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From policy to practice: Addressing bycatch for marine species-at-risk in Canada

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ABSTRACT

Unintended bycatch of depleted or vulnerable marine species is an unsolved conservation issue that undermines the sustainability of fisheries worldwide. In Canada, policy incentives to address bycatch of vulnerable species-at-risk have become more prominent in recent years. Yet bycatch risk has been difficult to quantify and mitigate, in part due to large data gaps in fisheries observation and monitoring. Here we suggest the use of novel modelling frameworks to optimize spatial management strategies for bycatch mitigation. We utilize spatiotemporal modeling of fisheries-independent survey data to predict high-risk regions for three at-risk skates (family Rajidae) in Atlantic Canada. We use these identified regions to evaluate the relative reduction in bycatch risk that can be expected by closing targeted bycatch-protection zones on the western Scotian Shelf to bottom-trawl fishing, and further examine the relative costs to the fishing industry that such closures may impose. We show that when closures are precisely targeted on high-bycatch risk areas, relative costs to industry are minimal by affected fishing area (1.25 ± 0.62 % total area) or displaced landings (0.28 ± 0.14 % by weight of catch). To reduce bycatch risk by 50 % for all three vulnerable skates, less than 10 % of landed catch weight is displaced. These results can be used to reduce bycatch encounters for any endangered, threatened or protected species through spatially targeted conservation measures. We conclude that new approaches to the analysis and mitigation of spatial-temporal bycatch patterns can help to meet regulatory or market-driven requirements for bycatch reduction at low cost.

1. Introduction

Bycatch, or the unintended catch of a non-target species, is a ubiquitous and deleterious occurrence in global fisheries [1-5]. It is a significant driver of overexploitation for many species, impedes the recovery of vulnerable marine populations [6], and can impact the health and resilience of marine ecosystems [7]. For many fisheries that employ non-selective gear such as trawls and long-lines, bycatch can comprise a significant fraction of the total catch [8-10,5,11]. While a single species may represent a small fraction of the total bycatch in a fishery, this can impose disproportionately greater impacts on the species in question if it is heavily depleted or endangered, as small populations of marine fishes are less resilient to additional mortality [12]. Most marine species are not distributed evenly throughout regional seascapes but concentrate in core habitats [13]. High bycatch rates in such habitats can give the false impression of an abundant population, an established phenomenon known as 'hyperstability' [14]. High fishing mortality can also erode the predictable spatial structure of a population and bring about unknown and adverse changes to abundance and resilience of the stock [15-17].

Regulatory bodies are increasingly aiming to address bycatch, often in response to a legal mandate to rebuild endangered, threatened and protected species' populations [18,19]. In addition to such regulatory pressure, many commercial fisheries are further incentivized to reduce bycatch and other environmental impacts by eco-certification bodies such as the Marine Stewardship Council (MSC). Economic incentives for bycatch avoidance have steadily grown in the fisheries marketplace as consumers become more socially conscious [20], and such pressure can help drive management reforms [21]. Elasmobranchs (including sharks, skates and rays) are often highlighted as key species of concern in regard to fisheries bycatch due to their slow life history traits that limit population resilience, including late maturity and low fecundity [8,22-24].

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Canada, as a country surrounded by three oceans, has a long history of commercial fishing. Over time, Canadian fish stocks have experienced substantial declines on both coasts [25], and in the 1990 s the collapse of northwest Atlantic cod stocks resulted in harvest moratoria for groundfish across much of the region [26]. However, fishing mortality likely continues to affect the viability of many non-target or vulnerable populations through incidental capture. Target species directly pursued by fisheries in Canada account for on average only about 50 % of total commercial catch in Canada [1], with the remainder composed of numerous bycatch species, which may either be retained or discarded at sea.

In direct response to ongoing bycatch challenges, the Canadian government introduced the Policy for Managing Bycatch [27] under the Sustainable Fisheries Framework, with a goal to address collateral impacts of commercial fishing, including incidental bycatch. This policy tool is intended to guide Fisheries and Oceans Canada (DFO) in developing ecosystem-based fisheries management plans with bycatch mitigation as a priority objective [27]. To date, however, bycatch often remains poorly understood and inadequately addressed in many Integrated Fisheries Management Plans, which guide the management and harvest decisions for marine fisheries in Canada (IFMPs; [1,3]). Particularly for groups of non-target species with little commercial value, a scarcity of at-sea monitoring of discarded bycatch species continues to hinder our understanding of bycatch patterns for species at risk in Canada [28,1,29]. There are no regional standards that govern the amount or spatial extent of fisheries observer coverage or discard monitoring on the east coast of Canada. In many fleets, vessels without an observer aboard are not required to identify non-retained species, recording only the sum weight of discarded catch [29]. These factors lead to many fishing trips, and consequently bycatch encounters, unobserved, and estimates of bycatch mortality remain uncertain [1].

Many non-target species that are impacted by commercial fisheries in Canada have been identified as at-risk by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (https://www.cosewic.ca/index.php/en-ca/). While some efforts are made to protect COSEWIC species, they are typically not receiving concerted conservation action unless listed for federal protection under the Species at Risk Act (SARA). As a result, COSEWIC-assessed species can be easily forgotten during decision-making processes. For example, formalized frameworks are set for the Canadian stock assessment process, which typically include discussion of bycatch issues relevant to a given fishery. These processes are led by the Canadian Science Advisory Secretariat (CSAS), which brings external experts and stakeholders into into the peer review process and organizes science advice for DFO to feed into the management decision-making process [30]. Vulnerable COSEWIC-assessed species are not necessarily afforded any formal consideration in setting the framework for a stock assessment process. Even then, it can take many years for COSEWIC-assessed species to gain status under SARA (Species At Risk Public Registry 2019) and recovery plans, if completed, are often unspecific in their recommendations [31,19,32]. Following amendments made to the Canadian Fisheries Act in 2019, there is now a legal obligation of the Canadian government to enact rebuilding strategies for depleted fish stocks [33]. Although bycatch is not explicitly addressed in the new legislation, there are many non-target groundfish species subject to incidental commercial catch whose populations require decisive action [34].

