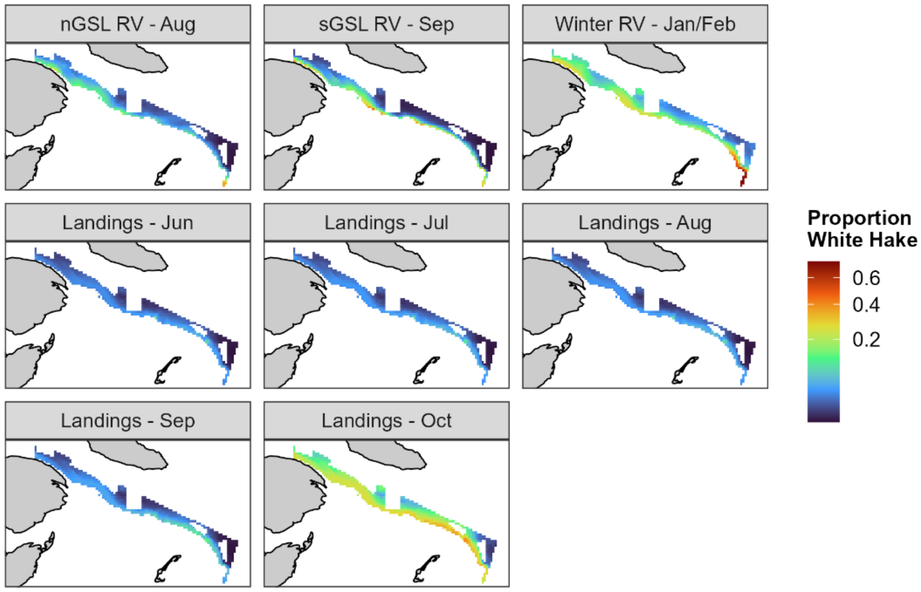

Figure 16. Model-predicted bycatch of White Hake in a Redfish fishery. Predictions were averaged across years. The minimum depth considered was 183 m. The legend is square-root transformed. Top row, left to right: predictions from the nGSL RV models (August), sGSL RV models (September), and Winter RV models (January and February). Middle row, left to right: predictions from the Landings model (June, July, August). Bottom row: Predictions from the Landings model (September, October).

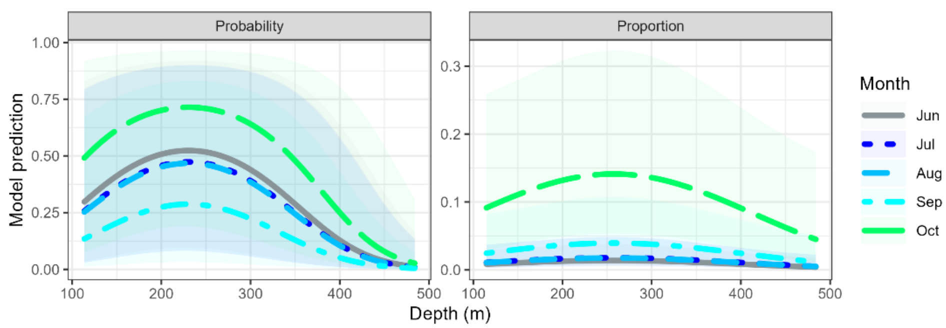

Figure 17. Conditional effect of depth on the probability (left) and proportion (right) of White Hake bycatch in a Redfish fishery. Estimates obtained from the Landings model.

Table 4. Predicted tonnes of White Hake bycatch in a Redfish fishery by model, month, and minimum fishing depth. Percent reduction is the change in tonnes of White Hake expected with the deeper minimum fishing depth (300 m) compared to the more shallow minimum fishing depth (183 m). Assumptions were 5,000 t TAC per month, and equal fishing effort over the available fishing area.

Model(s)	Month	White Hake (t) Min. depth 183 m	White Hake (t) Min. depth 300 m	Percent reduction
nGSL RV	Aug	29	12	59%
sGSL RV	Sep	41	8	80%
Winter RV	Jan/Feb	116	56	52%
Landings	Jun	11	8	27%
	Jul	13	9	31%
	Aug	13	9	31%
	Sep	18	11	39%
	Oct	139	101	27%
	Total	**194**	**138**	**28.9%**

Science advice

Based on current information on the fishery and the bycatch scenarios described above, the, science advice to minimize bycatch of White Hake in the Redfish fishery is as follows:

- Employ a minimum fishing depth of 300 m during summer months, with possibly deeper minimum fishing depths in winter months. Model-predicted bycatch was reduced by 27% to 80% by changing the minimum fishing depth from 183 m to 300 m. White Hake and other groundfish species move to deeper water in winter.

WHITE HAKE AND ATLANTIC HALIBUT

Bycatch risk and management considerations

Predictions from the Landings model indicated that the greatest risk of bycatch occurred in deeper waters along the northwest tip of Cape Breton and extended west along the Laurentian Channel to east of the Gaspé Peninsula (Figure 18). There were patches of more moderate risk just north of PEI. Areas north and southeast of Miscou Island, Chaleur Bay, and the waters around the Magdalen Islands had some of the lowest predicted bycatch risk. However, southeast of Miscou Island and the western portion of Chaleur Bay were also associated with pockets of high uncertainty (Figure A18). The minimum depth in landings data was 5 m, and both the probability and the proportion of White Hake bycatch increased with increasing depth (Figure 19).

The majority of fishing events were concentrated in areas of relatively low or moderate bycatch risk (Figures 7 and 18). However, in April, May, and June, fishing was concentrated in an area of moderate to high bycatch risk immediately north of Cape Breton (Figure 19), resulting in the largest predicted tonnes of White Hake (Table 5). Assuming an annual total landings of 1,500 t of Atlantic Halibut, 496 t (33%) of this would be expected to be caught during April through June. Over the same months, predicted bycatch of White Hake within the hotspot area was (Figure 19) 3.4 t, representing 69% of the annual expected bycatch of White Hake in the Atlantic Halibut fishery, and 81% of the bycatch expected over those months (4.2 t). For comparison, total reported landings of Atlantic Halibut in NAFO 4T averaged 480 t per year from 2018 to 2022. Reported average White Hake bycatch in the fishery was 2.4 t, but was estimated to be 2.5 t after adjusting for discarding (Turcotte et al. 2025).

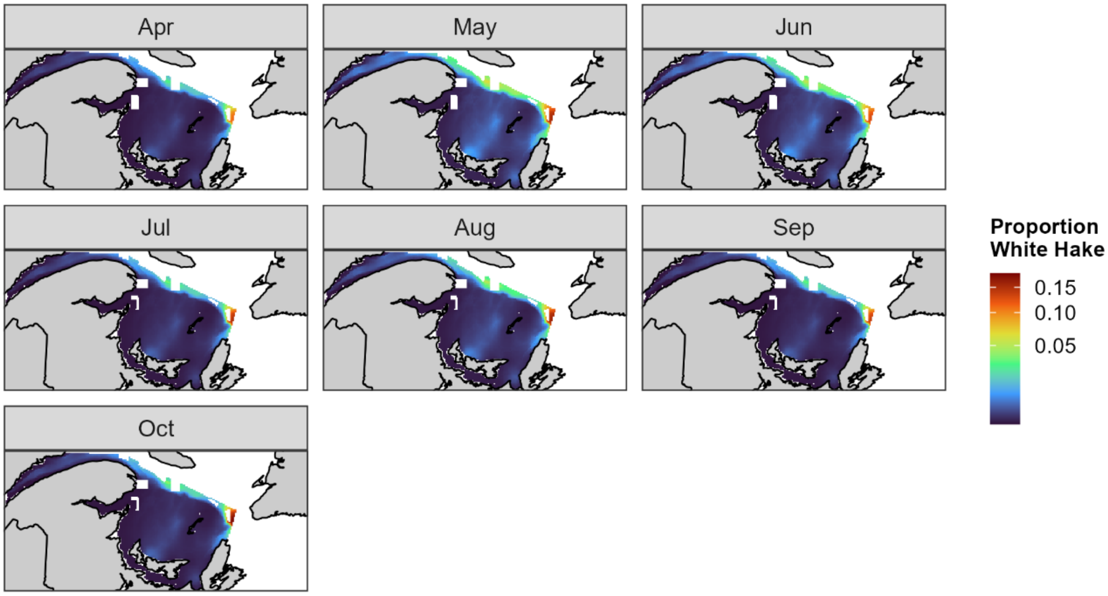

Figure 18. Model-predicted bycatch of White Hake in an Atlantic Halibut fishery. Predictions were averaged across years. The legend is square-root transformed. All predictions are based on the Landings model. Top row, left to right: predictions for April, May, and Jun. Second row, left to right: predictions for July, August, September. Bottom row: Predictions for October.

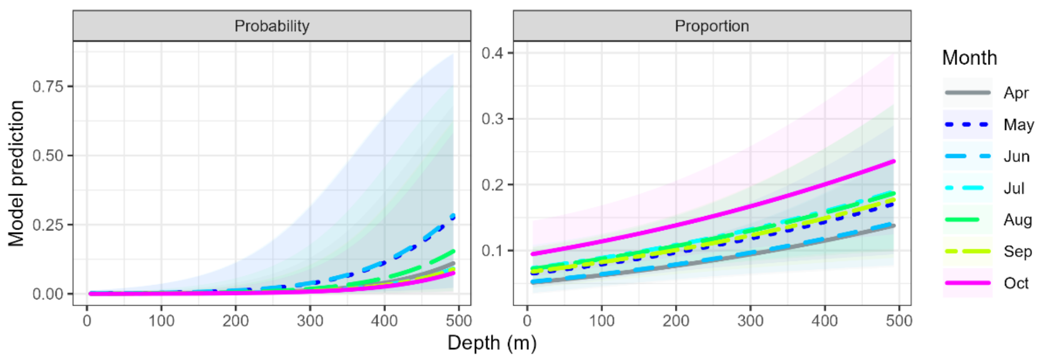

Figure 19. Conditional effect of depth on the probability (left) and proportion (right) of White Hake bycatch in an Atlantic Halibut fishery. Estimates obtained from the Landings model.

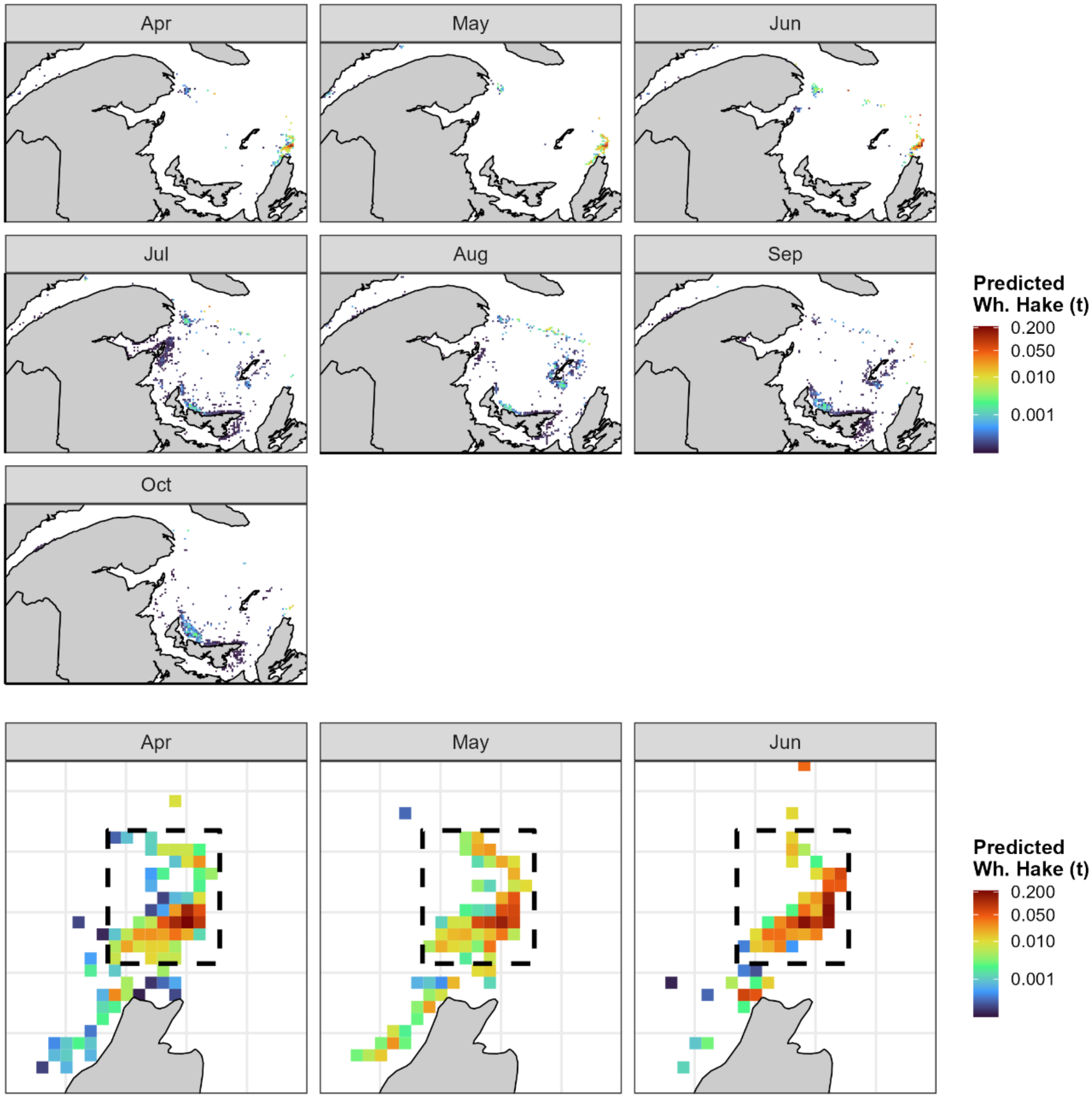

Figure 20. Predicted tonnes of White Hake bycatch in an Atlantic Halibut fishery with a NAFO Division 4T TAC of 1,500 t. Predictions were made in grid cells where Atlantic Halibut was caught in the commercial fishery in years 2018-2022. Grid cells are 4 x 4 km. Top row, left to right: Predicted tonnes of White Hake in April, May, and June. Second row, left to right: Predicted tonnes of White Hake in July, August, and September. Third row: Predicted tonnes of White Hake in October. Bottom row: same as top row but zoomed into indicate an area of high bycatch risk and high fishing effort show inside the polygon.

