A FRAMEWORK TO PREDICT AND MITIGATE BYCATCH RISK FOR VULNERABLE MARINE SPECIES

by

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This thesis is dedicated to the memory of

Danielle Moore and ***Angela Rehhorn*****,**

whose lives were lost on 10 March 2019 in Bishoftu, Ethiopia aboard
Ethiopian Airlines Flight 302.
Both were on their way to represent Canada as youth ambassadors to the
United Nations Environmental Assembly in Nairobi, Kenya.

I will always remember you as my dear friends, my classmates, my heroes,
and the keenest human 'beans'.

Knowing you was one of the greatest privileges of my life.

"Pura Vida"

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Abstract

Bycatch is a pressing concern impeding the sustainability of global fisheries. Yet, the severity of bycatch is often not well quantified and mitigated due to incomplete monitoring of catch and discards at-sea. In this thesis, I present a novel modelling approach to produce a generalizable bycatch risk assessment and mitigation framework. This framework aims to inform spatial management strategies for bycatch mitigation using fisheries-independent data. I utilized spatiotemporal modeling of scientific survey data to predict high-risk regions for three threatened skates (family Rajidae) in Atlantic Canada caught as bycatch in commercial bottom-trawl fisheries. I first identified bycatch risk hotspots for skates across the Scotian Shelf, and independently validated estimated bycatch risk through skate presence in at-sea observer datasets that monitor discarded bycatch directly. I found that bycatch risk as a function of species co-occurrence, modelled from fisheries-independent data, was predictive of species presence in observed fishing sets. I then evaluated the relative reduction in bycatch risk that can be expected by closing targeted zones to bottom-trawl fishing. When closures are precisely placed, a 50% reduction in bycatch risk for all skates would displace less than 10% of bottom-trawl landings by weight (4.9 ± 2.45%). I discuss the need for new approaches to analyze and mitigate bycatch of vulnerable species, and how these tools can help to meet regulatory or market-driven requirements for bycatch reduction at low cost.

List of Abbreviations Used

ASOP	At-sea observer program
BR	Bycatch risk
CHP	Cod-haddock-pollock fisheries complex
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CPUE	Catch-per-unit-effort
DFO	(Department of) Fisheries and Oceans Canada
EEZ	Exclusive Economic Zone
GLMM	Generalized linear mixed model
GSL	Gulf of St. Lawrence
IFMP	Integrated fisheries management plan
IUCN	International Union for the Conservation of Nature
MARFIS	Maritime Fisheries Information System
MPA	Marine protected area
MSC	Marine Stewardship Council
NAFO	Northwest Atlantic Fisheries Organization
NFLD	Newfoundland
NNGP	Nearest neighbour Gaussian process
NOAA	National Oceanographic and Atmospheric Administration
OECM	Other effective area-based conservation measure
RV	Research vessel
SARA	Species At Risk Act
SS	Scotian Shelf
SDG	Sustainable Development Goal
SST	Sea surface temperature
TMB	Template Model Builder

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Chapter 1 - Introduction

1.1 Bycatch of vulnerable species

Bycatch, or the incidental catch of a non-target species, is a ubiquitous occurrence in most fisheries (Davies et al. 2009, McDevitt-Irwin et al. 2015, Boudreau et al. 2017, Zeller et al. 2017, Savoca et al. 2020). It is a significant driver of overexploitation for many species, impedes the recovery of vulnerable marine populations (Sims & Quieroz 2016), and can impact the trophic dynamics of marine ecosystems (McCauley et al. 2015). For many fisheries that employ non-selective gear such as trawls and long-lines, bycatch can comprise a large fraction of the total catch (Huang & Liu 2010, Zeller et al. 2017, Hurley et al. 2019, Rozalska & Coffen-Smout 2020). Bycatch has been estimated to contribute up to 40% of total retained and discarded catch worldwide (Davies et al. 2009). Bycatch that is discarded at sea, alive or dead, is estimated to represent approximately 10% of reconstructed global catches (Zeller et al. 2017). Rates of discard mortality can differ between species and the types of gear the fishery employs. For example, post-release mortality for blue sharks (*Prionace glauca*) caught by pelagic longline was found to be about 19% (Campana et al. 2009), whereas for demersal thorny skate (*Amblyraja radiata*) caught by bottom trawl, discard mortality is estimated between 17-25% (Knotek et al. 2020), but can be as high as 50% (Mandelman et al. 2013).

Most marine species are not distributed evenly throughout regional seascapes but concentrate in core habitats (Probst et al. 2021) characterized by preferred environmental conditions, which can include temperature, latitude, substrate, salinity, and depth, among others (Rosenfeld et al. 2011, Macura et al. 2012, Moore et al. 2013, Tolimieri et al.

2020). Species co-occur, and when fishing directly targets one species it can indirectly intercept the core areas of non-targeted species. While a single species may represent a small fraction of the total bycatch in a fishery, this can impose disproportionally greater impacts on the non-target species in question if it is heavily depleted or endangered, as small populations of marine fishes are less resilient to additional mortality (Reynolds et al. 2005). Bycatch rates of the vulnerable non-targeted species can remain high for some time giving the impression of an abundant population, an established phenomenon known as 'hyperstability' (Rose & Kulka 1999, Erisman et al. 2021). 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 (Hutchings 1996, Ames 2004, Cianelli et al. 2013). Fishing pressure may drive populations to redistribute to areas that may be less ecologically suitable or predictable (Shackell et al. 2005, Last et al. 2011, Engelhard et al. 2014). For mixed-species fisheries such as those for groundfish, many species co-occur, and a population may be affected by the cumulative impacts of combined methods of fishing (Foster et al. 2015).

Traditional methods to mitigate deleterious effects of fishing and protect habitat involve static area closures, marine protected areas (MPAs) and modifications to fishing gear and practices (Cox et al. 2007, Poisson et al. 2014, Senko et al. 2014, Schram et al. 2019). However, fleet-wide strategies such as modification of fishing gear only go so far at reducing bycatch for a given species or fishery (Savoca et al. 2020), and can often be costly and logistically challenging to experimentally evaluate (Kennelly & Broadhurst 2021). Such strategies often result in trade-offs between protecting a species or habitat and maintaining economically viable fisheries (O'Keefe et al. 2014). Many regulatory bodies are increasingly supporting a push towards ecosystem-based fisheries management, where all aspects of the ecosystem are taken into consideration and regulations are updated based on continually added environmental or biological data (Pikitch et al. 2004, Smith et al. 2007, Hegland et al. 2015, Hazen et al. 2018, Cucuzza et al. 2021). Even when informed by robust data, however, static spatial approaches to mitigate bycatch, such as MPAs, are limited in that they do not inherently account for shifting species distributions in response to climate variability (Kleisner et al. 2017). As marine climates continue to change, species distributions and community compositions become less predictable. For example, the waters of the northwest Atlantic around the Scotian Shelf are warming at an accelerated rate compared to the global average (Saba et al. 2016), and latitudinal shifts in species distribution are already being observed in Gulf of Maine fisheries (Kleisner et al. 2017). A more dynamic ecosystem-based management approach, where regulations shift in space and time in a fluid response to changes in biological and oceanographic parameters, has been proposed as a better solution to bycatch challenges, especially for highly mobile species (O'Keefe & DeCelles 2013, Maxwell et al. 2015, Hazen et al. 2018).

In Canada, many fish stocks have experienced substantial declines on both coasts (Hilborn et al. 2020). Target species directly pursued by fisheries in Canada account for on average only 50% of total commercial catch (Boudreau et al. 2017), with the remainder composed of numerous bycatch species, which may either be retained or discarded at sea. The only direct observations of retained and discarded bycatch in Canada come from at-sea observer programs (ASOPs), which are required to identify and record all catch whether it is landed or not. The coverage of observers on fishing trips varies widely among Canadian fleets (Boudreau et al. 2017); only 13% of high-value fisheries are monitored on all trips. Employing observers is costly (Benoît & Allard 2009), and the very presence of an observer can influence fishing practices, referred to as 'observer effects' (Benoît 2006). On vessels without an observer, many fleets do not require identification of non-retained catch, and instead record the sum weight of all discards (Gavaris et al. 2010). Atlantic Canadian bottom-trawl fisheries use highly non-selective gear to target groundfish and typically less than 11% of fishing trips are observed at sea (Clark et al. 2015). Bycatch in these fisheries is estimated using stratified ratio estimators derived from the few observed trips (Campana et al. 2011). Yet, a report by the Pew Institute of Ocean Science used simulated fisheries data to show that observer coverage of at least 50% is required to reliably estimate bycatch of rare or depleted species (Babcock et al. 2003). Fisheries-derived data is presently inadequate for quantifying bycatch of rare or depleted species, thus there is a need to explore new approaches to evaluate and mitigate bycatch mortality for these species in the absence of complete catch monitoring at sea.

Several groundfish that are subject to incidental harvest remain at low abundance in the decades since the collapse of stocks on the eastern Scotian Shelf in the 1990s (Shackell et al. 2021). While the current system of catch monitoring in Canada is not sufficient to assess bycatch of endangered species, postponement of action until the issue of data quality is addressed will continue to result in further unknown bycatch mortality. Given the known gaps in bycatch observation and recording present in many jurisdictions, there is growing interest in using biogeographical data independent of fisheries to examine the risks present to vulnerable species over space and time. As the primary driver of bycatch is the spatiotemporal co-occurrence of target and non-target species, previous work has explored the use of relative spatiotemporal relationships to estimate the extent of bycatch potential and inform bycatch management strategies (Ward et al. 2015, Runnebaum et al. 2020).

In 2019, amendments were made to Canada's Fisheries Act which mandated the federal government to enact and implement measures to restore depleted or endangered fish stocks (Bill C-68, 2019). Although bycatch is not explicitly addressed in this legislation, it is a crucial aspect to consider reducing fishing mortality for vulnerable species. This new legally binding obligation followed Canada's commitment to the United Nations Sustainable Development Goals (SDGs) in 2015 -specifically SDG 14, "Life Below Water" (https://www.un.org/sustainabledevelopment/oceans/) which includes ensuring sustainable fishing practices and conserving marine habitats among its primary targets (Reimer et al. 2021). In addition to SDG 14, Canada has also renewed commitments to protect 30% of national waters by way of MPAs or other effective area-based conservation measures (OECMs). Sustainable fishing practices go hand-in-hand with bycatch reduction and habitat protection, and this thesis aims to align spatiotemporal area protection with bycatch mitigation as a primary conservation objective.

1.2 Skates of the Scotian Shelf

Elasmobranchs (Subclass Elasmobranchii, 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 and recovery (Dulvy et al. 2008, Hobday et al. 2011, Oliver et al. 2015, Au et al. 2015). Elasmobranchs are typically longlived and late to mature to reproductive age, making them intrinsically susceptible to additional fishing-induced mortality. Dulvy et al. found in 2014 that approximately 23.9% of chondrichthyan species (sharks, skates, rays and chimeras) were threatened under the International Union for the Conservation of Natures (IUCN) Red List of Threatened Species criteria. A further 46.8% of observed chondrichthyan taxa were found to be Data Deficient. Many populations of elasmobranchs have been depleted by overfishing worldwide, and several are at an elevated risk of extinction in the near future (Dulvy et al. 2014). Fishing pressure has been attributed as a driver of the near-extinction event of the barndoor skate (*Raja laevis*) in the Northwest Atlantic in the 1970s and 1980s (Casey & Myers 1998). Several other species of skate (family Rajidae) have declined by over 90% in the past half century (Figure 1.1), with bycatch determined to be a primary hindrance to their recovery potential (DFO 2017[a,b]).