Presently common strategies to protect vulnerable bycatch species include bycatch quotas, modification of fishing gear or practices, or spatial fisheries closures and marine protected areas (MPAs) [35-37]. It is expected that the implementation of spatial measures to conserve biodiversity will increase in the next decade, as Canada has renewed commitments to protect 30 % of its national waters by 2030 by way of MPAs or other effective area-based conservation measures (OECMs) [38]. In order to meet stated conservation goals, planning should incorporate the best available data on the risks present to a species over space and time. For many non-target, depleted or vulnerable groundfish species on the Scotian Shelf, fisheries-derived data are inadequate for accurate estimations of bycatch risk spatially and over time [29]. Observer coverage within Atlantic Canadian groundfish fleets averages less than 10 % [39], well below the recommended 50 % coverage necessary to derive reliable estimates of bycatch for rare or depleted species [28]. In these cases, the most complete and accurate data, especially for affected groundfish, come from annual scientific bottom trawl surveys.

In this paper, we present a new framework for assessing and conserving vulnerable bycatch species based on existing data. This method is based on the observation that spatial relationships between target and bycatch species have been shown to predict patterns of bycatch interactions [40-43]. In principle, such data can inform spatiotemporal conservation measures, such as closures and MPAs or bycatch quotas, to effectively mitigate bycatch risk of vulnerable species [44,45]. Here we apply such a bycatch risk assessment framework to three vulnerable skate species in need of management attention on the Scotian Shelf, using fisheries-independent data sources. We evaluate the risk reduction generated by closing fractions of the fished region and estimate the costs to the fishing industry that these potential closures might bring about.

Three species of skate (winter skate *Leucoraja ocellata*, thorny skate *Amblyraja radiata*, and smooth skate *Malacoraja senta*) are subject to bycatch in Atlantic Canadian groundfish fleets and have been evaluated as at-risk by COSEWIC (Table 1). Although they have declined in some regions by up to 98 % from historical abundances [46,47], no skate species in Canada has been afforded a proper stock assessment model. Skates on the Scotian Shelf are in dire need of proactive, precautionary management strategies to better inform and mitigate bycatch in commercial fisheries. The approach discussed in this paper addresses this policy gap by utilizing existing scientific survey data to prioritize bycatch mitigation for vulnerable species as part of Canada's marine conservation objectives. These approaches can be used in complement with other sources of information to support siting of MPAs and OECMs

Table 1
Study species and sample sizes. Shown are all species considered in bycatch risk analyses, and their assessment status from the Committee on the Status of Endangered Wildlife in Canada (COSEWIC; by designatable unit, if applicable). CHP represents the cod-haddock-pollock fisheries complex. Number of records with species presence in RV surveys are shown.

SKATES Species		COSEWIC Status	RV Survey Records 2015–2019
Smooth skate	*Malacoraja senta*	Endangered (Funk Island Deep), Special Concern (Laurentian-Scotian)	94
Thorny skate	*Amblyraja radiata*	Special Concern	39
Winter skate	*Leucoraja ocellata*	Endangered (Eastern Scotian Shelf/ Newfoundland), Not at Risk (George's Bank/Western Scotian Shelf)	70
TARGETS **Species or Complex**		**COSEWIC Status**	**RV Survey Records 2015–2019**
Redfish	*Sebastes spp.*	Threatened (*Sebastes fasciatus*)	307
Winter flounder	*Pseudopleuronectes americanus*	Not Assessed	124
CHP			
Atlantic cod	*Gadus morhua*	Endangered	192
Haddock	*Melanogrammus aeglefinus*	Not Assessed	482
Pollock	*Pollachius virens*	Not Assessed	245
		Total Sets	**491**

aimed at protecting marine biodiversity and species-at-risk.

2. Methods

2.1. Study area and species

In late summer every year, DFO conducts a research-vessel (RV) survey by bottom-trawl of the Scotian Shelf and Bay of Fundy to monitor the spatiotemporal abundance of groundfish and other benthic species. Surveys follow a random-stratified sampling design across depths 50–500 m, and each trawl is conducted at a speed of 3 knots for approximately 30 min. The RV survey has been ongoing since 1970, and in 1982 the vessel and net configuration were changed [48]. The present study uses RV survey data from the years 2015–2019 where all sampling protocols were consistent. In 2018, only the western half of the Scotian Shelf was sampled. This corresponded to Northwest Atlantic Fisheries Organization (NAFO) divisions 4X5Z, where the majority of bottom-trawl landings on the Scotian Shelf are caught [10]. Thus, our study area covered the western portion of the Scotian Shelf with an eastern boundary of 63.33°W, extending south to the continental shelf with an approximate area of 97 000 km^2 (Fig. 1).