Table 5. Predicted tonnes of White Hake bycatch in an Atlantic Halibut fishery by month, given an annual Atlantic Halibut TAC of 1,500 t. Predictions were made from a model fitted to Landings data. The righthand column refers to the polygon shown in the bottom row of Figure 20.

Month	Atlantic Halibut (t)	White Hake (t)	White Hake (t) in box	Percent White Hake in box
Apr	170.698	1.146	1.029	89.8%
May	81.968	1.112	0.928	83.4%
Jun	243.369	1.969	1.440	73.1%
Jul	516.575	0.173	-	-
Aug	253.340	0.248	-	-
Sep	147.782	0.187	0.003	1.8%
Oct	86.268	0.111	0.043	38.6%
Total	**1,500**	**4.946**	**3.113**	**62.9%**

Science advice

Based on current information on the fishery and the bycatch scenarios described above, the, science advice to minimize bycatch of White Hake in the Atlantic Halibut fishery is as follows:

- Introduce a dynamic area closure or other bycatch mitigation strategies for a bycatch hotspot off Cape Breton. Model predicted bycatch in the area represented 69% of the annual expected bycatch of White Hake in the Atlantic Halibut fishery, and 81% of the bycatch expected in the Atlantic Halibut fishery over months April through June.

WHITE HAKE AND WITCH FLOUNDER

The nGSL and sGSL RV models indicated substantial spatial and depth overlaps between Witch Flounder and White Hake (Figures 21 and 22). White Hake were more evenly distributed along the southern slopes of the Laurentian Channel, following depth contours, while Witch flounder appeared more patchily distributed along the same depths. Maximum catch densities were greater for Witch Flounder than for White Hake in the nGSL predictions, while the opposite pattern was observed in the sGSL predictions. Within the area where fishing has been recently concentrated (Figure 21), both models suggested greater densities of White Hake compared to Witch Flounder (Figure 21). There were spatial patches of moderate to higher uncertainty in model predictions over the fishing grid (Figure A20). For Witch Flounder, areas of higher uncertainty associated with nGSL RV predictions occurred west of Cape Breton and east of the Gaspé Peninsula. In contrast sGSL RV uncertainty was highest in deeper water, particularly in the northwest and northeast corners of the grid. For White Hake, nGSL RV predictions were low over most of the grid, with the exception of west of Cape Breton where uncertainty was the greatest. The northeast corner of the grid and east of the Gaspé Peninsula were associated with slightly higher uncertainty as well. The northeast corner and east of the Gaspé Peninsula were also associated with greater uncertainty in sGSL RV model predictions of White Hake catch densities, as well as a shallow band along the southern slopes of the Laurentian Channel between Cape Breton and just west of the Magdalen Islands.

Both the nGSL RV and sGSL RV model indicated sharp declines in White Hake deeper than 300 m. The sGSL RV model indicated a similar decline at 300 m for Witch Flounder, however the nGSL RV model indicated high densities of Witch Flounder persisting until approximately 400 m.

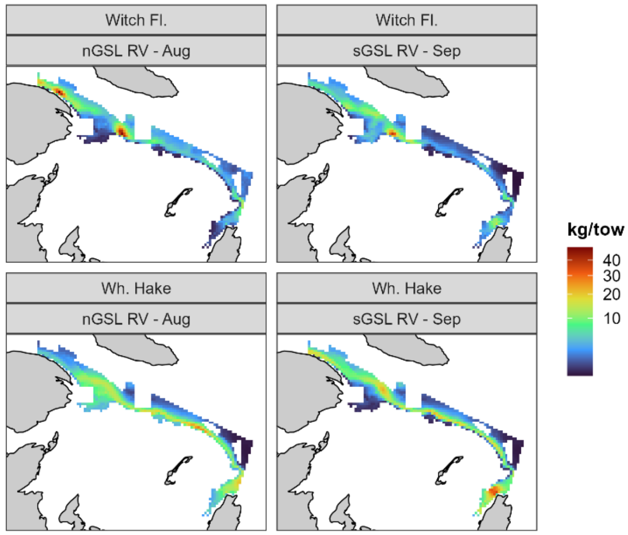

Figure 21. Model-predicted catch densities (kg/tow) of Witch Flounder and White Hake from Research Vessel (RV) models. Predictions were averaged across years. The legend is transformed. Top row, left to right: Witch Flounder predictions from the nGSL RV model (August), and sGSL RV model (September). Bottom row, left to right: White Hake predictions from the nGSL RV model (August), and sGSL RV model (September).

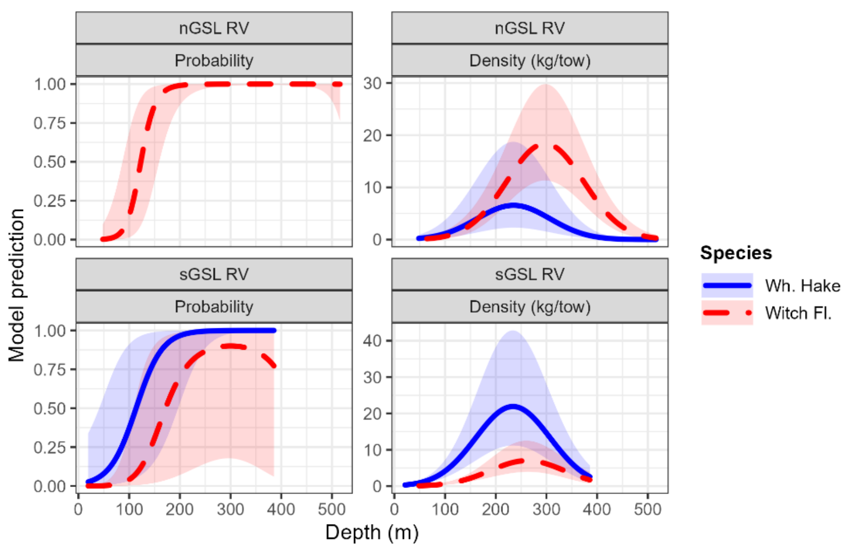

Figure 22. Conditional effect of depth on Witch Flounder and White Hake. Top row: Effect of depth on the probability of occurrence (left) and catch densities (right) based on the nGSL RV model. Bottom row: Effect of depth on the probability of occurrence (left) and catch densities (right) based on the sGSL RV model.

Bycatch risk and management considerations

Predictions from the nGSL RV models indicated that the greatest risk of bycatch occurred in the more shallow areas of the grid, from the northwest of Cape Breton to east of the Gaspé Peninsula (Figure 23). The nGSL RV models indicated a decrease of bycatch risk with deeper depths. In contrast, the sGSL RV models indicated high risk in all locations except for a small region to the southeast of the Banc-des-Américains Marine Protected Area. Based on nGSL RV predictions, minimum fishing depths of 200 m and 300 m decreased the predicted tonnes of White Hake by 84% and 91% compared to minimum fishing depths of 100 m (Table 6). However, the sGSL models indicated increases of 8% and 3%. For comparison, total reported landings of Witch Flounder averaged 46 t per year from 2018 to 2022 (this value excludes years 2020 and 2022, when no landings were reported from this fishery). Reported average White Hake bycatch over the same years in the fishery was 1.0 t (Turcotte et al. 2025).

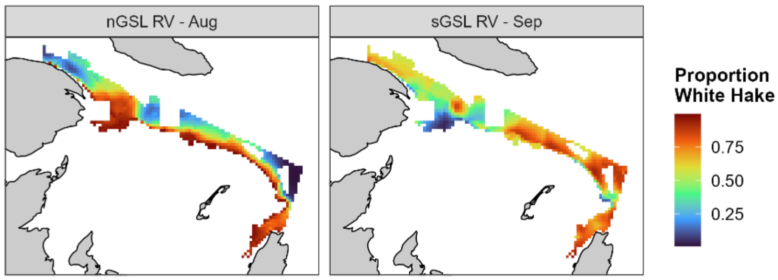

Figure 23. Model-predicted bycatch of White Hake in a Witch Flounder fishery. Predictions were averaged across years. Predictions are from the nGSL RV models (left) and sGSL RV models (right).

Table 6. Predicted tonnes of White Hake bycatch in a Witch Flounder fishery by model and month, given a monthly Witch Flounder TAC of 250 t. In the two righthand columns, negative values indicate reductions in White Hake, while positive numbers indicate increases in White Hake.

Model	**Month**	**White Hake (t) Min. depth: 100 m**	**White Hake (t) Min. depth: 200 m**	**White Hake (t) Min. depth: 300 m**	**Percent change between 100 m and 200 m**	**Percent change between 100 m and 300 m**
nGSL RV	Aug	1,859	292	161	-84%	-91%
sGSL RV	Sep	613	664	633	+8%	+3%

Science advice

Based on current information on the fishery and the bycatch scenarios described above, the, science advice to minimize bycatch of White Hake in the Witch Flounder fishery is as follows:

- Employ a minimum fishing depth of 300 m during summer months, with possibly deeper minimum fishing depths in winter months. Model predicted bycatch was reduced by 45% compared to a minimum fishing depth of 200 m, and by 91% compared to a minimum fishing depth of 100 m.

DISCUSSION

Despite a commercial fishing moratorium for sGSL White Hake since 1995, biomass is expected to continue to decline, and increased bycatch or declines in productivity could lead to more significant loss of biomass (Rolland et al. 2022; Turcotte et al. 2025). While overexploitation initially led to the stock decline, high natural mortality associated with predation by Grey Seals (*Halichoerus grypus*) is considered the primary factor currently preventing stock recovery (Swain et al. 2016; Neuenhoff et al. 2019). Even in the absence of all fishery removals, the stock is projected to continue to decline (Swain et al. 2016; Turcotte et al. 2025), making rebuilding unlikely. Although fisheries are not the main factor currently preventing stock recovery, bycatch mitigation will be important because as biomass of sGSL White Hake continues to decline, so will the stock's ability to sustain bycatch. Thus, the core management measure proposed in the rebuilding plan is to introduce new and/or stricter management measures in all fisheries that intercept sGSL White Hake so that if White Hake productivity conditions were to change, the stock retains the potential to rebuild (Moritz 2002; Hutchings 2015; Wolf et al. 2015).

Fishery removals of White Hake are limited to 30 t in the sGSL, and have averaged approximately 17 t annually since 2013. However, this value may be underestimated by as much as 30% on average, due to unreported discards (Turcotte et al. 2025). The vast majority of bycatch occurs in commercial fisheries targeting Greenland Halibut, Atlantic Halibut, and Witch Flounder, along with experimental and index fisheries for Redfish. The newly reopened commercial Redfish fishery has TAC of 60,000 t over NAFO 4RST. While it remains to be seen where and when fishing effort will be concentrated, potential bycatch of sGSL White Hake could have implications on how this fishery is prosecuted, and may also impact other fisheries. Consequently, identifying areas where bycatch risk is high is useful to support fisheries management.

This study aimed to develop scientific advice on ways to minimize bycatch of the depleted sGSL White Hake stock, without proposing decreases in TACs for fisheries targeting other, healthier groundfish stocks, so that sGSL White Hake bycatch does not become the limiting factor in other groundfish fisheries. This was achieved by proposing seasonal, area, and/or depth restrictions that should limit catches of sGSL White Hake, while simultaneously having minimal, if any, impact on catch rates of the healthier stocks. A summary table of our specific advice is presented at the end of this section.

GREENLAND HALIBUT FISHERY

The Greenland Halibut fishery occurs mainly in the St. Lawrence Estuary and western portion of the Gulf, off the northern Gaspé Peninsula. Bycatch predictions from the nGSL RV models were substantially larger than those from the Landings model. Over the period examined, reported White Hake bycatch averaged 10 t annually (Turcotte et al. 2025), and the Landings model predictions combined with our effort proxies also estimated 10 t of White Hake bycatch, assuming an annual catch of 655 t of Greenland Halibut. However, the nGSL RV model predictions estimated that 8.5 t of White Hake could be captured during the month of August alone, 4.7 times the August expectation from the Landings model. These differences could be based on several factors. One factor could be that a large proportion of bycatch is discarded in this fishery, and therefore goes unreported. Although we did not observe large differences between predictions from our Landings and ASO models, the latter only represents about 5% of all commercial fishing trips (Turcotte et al. 2025). A second factor is the gear used. The RV surveys are multispecies bottom trawl surveys meant to sample a diversity of species, whereas the Greenland Halibut fishery is a gillnet fishery. Commercial fishing regulations permit gear to remain in the water (soak time) for up to 72 hours. In practice, gillnets often remain in the water much longer, with 41% of the ASO data reporting soak times greater than 72 hours, reaching a maximum of 240 hours. Although soak time was not always reported in the landings records, existing data indicated a maximum of 300 hours, and 55% of available records had soak times of 72 hours or longer. Soak time was among the predictors in our ASO model, and showed an inverse relationship with proportion of White Hake. This relationship is similar to that between soak time and captured weight of Greenland Halibut (Chamberland and Benoît 2024). As White Hake is a round fish as opposed to a flatfish like Greenland Halibut, it is possible that White Hake decay at a faster rate than Greenland Halibut, meaning that with longer soak times a portion of the bycatch/mortality goes undetected and results in lower proportions of White Hake relative to Greenland Halibut.