The winter skate (*Leucoraja ocellata*) has declined by up to 98% of its historical abundance on eastern Scotian Shelf, Newfoundland and Gulf of St. Lawrence subpopulations (DFO 2017[a]) (NAFO 4VW, 4ST, Figure 1.1). Winter skate reach maturity by approximately 11-13 years of age for males and females respectively, and can grow to be 80cm in length for females, or 91cm for males. As all skates, winter skate are oviparous, depositing egg cases with a gestational period of 1.5-2 years (DFO 2017[a]). Both local subpopulations of winter skate have been designated as Endangered by COSEWIC, while the population on the western Scotian Shelf was assessed as Not At Risk. (Table 1). Following COSEWIC's 2015 review of all Atlantic populations, consultations began to consider listing the winter skate for federal protection under Canada's Species At Risk Act (SARA). If listed under SARA, the government would be legally compelled to enact a recovery strategy for the winter skate in its entire Canadian range. Currently, winter skate may be retained as bycatch only on the western Scotian Shelf.

The thorny skate (*Amblyraja radiata*) is one of the most widely distributed demersal elasmobranchs in the Canadian Atlantic and Arctic oceans. Similar to the winter skate, males are thought to mature earlier than females. The lifespan of thorny skate is unknown, however estimates suggest a longevity of at least 20 years (DFO 2017[b]). While they once were highly abundant within NAFO divisions 4VWX, they have declined in the region by approximately 98%, and the population currently fluctuates around the short term mean biomass of less than 1 Kiloton (DFO 2017[c]). Thorny skate was previously subjected to a directed fishery on the Grand Banks and other areas adjacent to the eastern Scotian Shelf. In 2005 the directed skate fishery was closed in divisions 4VW, however they may be retained as bycatch by fisheries operating on the Grand Banks outside of the Scotian Shelf bioregion. COSEWIC assessed Atlantic populations of thorny skate as Special Concern in 2012 (COSEWIC 2012). In divisions 4VWX5, all thorny skate must be returned to the water when caught as bycatch, but directives to fishers to avoid further bycatch by moving a distance away are voluntary. Smooth skate (*Malacoraja senta*) is presently one of the least abundant demersal fish on the Scotian Shelf, with many life history characteristics unknown. Smooth skate have declined by approximately 80% from their previous peak biomass of roughly 2 Kt (DFO 2017[b]).

Scotian Shelf groundfish have been a major target of regional fisheries for over 500 years (Lear 1998). Groundfish landings on the Scotian Shelf and Bay of Fundy totaled nearly 40 000 metric tonnes in 2018, the majority comprised of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and pollock (*Pollachius virens*), often referred to as the 'CHP fisheries complex'. Additional targets include Atlantic halibut (*Hippoglossoides hippoglossus*), Acadian redfish (*Sebastes* spp.) and silver hake (*Merluccius bilinearis*). The fishery generally operates in Northwest Atlantic Fisheries Organization's (NAFO) divisions 4VWX5 (Figure 1.1), the management boundaries straddling the Scotian Shelf and Bay of Fundy within the NAFO Convention Area. The fishery generally employs both fixed- and mobile-gears (e.g., longline and otter trawl, respectively), and inflicts mortality on numerous bycatch species (Peacock & Anand 2008). Among bycatch species affected by both primary gear types are the three skate species currently deemed at-risk by COSEWIC.

All skates caught in NAFO divisions 4VW must be returned to the water (DFO 2018), however only thorny skate must be returned in division 4X on the western Scotian Shelf. Winter and smooth skates, despite their weak population status, may still be retained as bycatch in this area though they are frequently discarded. All three species are assumed to have a post-release mortality rate of 50% in Canadian mobile-gear fisheries (DFO 2018). In commercial landings records, the catch weights of all skates are aggregated into a single taxon (DFO 2021[a]), which reduces the amount of useable data to estimate catch rates for individual species of skate. Species are disaggregated in informal assessments using the relative proportions each species represents within a NAFO area from limited at-sea observations. Despite some attempts to implement bycatch avoidance measures, no species of skate has been afforded a proper stock assessment or recovery plan in Canada, and whether or not measures in place are effective cannot be reliably inferred with sparse at-sea monitoring data (DFO 2018).

1.3 New tools to assess and mitigate bycatch

There is a dual need for new methodology to simultaneously assess and mitigate bycatch risk in Canada for existing major gear types, given that commonly used estimation methods at present are inadequate for data-limited species, including but not limited to threatened elasmobranchs. Spatiotemporal modelling has increasingly been used to predict species distributions as statistical techniques continue to improve (Ward et al. 2012, Li & Wang 2013). Advanced computational resources and user-friendly software now allow researchers to predict the presence and abundance of a species across space, as a function of an environmental gradient, and through time with relative ease. The use of these statistical models to elucidate the patterns of co-occurring species has been explored, and overlaid distributions of species have been shown to predict the incidence of bycatch (Ward et al. 2015, Runnebaum et al. 2020). This relationship is observed when both fisheries-derived (Ward et al. 2015, Hazen et al. 2018, Stock et al. 2020) and fisheries-independent data (Runnebaum et al. 2020) are used. Fisheries-independent data can in principle be used to predict spatial areas where the potential for a bycatch interaction is elevated, where commercial or ASOP data are inadequate.

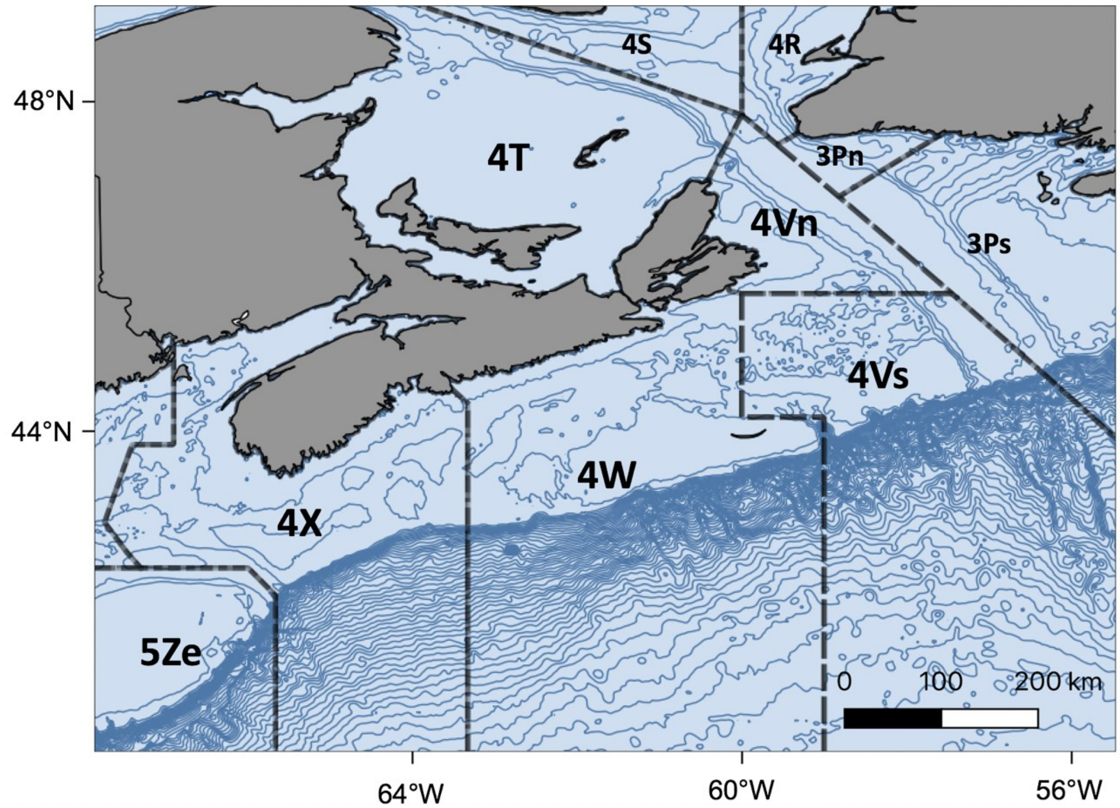

Figure 1.1. Scotian Shelf and Northwest Atlantic Fisheries Organization regulatory areas. Shown are NAFO division boundaries (dashed lines) on the Scotian Shelf and surrounding areas. Contour lines represent 100m depth intervals.

The most complete and high-quality source of fisheries-independent data for Atlantic Canadian groundfish communities come from scientific surveys. On the Scotian Shelf and surrounding waters, a bottom-trawl survey of the groundfish community is conducted annually in late August since 1970. Survey locations are randomly stratified across NAFO divisions 4VWX, and taxonomically complete and spatially referenced data on the presence and abundance of all fish species are collected. RV surveys are the only comprehensive source of biogeographical information for many species with little commercial value or those that are treated as groups, including but not limited to vulnerable skates. Having been conducted since 1970, the Scotian Shelf RV surveys contain 5 decades of quite robust data, making it a hugely valuable tool in exploring new spatial marine management applications. Using such a dataset to model distributions of target and non-target species on the Scotian Shelf can aid in evaluating spatial distribution of bycatch risk to a vulnerable species, and concurrently help inform strategies to mitigate bycatch mortality, at low cost to regulators.

1.4 Objectives of thesis

The goal of this thesis is to develop and apply a bycatch risk assessment and mitigation framework. In doing so I will explore several primary research questions in sequence: Firstly, as the primary driver of bycatch is the spatial co-occurrence of target and non-target species, I will address how independently modelled distributions between species can predict bycatch within commercial fisheries. Secondly, I will determine the magnitude of bycatch risk reduction attributed to implementing precise closures of bycatch risk hotspots to bottom-trawl fishing. The framework I present here to predict the spatial locations of bycatch for data-limited species serves the overall purpose of allowing fisheries managers to evaluate spatial bycatch risk on an ongoing basis. It can be a tool to monitor changes in risk potential to a vulnerable species, and to assess the use of spatial bycatch risk mitigation measures. This thesis is structured into two main chapters (Chapter 2 and 3), with a final chapter discussing the wider management implications of the results.

Chapter 2 describes a data-driven statistical modelling approach developed to estimate the relative risk of bycatch to a species over space and time. Using a novel R package purpose-built to analyze scientific survey data, individual species distribution models were fit for skates and commercial bottom-trawl targets. Historical distributions of skates were modelled to infer core areas where skates inhabited prior to being depleted by fishing. The relative overlap of present-day distributions between target species and vulnerable skates was then calculated and used to predict the presence of skate species in observed fishing sets. This chapter utilizes data from annual RV groundfish surveys to predict relative bycatch risk and validates these predictions against ASOP data available from bottom-trawl fisheries.

Chapter 3 will explore how a bycatch risk mitigation framework can be used to evaluate the relative reduction in risk, and associated costs, of implementing spatially discrete closures (such as MPAs or OECMs) to mitigate bycatch and protect sensitive species. The average reduction in bycatch risk was evaluated at increasing fractions of the region closed to fishing, and areas were identified for management consideration. The costs to fishing industry associated with closures of increasing efficacy were approximated by the proportion of bottom-trawl landings (kg) displaced in the areas where fishing is hypothetically prohibited. In addition to RV survey data, commercial bottom-trawl landings data from DFOs Maritime Fisheries Information System (MARFIS) database was spatially referenced and overlaid with identified closure zones.