The groundfish community of the Scotian Shelf and surrounding area has been exploited by commercial fisheries for centuries (Lear 1998). Today, fisheries operate using both fixed (e.g. bottom longlines) and mobile gear types (e.g. bottom trawls) to target groundfish. In the present study, we focus on bottom-trawl fisheries targeting several groundfish species. The majority of bottom-trawl fishing occurs on the western Scotian Shelf corresponding to Northwest Atlantic Fisheries Organization (NAFO) divisions 4×5Zc [10], following the introduction of harvest moratoria on the eastern Scotian Shelf in the 1990s [26]. Most landings from these trawl fisheries are comprised of gadoid fishes, namely cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and pollock (*Pollachius virens*) (sometimes referred to as the “CHP complex”). Other primary targets include redfish (*Sebastes spp.*), silver hake (*Merluccius bilinearis*) and winter flounder (*Pseudopleuronectes americanus*) [49].

Groundfish harvesting by bottom-trawl on the western Scotian Shelf affects a variety of bycatch species (Peacock & Anand 2008), including

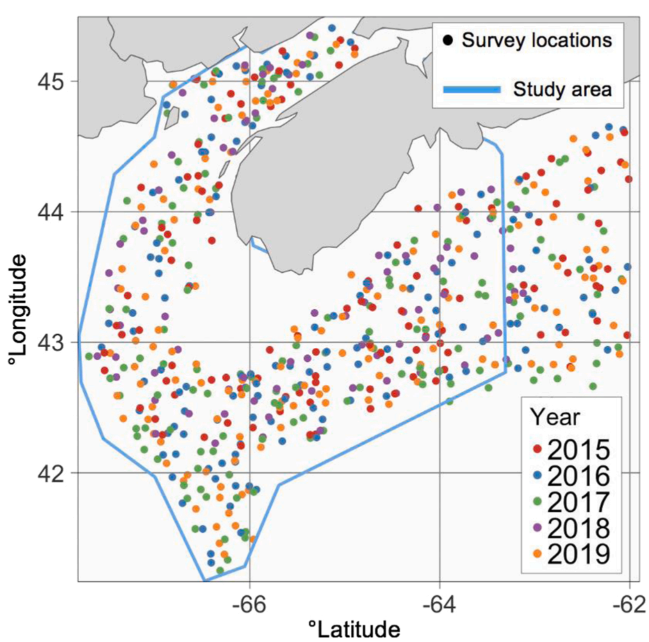

Fig. 1. Study area. Shown are the locations of each Research Vessel survey tow by year, 2015–2019. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

winter, thorny and smooth skates whom COSEWIC has designated as at-risk species (see Table 1 for details). Bycatch of skates in bottom-trawl fisheries is estimated to be high when fleets target the CHP complex, redfish and flatfishes [46,47]. In contrast, the use of separator grates in the silver hake fishery reduces skate bycatch to negligible levels [50]. In this study, we assess the risk of bycatch between vulnerable skates, and 5 primary commercial target species caught by trawl fleets that do not employ gear modifications: redfish, winter flounder, cod, haddock and pollock (Table 1).

2.2. Data

RV survey data from the years 2015–2019 were used in this study. Technicians onboard the RV survey sample the local abundance of all species within the benthic community, and fish species are identified to the genus level at minimum. We considered data from RV surveys for three species of at-risk skate, and 5 commercial target species representing 3 bottom-trawl fisheries (Table 1). RV data was extracted within the bounds of the study area on the western Scotian Shelf (Fig. 1). Variables that were used in analysis include the average latitude and longitude of each tow, as well as presence and total weight caught of each bycatch and target species of interest.

In addition to scientific survey data, we also considered commercial landings of groundfish by bottom trawl fleets, provided by DFO’s Maritime Fisheries Information System (MARFIS) database. We extracted all bottom-trawl groundfish landings by weight in the summer months (June-October, inclusive) within our study area for the years 2015–2019. These months were chosen to best represent the state of the Scotian Shelf during summer RV surveys, and to exclude colder months where species distributions may shift on a seasonal basis [51,52]. The sum total of landings for groundfish in all 5 years was then mapped across the study area on a 0.1°x 0.1° grid.

2.3. Bycatch risk analysis

Bycatch risk for all three skates was calculated within the study area for the years 2015–2019 following the framework from Jubinville et al. [40]. This framework utilizes the overlap of relative species’ distributions to determine areas of co-occurrence between target and non-target species. Where a target species shares high co-occurrence with a non-target species, the potential risk for bycatch of that non-target species is intrinsically greater. Jubinville et al. [40] validated that the relative degree of co-occurrence between target species and non-target skates is predictive of skate presence in observed fishing sets, and that the probability of catching a non-target species increases where bycatch risk, as predicted from fisheries-independent data, is shown to be greater.

Distributions were predicted separately for each species in Table 1 using two-stage generalized linear mixed models (‘hurdle’ models). The first stage modeled species presence (non-zero) versus absence (zero) using a Bernoulli distribution and log link function. The second stage modeled species abundance (log catch-per-unit-effort, logCPUE) from non-zero catches only, using a Gaussian distribution and identity link function. All analyses were conducted using R (version 3.6.3, R Core Team 2020). Models were fit using the R package *staRVe* [53], designed to fit models with spatiotemporal random effects to scientific survey data and make predictions in unsampled locations based on a nearest-neighbor Gaussian framework (E. Lawler et al. unpubl., preprint: https:// arxiv.org/ abs/ 2105.06902). Species presence and abundance were predicted across the study area on a 0.1° × 0.1° raster grid for all given years. Bycatch risk across the study area in each year and for each species of skate was calculated from the relative density of the skate multiplied by the relative summed densities of all targets, following Jubinville et al. [40].

