Spatiotemporal bycatch analysis of the Atlantic halibut (Hippoglossus hippoglossus) longline fishery survey indicates hotspots for species of conservation concern

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1 INTRODUCTION

Bycatch, the incidental catch of nontargeted species, is an omnipresent issue in fisheries (Anderson et al., 2011; Hammer, Childerhouse, & Gales, 2012; Lewison, Crowder, Read, & Freeman, 2004), contributing to over 40.4% of the global fisheries catch (Davies, Cripps, Nickson, & Porter, 2009). This catch of nontargeted species can lead to declines...
in bycaught populations and alter the structure, function and
trophic dynamics of marine ecosystems, with implications
for biodiversity conservation and sustainability of fisheries
(Lewison et al., 2004; Munoz et al., 2011). Several studies
have assessed the magnitude, spatial patterns and temporal
trends for bycatch in different fisheries and bycaught species
to propose possible solutions and management strategies
(Cosandey-Godin, Krainski, Worm, & Flemming, 2015;
Lewison, Soykan, & Franklin, 2009). Despite many general
issues, each fishery is distinct in terms of the gear used,
region and season fished, and species impacted, and thus
needs its own bycatch assessment and management
(O’Keefe, Cadrin, & Stokesbury, 2014).

Fisheries management authorities around the world aim
to move towards ecosystem-based management to sustain
both marine ecosystems and commercial fisheries (Pikitch
et al., 2004), with bycatch being important to consider when
quantifying the impact of a target fishery on other species or
the ecosystem. Techniques identified to reduce bycatch
levels include selective fishing gear, closed areas or seasons,
bycatch quotas and caps, and incentive programs (O’Keefe
et al., 2014). One incentive program is the Marine Steward-
ship Council (MSC) certification, which aims to promote
more sustainable fisheries practices and inform environmen-
tally conscious consumers (Bush, Toonen, Oosterveer, &
Mol, 2013). The certification scheme is built on three princi-
pies, with the second principle addressing bycatch, requiring
MSC-certified fisheries to harvest in a way that maintains
productive and diverse ecosystems (Bush et al., 2013).

In Atlantic Canada, the Atlantic halibut (Hippoglossus
hippoglossus; hereafter halibut) fishery is currently the sec-
ond most valuable commercial groundfish fishery (DFO,
2018a), with 85% of its landings by weight derived from a
directed bottom longline fishery (den Heyer et al., 2015;
Trzcinski & Bowen, 2016). This fishery was unregulated
until 1988, at which time a total allowable catch (TAC) and
minimum legal size were introduced (den Heyer et al.,
2015). Since 2006, halibut productivity on the Scotian Shelf
and Southern Grand Banks (Figure 1) has increased
(Trzcinski & Bowen, 2016) and currently the fishery is regu-
lated by a TAC, length restrictions, seasonal closures, effort
limitations, gear restrictions, and bycatch limits for Atlantic

![Maps of Atlantic Canada showing Atlantic halibut (a) habitat suitability (index) and (b) catch weight (kg per 2 min grid cell) from the
commercial halibut fishery from 2010 to 2014 (Butler & Coffen-Smout, 2017) overlaid with the locations of longline survey stations. Also shown are the
Northwest Atlantic Fisheries Organization (NAFO, solid lines) divisions S5c and 4XW on the Scotian Shelf and 3PO on the Southern Grand Banks as
well as the Canadian Exclusive Economic Zone (dashed lines) (adapted from French, Shackell, & den Heyer, 2018)
cod and skate species (den Heyer et al., 2015). In 2013, the fishery received MSC certification (Martell, Vincent, & Turris, 2013), and has been recently recertified (Mateo, Allain, & Smith, 2018).

The halibut fishery catches substantial amounts of non-targeted species, which are either kept and sold or discarded depending on regulations (Martell et al., 2013; Themelis & den Heyer, 2015). This includes species listed under the Species at Risk Act (SARA), which are afforded legal protection and must be immediately returned to the water with minimal harm (Martell et al., 2013), as well as species awaiting a listing decision based on assessments by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). COSEWIC is a scientific advisory panel that assesses depleted species and provides advice to a SARA-associated committee. COSEWIC-assessed species have no legal protection, and many can be legally retained. Some however, such as thorny skate, are recommended by Fisheries and Oceans Canada (DFO) to be returned to the water (Martell et al., 2018). In the recent MSC recertification, the halibut fishery scored 80% for overall actions taken to prevent bycatch, with the lack of spatial bycatch information identified as one of the greatest weaknesses (Mateo et al., 2018).

In the current study, we aimed to assess the species composition, proportion, temporal, and spatial trends in the bycatch in the halibut longline fishery, through an examination of the bycatch in the annual survey. We utilized the annual DFO—halibut fishing industry longline survey data from 1998 to 2016 across the Northwest Atlantic Fisheries Organization (NAFO) divisions 3NOPs4VWX5Zc (Figure 1). While these surveys were designed to monitor the halibut catch, the data were collected by at-sea observers who also monitored bycatch (den Heyer et al., 2015). Although the survey catch is a small percentage of the commercial fishery landings, our results provide insight into the proportion and species composition of bycatch in the bottom longline gear used for the commercial halibut fishery, and the spatiotemporal trends of total bycatch and bycatch of species of conservation concern, which can inform fishery management and marine conservation strategies.