Chapter 4 will synthesize the findings from this thesis, discuss the limitations, management implications, and major advances, while commenting on future research avenues.

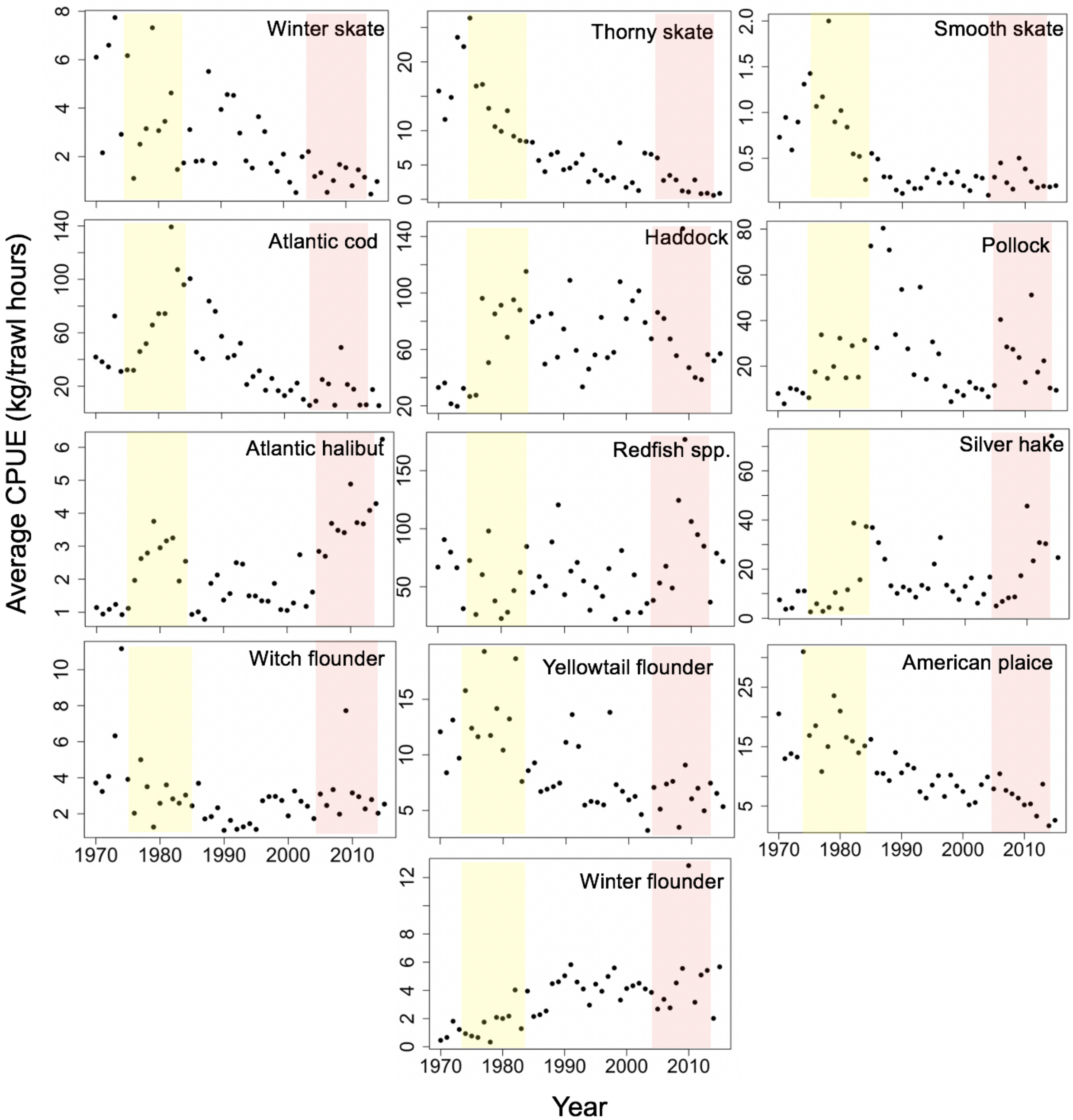

Figure 1.2 Recent trends in species relative abundance. Shown in mean CPUE (kg trawl hours^{-1}) derived from annual scientific bottom trawl surveys of the Scotian Shelf (1970-2017). Yellow shaded area represents the historical period before collapse of northern cod (1975-1985); red shaded area represents recent 10-year trend in abundance (2005-2015).

Chapter 2 - Distributions of threatened skates and commercial fisheries inform conservation hotspots

2.1 Introduction

2.1.1 Ecosystem-based fisheries management

Sustained exploitation of fisheries worldwide has left nearly half of scientifically assessed fish stocks currently in an overfished state (Hilborn et al. 2020) and has reduced many populations of incidentally caught species to low abundance (Beddington et al. 2007, Lewison et al. 2014, Sims & Quieroz 2016, Pacoureau et al. 2021). In response to these multi-species challenges, fisheries management authorities have aimed to move towards ecosystem-based approaches to ocean resource management (Smith et al. 2007, Hegland et al. 2015, Cucuzza et al. 2021). Ecosystem-based management aims to balance resource exploitation while avoiding ecosystem degradation and accounting for all ecosystem components, including non-commercial species and habitat. A primary objective of many ecosystem-based management strategies is to identify and rigorously manage spatial areas of conservation priority (Pikitch et al. 2004). These can include core areas of habitat or high abundance for protected species (Williams et al. 2014), or areas where the risk of anthropogenic impacts are elevated such as the risk of bycatch (Kirby & Ward 2014).

The basis of such ecosystem-based management is a comprehensive understanding of the spatial domains of habitats, species and human activities. In the past two decades, statistical modelling of species distributions has advanced considerably (Fink et al. 2010, Ward et al. 2012), with the spatial and temporal variation in abundance and correlations with climate and oceanographic parameters garnering particular interest (Lewison et al. 2009, Ward et al. 2015). Understanding the patterns and drivers of species distributions is critical to addressing broader fisheries management and conservation issues. For example, identification and protection of core areas for depleted species can increase population productivity (Rodwell et al. 2003, Shackell et al. 2005). Geostatistical tools have been applied to identify discrete regions of high species density (Morfin et al. 2012, O'Brien et al. 2012, Legare et al. 2015), and can enhance marine management and protected area effectiveness (Knip et al. 2012).

Another key application is mitigation of bycatch in commercial fisheries. Statistical modelling is instrumental in elucidating the spatial patterns of species and drivers of bycatch (Cosandey-Godin et al. 2015, Breivik et al. 2016, Breivik et al. 2017, Hazen et al. 2018, Hurley et al. 2019, Stock et al. 2020), and co-occurrence between species can inform where the probability of bycatch is elevated (Ward et al. 2015, Runnebaum et al. 2020). Within multi-species fisheries complexes, a comprehensive approach incorporating information from multiple affected target and non-target stocks should be taken when evaluating the spatial distribution of bycatch for a depleted, threatened or protected species.

Collective understanding of important risk areas of bycatch in the Scotian groundfish community is presently poor. All three species of at-risk skate are heavily depleted (Figure 1.2) and exist as remnants of their former populations whose current distributions may not reflect true core areas (Shackell et al. 2005, Carson et al. 2017). Bycatch of skates is estimated to be high within the CHP complex, redfish, and Atlantic halibut fisheries (DFO 2017[a,b]), however these estimates are complicated by problems with taxonomic identification of skates in landings records and by at-sea observers (Benoît 2006). Landings of skates are aggregated into one taxonomic category (DFO 2021[a]), resulting in a loss of species-specific information. Furthermore, observer coverage on vessels targeting groundfish on the Scotian Shelf is consistently low at 5-10% of fishing trips (Clark et al. 2015), well below the recommended 50% coverage required for reasonable estimates of bycatch for rare or depleted species (Babcock et al. 2003). As an added complication, at-sea observer data in Canada is screened to protect the privacy of individual fishing vessels. This involves spatially aggregating the observed catch from 5 different vessels or licenses into one centroid point (Butler & Coffen-Smout 2017) in what has been referred to as the "rule-of-5". In areas where fishing activity is high the spatial resolution of observer data is relatively high, and this aggregation of catch data does not result in a significant loss of spatial accuracy. In regions where the rule-of-5 cannot be satisfied without losing significant spatial resolution, the areas are removed from the dataset by DFO prior to release to the researcher

For skate species, the most taxonomically and spatially complete data come from annual research vessel (RV) surveys undertaken by the DFO on the Scotian Shelf each summer. These surveys cover the Scotian Shelf and Bay of Fundy areas (Figure 2.1) and directly sample the groundfish community by bottom trawling. The random stratified surveys account for all fish to the genus level at minimum and have been ongoing since 1970, prior to the expansion of Canadian domestic fisheries and harvest moratoria being implemented for Scotian Shelf groundfish stocks (Bundy 2005, Peacock & Anand 2008), and continuing to the present. The RV survey dataset, containing decades of presence and abundance data for all groundfish, can be used both to predict previous areas of high species abundance, and to evaluate present-day species co-occurrence. Species co-occurrence has been identified as a measure used to predict bycatch hotspots previously (Ward et al. 2015, Runnebaum et al. 2020).

2.1.2 Objectives of Chapter 2

The primary objective of Chapter 2 is to present a modelling approach to identify spatial regions of conservation concern for data-limited or rare species. A novel R package, *staRVe* (Lawler 2020), was used for fitting spatiotemporal models to research survey data (Lawler et al. 2021). First, I identified historical regions of high species density for skates, indicative of potential important habitat regions for rare species after sustained depletion (Shackell et al. 2005). Secondly, I predicted areas where present-day bycatch risk to skates is elevated based on a multi-species co-occurrence framework. The risk of bycatch to skates within 5 regional fisheries was evaluated, representing 10 commercial bottom-trawl targets. Finally, I present a proof-of-concept method to validate predictions of bycatch risk, using records of skate bycatch from at-sea observer data.

2.2 Methods

2.2.1 Annual Research Vessel (RV) survey data

To identify spatial areas of conservation priority for skates where fisheries-derived data is insufficient, data from a long-standing scientific bottom-trawl survey were used. DFO undertakes a bottom otter-trawl survey each summer on the eastern Scotian Shelf and Bay of Fundy. The survey area corresponds to NAFO divisions 4VWX and follows a random stratified design across depths between 50-500m, where tows are conducted at a speed of approximately 3 knots for 30 minutes. Onboard, DFO technicians sample fish and invertebrates caught and identify all fish to the genus level at minimum. Variables that were extracted from the RV dataset include the start and end latitude and longitude of the tow; the duration of the tow; and each species caught and their total catch weight. Catch-per-unit-effort (CPUE, kg trawl hours^{-1}) was calculated by dividing the total weight of the catch by the duration of the tow. In this chapter, the main study area covers the same region as the RV survey, extending approximately to the continental shelf boundary. The average latitude and longitude of each tow was used to represent the spatial locations of each set in the survey dataset. Figure 2.1 shows the locations of all RV survey sets within each study period.