2.4. Bycatch risk mitigation framework

'Bycatch risk reduction' for the purpose of this study is defined as the percent (%) reduction in the total per-cell bycatch risk of a species in a given region following a given spatial closure where fishing with bottom-contact gear (e.g. longline or bottom trawl) is theoretically prohibited, compared to the same region with no closed areas (the 'baseline'). We plotted the response of bycatch risk reduction to area closures focused precisely on hotspots for each skate species. We then mapped potential closure zones at increasing levels of risk reduction for each skate species individually and grouped. Finally, we evaluated potential costs to industry at increasing levels of bycatch risk reduction by overlaying these zones with spatially referenced commercial landings data and approximating the fraction of landings by weight that would be displaced.

2.4.1. Bycatch risk reduction response

Bycatch risk was calculated for all skates individually and combined between 2015 and 2019. Bycatch risk values for each species were then plotted across the study area on a 0.1° grid. To precisely target bycatch risk hotspots, the cells with the highest bycatch risk values in each year were iteratively extracted from the grid in steps of 0.05 (e.g., all cells where the bycatch risk value $\geq$ 0.95 are extracted, then all cells where bycatch risk value $\geq$ 0.90, and so forth) until the highest remaining value was 0.1, after which cells were extracted in steps of 0.02. At each step, the sum of remaining cells was recorded to determine percent bycatch risk reduction from the baseline, given the closure of a high-risk area of increasing size (represented by the increasing number of extracted cells). The difference in approximate area closed to fishing was also calculated at each step from the sum area of remaining cells. A 5-year mean bycatch risk reduction was plotted as a function of the fraction of area closed for each species of skate individually and together.

2.4.2. Bycatch risk reduction mapping

Bycatch risk reduction is defined as the percent reduction in bycatch risk, as defined by high co-occurrence between target species and non-target skates. Bycatch risk reduction responses were used to approximate the upper limit of bycatch risk values that would provide a specific level of reduction. These bycatch risk values, hereafter referred to as 'threshold values', were identified to establish 5-year mean bycatch risk reductions of 10 %, 25 %, 50 % and 75 % over the study area. Because of their varying distributions, threshold values for each level of reduction differed between species. Cells that met and/or exceeded threshold values for each level of reduction were extracted and converted to polygons. These polygons corresponded to the size and geography of the closure that would provide that level of reduction.

2.4.3. Estimating cost to fishing industry

Spatial polygons representing potential closed areas were mapped for skates at each level of reduction (10 %, 25 %, 50 % or 75 %). These polygons were then overlaid with total summer landings of groundfish bottom-trawl fisheries from DFO's MARFIS database, plotted on a 0.1° grid. Cells which fell inside polygons were removed, and the percentage of landings by weight (kg) that would be displaced by closing the polygon to bottom-trawling was calculated. Costs to industry were evaluated at each level of bycatch risk reduction for each skate individually and together.

3. Results

A total of 491 RV survey tows were completed between 2015 and 2019 across the study area. The number of tows in which each species was present can be found in Table 1. Individual species distributions modeled from RV data are shown in Fig. 2. Each species showed very patchy patterns of abundance across the study area, consistent with their depleted population status. Bycatch risk within bottom-trawl fisheries was predicted for at-risk skates individually and together. Risk hotspots were very distinct and varied by location for each species of skate (Fig. 3). Smooth skate showed a unique hotspot at the edge of the study area and Canadian Exclusive Economic Zone, and all three species shared a similarly located hotspot north of the Fundian Channel (located approximately 42.7°N 66.0°W).

The reduction of bycatch risk associated with proposed targeted closed areas was expressed as the percent reduction in total per-cell bycatch risk as a function of increasing fractions of the study area closed to fishing (Fig. 4). Each species showed comparable trends in bycatch risk reduction with increasing proportions of area closed to fishing. When winter skate was evaluated individually, intermediate bycatch risk reductions required a smaller fraction of area closed when compared to the other individual species trends. At the lower and upper ends of bycatch risk reductions, trends between skates individually and combined were similar.

Spatial polygons that corresponded to different levels of 5-year mean bycatch risk reduction (10 %, 25 %, 50 %, 75 %) were generated from cells that exceeded threshold values for the given level of reduction. Polygons were generated for individual and combined skates and overlaid with total summer bottom-trawl landings (2015–2019) plotted on a 0.1° grid (Fig. 5). The percentage of landings by weight that would be displaced from the polygon closure is shown in Fig. 6. For all analyses, 10 % and 25 % bycatch risk reduction resulted in less than 1 % of landings displaced on average (0.1 $\pm$ 0.05 % and 0.58 $\pm$ 0.29 %, respectively). Bycatch risk reduction greater than 25 % resulted in minute proportions of landings displaced that somewhat varied depending on the size and location of the polygon corresponding to that reduction level with respect to catch location (Fig. 5). A bycatch risk reduction of 50 % in all cases resulted in less than 10 % of landings displaced. Average landings displacement for a 50 % bycatch risk reduction was 4.9 $\pm$ 2.45 %. A bycatch risk reduction of 75 % resulted in displaced landings greater than 40 % by weight for all species skates individually, whereas when considered together the same reduction would displace 76 % of landings. The mean displaced landings by weight (kg) for a bycatch risk reduction of 75 % was found to be 59.4 $\pm$ 29.7 %.