Despite limited overlap in spatial distributions of Greenland Halibut and White Hake, this fishery accounts for some of the largest amounts of White Hake bycatch. This may be in part because the TAC for this fishery is large and covers a relatively narrow spatial area. Shifting the eastern latitude limit north from Cap Gaspé (48.75°N) to Les Trois-Ruisseaux (48.92°N) would have minimal impact on the Greenland Halibut fishery, but is expected to result in a sizeable decrease in White Hake bycatch. Shifting the extent of this fishery would also reduce bycatch of sGSL Atlantic Cod (Sutton et al. 2025).

Given that there are some differences in depth-use profiles between Greenland Halibut and White Hake, depth-specific bycatch mitigation strategies could also be considered if further reductions of White Hake catches are deemed necessary, or if the Greenland Halibut TAC should increase. We focused primarily on bycatch mitigation strategies where the bulk of bycatch occurred and not on depth based restrictions in the Estuary itself, in part because there are remaining questions as to whether the White Hake in the Estuary belong to the sGSL or the Atlantic DU (Turcotte et al. 2025).

REDFISH FISHERY

Taking discards into account, the experimental and index Redfish fisheries accounted for the second largest amount of White Hake bycatch in recent years, despite having annual TACs under 10,000 t. With the reopening of the commercial fishery in 2024 and a TAC of 60,000 t, White Hake bycatch has the potential to increase substantially. The greatest concentrations of White Hake bycatch in the Redfish fishing grid occurred along the southern slopes of the Laurentian Channel, particularly north and east of the Magdalen Islands For Redfish, fishing deeper than 300 m during summer months could help decrease bycatch of White Hake and simultaneously increase catches of Redfish. Furthermore, deeper than 300 m, the proportion of the sGSL DU of White Hake decreases as White Hake are more commonly of the Atlantic DU type (Swain et al. 2012). A minimum fishing depth of 300 m coincides with the depth limits in place from July through November for the 2024 fishing season. In the winter months, White Hake and other groundfish move to deeper waters (Rolland et al. 2022), suggesting that minimum fishing depths would need to be deeper than 300 m to minimize bycatch. The depth limits in place for the 2024 - 2025 winter season are that fishing must be carried out deeper than 183 m between December 1 and March 31 in NAFO 4Vn. As the Redfish fishery continues to develop, it will be critical to closely monitor sGSL White Hake bycatch. Currently, it remains unclear how this fishery will occur in practice, and it is possible that bycatch rates in the commercial Redfish fishery may be lower than predicted for various reasons, including improvement in the fishing technology, fishing timing, and location and depth where fishing activities will be concentrated.

ATLANTIC HALIBUT FISHERY

The Atlantic Halibut fishery in NAFO 4T has a bimodal depth pattern, with the vast majority of effort shallower than 100 m. The management measures currently in place for these shallower fishing depths appear largely sufficient to minimize White Hake bycatch, however, a small number of fishing events north of PEI had some of the highest proportions, so caution may be required if fishing effort in the area were to increase. Bycatch proportions were greater for fishing events that took place in water deeper than 100 m, particularly in certain locations. From April to June, fishing was concentrated in a moderate to high bycatch risk area off Cape Breton, and accounted for nearly 70% of the annual predicted White Hake bycatch in the Atlantic Halibut fishery. While bycatch of White Hake in this area was high, other locations with large catches of Atlantic Halibut were associated with much lower risk of bycatch. Dynamic, seasonal closures north of Cape Breton may aid in decreasing bycatch in this fishery. In the future, fitting separate models to fishing events shallower or deeper than 100 m may help with model convergence, allowing the largest bycatch events to be included during model fitting.

WITCH FLOUNDER FISHERY

The Witch Flounder fishery was the most limited fishery considered, both in terms of spatial scale and annual landings. Furthermore, in recent years there were very few fish harvesters targeting Witch Flounder. Predicted catch densities for White Hake and Witch Flounder between the two RV surveys had similar spatial patterns over the area open to the Witch Flounder fishery. However, the estimated bycatch of White Hake differed substantially between the two sets of models, because Witch Flounder catch densities were greater than White Hake catch densities in the nGSL RV survey, and the opposite pattern occurred in the sGSL RV surveys. As each species was less often observed in the sGSL RV data (<25% of tows in the sGSL RV compared to >60% of tows in the nGSL RV), the nGSL RV models may offer more robust insight into bycatch risk. Nevertheless, predicted tonnes of White Hake greatly exceeded that reported in commercial landings data (2 t annually, with White Hake present in >70% of fishing events), and based on the limited ASO coverage (ASO onboard in 2 of the 10 years examined) this fishery did not exhibit discarding (Turcotte et al. 2025). In this instance, the differences in gear, month, and time of day may contribute to differences between model predictions and reported bycatch, as the commercial fishery primarily operates earlier in the year, and mainly uses seines. With respect to time of day, diel differences in catchability for each species might contribute to the high rates of White Hake presence combined with low proportions of White Hake in the Landings data. Witch Flounder exhibit greater catchability at night than during the day in bottom-trawl surveys (Swain and Poirier 1998; Benoît and Swain 2003b; Ricard 2022), and there is a positive slope between relative catchability at body size (Benoît and Swain 2003b), meaning that larger Witch Flounder such as those targeted by the fishery (>30 cm) are even more catchable at night compared to small Witch Flounder. However, for White Hake, small individuals (12 cm) are 75 times more catchable at night than during the day, while larger individuals (35 cm) display no diurnal differences in catchability (Benoît and Swain 2003b). Thus, if the fishery primarily operates at night, it may be targeting large Witch Flounder and small White Hake, which would result in high presence but low proportions by weight of White Hake in the Landings, assuming that the diel patterns in catchability with bottom-trawls remain consistent for seines.

The Witch Flounder fishery has high latent potential for bycatch of sGSL White Hake, 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 and TAC increases, interest in this fishery could be renewed along with increased numbers of harvesters. Consequently, the potential for White Hake 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. 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.

ADDITIONAL CONSIDERATIONS

Although sGSL White Hake was once abundant enough to be ranked third or fourth in annual landings, the directed fishery has been closed since 1995 due to low abundance (Turcotte et al. 2025). Since the early 2000s the largest densities in NAFO Division 4T have been concentrated from the Cape Breton Trough, along the southern slopes of the Laurentian Channel all the way to the northeast of the Gaspé Peninsula (Turcotte et al. 2025), coinciding with focal areas of several other NAFO Division 4T fisheries. This study focused solely on NAFO Division 4T as this is the management unit identified in the rebuilding plan, however, sGSL White Hake also dominated in genetic samples collected in the northwest portion of NAFO Subdivision 4Vn (Roy et al. 2012; Swain et al. 2012). As a result, COSEWIC (2013) defined the area occupied by the sGSL DU as all of NAFO Division 4T and the northern portion of Subdivision 4Vn. Future research into the spatial extent of the sGSL White Hake management unit could offer insight about the risk of bycatch of this stock outside of the area covered in this study, such as NAFO Division 4Vn. As the Laurentian Channel, likely including NAFO 4Vn, represents overwintering habitat for sGSL White Hake and other low abundance stocks, we would advise additional caution for fisheries operating in these areas during winter. Finally, revisiting these spatiotemporal analyses on regular basis will be important to account for possible distribution changes of species and/or fishing effort.

SUMMARY OF SCIENTIFIC ADVICE

Table 7. Summary of scientific advice to minimize potential bycatch of White Hake in other fisheries.

Fishery	Advice	**Rationale**
Greenland Halibut	Shift the eastern latitude limit north from Cap Gaspé to Les Trois-Reseaux. Adherence to gear soak time regulations (i.e., maximum of 72 hours).	Avoids an area with high densities of White Hake and low densities of Greenland Halibut. Longer soak times likely lead to undetected bycatch and unaccounted fishing mortality.
Redfish	Minimum fishing depth of 300 m during summer months. Possibly deeper in winter.	Model predicted bycatch was substantially reduced by changing the minimum fishing depth from 183 m to 300 m. White Hake and other groundfish species move to deeper water in winter.
Atlantic Halibut	Introduce dynamic area closure or other bycatch mitigation strategies in a bycatch hotspot off Cape Breton. The Atlantic Halibut fishery follows a bimodal distribution, with the vast majority of effort concentrated in water shallower than 100 m. At this time, we do not advise additional measures to minimize bycatch of White Hake in water shallower than 100 m, other than those currently in existence.	Avoids an area with high densities of White Hake. Model predicted bycatch in the area represented a large proportion of the bycatch of White Hake in the Atlantic Halibut fishery.
Witch Flounder	Minimum fishing depth of 300 m during summer months. Possibly deeper in winter.	Model predicted bycatch substantially reduced compared to minimum fishing depths of 100 m or 200 m. Predictions based on a nGSL RV model only. White Hake and other groundfish species move to deeper water in winter.

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APPENDIX

SUPPORTING TABLES

Table A1. Coefficients from models fitted to nGSL RV survey data.

Species	Model structure	Response	Term	Estimate	St. error	L95	U95
White Hake	non-hurdle	density	(Intercept)	0.64	0.53	-0.41	1.68
			poly(depth_scaled, 2)1	-11.24	2.31	-15.77	-6.70
			poly(depth_scaled, 2)2	-27.40	2.64	-32.58	-22.22
Redfish	non-hurdle	density	(Intercept)	2.73	0.52	1.71	3.76
			poly(depth_scaled, 2)1	9.52	2.28	5.05	13.99
			poly(depth_scaled, 2)2	-13.82	2.20	-18.12	-9.51
			fyear2014	0.34	0.39	-0.43	1.11
			fyear2015	0.89	0.45	0.01	1.76
			fyear2016	1.91	0.48	0.96	2.85
			fyear2017	2.12	0.50	1.14	3.11
			fyear2018	2.20	0.51	1.20	3.20
			fyear2019	2.42	0.53	1.39	3.46
			fyear2020	1.62	0.54	0.56	2.69
			fyear2021	1.95	0.53	0.91	2.99
			fyear2022	1.24	0.54	0.19	2.30
Greenland Halibut	non-hurdle	density	(Intercept)	2.57	0.74	1.12	4.02
			poly(depth_scaled, 2)1	27.14	1.34	24.51	29.76
			poly(depth_scaled, 2)2	-11.75	1.55	-14.78	-8.72
Witch Flounder	hurdle	presence	(Intercept)	6.74	1.91	3.00	10.48
			poly(depth_scaled, 2)1	71.71	15.20	41.92	101.50
			poly(depth_scaled, 2)2	-38.86	13.23	-64.79	-12.93
			fyear2014	-2.05	1.66	-5.30	1.21
			fyear2015	-2.45	1.59	-5.56	0.66
			fyear2016	1.87	1.70	-1.47	5.21
			fyear2017	-0.76	1.73	-4.16	2.64
			fyear2018	-0.90	1.74	-4.32	2.51
			fyear2019	-1.64	1.74	-5.05	1.76
			fyear2020	-2.41	1.67	-5.68	0.86
			fyear2021	-2.57	1.70	-5.90	0.76
			fyear2022	-0.43	1.45	-3.27	2.41
		density	(Intercept)	1.67	0.24	1.19	2.15
			poly(depth_scaled, 2)1	12.89	3.24	6.53	19.25
			poly(depth_scaled, 2)2	-24.96	3.21	-31.26	-18.66
			fyear2014	-0.30	0.25	-0.80	0.20
			fyear2015	-0.57	0.24	-1.03	-0.11
			fyear2016	-0.49	0.25	-0.98	-0.01
			fyear2017	-0.42	0.24	-0.90	0.05

Species	Model structure	Response	Term	Estimate	St. error	L95	U95
			fyear2018	-0.27	0.25	-0.76	0.21
			fyear2019	0.31	0.26	-0.21	0.82
			fyear2020	-0.58	0.26	-1.09	-0.06
			fyear2021	-0.13	0.26	-0.63	0.37
			fyear2022	0.24	0.25	-0.24	0.72

Table A2. Coefficients from models fitted to sGSL RV survey data.