Two decades of survey data were considered separately in this study. To identify historically important habitat areas for at-risk skates, I fitted spatiotemporal models to RV data extracted for the years 1975-1985. These years correspond to the approximate time in Canadian fisheries governance when foreign fisheries were expelled from the 200 nautical mile exclusive economic zone (EEZ) in 1977 (UN General Assembly, 1982) but prior to the proliferation of local fisheries, leading to an increase in many groundfish species' abundances (Lear 1998, DFO 2017[c]). To predict current hotspots of bycatch, relative abundances of skates and other groundfish species were modelled using RV data extracted for the years 2005-2015. This was a period of relative stability in terms of fisheries legislation, but where some groundfish populations (including at-risk skates) remained at low abundance (Figure 1.2). The relative spatial abundances of at-risk skates were overlaid with those of 10 high value commercially fished groundfish species on the Scotian Shelf. A list of all species considered in each analysis is shown in Table 2.1.

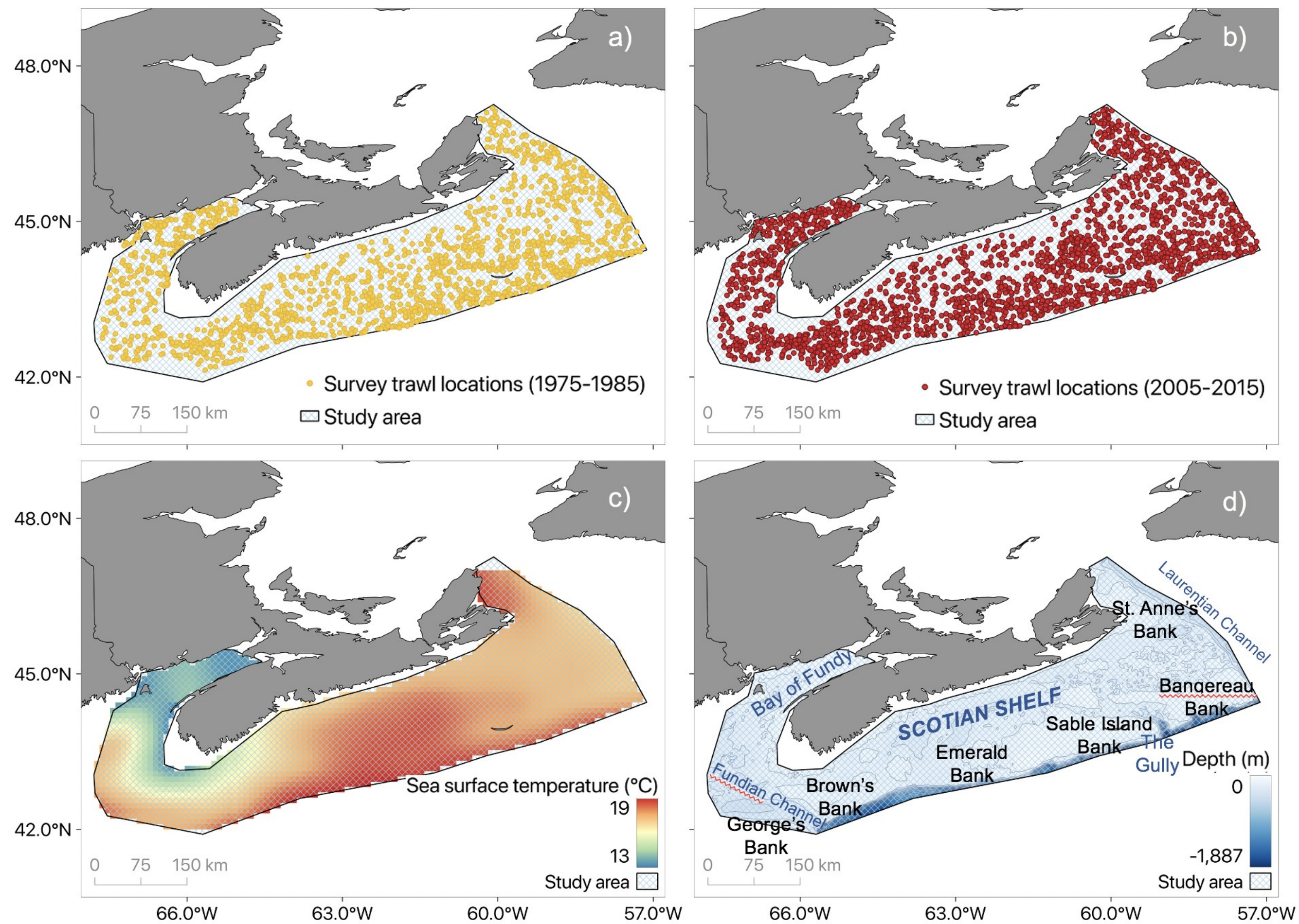

Figure 2.1. Study area and data. Maps of Atlantic Canada showing a) RV survey trawl locations within the study area years 1975-1985 (yellow), b) RV survey trawl locations within the study area for the years 2005-2015 (red); c) mean August sea surface temperature within and around the study area for the years 2005-2015. Temperature is reported at a 0.1° resolution; d) Depth within the study area reported at a resolution of 1 arcminute. Contour lines represent 100m intervals. Shelf features are noted for reference with results

Table 2.1. Study species and RV survey sample sizes. Shown is a list of skate bycatch and commercial bottom-trawl target species and the number of RV survey tows which recorded the presence of each species. Also shown is the assessment status by Committee on the Status of Endangered Wildlife in Canada (COSEWIC, by designatable unit, if applicable) for each species. CHP represents the cod-haddock-pollock fisheries complex. Grey italicized values were not used in the analysis for that time period. Data collected annually in late summer by DFO in random-stratified bottom trawl survey of the Scotian Shelf. SS= Scotian Shelf, NFLD = Newfoundland, GSL = Gulf of St. Lawrence.

SKATES			**# RV Sets with species present**	
Species		**COSEWIC Status**	**1975-1985**	**2005-2015**
Smooth Skate	*Malacoraja senta*	Endangered (Funk Island Deep), Special Concern (Laurentian-Scotian)	389	335
Thorny Skate	*Amblyraja radiata*	Special Concern	1088	589
Winter Skate	*Leucoraja ocellata*	Endangered (East SS/NFLD, GSL), Not At Risk (West SS)	210	255
TARGETS			**# RV Sets with species present**	
Species or Complex		**COSEWIC Status**	**1975-1985**	**2005-2015**
Atlantic Halibut	*Hippoglossoides hippoglossus*	Not At Risk	*281*	563
Silver Hake	*Merluccius bilinearis*	Not Assessed	*578*	1375
Redfish	*Sebastes spp.*	Threatened (*Sebastes fasciatus*)	*520*	1153
CHP				
Atlantic Cod	*Gadus morhua*	Endangered	*1154*	1172
Haddock	*Melanogrammus aeglefinus*	Not Assessed	*994*	1475
Pollock	*Pollachius virens*	Not Assessed	*404*	618
Flatfishes				
American Plaice	*Hippoglossoides platessoides*	Threatened	*981*	1421
Witch Flounder	*Glyptocephalus cynoglossus*	Not Assessed	*604*	1150
Yellowtail Flounder	*Limanda ferruginea*	Not Assessed	*475*	851
Winter Flounder	*Pseudopleuronectes americanus*	Not Assessed	*181*	511
		Total Sets	**1595**	**2234**

2.2.2 Environmental data

In addition to the RV set locations, two spatially referenced environmental variables, sea surface temperature (SST) and depth, were included in analysis of RV data to explore the degree to which these variables influence presence of a given species. These covariates were selected as common abiotic factors that predict distribution of demersal fishes (Muetter and Norcross 1999). Thorny skate (*A. radiata*) are known to associate closely with cooler, deeper waters (Sguotti et al. 2016), and both thorny and winter skate (*L. ocellata*) have been shown to occupy greater depths as their abundances have declined (Nye et al. 2009). For analyses examining the years 1975-1985, sea surface temperature (SST) was extracted as a decadal summer mean temperature from World Ocean Atlas (Boyer et al. 2018). High-resolution SST data for years 2005-2015 were derived from NOAA High-Resolution Blended Analysis of Daily SST (NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, https://psl.noaa.gov/) and used in present bycatch risk analyses. Mean August SST (°C) was extracted within the study area at a resolution of 0.25° x 0.25°. Survey tows occur on different days of the month each year, thus I used the monthly mean temperature to reduce computational burden. Although temperature at the seafloor is recorded in the RV survey, there were many missing values making interpolation unreliable. As a proxy, depth (m) values were extracted from the National Oceanographic and Atmospheric Administration (NOAA) ETOPO1 Global Relief Model raster (Amante and Eakins 2009), which is provided at a resolution of 1 arcminute x 1 arcminute (0.0167° x 0.0167°)

Raw values for oceanographic data in their native resolutions are shown in Figure 2.1. All oceanographic data were bilinearly resampled to a common grid with a resolution of 0.1° x 0.1° within the extent of the study area. This spatial scale was used to maximize the resolution of the model output while avoiding over-interpolation of environmental variables and maintaining reasonable computation time in later analyses. All annual SST (°C) raster layers were stacked, and the depth (m) raster layer was replicated for each year in the 2005-2015 analysis (n = 11) and stacked. SST and depth data were compiled to a common covariates file according to *staRVe* package documentation (Lawler 2020). Spatial operations were performed using the *raster* package (Hijmans 2020) in R version 3.6.3 (R Core Team 2020).

2.2.3 At-sea observer data

Because the RV survey employs a bottom trawl, I used data provided from at-sea observer programs from two bottom trawl fisheries: 4X5Ygroundfish bottom trawl (CHP directed) and Unit 3 redfish bottom trawl. Catch data for each species, including the total catch weight, mean catch weight, and total count were provided by DFO, aggregated into two 5-year intervals (2005-2009, 2010-2014) across a 2-arc-minute hexagonal grid. The centroid of each grid cell was extracted to represent the approximate spatial location of the catch (Figure 2.2). For each hexagon, the number of fishing sets was calculated from the summed total weight of catch divided by the mean weight of catch of the primary directed species, the most abundant in the datasets. The total counts (kept and discarded) for each species of skate, number of fishing trips, and corresponding latitude and longitude were extracted from the shapefile at each centroid point for each time interval and each fishery. Data extraction was completed in QGIS version 3.12.0 (QGIS.org 2020), and subsequent operations were performed in R. The kept and discarded counts were summed, and bycatch data were compiled into a data-frame, containing the latitude and longitude for each centroid point, the total number caught for each skate species, and the respective time interval.

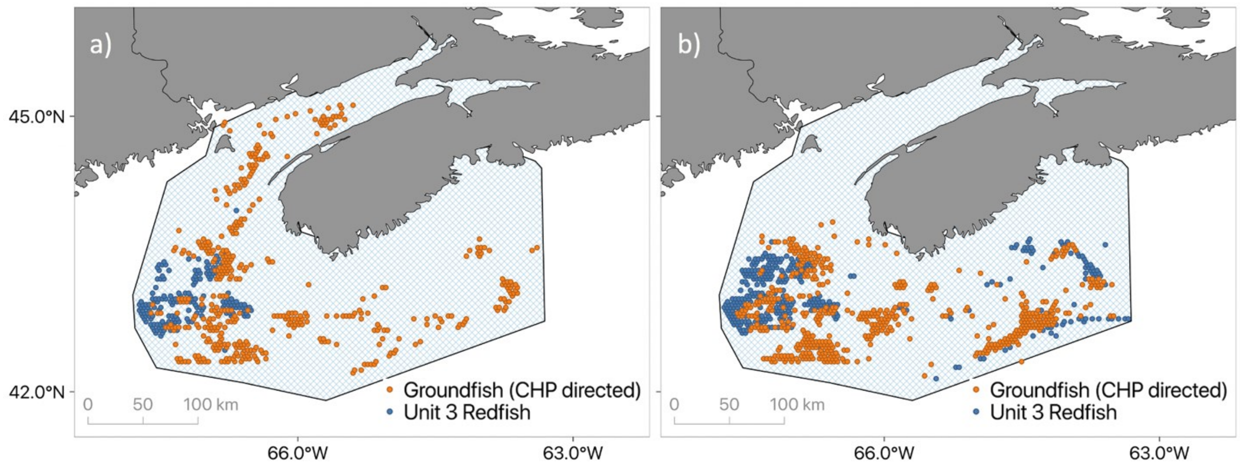

Figure 2.2. At-sea observer locations. Shown are points of at-sea observer records within a subset of the study area, for two directed fisheries used to validate bycatch risk predictions. Symbols represent centroid points from 5 aggregated vessels for the 4VWX groundfish bottom-trawl fishery (CHP, orange symbols) and the Unit 3 redfish bottom-trawl fishery (red symbols), 2005-2009 and 2010-2014.