4. Discussion

Bycatch in commercial fisheries is a widespread management problem with significant implications for the conservation and recovery of vulnerable species in Canada and elsewhere. Here we present a new approach to evaluate and mitigate bycatch risk for data-poor species where fisheries-dependent data are insufficient. We modeled the summertime distributions of 5 bottom-trawl target species and 3 vulnerable skate species from scientific bottom-trawl surveys. Relative bycatch risk was predicted from the overlap of target species and skates across the western Scotian Shelf individually and in combination (Fig. 3). Within the combined distributions of commercial bottom-trawl targets, bycatch risk was highest in the areas of greatest skate abundance (Fig. 2). Bycatch risk reduction was defined as the percent reduction in sum bycatch risk over the study area following a spatial closure. The predicted reduction of bycatch risk to increasingly larger area closures showed similar trends for smooth skate, thorny skate and all skates combined. Only winter skate required a smaller closed-area size to achieve the same level of risk reduction (Fig. 4). We mapped potential closure zones to reduce bycatch risk incrementally and overlaid these with spatially referenced bottom-trawl landings from DFO's MARFIS database (Fig. 5). The impact to the fishing industry was approximated by the proportion of landings displaced by closing each zone (Fig. 6). A bycatch risk reduction of 50 % or less in all cases resulted in less than 10 % displacement of bottom-trawl landings on the western Scotian Shelf. In this case study, our results demonstrate that when area closures to mitigate bycatch risk are precise in their placement, costs to industry by way of exploitable area and displaced landings can be minimized.

The risk-mitigation framework we present here can also be used to

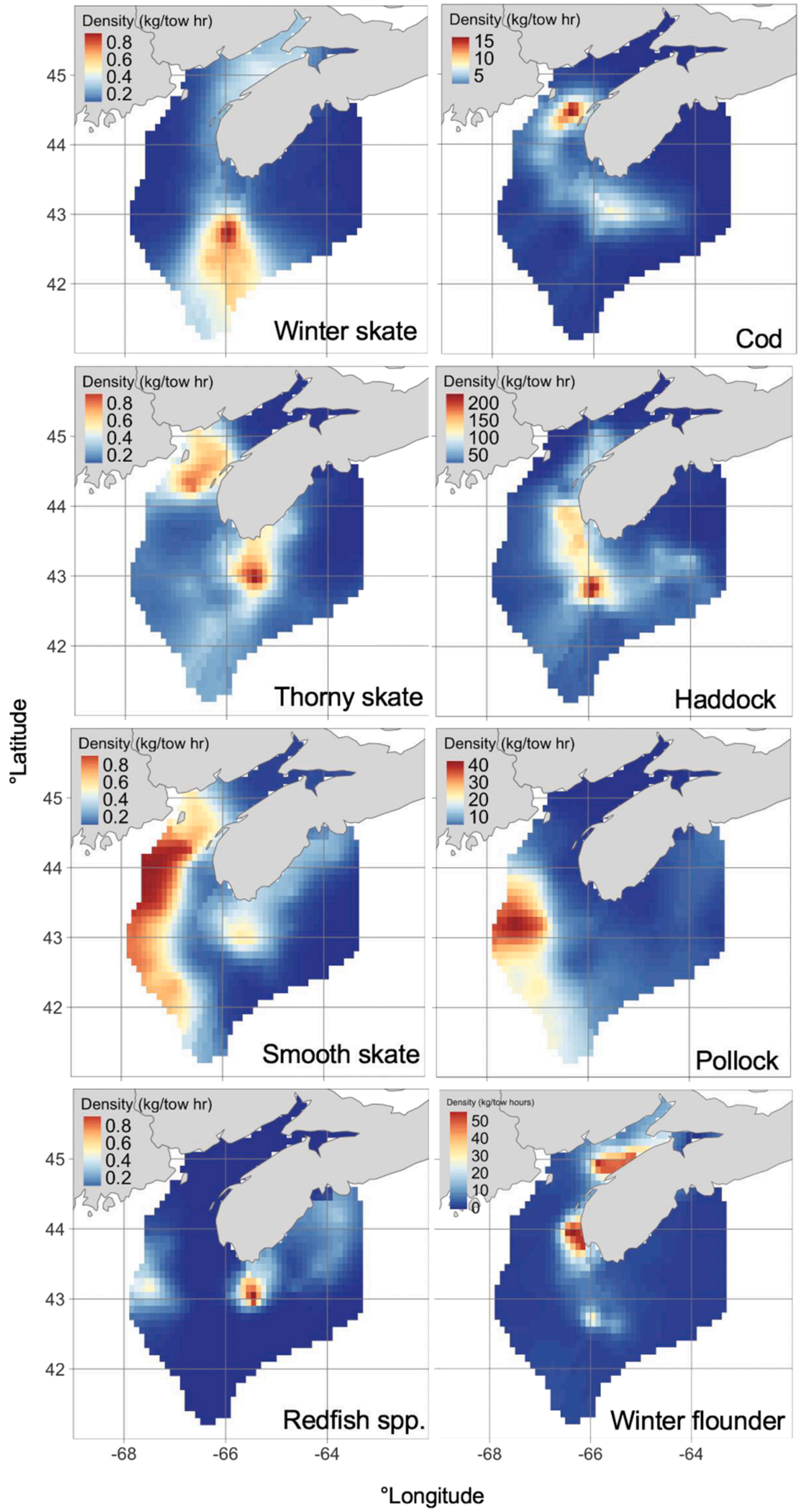

Fig. 2. Species distributions. Shown are the mean estimated distributions within the study area of three at-risk skate species and 5 major bottom-trawl target species for the years 2015–2019. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