2 METHODS

2.1 Survey design

The halibut longline survey and stock management area span NAFO divisions 3NOPs4VWX5Zc, with high habitat suitability and commercial catch rates along the southern Scotian Shelf and southern edge of the Southern Grand Banks (Figure 1; French et al., 2018). The survey is a collaboration between DFO and industry partners, and is completed by commercial fishers, with at-sea observers collecting halibut data and monitoring the fishing (Zwanenburg & Wilson, 2000). The survey has occurred annually since 1998, between May and July (DFO, 2018a), and utilizes a fixed station design, with stations assigned to three strata based on commercial catch rates from 1995 to 1997 (Zwanenburg & Wilson, 2000). To match the survey to commercial practices, survey protocol was defined as longline gear with ~1,000 circle hooks size 14 or greater affixed via gangions, and soak times between 6 and 12 hr (Zwanenburg & Wilson, 2000). We used all survey data from 1998 to 2016 from NAFO divisions 3NOPs4VWX, as 5Zc was data deficient. This included on average 210.4 (±7.1) stations fished per year, with 947.5 (±1.3) hooks and 8.5 (±1.3) hr soak time.

2.2 Bycatch identification

Certified fisheries observers recorded weight and number of individuals of each species caught in each longline set. While weight was recorded consistently, number of individuals was sometimes missing; thus, we only used weight data for trend analysis. Because of halibut's large size (maximum 320 kg; http://www.fishbase.ca/; survey average 14.27 ± 0.19 kg), we also analyzed bycatch species composition and proportion by number of individuals, as this can provide information for smaller species which may otherwise go unnoticed. All halibut were included in halibut catch, including those below commercial size limits. All identified species were considered separately, except a few species merged under one name if a record was likely mislabeled (Table 1). We also reviewed the reported distribution of infrequently captured species in FishBase (http://www.fishbase.ca/) to ensure that they inhabit the survey area. All species were queried against the SARA registry (http://www.registrelep-sararegistry.gc.ca/sar/index/default_e.cfm) to determine if they were listed under SARA or assessed by COSEWIC and thus of conservation concern. We also checked their status under the International Union for Conservation of Nature (IUCN, https://www.iucnredlist.org/) to determine their conservation concern more broadly.

2.3 Proportion of bycatch

We calculated the total weight (kg) and total number of individuals of each species caught in the surveys from 1998 to 2016 across all NAFO divisions. Data were summed to derive total catch (including halibut) and total bycatch (excluding halibut). The proportion of the total catch consisting of halibut and each bycatch species was determined by weight and by number. All data processing and analyses were done in R (R version 3.2.1, R Core Team, 2016).