Species presence (0 = absent, 1 = present) was defined as a count greater than or equal to 1 for each skate species at each centroid point. Although bycatch risk hotspots were analyzed for the Atlantic halibut and silver hake fisheries, predictions were validated using only data from comparable bottom-trawl fisheries to reduce uncertainty due to differences in catchability between gear types. Because the Atlantic halibut fishery employs long-lines and the 4VWX silver hake fishery mandates the use of 40mm separator grates on trawls (Showell et al. 2010), observer data from these fisheries were not included in the analysis. However, Atlantic halibut are still periodically caught and may be retained in bottom-trawl fisheries (Rosalska & Coffen-Smout 2020), and thus their co-occurrence with vulnerable skates is of interest.

2.2.4 Statistical analysis

Generalized linear mixed models (GLMMs) with spatiotemporal random effects were used to predict the distributions of skates and groundfish species on the Scotian Shelf. Models were fit using the *staRVe* package (Lawler 2020) in R. The package interfaces with the Template Model Builder (TMB) package in R and provides estimations of presence and/or abundance of surveyed species in both sampled and non-sampled areas at high resolution and with relatively fast computation time. *staRVe* uses a generalized linear mixed model framework, assuming univariate spatiotemporally referenced point data in continuous space $\mathbf{s}$ and time t. The model is comprised of two components, the first of which is the process model describing presence (or abundance) of a species in space through time via a latent random field, $\mathbf{W_t}$ at location $\mathbf{s}$. The second component is the observation model which captures the RV survey sampling data generating process. The fully realized model is interpreted as a time-series of spatial processes, for which a nearest-neighbour Gaussian process (NNGP) gives spatial structure to the data while maintaining reasonable computation time, where the nearest 10 (or any number of) points inform the response of the next. Note that $\mathbf{W_t}$ is not directly observed and $C(\mathbf{s_1}, \mathbf{s_2})$ represents its spatial correlation:

$$\mathbf{W_t}(\mathbf{s}) \sim \text{NNGP}\ (0, C(\mathbf{s_1}, \mathbf{s_2})). \tag{2.1}$$

Covariate effects, such as those given by environmental or oceanographic covariates, are specified in the model through the term $X_{i,t}(\mathbf{s})ß$, where $X_{i,t}(\mathbf{s})$ is the covariate matrix for observation *i* at time *t* and location **s**, and ß is the vector of covariate effects. μ denotes the non-spatial probability of species presence given the value of the spatial random field $w_t(\mathbf{s})$. $\mu_{i,t}$ represents the expected value of the response distribution for *Y_i,t* and is connected to spatiotemporal random effects and covariate effects through an inverse link function (g^{-1}):

$$\mu_{i,t}(\mathbf{s}) = g^{-1}\ [ß_0 + X_{i,t}(\mathbf{s})ß + w_t(\mathbf{s})]. \tag{2.2}$$

The subscripts *P* and *C* in equations 2.3-2.6 below help to describe the two-part hurdle model used for relative species abundance. A hurdle model was used due to the high frequency of zeroes in catch data (Lewin et al. 2010). The first part models species presence (*P*) probability using a Bernoulli distribution and logit link function. Where oceanographic parameters are included in the analysis, they are denoted by the term $X_{i,t,P}(\mathbf{s})\ ß$. Environmental covariates were included in the presence stage of the model to preserve more data points than would be available from the zero-truncated dataset. $Y_{i,t,P}$ and $y_{i,t,P}$ represent the Bernoulli random variable for presence/absence of the species and realization for the *i*th observation at time t and location **s** and $ß_0$ denotes the intercept value:

$$Y_{i,t,P}(\mathbf{s}) \mid w_{t,P}(\mathbf{s}) = \text{Bernoulli}[y_{i,t,P}(\mathbf{s});\ \mu_{i,t,P}(\mathbf{s})] \tag{2.3}$$

$$\mu_{i,t,P}(\mathbf{s}) = \text{invlogit}[ß_{0,P} + X_{i,t,P}(\mathbf{s})\ ß + w_{t,P}(\mathbf{s})] \tag{2.4}$$

The second part of the hurdle model involves a Gaussian distribution and identity link function for $Y_{i,t,C}$ where $y_{i,t,C}$ is the ith observation of (nonzero) logCPUE at time t and location **s**. σ^2 represents the variance of logCPUE :

$$Y_{i,t,C}(\mathbf{s}) \mid w_{t,C}(\mathbf{s}) = \text{Gaussian}[y_{i,t,C}(\mathbf{s});\ \mu_{i,t,C}(\mathbf{s}),\ \sigma^2] \qquad (2.5)$$

$$\mu_{i,t,C}(\mathbf{s}) = \beta_{0,C} + w_{t,C}(\mathbf{s}) \qquad (2.6)$$

Fitted models were then used to generate predictions for presence probability and logCPUE. In each analysis and for each species of interest, the probability of presence was predicted across the study area on a 0.1° x 0.1° raster grid for all given years as a function of observed values for SST and depth (Figure 2.1c,d). logCPUE was predicted for each year on the same grid. Yearly predicted presence (*Pr*) and predicted logCPUE in each grid cell were multiplied to create annual predictions for total density ($D_{sp,t}$) for each species *sp* at year *t*:

$$D_{sp,t} = Pr_{sp,t}\ x\ e^{logCPUE\ sp,t} \qquad (2.7)$$

Annual estimations of standard error for species density (SE_D) were calculated using equation 8, where *Pr* represents presence probability as predicted from the presence part of the model, *CPUE* represents log catch-per-unit-effort as predicted from the positive catch part of the model, and SE_{Pr} and SE_{CPUE} represent the estimated standard errors of each:

$$SE_D = [\ (SE_{Pr}\ x\ SE_{CPUE}) + (SE_{Pr}\ x\ CPUE) + (SE_{CPUE}\ x\ Pr)\ ] \qquad (2.8)$$

Mean species density ($\overline{D_{sp}}$) in each grid cell was calculated from annual predictions in each grid cell for all species examined in each analysis.

2.2.5 Identification of historical core areas

Separate GLMMs were fit for each species of skate (Table 1) to RV data from the years 1975-1985 using the *staRVe* package. Oceanographic covariates (SST and depth) were included in the presence part of the model. The models were used to generate annual predictions of presence probability and relative abundance for each species across a 0.1° x 0.1° grid over the defined spatial extent. Predicted annual presence and relative abundance were multiplied and mean estimated density was calculated for each skate species for the years indicated. The top 10% of density values were extracted to show important habitat areas for each species.

2.2.6 Identification of bycatch-risk hotspots

Separate models were constructed for each species of skate and commercial target (Table 1) to predict their distributions for the years 2005-2015. Models were fit to RV data, and depth and SST were specified as oceanographic covariates in the presence stage of the model. Annual predictions of presence probability and CPUE were generated across a 0.1° x 0.1° grid over the study area and annual predicted density was calculated using equation 1. Standard error for species densities were calculated using equation 2.

To compare between species, predicted species density was standardized between 0 and 1. Annual bycatch risk ($BR_{sp,t}$) hotspots were then identified by the multiplicative overlap of estimated relative spatiotemporal abundance of at-risk skates with commercial targets. For species that are targeted as multi-species complexes (such as cod-haddock-pollock or flatfishes [Table 1]), annual density estimates for each species in the complex were summed together before being scaled and treated as a single target. Scaled annual density rasters were then summed for all at-risk skates ("Skates"), as well as all targets ("Targets"). Hotspots were defined in two ways: first, a species-at-risk centric approach was taken in order to examine regions of high bycatch risk for one at-risk skate within multiple fisheries. The predicted scaled relative abundance of a single skate species was multiplied with the summed scaled relative abundances for all fisheries targets. For example, a species-at-risk approach to identify bycatch hotspots for winter skate:

$$BR_{W.Skate,t} = D_{W.Skate,t} \text{ x } \sum D_{Targets,t} \tag{2.9}$$

A fisheries-centric approach was secondarily used to generate maps of bycatch risk areas particular to high-value fisheries targets. Here, the target species' relative abundance was multiplied with the summed relative abundance of all at-risk skates. For example, a fisheries-centric approach to identify bycatch risk hotspots for all threatened skates that are particular to the Atlantic halibut fishery is as follows:

$$BR_{Halibut,t} = D_{Halibut,t} \text{ x } \sum D_{Skates,t} \tag{2.10}$$

Standard errors for predicted bycatch risk were estimated by first calculating the standard error for combinations of species ("Skates" and "Targets"; Eq. 2.11) and subsequently calculating standard error for bycatch risk predictions between skates and commercial species (Eq. 2.12). For example, to calculate the standard errors for bycatch risk between winter skate and 9 commercial fisheries targets:

$$SE_{Targets} = \frac{1}{k}\left(\sum_{i=1}^{k} \sqrt{SE_{Target,i}}\right)^2 \quad (2.11)$$

$$SE_{BR} = \sqrt{(D_{Targets}\ x\ SE_{W.Skate})^2 + (D_{W.Skate}\ x\ SE_{Targets})^2 + (SE_{W.Skate}\ x\ SE_{Targets})^2} \quad (2.12)$$

Mean bycatch risk for each skate species ($\overline{BR_{sp}}$) was calculated from annual predictions of bycatch risk in equations 3 and 4. High values in resulting maps indicate where co-occurrence is greater between one or more at-risk skate, and one of more commercial fishing target. All output maps for both approaches were then scaled between 0 (low bycatch risk) and 1 (high bycatch risk).

2.2.7 Proof of concept to validate bycatch hotspots predictions using at-sea observer data

To validate predictions of relative bycatch risk, similar GLMMs were fit to skate presence data from at-sea observers over a subset of the initial study area (Figure 2.2). This model included spatial bycatch risk as a covariate in order to estimate its effect size on predicted skate presence in observed fishing sets. Annual bycatch risk predictions for each species of skate were averaged over two time intervals (2005-2009, 2010-2014), and the 5-year mean value for bycatch risk at that location was extracted for each point in the observer dataset.

A spatiotemporal model was fit to records of skate catch from observer data to model the presence probability of skates as a function of predicted bycatch risk. The time-series contained only two steps; 2005-2009, and 2010-2014, as data were provided by Fisheries and Oceans Canada aggregated over these intervals. Bycatch risk as predicted from RV data was included as a covariate for each respective skate species. Species presence was modelled using the *staRVe* package in R. Estimated presence probability was corrected for the number of observed fishing trips and was modelled using the "atLeastOneBinomial" distribution implemented in the *staRVe* package, with a logit link function to estimate the probability of an encounter in one fishing trip. The parameter estimate for bycatch risk was then extracted from the model output. An estimated value for the bycatch risk parameter greater than zero indicates that fisheries observers have a higher chance of recording bycatch of this skate species, in areas where bycatch risk is predicted to be higher from fisheries-independent RV data.