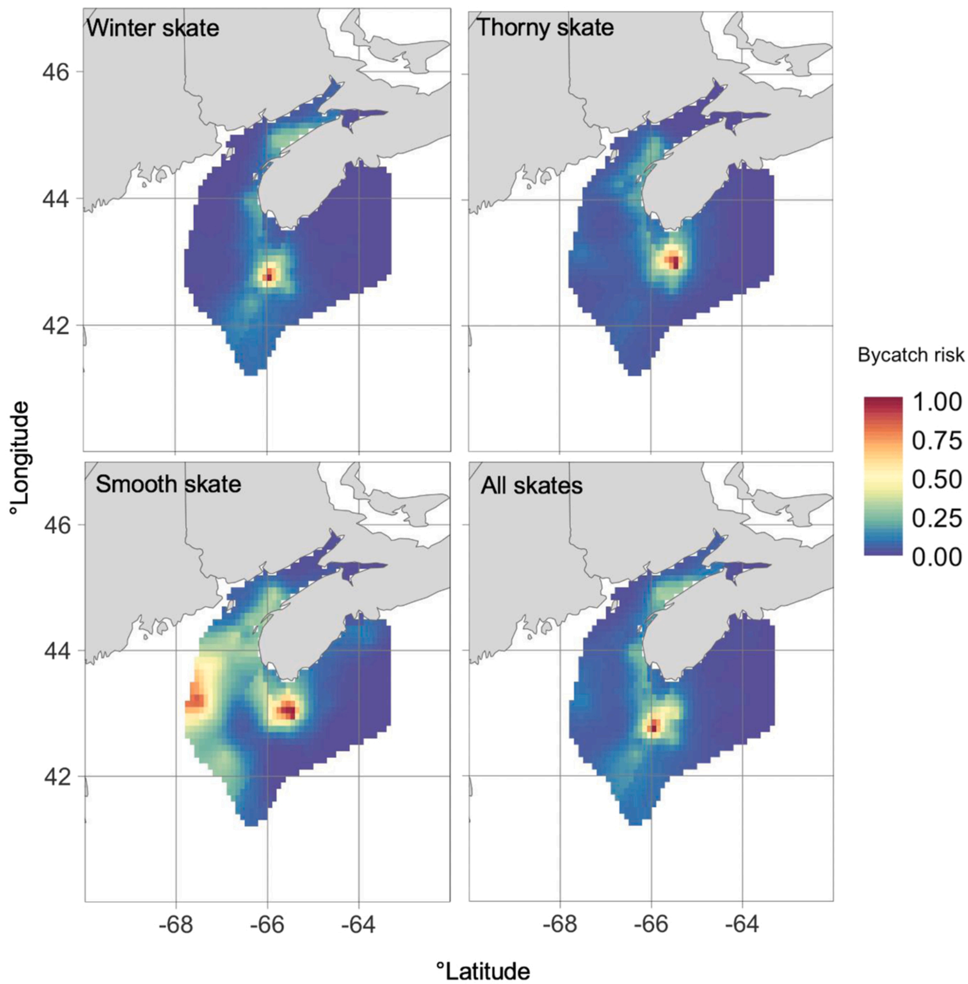

Fig. 3. Bycatch risk. Shown are the 5-year mean bycatch risk estimates within the study area for three species of at-risk skates, calculated against 5 commercial target species. High bycatch-risk areas (red) indicate a high degree of co-occurrence between the at-risk skate and one or more target fisheries. Low-risk areas (blue) indicate low co-occurrence between at-risk skates and fisheries targets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

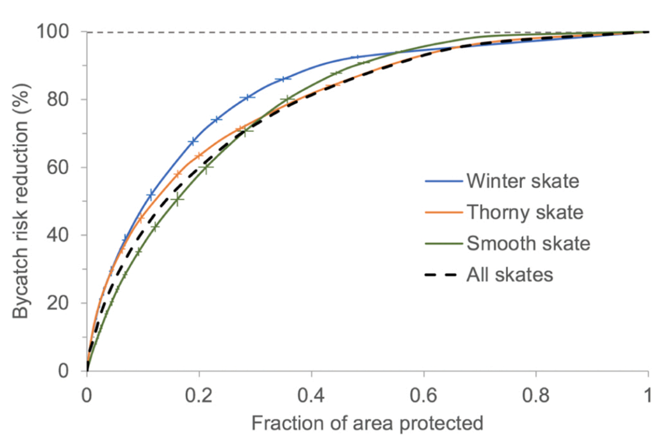

Fig. 4. Bycatch risk reduction by area closures. Bycatch risk reduction is defined as the percent (%) reduction in sum total bycatch risk across the study area that arises from closing increasing fractions of area across the region (see Fig. 5).

evaluate whether or not spatial measures are an appropriate strategy for a given conservation objective. For example, if the distribution of the species (and thus bycatch risk) is continuous and widespread, spatial measures of reasonable size would not be as effective. Such an effect would be apparent as a much more gradual response curve between bycatch risk and closures of increasing size. Conversely, a depleted species that persists in smaller, more discrete areas would benefit more from a focused spatial closure. This is demonstrated here in the case of winter skate, where the bycatch risk response showed a somewhat steeper increase in bycatch reduction versus area closed than other cases (Fig. 4), as the winter skate is found in more concentrated aggregations within the study area (Fig. 2). As a species subject to recent consideration for listing under SARA in Canada, it would appear that reducing overall bycatch risk for winter skate by 50 % would result in minimal displacement of bottom-trawl landings (2.5 %). Cost minimization may be enhanced further by prioritizing functional groups of threatened species within the same framework. Because bycatch risk hotspots overlapped in some areas for all species of skates (Fig. 3), the overall cost of reducing combined skate bycatch risk by 50 % is less than the cost of doing the same for smooth or thorny skates individually, and comparable to a 50 % reduction for winter skate individually (Fig. 6). Managers may seek to protect areas that balance conservation across several species or functional groups, rather than approach conservation efforts from a single-species manner.