Species	Model structure	Response	Term	Estimate	St. error	L95	U95
White Hake	hurdle	probability	(Intercept)	-2.07	1.40	-4.83	0.68
			poly(depth_scaled, 2)1	111.11	13.88	83.90	138.32
			poly(depth_scaled, 2)2	0.70	11.26	-21.36	22.76
			fyear2014	0.18	0.64	-1.07	1.42
			fyear2015	0.84	0.60	-0.34	2.01
			fyear2016	-0.05	0.64	-1.31	1.20
			fyear2017	1.00	0.64	-0.25	2.25
			fyear2018	0.12	0.68	-1.22	1.45
			fyear2019	1.03	0.63	-0.21	2.26
			fyear2020	0.96	0.66	-0.34	2.26
			fyear2021	1.79	0.58	0.65	2.93
			fyear2022	1.18	0.67	-0.13	2.50
			fyear2023	0.24	0.65	-1.03	1.51
		density	(Intercept)	-0.20	0.28	-0.75	0.34
			poly(depth_scaled, 2)1	33.29	3.85	25.75	40.83
			poly(depth_scaled, 2)2	-23.41	2.59	-28.50	-18.33
			fyear2014	0.97	0.31	0.37	1.58
			fyear2015	0.58	0.29	0.01	1.15
			fyear2016	0.58	0.32	-0.04	1.20
			fyear2017	0.51	0.31	-0.09	1.12
			fyear2018	0.60	0.32	-0.03	1.24
			fyear2019	1.11	0.31	0.50	1.71
			fyear2020	0.95	0.32	0.33	1.58
			fyear2021	0.91	0.28	0.36	1.45
			fyear2022	0.82	0.32	0.20	1.44
			fyear2023	0.00	0.33	-0.65	0.64
Redfish	hurdle	probability	(Intercept)	1.09	0.64	-0.17	2.34
			poly(depth_scaled, 2)1	168.89	44.73	81.22	256.56
			poly(depth_scaled, 2)2	36.02	23.12	-9.28	81.33
			fyear2014	-0.54	0.43	-1.39	0.32
			fyear2015	-1.01	0.44	-1.87	-0.14
			fyear2016	-1.16	0.45	-2.04	-0.28
			fyear2017	-1.44	0.48	-2.38	-0.51

Species	Model structure	Response	Term	Estimate	St. error	L95	U95
			fyear2018	-1.24	0.49	-2.21	-0.27
			fyear2019	-1.71	0.50	-2.69	-0.73
			fyear2020	-2.24	0.57	-3.35	-1.13
			fyear2021	-1.13	0.45	-2.00	-0.25
			fyear2022	-0.31	0.47	-1.24	0.62
			fyear2023	-1.03	0.46	-1.94	-0.12
		density	(Intercept)	-2.64	0.32	-3.27	-2.00
			poly(depth_scaled, 2)1	99.21	4.48	90.43	107.99
			poly(depth_scaled, 2)2	-19.73	3.52	-26.63	-12.83
			fyear2014	0.34	0.38	-0.40	1.08
			fyear2015	0.54	0.39	-0.23	1.30
			fyear2016	1.53	0.40	0.74	2.31
			fyear2017	1.10	0.45	0.22	1.98
			fyear2018	0.79	0.44	-0.08	1.66
			fyear2019	1.36	0.46	0.47	2.25
			fyear2020	1.45	0.50	0.47	2.44
			fyear2021	1.77	0.40	0.98	2.55
			fyear2022	2.06	0.42	1.24	2.88
			fyear2023	1.00	0.45	0.12	1.88
Witch Flounder	hurdle	probability	(Intercept)	-4.50	1.24	-6.92	-2.08
			poly(depth_scaled, 2)1	98.65	17.69	63.98	133.32
			poly(depth_scaled, 2)2	-33.83	9.45	-52.35	-15.30
		density	(Intercept)	-1.33	0.30	-1.93	-0.74
			poly(depth_scaled, 2)1	48.03	5.47	37.32	58.75
			poly(depth_scaled, 2)2	-23.33	3.55	-30.29	-16.36

Table A3. Coefficients from models fitted to Winter RV survey data.

Species	Model structure	Response	Term	Estimate	St. error	L95	U95
White Hake	non-hurdle	density	(Intercept)	1.13	0.47	0.21	2.05
			poly(depth_scaled, 2)1	0.96	1.18	-1.36	3.28
			poly(depth_scaled, 2)2	-4.06	1.10	-6.21	-1.90
Redfish	non-hurdle	density	(Intercept)	3.55	0.32	2.92	4.18
			depth_scaled	1.31	0.24	0.84	1.77

Table A4. Coefficients from models fitted to Landings and At-Sea Observer (ASO) data.

Fishery	Response	Term	Estimate	St. error	L95	U95
Redfish	probability	(Intercept)	-0.78	1.20	-3.13	1.56
		poly(depth_scaled, 2)1	-23.45	4.16	-31.62	-15.29
		poly(depth_scaled, 2)2	-13.09	3.13	-19.21	-6.96
		fmonth07	-0.20	0.17	-0.54	0.14
		fmonth08	-0.22	0.22	-0.66	0.21
		fmonth09	-1.00	0.35	-1.69	-0.32

Fishery	Response	Term	Estimate	St. error	L95	U95
		fmonth10	0.82	0.59	-0.33	1.97
		fyear2014	-0.59	0.53	-1.63	0.46
		fyear2015	0.18	0.53	-0.86	1.22
		fyear2016	0.20	0.52	-0.81	1.21
		fyear2017	-0.36	0.53	-1.39	0.68
		fyear2018	-0.07	0.56	-1.17	1.03
		fyear2019	-0.70	0.55	-1.77	0.38
		fyear2020	0.20	0.53	-0.85	1.24
		fyear2021	-0.97	0.54	-2.03	0.10
		fyear2022	-1.25	0.61	-2.44	-0.06
	proportion	(Intercept)	-3.09	0.40	-3.88	-2.30
		poly(depth_scaled, 2)1	-5.31	3.12	-11.42	0.81
		poly(depth_scaled, 2)2	-4.54	2.25	-8.94	-0.13
		fmonth07	0.26	0.09	0.07	0.44
		fmonth08	0.24	0.13	-0.02	0.49
		fmonth09	1.08	0.18	0.73	1.42
		fmonth10	2.46	0.20	2.06	2.86
		fyear2014	-0.09	0.41	-0.90	0.72
		fyear2015	0.06	0.41	-0.74	0.86
		fyear2016	1.00	0.39	0.24	1.76
		fyear2017	0.34	0.43	-0.51	1.19
		fyear2018	0.11	0.42	-0.72	0.93
		fyear2019	-0.03	0.42	-0.85	0.79
		fyear2020	-1.07	0.44	-1.94	-0.20
		fyear2021	-0.59	0.41	-1.39	0.21
		fyear2022	-1.30	0.57	-2.41	-0.19
Greenland Halibut	probability	(Intercept)	-5.22	0.67	-6.54	-3.90
		depth_scaled	-0.33	0.09	-0.51	-0.16
		fyear2014	-0.17	0.68	-1.51	1.18
		fyear2015	-1.54	0.82	-3.16	0.07
		fyear2016	0.04	0.72	-1.37	1.46
		fyear2017	0.05	0.71	-1.35	1.44
		fyear2018	0.77	0.72	-0.63	2.18
		fyear2019	1.14	0.72	-0.28	2.55
		fyear2020	1.92	0.69	0.56	3.28
		fyear2021	3.30	0.76	1.81	4.78
		fyear2022	3.31	0.76	1.83	4.79
	proportion	(Intercept)	-3.27	0.22	-3.70	-2.85
		depth_scaled	-0.21	0.04	-0.30	-0.12
		fyear2014	-0.26	0.20	-0.64	0.12
		fyear2015	-0.52	0.23	-0.97	-0.07
		fyear2016	-0.27	0.21	-0.68	0.14
		fyear2017	0.18	0.19	-0.19	0.55

Fishery	Response	Term	Estimate	St. error	L95	U95
		fyear2018	0.49	0.19	0.12	0.86
		fyear2019	0.21	0.19	-0.17	0.59
		fyear2020	0.38	0.18	0.03	0.74
		fyear2021	0.35	0.19	-0.03	0.72
		fyear2022	0.49	0.19	0.12	0.86
Greenland Halibut, ASO	probability	(Intercept)	-0.19	1.21	-2.57	2.19
		depth_scaled	-0.18	0.16	-0.49	0.13
		soak.time	-0.02	0.00	-0.03	-0.01
		fmonth5	-0.08	1.08	-2.19	2.04
		fmonth6	0.08	0.98	-1.84	2.00
		fmonth7	-0.69	0.98	-2.60	1.23
		fmonth8	-1.45	0.98	-3.37	0.47
		fmonth9	-1.55	1.02	-3.54	0.44
		fmonth10	-1.89	1.04	-3.92	0.14
		fyear2014	-1.01	0.79	-2.56	0.54
		fyear2015	-2.79	1.06	-4.86	-0.71
		fyear2016	0.67	0.85	-0.99	2.34
		fyear2017	1.47	0.81	-0.13	3.06
		fyear2018	2.90	0.83	1.27	4.53
		fyear2019	3.77	0.93	1.94	5.60
		fyear2020	4.25	0.92	2.45	6.05
		fyear2021	3.89	0.98	1.97	5.81
		fyear2022	5.50	1.30	2.94	8.06
	proportion	(Intercept)	-4.28	0.39	-5.05	-3.51
		depth_scaled	-0.27	0.06	-0.38	-0.16
		soak.time	-0.01	0.00	-0.01	0.00
		fmonth5	0.14	0.32	-0.49	0.76
		fmonth6	0.19	0.26	-0.32	0.69
		fmonth7	0.21	0.26	-0.31	0.73
		fmonth8	-0.22	0.26	-0.73	0.30
		fmonth9	-0.17	0.28	-0.72	0.38
		fmonth10	-0.18	0.27	-0.72	0.36
		fyear2014	0.22	0.36	-0.49	0.93
		fyear2015	0.13	0.63	-1.11	1.37
		fyear2016	-0.04	0.36	-0.73	0.66
		fyear2017	0.35	0.34	-0.32	1.02
		fyear2018	0.83	0.32	0.20	1.47
		fyear2019	1.31	0.35	0.63	1.99
		fyear2020	0.71	0.34	0.03	1.38
		fyear2021	0.98	0.35	0.30	1.67
		fyear2022	0.63	0.39	-0.13	1.39
Atlantic Halibut	probability	(Intercept)	-6.66	0.80	-8.23	-5.08

Fishery	Response	Term	Estimate	St. error	L95	U95
		depth_scaled	0.76	0.14	0.49	1.02
		fmonth05	1.12	0.19	0.74	1.50
		fmonth06	1.16	0.20	0.78	1.55
		fmonth07	-0.22	0.30	-0.80	0.36
		fmonth08	0.38	0.28	-0.17	0.94
		fmonth09	-0.24	0.35	-0.94	0.45
		fmonth10	-0.42	0.38	-1.17	0.33
		fyear2014	0.89	0.28	0.35	1.43
		fyear2015	0.88	0.25	0.38	1.38
		fyear2016	0.95	0.24	0.47	1.43
		fyear2017	-0.50	0.27	-1.02	0.02
		fyear2018	-1.00	0.31	-1.61	-0.39
		fyear2019	0.20	0.26	-0.31	0.71
		fyear2020	-1.20	0.38	-1.93	-0.46
		fyear2021	0.33	0.28	-0.22	0.88
		fyear2022	1.16	0.26	0.64	1.67
	proportion	(Intercept)	-3.26	0.24	-3.73	-2.79
		depth_scaled	0.14	0.05	0.04	0.25
		fmonth05	0.25	0.12	0.02	0.49
		fmonth06	0.03	0.12	-0.21	0.27
		fmonth07	0.38	0.18	0.02	0.74
		fmonth08	0.36	0.18	0.00	0.72
		fmonth09	0.30	0.24	-0.17	0.77
		fmonth10	0.66	0.24	0.18	1.13
		fyear2014	0.19	0.18	-0.16	0.53
		fyear2015	0.27	0.16	-0.04	0.57
		fyear2016	0.16	0.15	-0.14	0.45
		fyear2017	-0.17	0.18	-0.53	0.19
		fyear2018	-0.12	0.23	-0.56	0.33
		fyear2019	-0.09	0.17	-0.42	0.24
		fyear2020	0.17	0.26	-0.33	0.68
		fyear2021	0.29	0.17	-0.05	0.62
		fyear2022	0.47	0.15	0.17	0.77

SUPPORTING FIGURES

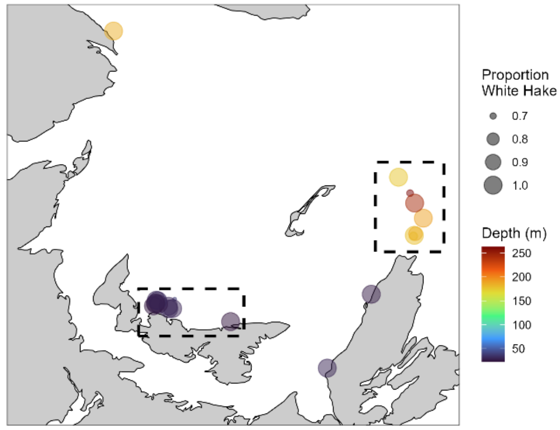


Figure A1. Locations of 21 Atlantic Halibut fishing events associated with high proportions (>0.65) of White Hake. Boxes outline clusters of 11 fishing events north of PEI, and 7 fishing events north of Cape Breton.

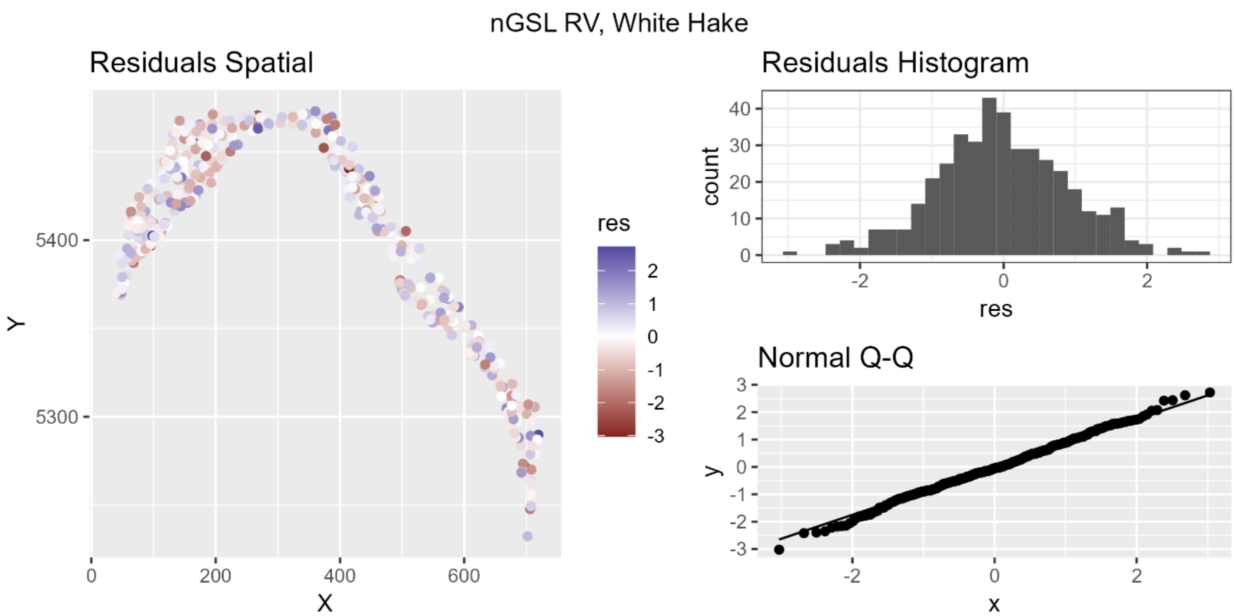


Figure A2. Model diagnostics for the nGSL RV White Hake model.