2.4 Temporal trends

Because surveys only occurred from May to July (DFO, 2018a), no seasonal analysis was possible so we focused on annual trends. To have sufficient data, trends were analyzed for weight (see above) and only for species contributing >5% of the total catch by weight. Survey data were
| Common name | Latin name | SARA | COSEWIC | IUCN | Total weight (kg) | Total number |
|-------------|------------|------|---------|------|------------------|--------------|
| Threatened species | | | | | | |
| Northern wolffish | Anarhichas denticulatus | T | T | | 6,704 | 341 |
| Spotted wolffish | Anarhichas minor | T | T | | 1,673 | 222 |
| Atlantic/striped wolffish | Anarhichas lupus | SC | SC | | 6,940 | 792 |
| Atlantic cod | Gadus morhua | SC | E | VU | 90,113 | 20,564 |
| Cusk | Brosme brosme | E | | | 45,972 | 9,030 |
| Porbeagle shark | Lamna nasus | E | | VU | 2,272 | 34 |
| Roundnose grenadier | Coryphaenoides rupestris | E | | CR | 19 | 10 |
| Smooth skate | Malacoraja senta | E | | EN | 946 | 281 |
| Winter skate | Leucoraja ocellata | E | | EN | 20,499 | 4,528 |
| American eel | Anguilla rostrata | T | | EN | 16 | 19 |
| American plaice | Hippoglossoides platessoides | T | | | 1875 | 1,189 |
| Redfish | Sebastes fasciatus | T | | EN | 506 | 196 |
| White hake | Urophycis tenuis | T | | | 125,881 | 24,169 |
| Basking shark | Cetorhinus maximus | SC | | VU | 800 | 1 |
| Roughhead grenadier | Macrourus berglax | SC | | | 121 | 59 |
| Shortfin mako | Isurus oxyrinchus | SC | | VU | 1,316 | 22 |
| Spiny dogfish | Squalus acanthias | SC | | VU | 228,307 | 60,073 |
| Thorny skate | Amblyraja radiata | SC | | VU | 76,193 | 7,611 |
| Finfish | | | | | | |
| Greenland halibut | Reinhardtius hippoglossoides | | | | 5,405 | 933 |
| Winter flounder | Pseudopleuronectes americanus | | | | 108 | 65 |
| Witch flounder | Glyptocephalus cynoglossus | | | | 24 | 17 |
| Yellowtail flounder | Pleuronectes ferrugineus | | | VU | 15 | 6 |
| Turbot | Scophthalmus maximus | | | | 4 | 1 |
| Greenland cod | Gadus ogac | | | | 24 | 15 |
| Atlantic tomcod | Microgadus tomcod | | | | 13 | 4 |
| Haddock | Melanogrammus aeglefinus | | | LC | 11,822 | 3,649 |
| Pollock | Pollachius pollachius | | | LC | 2,657 | 791 |
| Blue antimora | Antimora rostrata | | | | 1 | 2 |
| Hake sp. | Urophycis sp. | | | | 540 | 3 |
| Red hake | Urophycis chuss | | | | 444 | 326 |
| Longfin hake | Physic chesteri | | | | 2 | 2 |
| Offshore hake | Merluccius albidos | | | LC | 204 | 87 |
| Silver hake | Merluccius bilinearis | | | NT | 333 | 65 |
| Blackbelly rosefish | Helicolenus dactylopterus | | | LC | 1 | 2 |
| Grenadier sp. | Macrouridae | | | | 519 | 213 |
| Longnose grenadier | Coelorhynchus carminatus | | | | 5 | 1 |
| Marlin-spine grenadier | Nezumia bairdii | | | | 27 | 3 |
| Roughnose grenadier | Trachyrincus murrayi | | | | 35 | 9 |
| Wolffish sp. | Anarhichas sp. | | | | 180 | 30 |
| Sculpin sp./Sculpin (NS)* | Myxocelphalus sp. | | | | 43 | 22 |
| Longhorn sculpin | Myxocelphalus octodecemspinus | | | | 100 | 45 |
| Shorthorn sculpin | Myxocelphalus scorpius | | | LC | 22 | NA |
| Twohorn sculpin | Icelus bicornis | | | | 2 | 3 |
| Conger eel/Eel Conger* | Congridae | | | LC | 35 | 32 |
| Ariosoma congrid eel | Ariosoma sp. | | | | 9 | 7 |
| Cusk eels | Ophidiidae | | | | 4 | 0 |
| Atlantic eelpout | Lycodes atlanticus | | | | 71 | 6 |
| Laval's eelpout | Lycodes lavalaei | | | | 2 | 1 |
| Common name          | Latin name                  | SARA | COSEWIC | IUCN | Total weight (kg) | Total number |
|----------------------|-----------------------------|------|---------|------|------------------|--------------|
| Common ocean pout    | Zoarces americanus          | 59   |         |      | 6                | 6            |
| Wrymouth             | Cryptacanthodes maculatus   | 136  |         | 23   |                  |              |
| Lumpfish             | Cyclopteridae               | 3    |         | 1    |                  |              |
| Monk–Goose/Anglerfish| Lophiidae                   | 846  |         | 181  |                  |              |
| Northern stone       | Synanceiidae                | 37   |         | 17   |                  |              |
| Sea raven            | Hemitripteridae             | 336  |         | 205  |                  |              |
| Tile fish            | Malacanthidae               | 41   |         | 4    |                  |              |
| Northern hagfish     | Myxine glutinosa            | LC   |         | 5    |                  |              |
| Eel sp.              |                             | 13   |         | 3    |                  |              |
| Dolphin fish         | Coryphaena hippurus         | LC   |         | 1    |                  |              |
| Atlantic herring     | Clupea harengus             | LC   |         | 2    |                  |              |
| Unidentified fish    | NA                          | 2    |         | 2    |                  |              |
| Elasmobranchs        |                             |      |         |      |                  |              |
| Greenland shark      | Somniosus microcephalus     | NT   |         |      | 12,942           | 42           |
| Blue shark           | Prionace glauca             | NT   |         |      | 6,063            | 127          |
| Black dogfish        | Centroscyllium facricii     | LC   |         | 1,014|                  |              |
| Skate sp.            | Rajidae                     |      |         |      | 3,097            | 957          |
| Arctic skate         | Amblyraja hyperborea        | LC   |         | 1    |                  |              |
| Jensen's skate       | Amblyraja jenseni           | LC   |         | 4    |                  |              |
| Barndoor skate       | Dipturus laevis             | EN   |         |      | 66,293           | 3,830        |
| Little skate         | Leucoraja erinacea          | NT   |         | 115  |                  |              |
| Round skate          | Rajella fylae               | LC   |         | 8    |                  |              |
| Spiny tail skate     | Bothyraja spinicauda        | NT   |         | 19   |                  |              |
| White skate          | Rostroclara alba            | EN   |         | 5    |                  |              |
| Smalleyed rabbitfish | Hydrologus affinis          | LC   |         | 0    |                  |              |
| Invertebrates        |                             |      |         |      |                  |              |
| American lobster     | Homarus americanus          | LC   |         |      | 606              | 193          |
| Snow crab            | Chinoecetes opilio          |      |         |      | 293              | 246          |
| Atlantic rock crab   | Cancer irroratus            | 3    |         | 3    |                  |              |
| Jonah crab           | Cancer borealis             | 50   |         | 52   |                  |              |
| Deep sea red crab    | Chaceon quinquedens         |      |         |      | 13               | 13           |
| Arctic lyre crab     | Hyas coarctatus             | 1    |         | 1    |                  |              |
| Toad crab            | Hyas araneus                | 4    |         | 1    |                  |              |
| Spiny crab           | Lithodes maia               | 2    |         | 1    |                  |              |
| Hermit crab/Paguroidea | Paguroidea                | 3    |         | 3    |                  |              |
| Barnacles            | Cirripedia                  | 4    |         | 5    |                  |              |
| Sea urchin sp.       | Echnioida                   |      |         |      | 3                | 0            |
| Green sea urchin     | Strongylocentrotus droebachiensis | 2 |         | 2    |                  |              |
| Sea cucumbers        | Cucumaria frondosa          | 6    |         | 2    |                  |              |
| Basket star          | Euryalina                   | 9    |         | NA   |                  |              |
| Basket stars         | Gorgonocephalus sp.         | 2    |         | 3    |                  |              |
| Sea stars            | Asteroidea                  | 56   |         | 13   |                  |              |
| Sea stars            | Asterias sp.                | 5    |         | 6    |                  |              |
| Sun star             | Crossaster papposus         | 2    |         | 0    |                  |              |
| Molluscs             | Mollusca                    | 5    |         | NA   |                  |              |
| Iceland scallop      | Chlamys islandica           | 3    |         | 2    |                  |              |
| Sea scallop          | Placopecten magellanicus    | 27   |         | 28   |                  |              |
| Snails and slugs     | Gastropoda                  | 10   |         | 5    |                  |              |
| Conch                | Strombidae                  | 1    |         | 4    |                  |              |
| Whelk                | Buccinidae                  | 84   |         | 1    |                  |              |
| Bubble gum coral     | Paragorgia arborea          | 7    |         | NA   |                  |              |
| Red trees            | Primnoa resedaeformis       | 5    |         | NA   |                  |              |
standardized by survey effort to derive weight (kg) per 1,000 hooks and 10 hr of soak time. We used boxplots to visualize temporal trends of standardized weight of (a) halibut catch, (b) total bycatch, and (c) species of conservation concern for NAFO regions 4X, 4W, 4V, 3P, 3O and 3N to relate our results to general management areas.