2.3 Results

2.3.1 Identification of historical core areas

A total of 1595 RV survey trawl sets were completed between 1975-1985. Within these sets there were 1088 records of thorny skate, 210 records of winter skate, and 389 records of smooth skate (Table 2.1). Models fit to these data were used to predict the distribution and density (kg trawl hour^{-1}) of each skate species within the study area during this time period of high groundfish abundance. All species exhibited spatiotemporal variation in presence and density. The top 10% of density values are shown to be important areas of habitat (Figure 2.3). Parameter estimates for SST and depth in historical species presence models varied in effect size and significance (Figure 2.5). Winter skate presence probability was found to be negatively influenced by SST; depth did not significantly impact winter skate presence, nor did SST or depth for thorny and smooth skate presence. Thorny skate was concentrated on Banquereau Bank, with a small additional hotspot in the Bay of Fundy. Winter skate hotspots were present along Sable Island and Banquereau Banks and in the Bay of Fundy. Smooth skate hotspots occurred in several areas along Sable Island and Emerald Banks, Georges Bank and in the Bay of Fundy (locations for reference in Figure 2.1d).

2.3.2 Identification of bycatch-risk hotspots

The number of records of each species within the RV survey dataset for the years 2005-2015 are shown in Table 1. Spatiotemporal models fit to RV data were used to generate predictions of density for skates and target species across the study area (Figure 2.4). Effects of environmental covariates on species presence varied by species (Figure 2.5). Winter skate presence probability was significantly negatively influenced by SST. Depth was shown to have a significant positive influence on presence probability of yellowtail and winter flounders, and negatively influence redfish presence. All other covariate effects were non-significant.

The spatiotemporal distribution for each species was predicted and multi-species co-occurrence trends were mapped to predict potential bycatch hotspots. A species-at-risk approach to evaluating bycatch risk for thorny skate, winter skate and smooth skate revealed spatially explicit bycatch risk hotspots for each species, where co-occurrence with one or more fisheries targets was high (Figure 2.6). Thorny skate bycatch hotspots were detected on Banquereau Bank and in the Bay of Fundy. Winter skate bycatch risk was concentrated in an area near the Fundian Channel and Brown's Bank. Smooth skate bycatch risk was high in the Bay of Fundy and onto the western Scotian Shelf, with a small additional hotspot near the Gully, an extensive submarine canyon east of Sable Island (location references in Figure 2.1d).

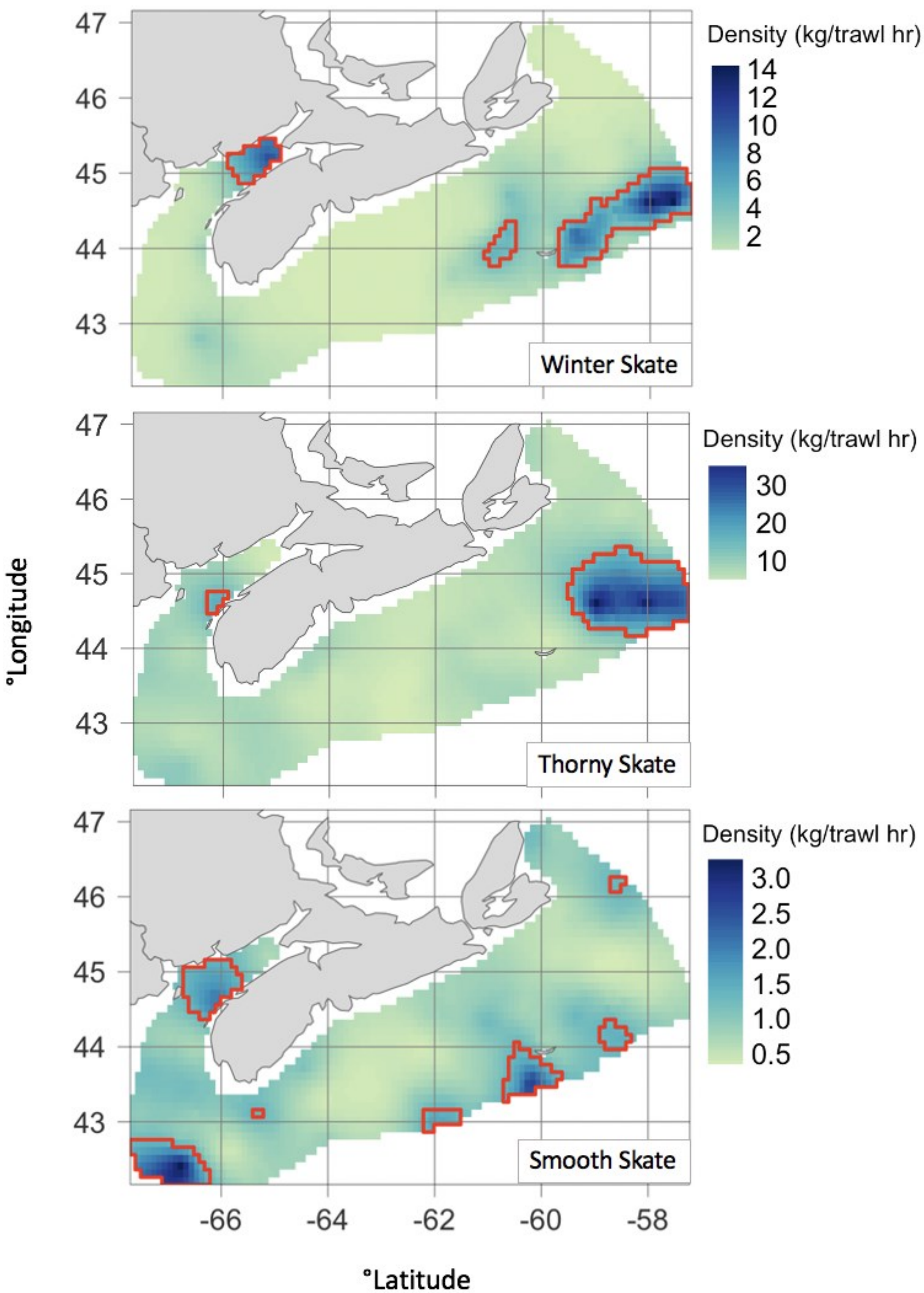

Figure 2.3. Historical species distributions. Shown are mean densities of three at-risk skates (thorny skate, winter skate and smooth skate) within the study area for the years 1975-1985. Red contours represent core habitat shown by the top 10% of density predictions.

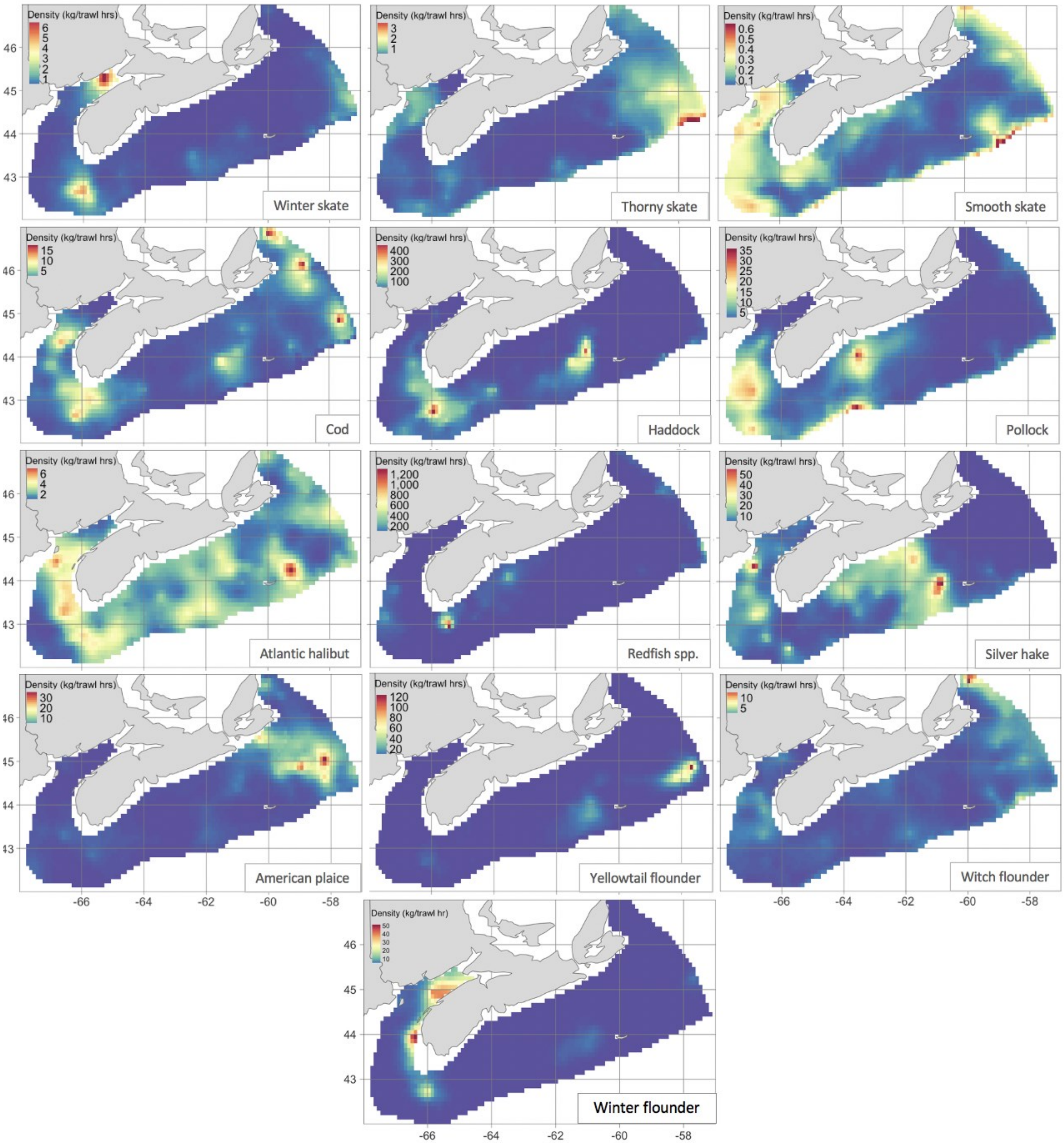

Figure 2.4: Present mean species distributions. Shown is the mean relative density (kg/trawl hour) for each species as predicted from from RV survey data, 2005-2015.