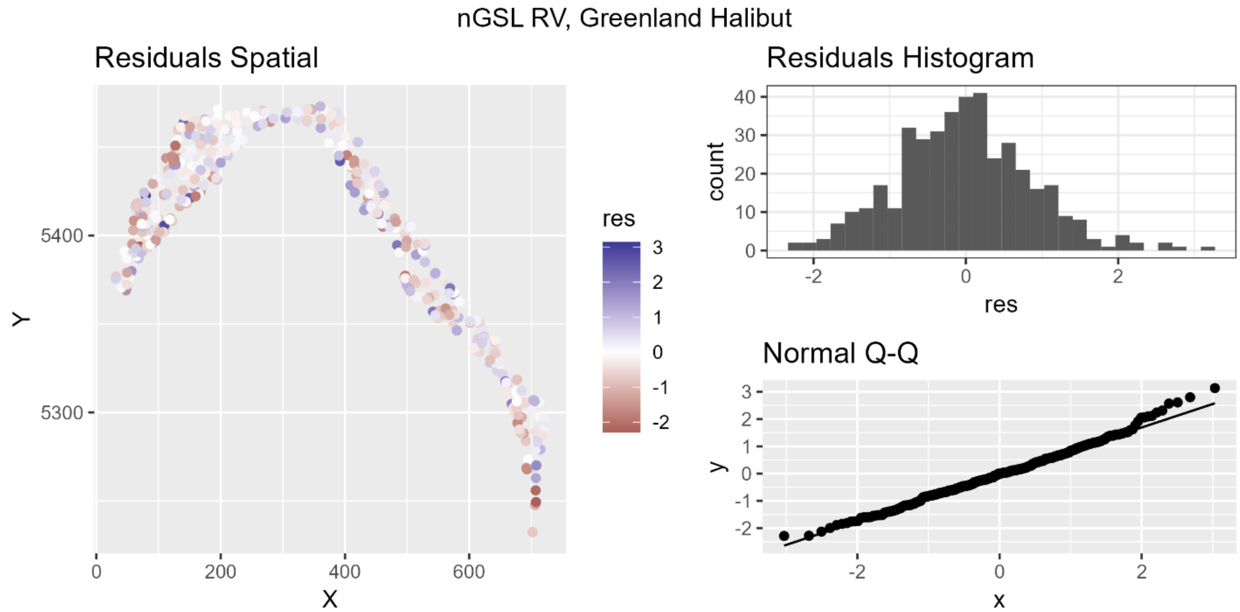


Figure A3. Model diagnostics for the nGSL RV Greenland Halibut model.

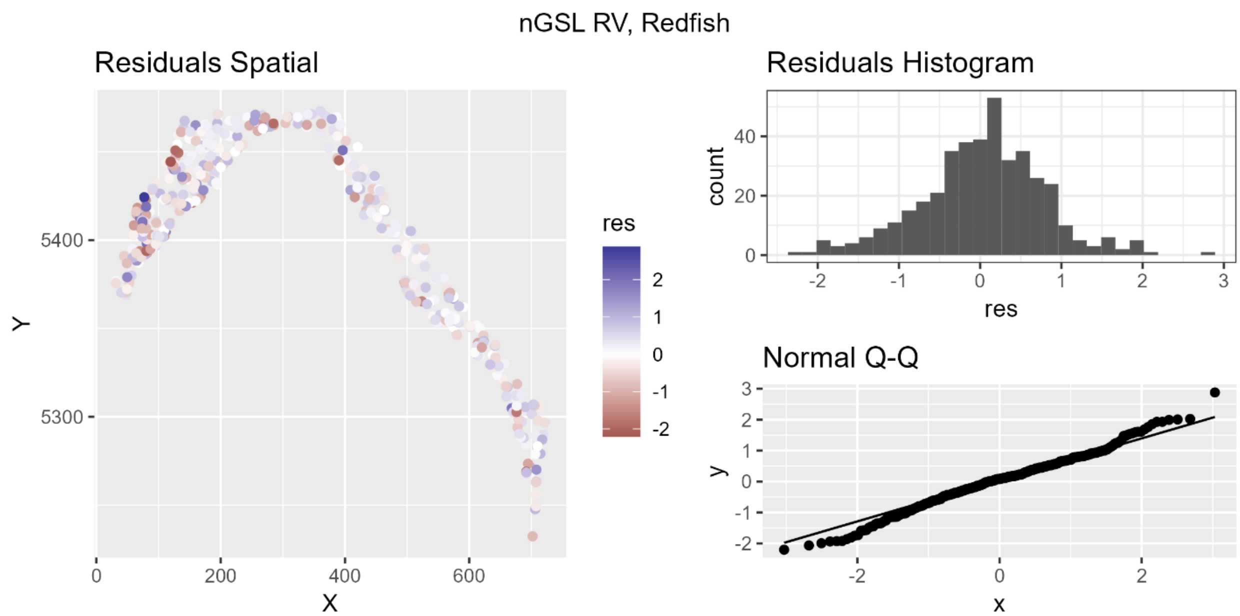


Figure A4. Model diagnostics for the nGSL RV Redfish model.

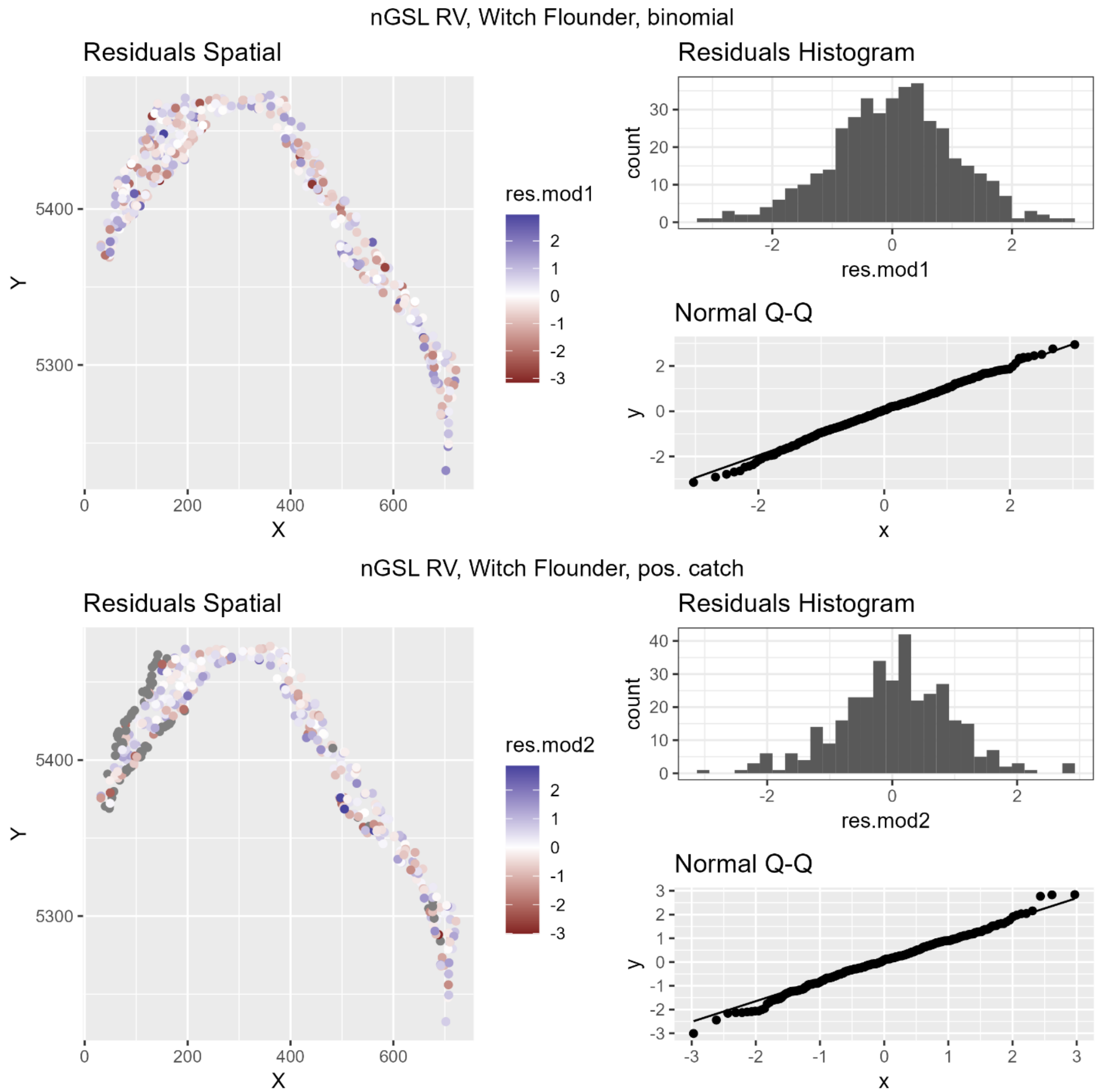


Figure A5. Model diagnostics for the nGSL RV Witch Flounder model.

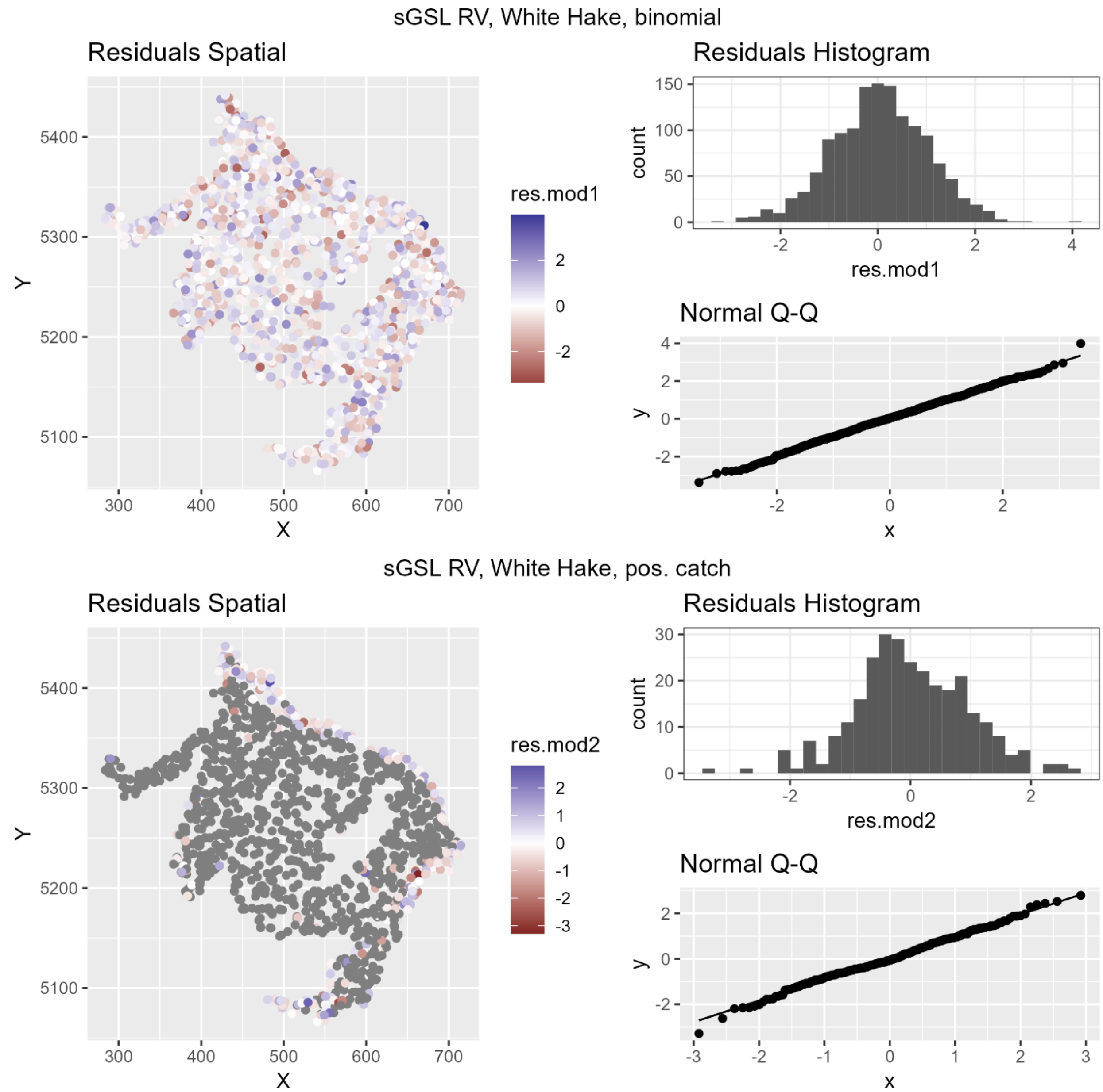


Figure A6. Model diagnostics for the sGSL RV White Hake model.