Trends in bycatch rates over time, with NAFO region as a factor, were analyzed using a two-stage gamma (“hurdle”) model in R. We chose this generalized linear model (GLM) due to the zero-inflation in our data, coupled with a continuous distribution (weight). NAFO region was a categorical and time a continuous explanatory variable. The first stage modeled the probability of the presence (nonzero) compared to the absence (zero) of catch using a GLM with a binomial distribution and a logit link function. The second stage modeled the catch data only, using a GLM with a gamma distribution and a log link function. Residuals were checked to ensure that model assumptions were met. NAFO division 4X was used as the reference (contrast) level in the GLMs, as it had the most consistent data over time for all analyzed species. We used a Type I error rate of 5% throughout.

### 2.5 Spatial patterns

Bycatch across the Scotian Shelf and Southern Grand Banks was mapped using the R package SpatialHub v1.0 (Hubley, 2017). Maps were produced for the average standardized weight (kg per 1,000 hooks and 10 hr soak time) across the survey period from 1998 to 2016 for (a) halibut catch, (b) total bycatch, (c) bycatch of species of conservation concern that contributed >5% of the total catch by weight, and (d) additional SARA-listed species. A grid cell size of 25 km² was chosen for mapping, as it effectively displayed the spatial patterns.

### 3 RESULTS

#### 3.1 Species composition

A total of 110 species, 142,670 individuals, and 737,411 kg were reported as bycatch in the survey between 1998 and 2016 (Table 1). This included 63,381 finfish from 52 species, 61,313 sharks from 8 species, 17,359 skates from 11 species, 589 invertebrates from 30 species, 25 seabirds from 7 species, and three marine mammals. Of conservation concern were four SARA- and 14 COSEWIC-assessed species (Table 1), which together accounted for 129,141 individuals and 610,153 kg. Most of these species were also listed by IUCN (Table 1). The bycatch also included commercial invertebrate species, such as American lobster (Homarus americanus) and Jonah crab (Cancer borealis) (Table 1).

#### 3.2 Proportion of bycatch

From 1998 to 2016, 70% of the survey catch by weight and 85% by number of individuals was bycatch. By weight, spiny dogfish (Squalus acanthias), white hake (Urophycis tenuis), Atlantic cod (Gadus morhua), thorny skate (Amblyraja radiata), and banded skate (Dipturus laevis) each contributed to >5% of the total catch, with the remaining less common species making up 15% of the total catch (Figure 2a). By number, spiny dogfish contributed a twofold greater proportion of the total catch than halibut (Figure 2b), Atlantic cod and white hake were caught at nearly equal

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**Note.** Those marked with a * have been merged under a common name. Species are first ordered by threat status under SARA and COSEWIC, respectively ([http://www.registrelep-sararegistry.gc.ca/sar/index/default_e.cfm](http://www.registrelep-sararegistry.gc.ca/sar/index/default_e.cfm)) as E: endangered, T: threatened; SC: special concern, and afterwards by taxonomic group. We also indicate the IUCN ([https://www.iucnredlist.org/](https://www.iucnredlist.org/)) status of all species as CR: critically endangered; EN: endangered; LC: least concern; NT: near threatened; VU: vulnerable.
proportions as halibut, followed by cusk (*Brosme brosme*), and all remaining species made up 18% (Figure 2b).