Social and economic considerations are increasingly at the forefront of fisheries stakeholder discussions. While government responses to bycatch, particularly in Canada, have been slow to materialize, greater public awareness of consumers over the consequences of overfishing has led to a rise of private governance measures in fisheries [20]. Third-party certifications of sustainability aim to incentivize fishing companies to use sustainable harvest practices using the purchasing influence of seafood consumers. The Marine Stewardship Council (MSC) requires certified fisheries to maintain not only sustainable levels of target stocks, but also the careful management of co-occurring species. However, MSC has been criticized in the past for its lenient

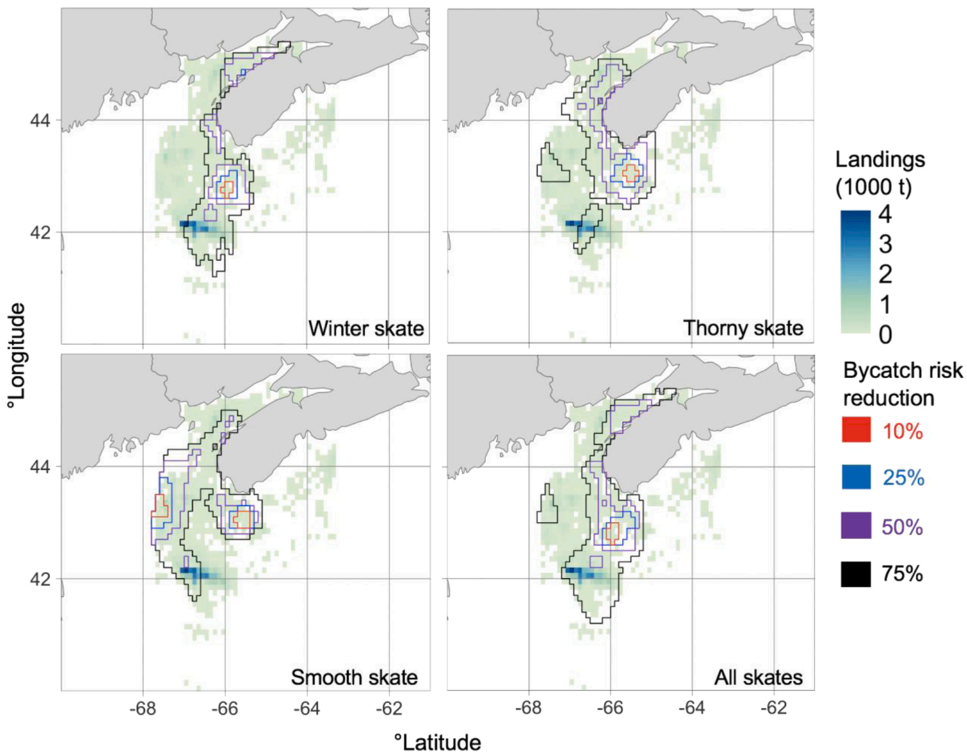

Fig. 5. Area closures to reduce bycatch risk. Shown are polygons representing potential management areas required to be closed to bottom trawl fisheries in order to reduce bycatch with increasing effectiveness (red= 10 %, blue = 25 %, purple = 50 %, black = 75 % reduction in total bycatch risk). Polygons are overlaid with color-coded total bottom-trawl landings, 2015–2019. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

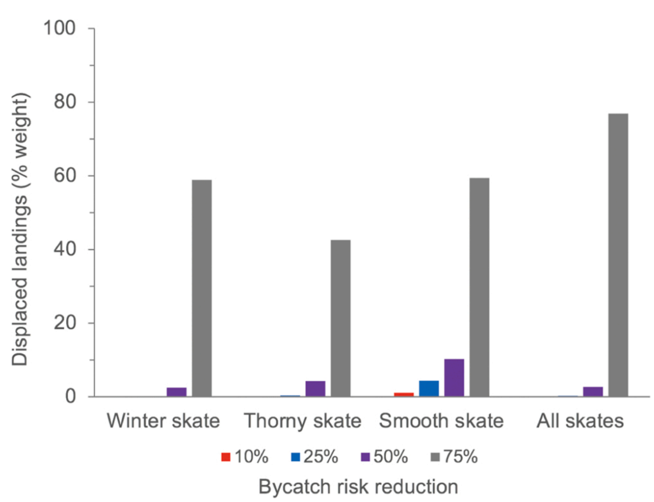

Fig. 6. Displaced landings. Shown are the percentages of total bottom-trawl landings within the study area (2015–2019) that would be displaced by closing high-risk areas to achieve increasing thresholds of bycatch risk reduction for vulnerable skates (red = 10 %, blue = 25 %, purple = 50 %, gray = 75 % reduction of bycatch risk). Note that the Y-axis maximum is not 100 %. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interpretations of sustainable practices, especially for bycatch species [54,55]. Bycatch minimization is a criterion in the MSC certification process, however, in Canada, there is still insufficient data to characterize the impact of bycatch, leading to an underestimation of the true scope of bycatch across Canadian fleets. As bycatch has yet to be fully prioritized in fisheries management and monitoring plans, MSC-certified fisheries in Canada continue to discard large amounts of non-target species [1]. While the onus is on MSC to ensure its own certification standards are scientifically appropriate, public pressure can influence regional fisheries management organizations (RFMOs) to implement their own uniform and stringent sustainability standards outside of third-party certifications [21], including those to reduce bycatch of non-target species. In using existing data from a longstanding and continually funded bottom-trawl survey, this framework can support this endeavor by identifying high-risk regions to avoid at low cost, and in principle these methods are applicable to any region or jurisdiction where scientific surveys of fish stocks are conducted.