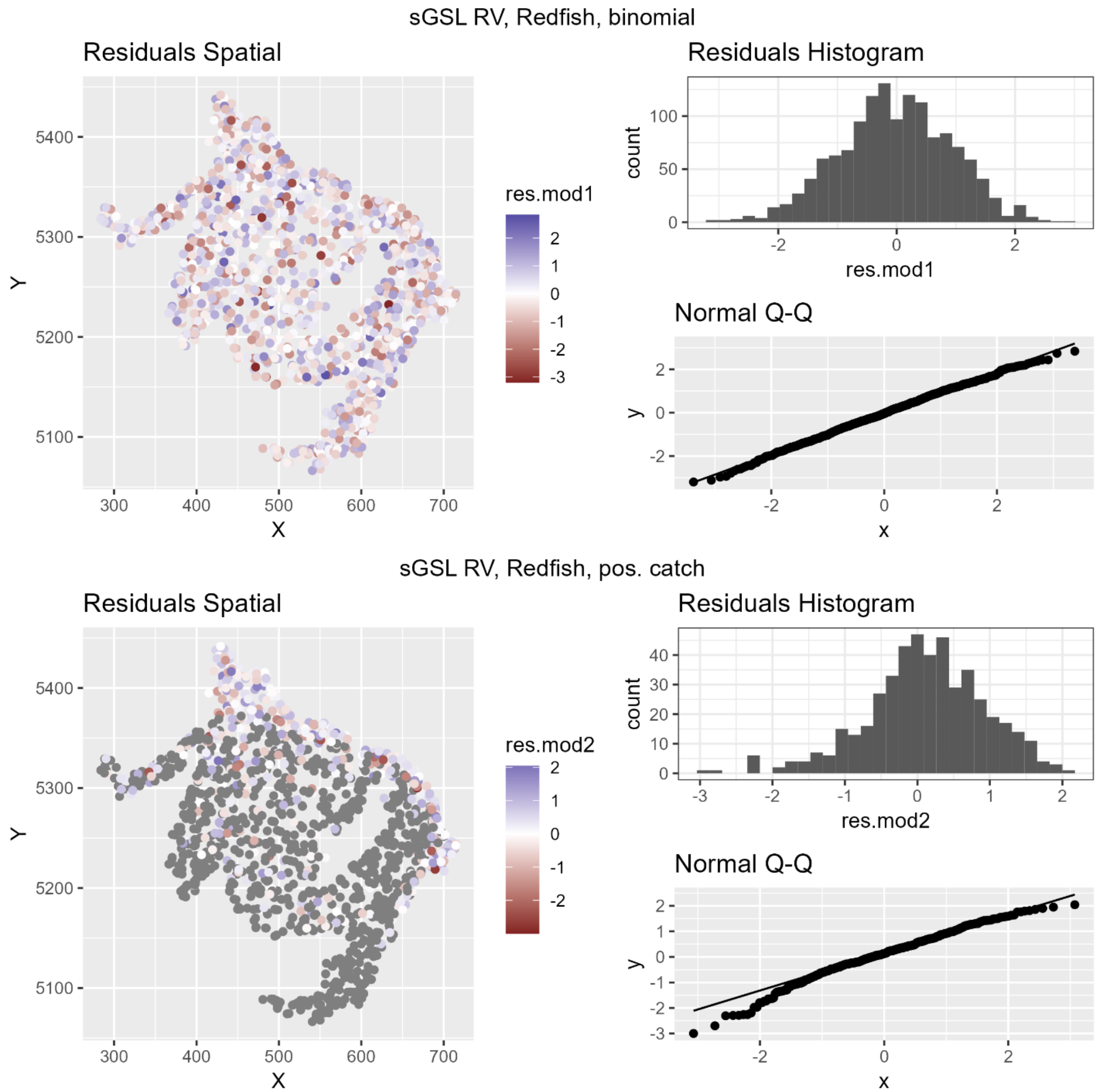


Figure A7. Model diagnostics for the sGSL RV Redfish model.

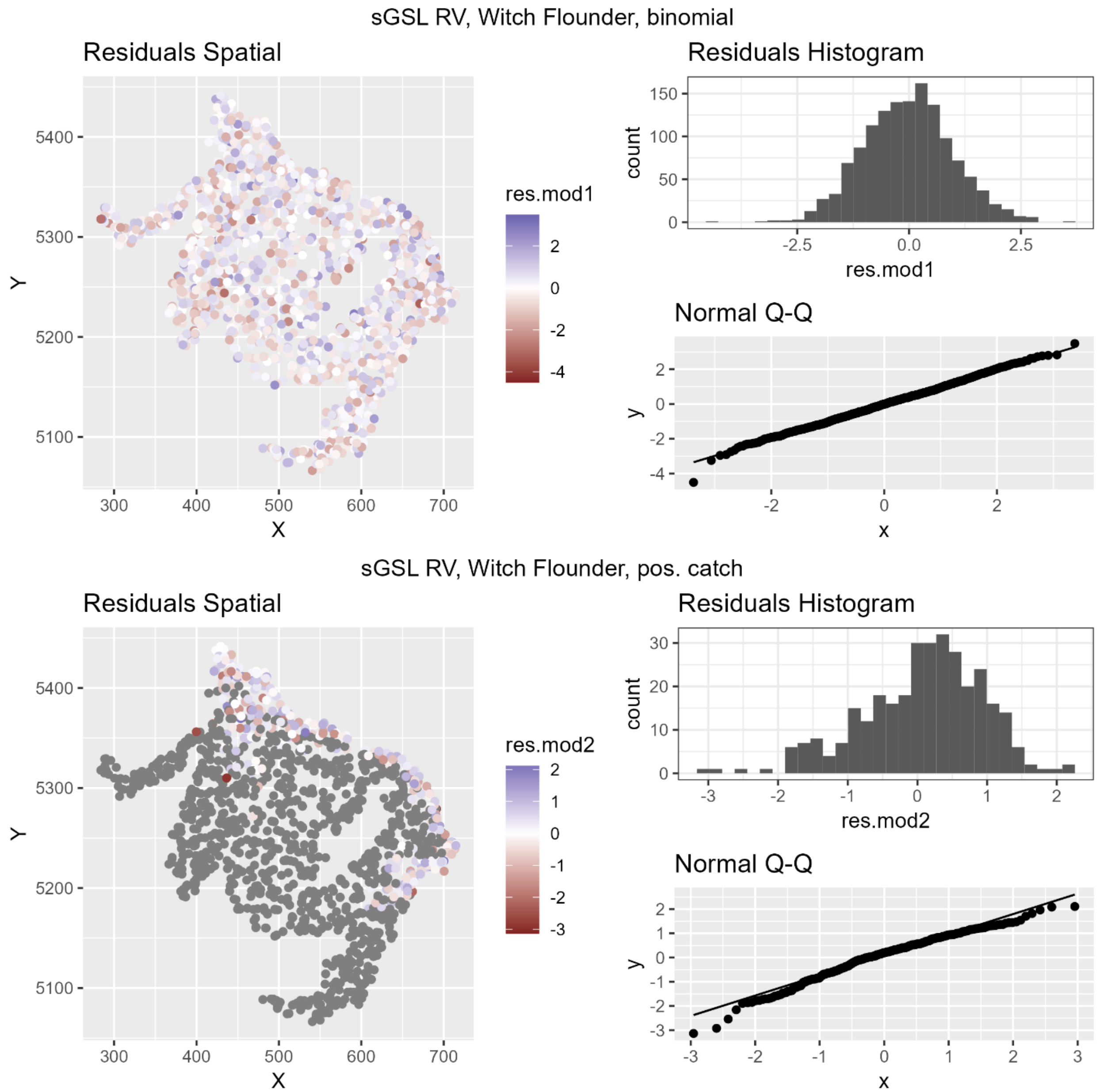


Figure A8. Model diagnostics for the sGSL RV Witch Flounder model.

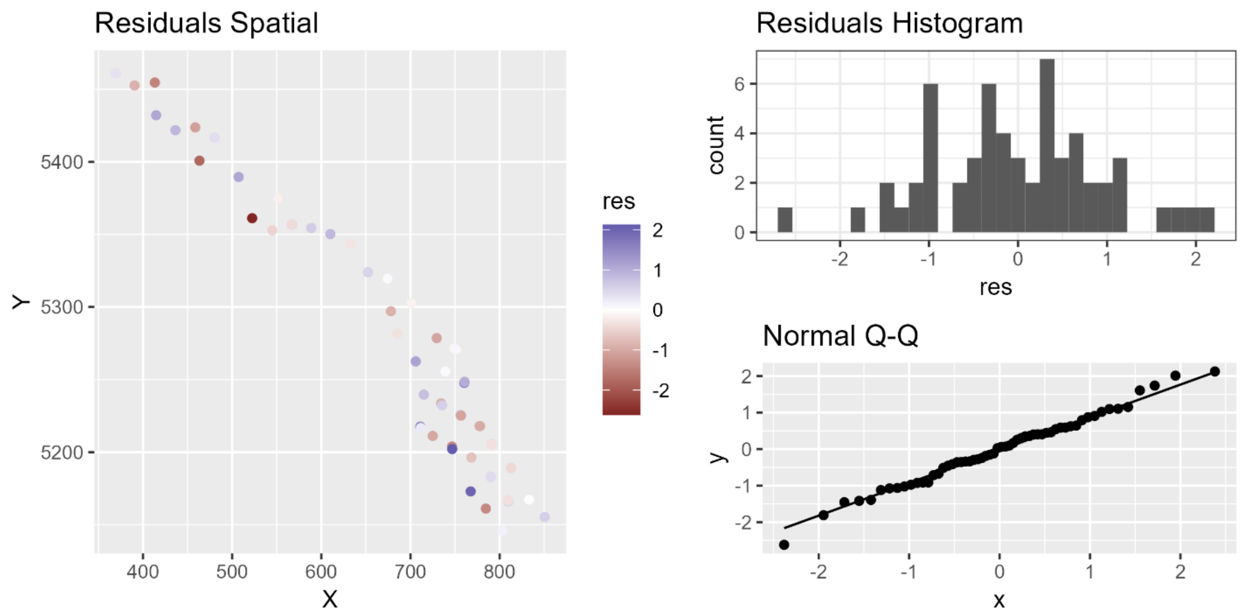


Figure A9. Model diagnostics for the Winter RV White Hake model.

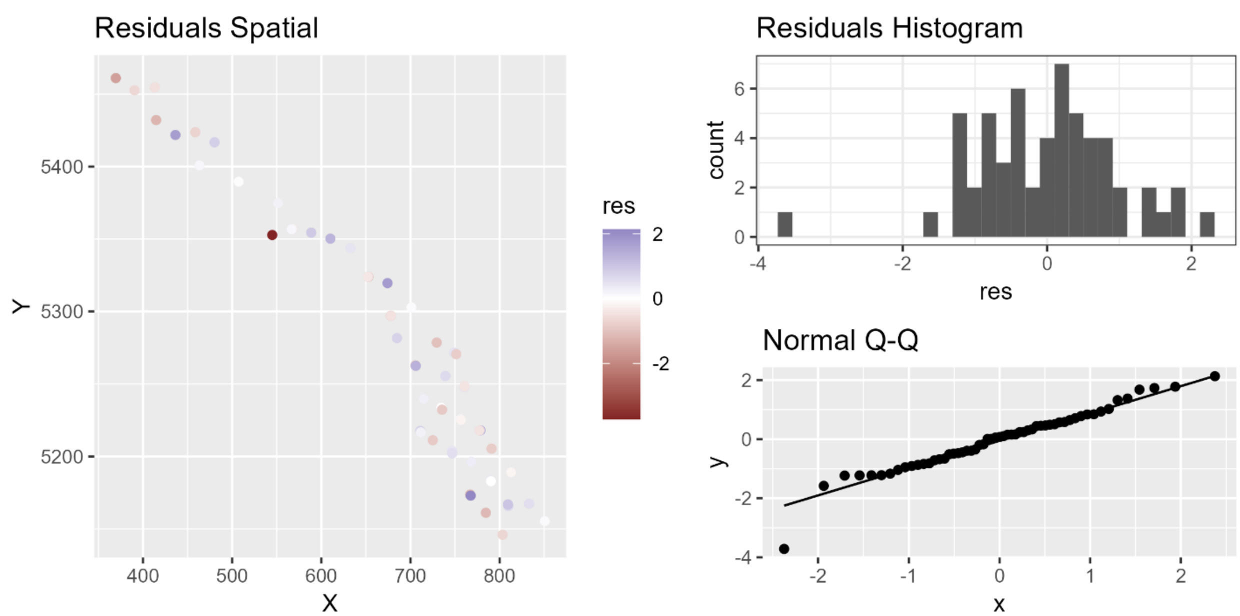


Figure A10. Model diagnostics for the Winter RV Redfish model.