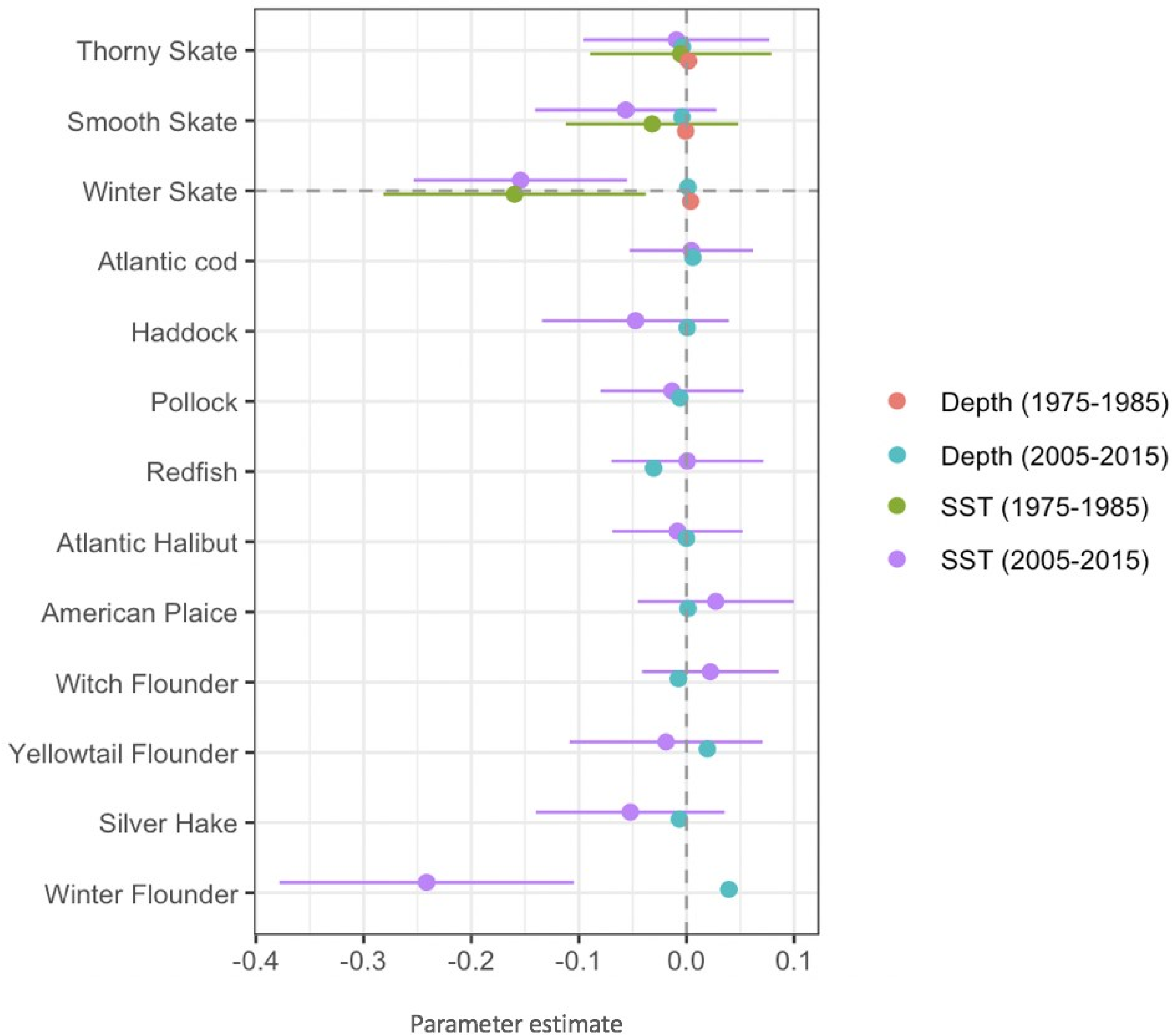

Figure 2.5. Environmental covariates: Shown are point estimates and 95% confidence intervals for depth (red=1975-1985, blue=2005-2015) and sea surface temperature (SST, green=1975-1985, purple=2005-2015) in Bernoulli-distributed presence models fit to RV survey data. Historical models (1975-1985) were fit only for skates, thus paired covariate estimates are shown for those species only.

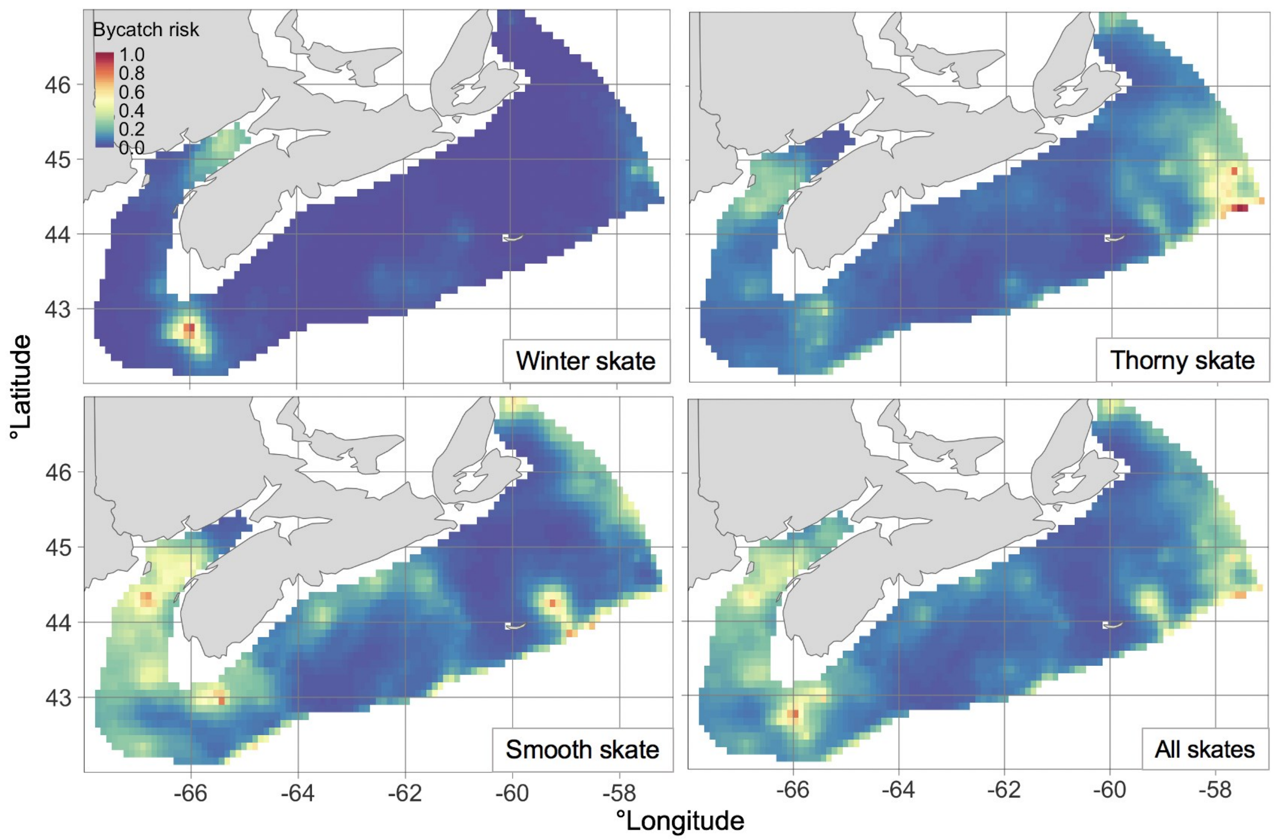

Figure 2.6: Present bycatch risk of threatened species. Shown is the mean relative bycatch risk (2005-2015) within all target fisheries' distributions for three at-risk skate species: thorny skate, winter skate and smooth skate. 'Hotspots' (red) indicate a high degree of co-occurrence between the at-risk skate and one or more target fisheries. Low-risk areas (blue) indicate low co-occurrence between at-risk skates and fisheries targets.

Bycatch risk hotspots in target fisheries were identified (Figure 2.7). Skate bycatch hotspots within the range of Atlantic halibut were identified in the Bay of Fundy/Fundian Channel and The Gully. Hotspots for skate bycatch in CHP-directed fisheries were identified on Brown's Bank, Georges Bank the Bay of Fundy. For redfish, one hotspot was identified north of Brown's Bank. For flatfishes, skate bycatch risk was concentrated on Banquereau Bank. A cumulative map of co-occurrence between all skates and all fisheries targets shows overall hotspots on Browns Bank near the Fundian Channel, in the Bay of Fundy, and along Banquereau Bank (location references in Figure 2.1d)

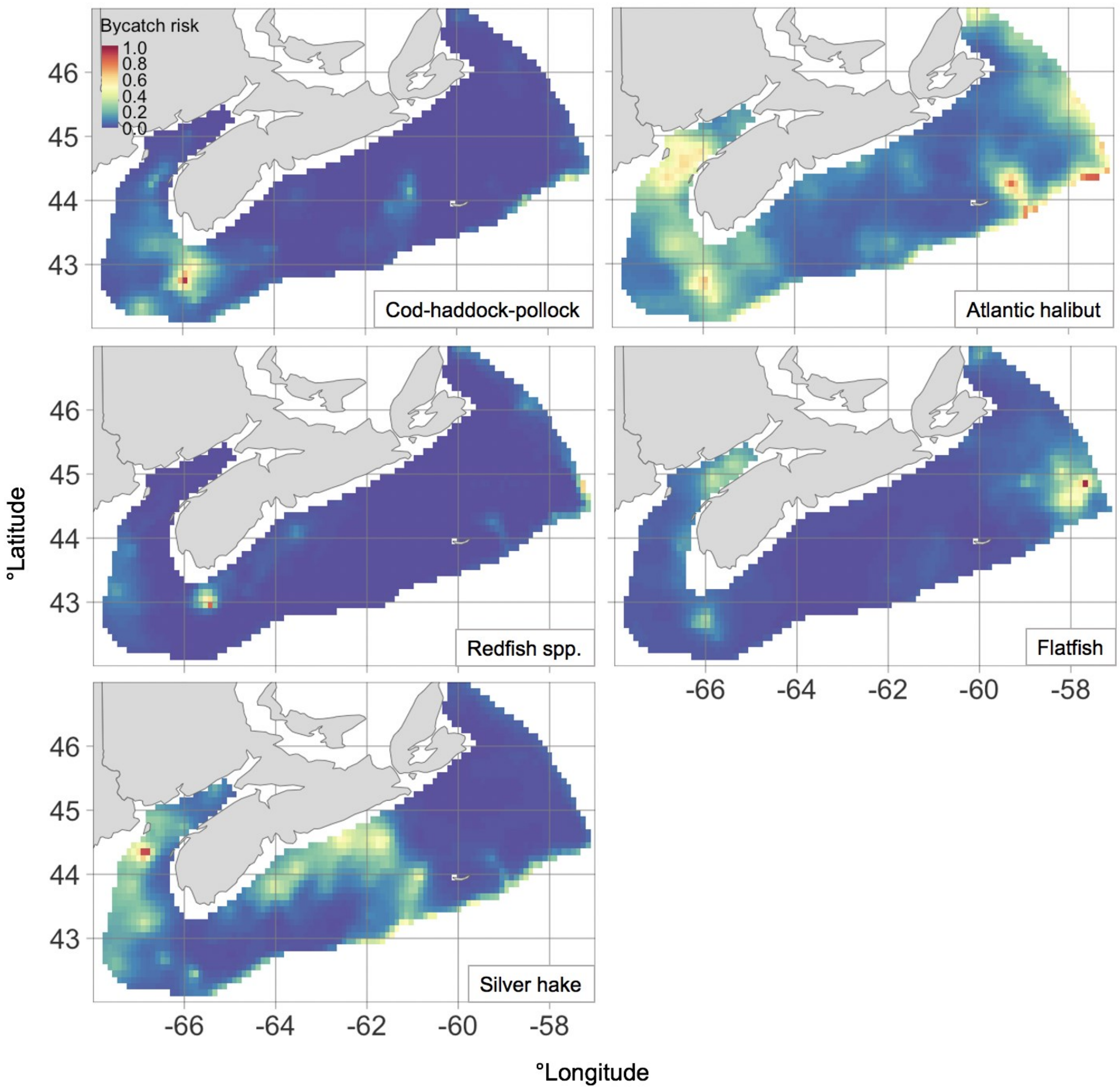

Figure 2.7. Threatened skate bycatch risk for individual target fisheries. Shown is the mean relative bycatch risk (2005-2015) to all threatened skate species within the distribution of 5 target fisheries: Atlantic halibut, CHP (cod/haddock/pollock), redfish, silver hake, and flatfish (witch, yellowtail, and winter flounders). Bycatch risk hotspots (red) indicate a high degree of co-occurrence between the fisheries target and any at-risk skate. Blue areas indicate low co-occurrence between the fisheries target and at-risk skates.