### 3.3 Temporal trends

The standardized weight (i.e., kg per 1,000 hooks and 10 hr fishing) of halibut catches generally increased across the region from 1998 to 2016 (Figure 3). GLMs indicated that both the probability of the presence of halibut catch over no catch (Stage 1, referred to as presence hereafter) and the standardized weight (Stage 2) significantly increased over time (Year effects, $p < 0.01$, Table S1, Supporting information). NAFO regions 4W, 4V, and 3O had significantly higher halibut presence than 4X (the designated reference region; Stage 1, Region effects, $p < 0.01$) and significant year-by-region interactions suggested lesser rates of increases in these regions over time (Stage 1, Interactions, all $p < 0.05$). There were no region or interaction effects on weight (Stage 2).

Total bycatch was relatively stable in NAFO regions 4X, 4W, and 4V with some fluctuations in 3P, 3O, and 3N (Figure 3). GLMs indicated that total bycatch presence significantly increased while weight decreased over time with some year-by-region interactions (Table S1). Bycatch presence showed significant increases over time with no year-by-region interaction (Table S1). The presence was significantly higher in 4V and lower in 4W, 4V, and 3O, with negative interaction coefficients in 4W (stronger decline) and positive ones (increases) in 4V, 3P, and 3O. The weight was significantly lower in 4W, 4V, and 3O and significantly positive interaction coefficients suggested faster increases over time.

White hake had high bycatch in all NAFO regions except 3N (Figure 3). Both white hake presence and weight showed significant decreases over time with some year-by-region interactions (Table S1). The presence was significantly lower in 4W and the positive interaction coefficient suggested a greater rate of increase than in 4X. The weight was significantly lower in 4W, 4V, and 3P and positive interaction coefficients suggested increases in these regions.

Thorny skate bycatch occurred in all NAFO divisions (Figure 3). Both presence and weight showed significant decreases over time with some year-by-region interactions (Table S1). The presence was significantly lower in 4W and the positive interaction coefficient suggested an increase.

Barndoor skate bycatch was concentrated in NAFO divisions 4X, 4W, and 4V (Figure 3). The presence of bycatch showed significant increases over time with no year-by-region interaction (Table S1). The weight showed no significant year effect, but 4W had significantly less bycatch and a positive interaction coefficient suggesting an increase over time.
3.4 Spatial patterns

From 1998 to 2016, the average standardized halibut catch was highest (>100 kg per 1,000 hooks and 10 hr fishing) along the continental shelf edge of the Southern Grand Banks (Figure 4). Other areas with high halibut catch included the northern tip of Nova Scotia and the central and southern portion of the Scotian Shelf. Bycatch occurred throughout the region (Figure 4), with some hotspots of >250 kg per 1,000 hooks and 10 hr fishing on the southern Scotian Shelf and the continental shelf edge of the Southern Grand Banks, overlapping with high halibut catches.

Bycatch of species of conservation concern was not evenly distributed. Spiny dogfish bycatch was concentrated on the Scotian Shelf, particularly its southern portion (Figure 5). Atlantic cod had higher bycatch concentrations on the Southern Grand Banks (Figure 5). Similarly, white hake and thorny skate (Figure 5) had highest bycatch concentrations on the Southern Grand Banks, while barndoor skates were caught primarily on the Scotian Shelf (Figure 5). We also mapped additional SARA-listed species. Northern and Atlantic wolffish bycatch was concentrated along the continental shelf, each with one grid cell on the Southern Grand Banks with particularly high...
Bycatch of spotted wolffish was restricted to very few grid cells on the Scotian Shelf and concentrated with >50 kg per 1,000 hooks and 10 hr fishing in one grid cell (Figure 5). Checking with the original survey data revealed that spotted wolffish bycatch was consistent over the study period, while Northern and Atlantic wolffish bycatch had a few occasions of high catch levels.