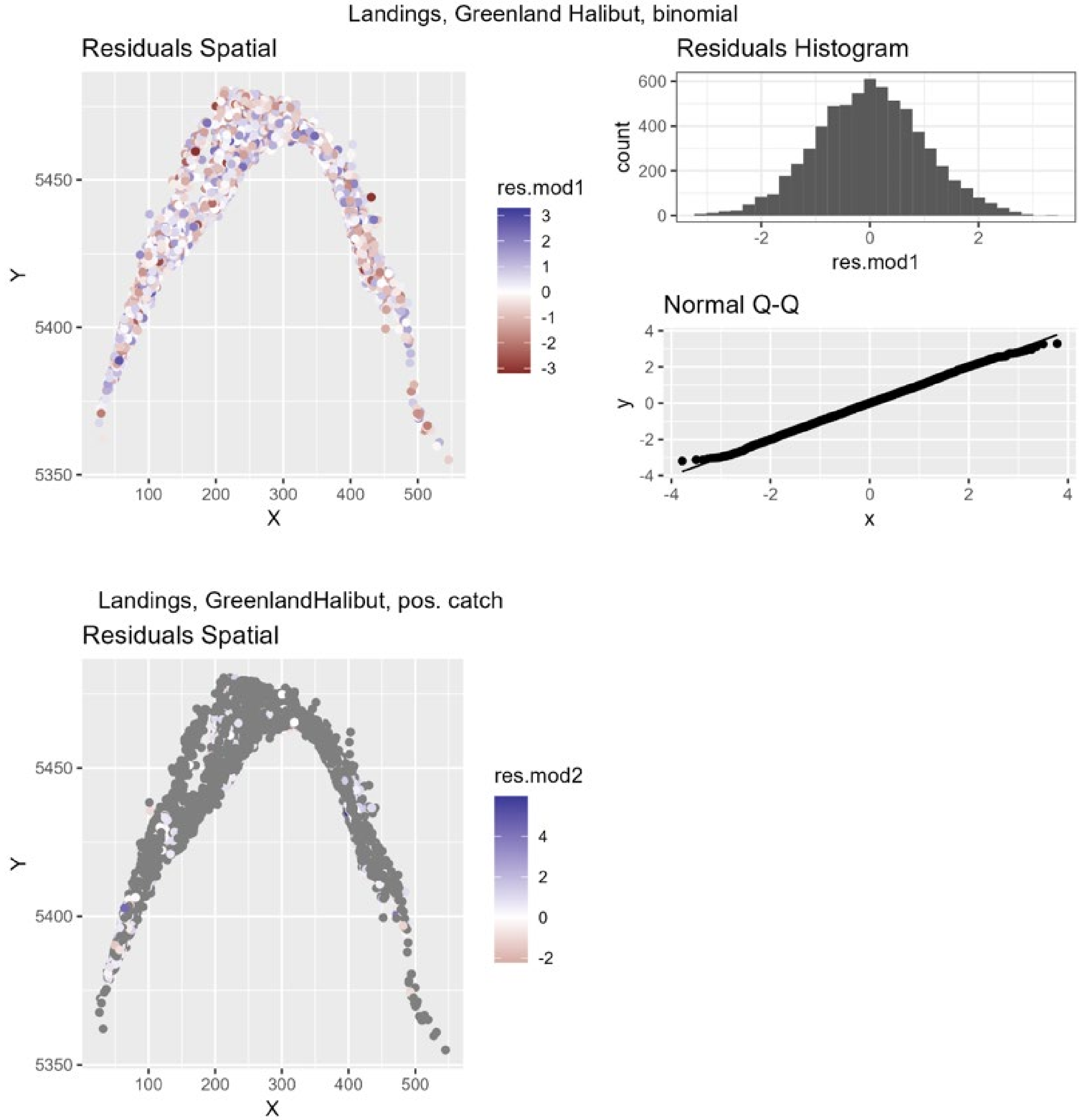


Figure A11. Model diagnostics for the Greenland Halibut Landings model.

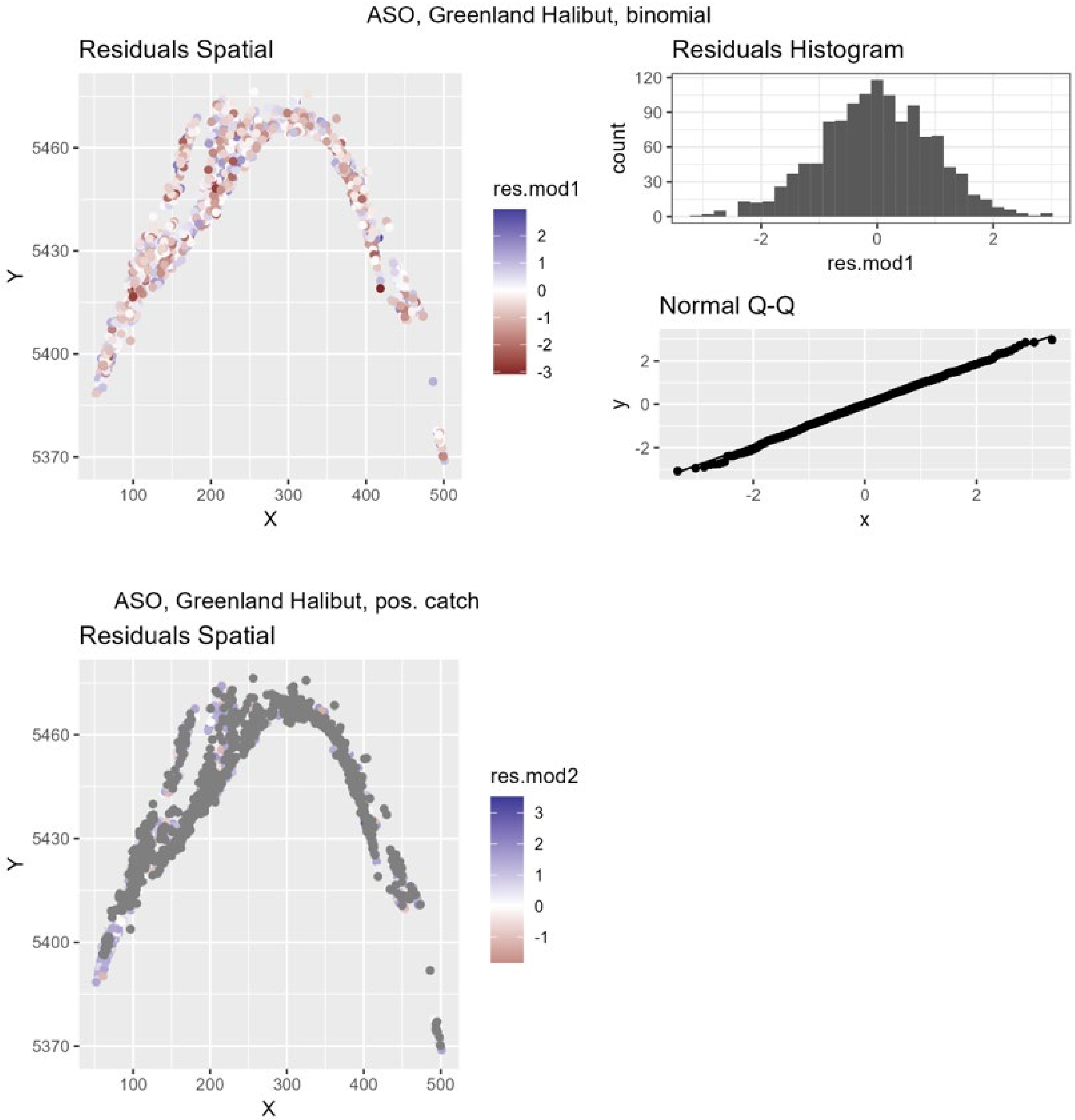


Figure A12. Model diagnostics for the Greenland Halibut ASO model.

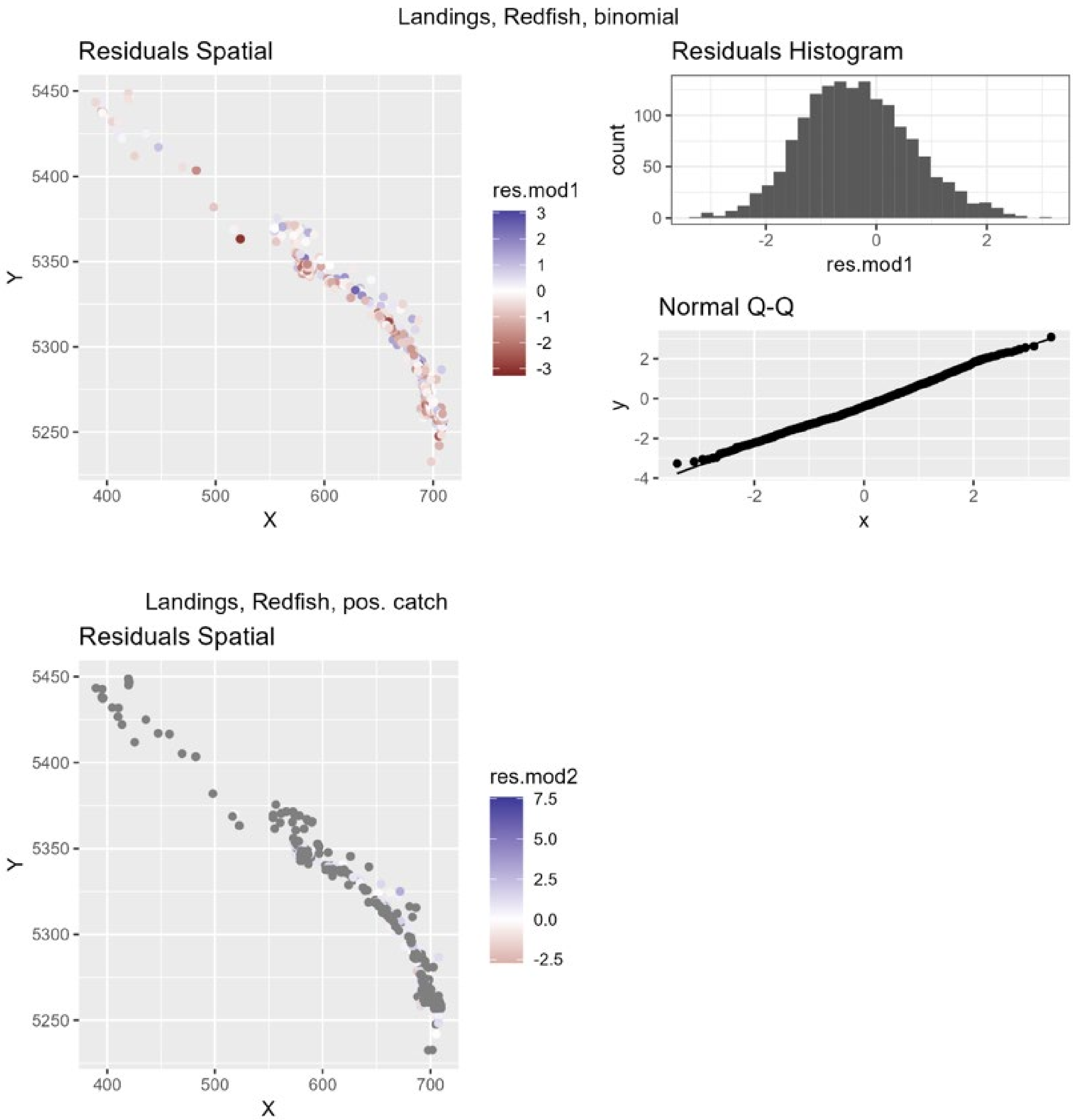
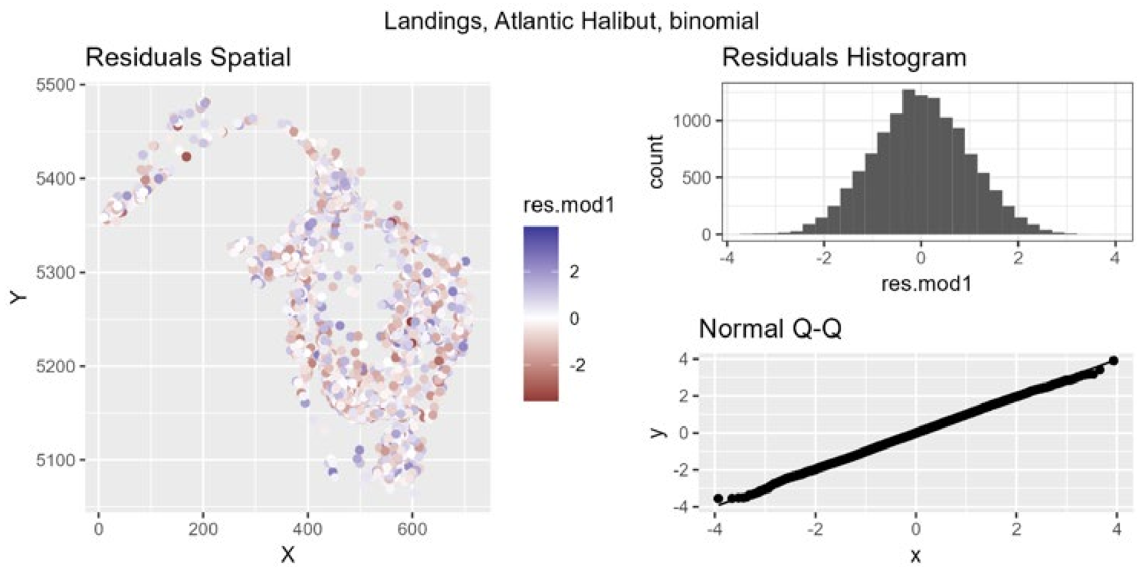


Figure A13. Model diagnostics for the Redfish Landings model.



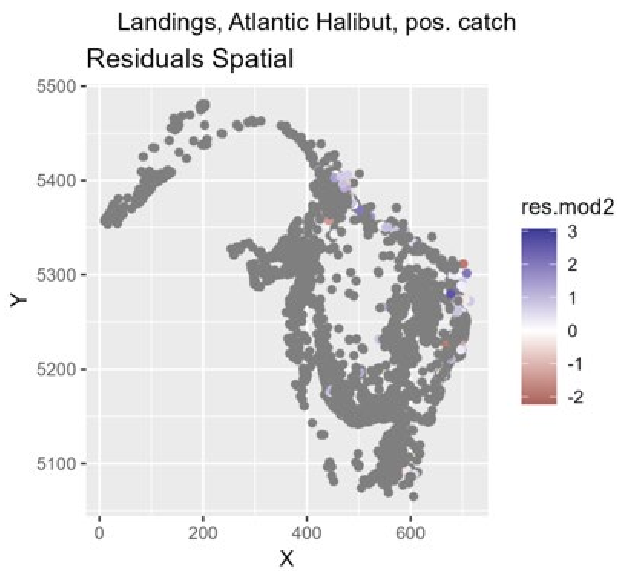


Figure A14. Model diagnostics for the Atlantic Halibut Landings model.