Canada has made progress towards enacting its sustainable fisheries commitments. Bycatch has consistently been identified as both an ecological and economic concern of commercial fishing industries for decades [56,57]. Despite this, and the Canadian government's efforts to address bycatch in policy [27], there remain wide gaps in regulators' ability to accurately assess and mitigate bycatch risk in Canadian fisheries in practice. The most prominent shortfall is the availability and accessibility of at-sea monitoring data. Only 13 % of MSC certified Canadian fisheries employ at-sea observers on 100 % of fishing trips, and often not evenly distributed across the fishing area. Catch-monitoring and reporting protocols from any given fleet are not standardized across Canada, and accessing at-sea monitoring data from third-party fisheries observer companies is not always timely [1]. For these reasons among others, scientists and managers alike have an incomplete picture of the bycatch issue within most fleets in Canadian waters. Several ocean conservation groups have made recommendations to DFO to address bycatch by ensuring sufficient monitoring of retained and discarded catch, as well as data transparency and accessibility (including Oceana Canada [https://www.oceana.ca/en] and Living Oceans Society [https://www.livingoceans.org/]). However, data improvements are unlikely to be implemented in the short term and new tools must be adopted to mitigate the impacts of bycatch in the interim while catch-monitoring protocols are improved [31,34].

There is a growing catalogue of work developing more adaptive tools to estimate the extent of bycatch using both fisheries-dependent [42,58] and fisheries-independent data sources [40,41,59,43,60]. Some fisheries management jurisdictions have begun the process of testing and adopting similar data-driven tools to optimize catch, minimize bycatch and support dynamic ocean management strategies. EcoCast (https

://coastwatch.pfeg.noaa.gov/ecocast/), for example, is an experimental fishery sustainability tool that predicts the distributions of species from near-real time environmental data and weights each species' distribution to reflect management priorities and recently documented catch events [60]. As of 2020, EcoCast was deployed on a voluntary-use basis in the California Drift Gillnet (DGN) fishery with a focus on reducing bycatch interactions of vulnerable marine megafauna such as leatherback turtles or sharks [61]. By using a precisely directed spatial management measure, as well as one that dynamically accounts for species shifts under changing oceanic conditions, Hazen et al. [60] found that areas closed to fishing could be significantly smaller while remaining effective. While fully implementing a similar tool for Canadian fisheries is impractical at present, the success of EcoCast and support from previous studies makes a strong argument for employing data-driven frameworks to both mitigate bycatch risk of vulnerable species and reduce costs to fishers. Innovation and adoption of these tools is crucial to help fill in knowledge gaps for data-poor species given the urgency and legal mandate, to rebuild and recover depleted and endangered stocks in Canadian waters.

Of course, this approach has some limitations, related to the timing and specificity of the sampling gear. We considered data from a long-standing bottom-trawl survey conducted annually in the late summer. For this reason, we cannot infer patterns of bycatch distribution in winter months, or those from fisheries using alternate gears such as long-lines or gillnets. Several species of Scotian Shelf groundfish undergo seasonal migrations to deeper waters [51,52], where they are not effectively sampled. Further, bycatch of skates is a significant concern in demersal long-line fisheries for Atlantic halibut (*Hippoglossus hippoglossus)* [46,47,9], which is not directly addressed in this paper. To fill this gap, the framework outlined here could be applied to annual surveys of the Atlantic halibut long-line fishery, taking into consideration the limitations of those data. These surveys are conducted in cooperation by DFO and fisheries observers and cover the entire Scotian Shelf and Southern Grand Banks, where the fishery catches several COSEWIC-assessed species as bycatch [9].

5. Conclusions

In the current study, we focused on presenting a new framework for bycatch reduction by identifying the costs and benefits of area closures to species-at-risk using fisheries independent data. Though Canada has strong bycatch-mitigation commitments through the Sustainable Fisheries Framework and Policy on Managing Bycatch [27], as well as recent updates to the Fisheries Act [33], concrete actions are yet to be taken to systematically address bycatch in practice. Given the low abundance of many Canadian fish stocks [25], including Atlantic Canadian groundfish [34], there is an urgent need to enact recovery plans that reduce the impacts of bycatch for both target and non-target species. While there are many gaps in knowledge that can only be addressed by increased monitoring of retained and discarded catch, there is strong support to predict bycatch hotspots from fisheries-independent data. We demonstrate the identification of high-risk regions of skate bycatch to bottom-trawling, and approximate costs that may be experienced by the fishing industry at increasing levels of protection. The risk mitigation framework presented here can help to support the development of bycatch reduction frameworks even in the absence of adequate fisheries-observer data for depleted species. Using readily available data, these frameworks can be used within the larger decision-making and management processes of multi-species commercial fisheries, and address long-standing concerns about the unintended collateral damage of commercial fisheries in Canada, and elsewhere.

CRediT authorship contribution statement

Isabelle Jubinville: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Nancy Shackell:** Conceptualization, Writing – review & editing. **Boris Worm:** Conceptualization, Supervision, Writing – review & editing.

Data availability

The authors do not have permission to share data.

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