4 | DISCUSSION

Our study aimed to evaluate the species composition, proportion, temporal and spatial trends in the bycatch of the halibut longline fishery on the Scotian Shelf and Southern Grand Banks, with a focus on species of conservation concern. We used annual longline survey data from 1998 to 2016 which provide indices of abundance and distribution for species caught in the halibut longline fishery. Bycatch in the survey was high, accounting for 70% of the total catch by weight and 85% by number of individuals from 1998 to 2016. As well, several species of conservation concern made up substantial proportions of this bycatch. Temporal trends indicate declines in many species over time, while halibut catches increased. Regions of particularly high bycatch rates included the southern portion of the Scotian Shelf and southern edge of the Southern Grand Banks, coinciding with high halibut catch rates. Our results can help inform fisheries management and marine conservation to reduce overall bycatch levels and bycatch of threatened species.
4.1 | Species composition

More than 100 species from many taxonomic groups and trophic levels were present in the bycatch of Longline fisheries. Longline fisheries have long been recognized to incidentally catch a wide variety of species due to their relatively unselective gear (Anderson et al., 2011; Hammer et al., 2012; Lewison

FIGURE 5  Average standardized weight (kg per 1,000 hooks and 10 hr soak time) per 25 km² grid cell of spiny dogfish, white hake, Atlantic cod, thorny skate, barndoor skate, northern wolffish, Atlantic wolffish, and spotted wolffish from 1998 to 2016 across the Scotian shelf and southern grand banks based on the longline fishery survey data. The dashed line indicates the Canadian Exclusive Economic Zone and purple lines the depth contours; see Figure 1 for location names and NAFO areas.
et al., 2004); thus, it is unsurprising that sharks, skates, finfish, seabirds, marine mammals, and benthic invertebrates were observed. Some species were regularly caught, suggesting relatively high abundance, overlapping distribution or high catchability, while others were only occasionally caught.

Among the bycaught species, fish were the most common taxa identified. Certain species, such as some sharks, are more likely to be caught in pelagic or bottom longline than in trawl or purse seine fisheries (Chuenpagdee, Morgan, Maxwell, Norse, & Pauly, 2003; Gavaris, Clark, Hanke, Purchase, & Gale, 2010). Spiny dogfish, assessed as special concern by COSEWIC and as vulnerable and decreasing by IUCN, was the most frequently caught small shark. Similar concerns by COSEWIC and as vulnerable and decreasing by IUCN, was the most frequently caught small shark.

Bycatch of SARA-listed or COSEWIC-assessed species is of particular conservation concern, and many of these species have also been identified to be of conservation concern by IUCN. The three SARA-listed wolffish species prefer similar deep-water habitat on continental shelves as halibut; so, it is unsurprising that wolffish are halibut bycatch (Carnegielli, Griesbach, & Morse, 1999; DFO, 2013a). Both SARA and COSEWIC identify bycatch mortality as the primary threat to these wolffish species (DFO, 2013a), which also includes bycatch in trawl fisheries (Gavaris et al., 2010; Grant, Hiscok, & Brett, 2005), thus bycatch must be minimized to avoid further population declines. Current efforts detailed in SARA’s wolffish management plans in Atlantic Canada include safe release practices of bycaught individuals, educational programs, further research into their life-history, and development of strategies to minimize human impact, including bycatch (DFO, 2013a). In contrast, COSEWIC-assessed species have little to no policy implications or related government responsibility (Mooers, Prugh, Festa-Bianchet, & Hutchings, 2007). The halibut bycatch included another 14 COSEWIC-assessed and 14 IUCN-listed species (Table 1), which can be as imperiled but may not be included under SARA due to uncertainty or economic concerns (Mooers et al., 2007). The endangered cusk and porbeagle shark have not been listed under SARA due to potential negative effects on directed fisheries (Powles, 2011), although the porbeagle is currently under review (DFO, 2018b). COSEWIC-assessed and IUCN-listed species still require management strategies to minimize bycatch to safeguard their populations from further declines.

Seabirds and marine mammals are also commonly caught in longline fisheries worldwide while attempting to feed on the bait or caught fish (Anderson et al., 2011; Hammer et al., 2012; Lewison et al., 2004). The halibut survey bycatch included seven seabird species, such as Northwestern gannets (Morus bassanus), but in low numbers as in the commercial halibut longline fishery (Mateo et al., 2018). Similarly, few marine mammals were caught in the halibut survey, specifically unidentified seals. Still, these findings remain noteworthy as the commercial halibut fishery may have an order of magnitude higher catches than the survey (DFO, 2018a). Various benthic invertebrates were identified in the bycatch, including commercially important lobster and crabs and species providing three-dimensional habitat, namely sponges. Weighted longlines are known to accidentally catch benthic invertebrates while actively pursuing the bait or being passively caught by moving lines (Munoz et al., 2011).

### 4.2 Proportion of bycatch

Between 1998 and 2016, 70% of the total catch by weight and 85% by number of individuals constituted bycatch in the halibut survey. High bycatch levels are not uncommon in commercial fisheries; in pelagic swordfish and tuna fisheries, bycatch can be >80% of total catch by number of individuals, often with high numbers of sharks (Cosandey-Godin et al., 2013). In bottom-trawl fisheries for groundfish or shrimp bycatch can be 22.7–83.9% of total catch (Davies et al., 2009).

Importantly, all bycatch species contributing >5% of the total catch by number or weight, except the barndoor skate, have been assessed by COSEWIC and are either waiting for a SARA listing decision or were not listed due to economic factors. Of these, spiny dogfish, the most common bycatch species, is often discarded (Martell et al., 2013), whereas Atlantic cod, white hake, and cusk are often landed (Themelis & den Heyer, 2015). That is, there is no legal obligation to protect COSEWIC assessed species.