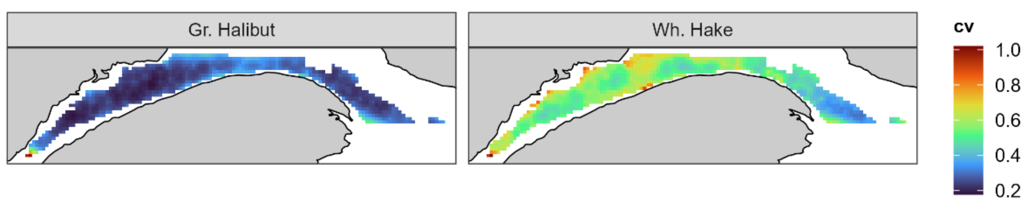


Figure A15. Uncertainty in nGSL Research Vessel model-predicted catch densities of Greenland Halibut (left) and White Hake (right), over the Greenland Halibut fishing grid. Predictions were averaged across years.

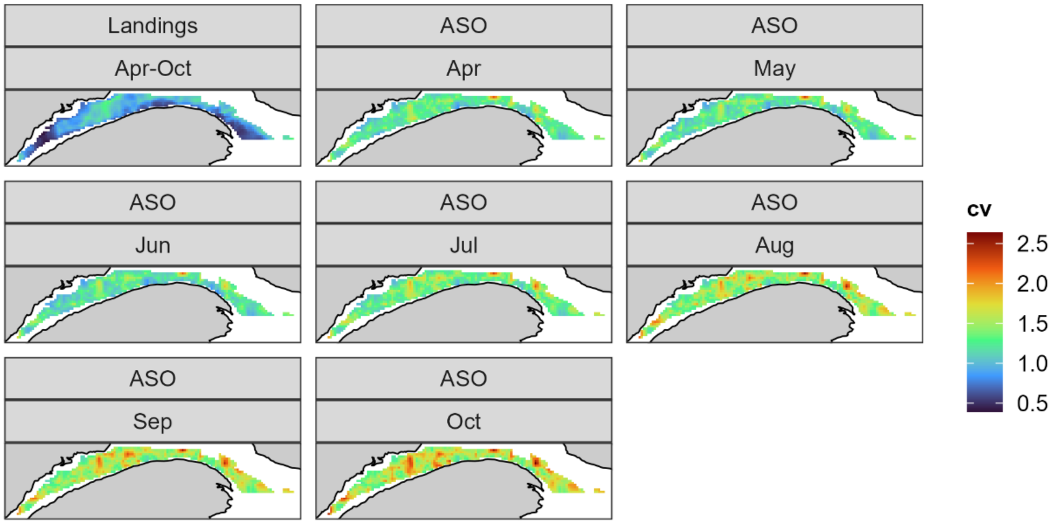


Figure A16. Uncertainty in Landings and ASO model-predicted bycatch of White Hake in a Greenland Halibut fishery, over the Greenland Halibut fishing grid. Predictions were averaged across years. Top row, left to right: uncertainty in model predictions from the Landings (April – October) model, and the ASO model (April, May). Middle row, left to right: Uncertainty in predictions from the ASO model (June, July, August). Bottom row, left to right: Uncertainty in predictions from the ASO model (September, October).

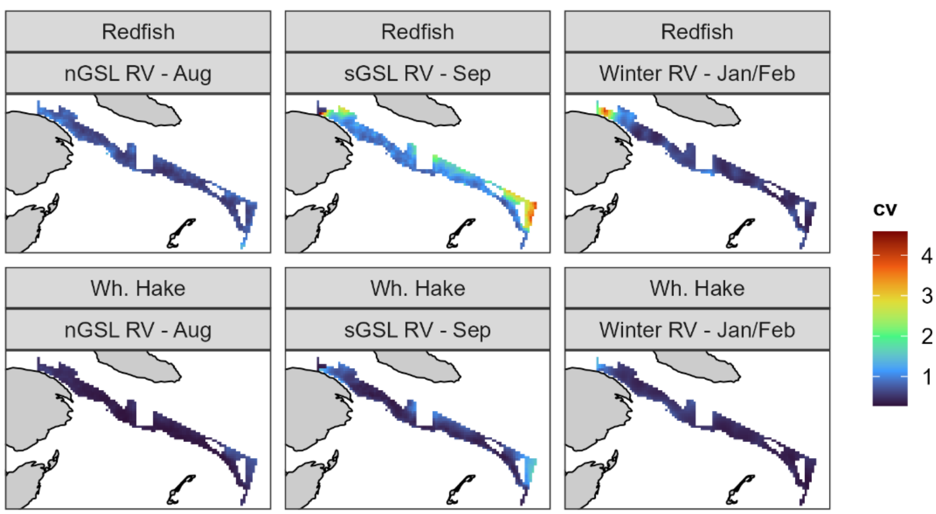


Figure A17. Uncertainty in Research Vessel model-predicted catch densities of Redfish and White Hake, over the Redfish fishing grid. Predictions were averaged across years. Top row, left to right: uncertainty in predictions of Redfish catch densities from the nGSL RV (August), sGSL RV (September), and Winter (January/February) models. Bottom row, left to right: uncertainty in predictions of White Hake catch densities nGSL RV (August), sGSL RV (September), and Winter (January/February) models.

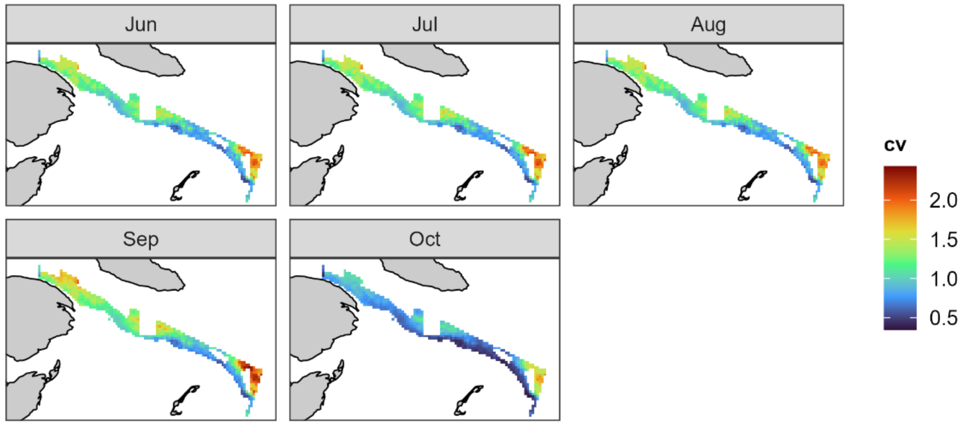


Figure A18. Uncertainty in Landings model-predicted bycatch of White Hake in a Redfish Fishery, over the Redfish fishing grid. Predictions were averaged across years. Top row, left to right: months June, July, August. Bottom row, left to right: months September, October.

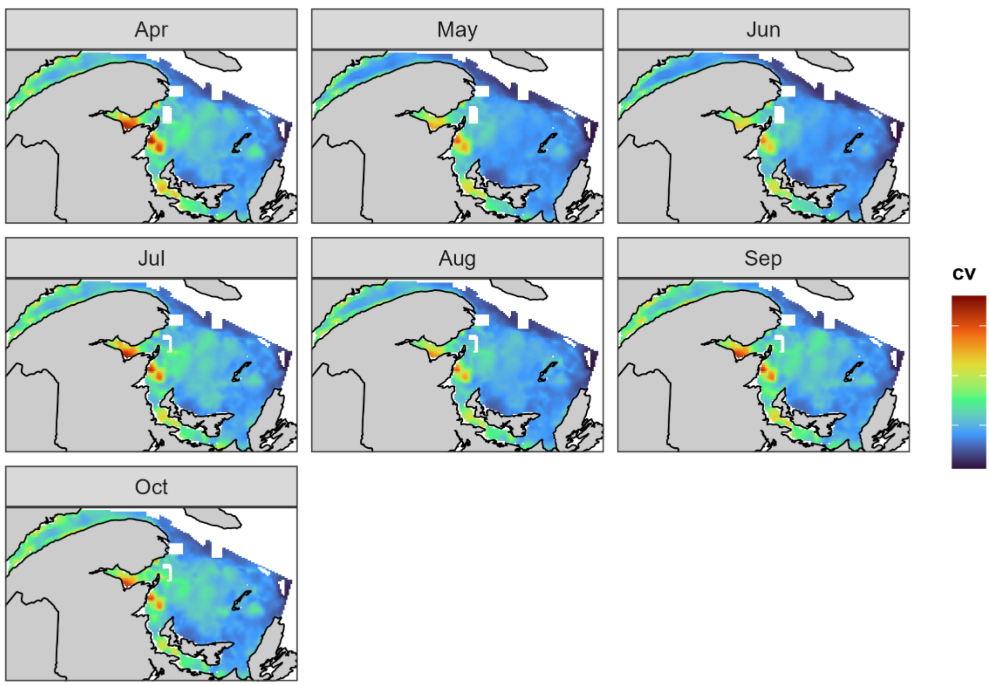


Figure A19. Uncertainty in Atlantic Halibut-target Landings model-predicted bycatch of White Hake, over the Atlantic Halibut fishing grid. Predictions were averaged across years. Top row, left to right: months April, May, June. Middle row, left to right: months July, August, September. Bottom row: October.

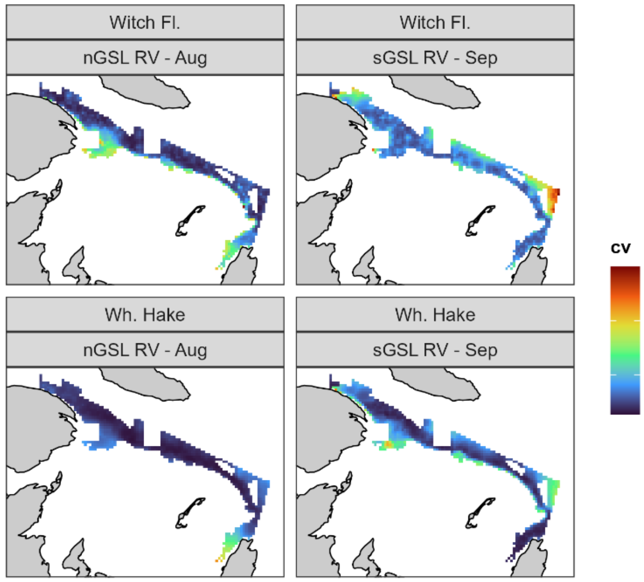


Figure A20. Uncertainty in Research Vessel model-predicted catch densities of Witch Flounder and White Hake, over the Witch Flounder fishing grid. Predictions were averaged across years. Top row, left to right: uncertainty in predictions of Witch Flounder catch densities from the nGSL RV models (August) and sGSL RV models (September). Bottom row, left to right: uncertainty in predictions of White Hake catch densities from the nGSL RV models (August) and sGSL RV models (September).

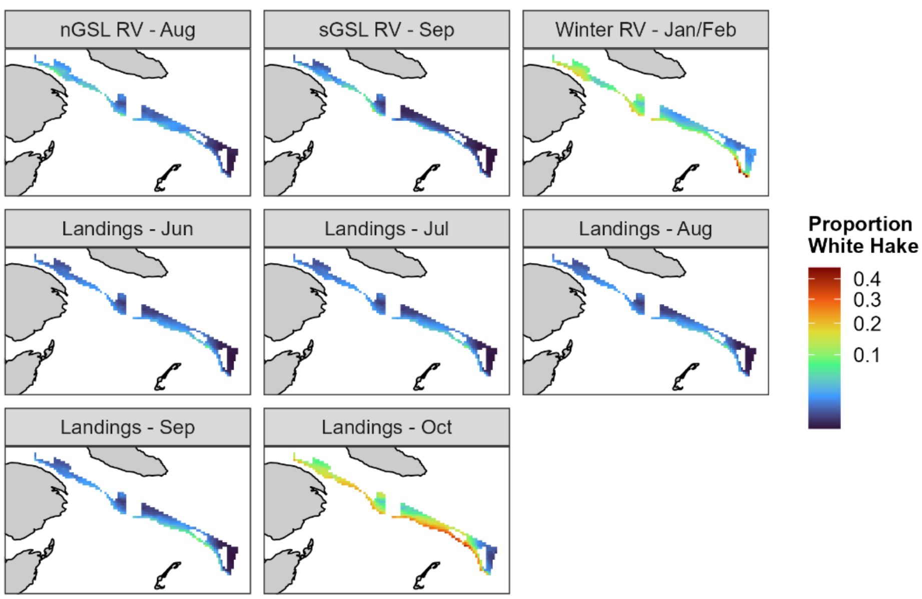


Figure A21. Model-predicted bycatch of White Hake in a Redfish fishery. Predictions were averaged across years. The minimum depth considered was 300 m. The legend is square-root transformed. Top row, left to right: predictions from the nGSL RV models (August), sGSL RV models (September), and Winter RV models (January and February). Middle row, left to right: predictions from the Landings model (June, July, August). Bottom row: Predictions from the Landings model (September, October).