Moreover, all species contributing >5% of the total catch by number or weight in the halibut survey, as well as several sharks, skates, and other species, have also been identified as high-bycatch species in other groundfish fisheries on the Scotian Shelf (Gavaris et al., 2010). This suggests that consistent bycatch assessments across all fisheries in Atlantic Canada are needed to determine overall bycatch levels for all species, including mortality or post-release survival (Gavaris et al., 2010), to be used in fisheries management and conservation planning to set bycatch quotas and inform release practices.

Bycatch can be quantified in terms of weight or number of individuals (Keledjian et al., 2014). In fisheries where the weight of target and bycatch species are comparable, both metrics should reveal similar results. However, halibut's large size may mask the magnitude of bycatch of most other smaller species, such as cod (maximum 16.5 kg; average-survey 9.1 kg), spiny dogfish (maximum 9.1 kg; average-survey 3.2 kg) or Northern wolffish (maximum 20.0 kg;
average-survey 8.8 kg) when looking at weight. In the halibut survey, despite numbers being less consistently well recorded, bycatch levels were still greater by number (85%) than weight (70%), and some species, such as cusk (30 kg; 9.1 kg) contributed >5% of total catch only by number, not weight. Despite their relatively small size, thorny (11.4 kg; 3.2 kg) and barndoor skate (18 kg; 9.1 kg) each contributed >5% of total catch by weight but not number, which may highlight the above-mentioned issue of inconsistent counts compared to more reliable weight estimates. Having consistent counts as well as individual size estimates in the survey data would be highly valuable to assess the number of individuals being affected as bycatch, particularly for endangered species, and the potential effect of gear modifications, such as more selective larger hooks targeting larger halibut but fewer smaller species.

4.3 | Temporal trends

The halibut population has increased on the Scotian Shelf and Southern Grand Banks over time (den Heyer et al., 2015; DFO, 2018a; Trzcinski & Bowen, 2016), which is reflected in survey catch records (Figure 3) and is expected to continue due to recent high recruitment levels (den Heyer et al., 2015; Shackell, Frank, Nye, & den Heyer, 2016). This has led to TAC increases from 1855 kg in 1998 to 3,149 kg in 2016 (DFO, 2018a). With proportionally more abundant halibut, there could be lower bycatch levels; however, with increasing TAC and fishing effort, even if the proportion of bycatch decreases, its weight or number of individuals may still increase. This may pose more threat on already endangered or threatened species and may require stronger actions to reduce bycatch.

From 1998 to 2016, the total bycatch rate in the halibut fishery has generally decreased across the region, with some increases in NAFO areas 4W, 4V, and 3O (Figure 3). Given the low average number of halibut (11.25 ± 0.28) and bycaught individuals (29.76 ± 1.94) caught per 1,000 hooks and 10 hr soak time, this decrease in total bycatch is likely not a function of hook competition with increasing halibut abundance, but instead reflects changes in the abundance of bycaught species or their catchability through shifts in size (e.g., smaller individuals may not be caught by longline gear aimed at larger species and individuals) or distribution. Most bycatch species have experienced population declines in the study region (ECC 2017); thus, decreasing trends are consistent with other survey and fisheries data. If conservation efforts would successfully aid the recovery of these species, bycatch rates in the halibut fishery could rise again. One such example is spiny dogfish. Until 2002, its fishery on the Scotian Shelf was unregulated before regulations were implemented due to dramatic population declines (DFO 2014), which is reflected in the survey data (Figure 3). Spiny dogfish has since begun to recover (DFO 2014), also reflected in the recent increasing bycatch in NAFO division 4X (Figure 3).

Cod populations continued to decline, following the collapses in the early 1990s (Mohn & Rowe, 2011). This decline is reflected in the overall survey data trends (Figure 3) and cod's listing by SARA and COSEWIC (Table 1); however, we also found some recent increases in the amount of cod caught in 4V and 3O (Stage 2), while its presence decreased (Stage 1). It has been suggested that overall bycatch of Atlantic cod in all fisheries is negligible in NAFO divisions 4W and 4V, and thus unlikely to affect the population's recovery potential (Mohn & Rowe, 2011).

White hake has also experienced population declines across the region (COSEWIC, 2013), which is reflected in the overall survey data trends (Figure 3) and its COSEWIC listing. Our data also suggest some recent increases in bycatch rates in 4W, 4V, and 3P which could be due to a change in distribution, catchability or abundance. The Scotian Shelf population is extremely low, with no directed fishery and only bycaught individuals can be landed; however, a directed fishery operates on the Southern Grand Banks (COSEWIC, 2013). Thorny skates have declined by 82% since 1970 on the Scotian Shelf, leading to their COSEWIC special concern listing (COSEWIC, 2012). This general decline is also observed in our survey data (Figure 3), except a recent increase in the amount caught in 3N. The only bycaught species showing a general increase in presence across the region, and some increase in bycatch amount in 4W, was barndoor skate (Figure 3), consistent with results of a DFO summer research survey on the Scotian Shelf showing increases since 1996 (COSEWIC, 2010).

Overall, these temporal results provide information on the status and trend of bycatch species in the halibut longline fishery and can be used to inform COSEWIC and SARA assessments as well as fisheries management (e.g., bycatch quotas) and recovery planning.

4.4 | Spatial patterns

The spatial patterns of halibut catch and total bycatch in the survey data were similar, with high levels along the continental shelf edge of the Southern Grand Banks and Scotian Shelf, and on the southern and parts of the central Scotian Shelf, which is comparable to patterns of the commercial halibut catch (Figure 1b; French et al., 2018). Given the spatial overlap between the commercial longline fishery and survey (Figure 1b), as well as similar fishing gear (e.g., hook size, number of hooks per line) and practices (e.g., soak times; see Zwanenburg & Wilson, 2000) used to ensure the same selectivity, bycatch rates should be comparable. However, overall bycatch levels would be higher in the more intense commercial fishery. Notably, spatial bycatch patterns differed among species of conservation concern, which could inform zoning in the halibut and other fisheries. Such spatial information is urgently needed to inform recovery
strategies for threatened species (DFO, 2013a) and MSC certification (Mateo et al., 2018) and core areas for inclusion in marine protected area (MPA) planning (Horsman & Shackell, 2009; Shackell, Frank, & Brickman, 2005).

Bycatch of spiny dogfish was concentrated on the Southern Scotian Shelf (Figure 5), which is where sexually mature and pregnant females migrate during the summer (Campana, Joyce, & Kulka, 2009). To aid this species’ recovery, spatial zoning could reduce fishing effort in, or close some of these high bycatch areas. White hake, Atlantic cod and thorny skate bycatch occurred throughout the six NAFO divisions but concentrated on the Southern Grand Banks (Figure 5), where similar measures of spatial zoning could be considered to aid these species’ recovery. Conversely, barndoor skates were caught primarily on the Scotian Shelf, where certain grid cells of high bycatch along the continental shelf offer potential for spatial zoning (Figure 5).

Bycatch of SARA-listed Northern and Atlantic wolffish was concentrated along the continental shelf, each with one particularly high 25 km²-grid cell on the Southern Grand Banks (Figure 5), whereas most spotted wolffish bycatch was found in one 25 km²-grid cell on the Scotian Shelf (Figure 5). Generally Northern and Atlantic wolffish bycatch was less consistent than spotted wolffish over time and space, so their results should be used with caution. In their recovery strategy for wolffish species, DFO called for studies into the spatial distribution of human impacts (DFO, 2013a). Our maps provide such information and could inform spatial zoning strategies to aid wolffish recovery.

The feasibility of implementing spatial zoning likely depends on whether or how much any exclusion zones would affect the commercial halibut or other fisheries. Based on the halibut survey (Figure 4) and commercial (Figure 1b) catch maps, excluding some high-bycatch areas for Northern or spotted wolffish may not severely affect overall halibut catches yet help these species’ recovery (DFO, 2013a). For other species of conservation concern with larger high-bycatch areas spatial zoning could have greater impacts on the fishery, although smaller well-chosen exclusion areas could help some threatened species and contribute to the sustainability and MSC-certification of the halibut fishery. Ideally, a spatial bycatch analysis across all commercial fisheries in Atlantic Canada could identify core areas of species of conservation concern (Horsman & Shackell, 2009; Shackell et al., 2005) to inform spatial zoning with maximum benefit to threatened species and minimum impact on commercial fisheries.

4.5 Limitations and conclusions

One limitation of the halibut longline survey is its seasonal restriction (May–July); thus, all results and associated recommendations only reflect this time of year. However, although the commercial halibut fishery operates year-round, most fishing takes place from May to July, with some increases from January to May since 2010 (Themelis & den Heyer, 2015). Year-round observer data from the commercial fishery, although with limited and variable coverage (Mateo et al., 2018; Themelis & den Heyer, 2015), could also be mapped to identify high-bycatch areas and inform managers on whether seasonal closures, or a shift in the main fishing season could help avoid bycatch of certain species or high bycatch levels.

Understanding the impact of the halibut longline fishery on threatened species in the marine ecosystem is important, as the fishery is MSC certified, thereby marketed as having minimal impact on the environment (Bush et al., 2013). As bycatch is a major threat to SARA-listed wolffish species (DFO, 2013a), reducing bycatch levels in the halibut and other fisheries is critically important. Our spatial analyses could inform fisheries management to avoid high-bycatch regions of species of conservation concern, and may be particularly valuable for wolffish, cusk, and other species that are not well sampled by the DFO research vessel trawl survey (Horsman & Shackell, 2009). Importantly, we recommend consistent bycatch assessments across all commercial fisheries to determine the spatial overlap of high bycatch areas for threatened species across all fleets (Gavaris et al., 2010). Finally, our results can inform COSEWIC and SARA assessments and recovery strategies for threatened species, such as setting bycatch quotas, promoting more selective gear, improving release practices and identifying core areas for protection. This would address key objectives in The Policy on Managing Bycatch in Canada, including the decrease of both retained and discarded bycatch species, and the development of techniques to avoid bycatch (DFO, 2013b).

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