2.3.3 Proof of concept to validate bycatch hotspots predictions using at-sea observer data

A total of 1578 spatially- and temporally aggregated records of skate species presence or absence were represented in the at-sea observer dataset (Table 2.2). Spatiotemporal models fit to at-sea observer records of skate bycatch were used to validate predicted bycatch risk values on the Scotian Shelf. Parameter estimates for bycatch risk are shown in Figure 2.8. The parameter estimate was greater than zero for all skates (winter skate = 3.65, thorny skate = 5.65, smooth skate = 9.64, combined = 4.12)

Table 2.2. Observer dataset sample sizes. Number of aggregated records (i.e., centroid points) from at-sea observers in each directed fishery aggregated June-October for each year in 2005-2009 and 2010-2014.

Target Fishery	2005-2009	2010-2014
4VWX Groundfish	424	528
Unit 3 Redfish	198	428
Total	**622**	**956**

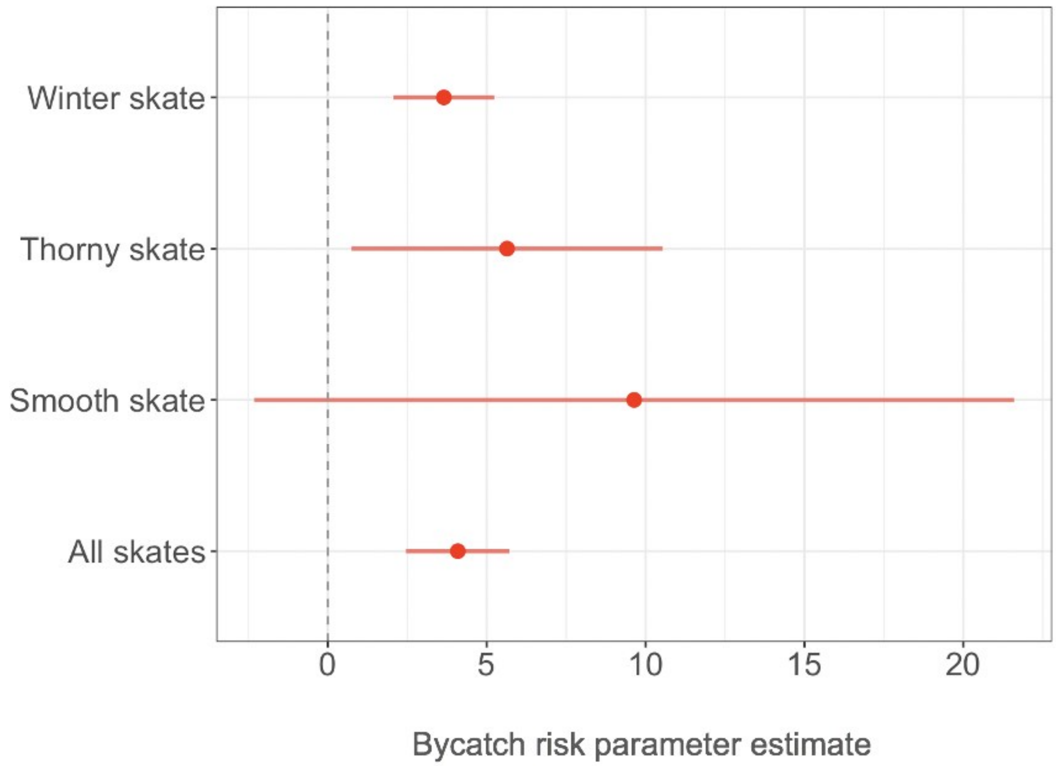

Figure 2.8. Bycatch risk validation results. Parameter estimates + estimated 95% confidence intervals for bycatch risk as a covariate predicting species presence from at-sea observer datasets. Parameter estimates greater than 0 indicate that the likelihood of catching a skate increases in areas where bycatch risk, as predicted from fishery-independent data, is predicted to be high.

2.4 Discussion

This chapter aimed to present a modelling framework to identify spatial areas of conservation priority for depleted species affected as bycatch by multiple fisheries. The framework presented builds on efforts to incorporate data-driven and ecosystem-based fisheries management practices in response to the global overexploitation of fish stocks (Hilborn et al. 2020). This approach was used to identify historical and present habitat areas for three at-risk species of skate (winter skate, thorny skate and smooth skate) as well as present-day bycatch hotspots for those skates within 5 commercial fisheries comprised of 10 species on the Scotian Shelf (Table 2.1).

Current geospatial catch-monitoring data such as those from at-sea observer programs are limited by inconsistent taxonomic identification and observer effects (Benoit 2006) as well as low overall coverage (Clark et al. 2015), thus making use of fisheries-independent data to identify potential conservation hotspots of particular interest. I used a longstanding scientific RV survey dataset and generalized linear mixed models with spatiotemporal random effects to estimate the distribution of skates prior to heavy exploitation in order to map important habitat areas for each species. I then used similar models to estimate the present distribution of skates, as well as 10 commercial target species. Bycatch risk hotspots were identified from the magnitude of co-occurrence between skates and targets. Hotspots were estimated in the context of species-at-risk (Figure 2.6) and in the context of individual fisheries (Figure 2.7). I then validated estimated bycatch risk values using similar spatiotemporal models fit to records of skate bycatch from at-sea observer data. These results demonstrate a widely applicable framework to identify areas of conservation priority for depleted or rare species and support growing interest in employing data-driven, ecosystem-based tools in fisheries management

2.4.1 Identification of historical core areas

For all three species of at-risk skate, historical patterns of high abundance (Figure 2.3) differed from current high-density areas (Figure 2.4) suggesting that skates may have been fished out of those areas during the height of the fishery. There was no difference between the effect sizes of depth and SST between historical and present analyses, however it is possible that these covariates do not vary sufficiently within the study area to detect any potential impacts of temperature or depth.

For both thorny skate and winter skate, historically important habitat was identified on Banquereau Bank, a region which has been heavily impacted by a surf-clam dredge fishery since 1986 (Roddick et al. 2007). Both species were also affected heavily as bycatch on the eastern Scotian Shelf following the expansion of Canadian inshore fisheries. Thorny skate was highly co-occurrent with cod around Banquereau Bank from the late 1970's to early 1990's, and areas occupied by thorny skate on Banquereau Bank were eroded due to directed fishing effort (Shackell et al. 2005). Although harvest moratoria for groundfish on the eastern Scotian Shelf were introduced in 1993 (Bundy 2005), thorny skate and winter skate abundance remains low on Banquereau Bank and current areas of high density are primarily along the edge of the bank (Figure A1). Several causes for a lack of recovery of skate on the eastern Scotian Shelf have been investigated, including increased predation by a recovering population of grey seals (Swain et al. 2019). However, the ongoing surf clam dredge fishery reduces the forage base and greatly alters the affected seabed (Gilkinson et al. 2003). As such, core habitat for thorny skate and winter skate may have been altered in a significant way, particularly for two species who prey largely on benthic invertebrates.

2.4.2 Identification of bycatch risk hotspots

There are increasing efforts to identify the spatial patterns and drivers of bycatch using spatiotemporal distributions of co-occurring species (Ward et al. 2015, Hazen et al. 2018) This was recently highlighted by Runnebaum and colleagues (2020) where fishery-independent data was used to generate predictions of habitat suitability, and bycatch hotspots were inferred from overlapping suitable habitat between American lobster (*Homarus americanus*) and cusk (*Brosme brosme*). In multi-species groundfish complexes, species at risk may be exploited in multiple target fisheries, therefore a more comprehensive approach to identification of bycatch hotspots is necessary. The main objective of this chapter was to present a framework to evaluate spatial patterns of bycatch risk for a data-limited species exploited by multiple fisheries in a given region. These results demonstrate a framework that can be applied on a dynamic temporal basis to identify and address changes in bycatch risk between fishing seasons and evaluate the efficacy of spatial fisheries closures or protected areas. This framework can provide an additional tool to fisheries managers and conservation authorities to examine relative bycatch pressure and protect vulnerable species within multiple fisheries.

Both a species-at-risk approach and a fisheries-centric approach were taken to identify bycatch risk hotspots for threatened skates. Though the primary interest of this thesis was to identify bycatch hotspots pertaining to species at risk (Figure 2.6), an alternative approach presenting bycatch hotspots for a group of species at risk within a target fishery may be of particular interest to fisheries managers (Figure 2.7). A cumulative map of co-occurrence between at-risk species and target fisheries (Figure 2.6) is useful to show a general overview of bycatch risk patterns for a group of closely associated species or functional groups, such as skates, which are not reliably separated and identified in available fisheries data (Benoît 2006, DFO 2021[a]). Results from both approaches suggest that bycatch hotspots for at-risk skates are largely dependent on discrete high-density areas for those skates. Winter skate shares a bycatch hotspot with hotspots identified in the Atlantic halibut and CHP distributions (Figures 2.6, 2.7). From comparing the results of both approaches, one can surmise that in this area, skates recorded as bycatch within those fisheries would likely be winter skate. However, realized bycatch risk can only be inferred when results are examined within the full context of the fishery. For example, smooth skate shares a bycatch hotspot with silver hake in the outer Bay of Fundy (Figures 2.5, 2.6). In reality, harvesters in the 4VWX silver hake bottom trawl fishery are required to affix separator grates with 40mm spacing bars to their gear intended to reduce bycatch of larger demersal fish, and skates represented less than 0.05% of observed bycatch in this fishery from 2000-2009 (Showell et al. 2010). Similarly, although bycatch hotspots were identified in areas of the eastern Scotian Shelf for some skates and fisheries, commercial fishing effort in these areas is greatly limited since the introduction of harvest moratoria in the 1990s and realized bycatch risk is likely small. Actual spatial patterns of true bycatch risk are more informative when the results of this framework are examined alongside the spatial footprints of fishing effort.

These results build on a growing body of work supporting data-driven and ecosystem-based approaches to spatial conservation and fisheries management. The information that fisheries managers can extract from these methods has broad applications, from near-real time direction of fishing effort away from high-risk areas (O'Keefe & DeCelles 2013) to informing and evaluating the efficacy of static or dynamic fisheries closures (Hazen et al. 2018).

2.4.3 Proof of concept to validate bycatch hotspots predictions using at-sea observer data

Many fisheries management jurisdictions employ at-sea observer programs to directly record kept and discarded species, however these data can be limited in coverage and taxonomic resolution (Benoit 2006, Clark et al. 2015). In Atlantic Canada, at-sea observer data is screened and aggregated for every 5 fishing vessels in order to protect the privacy of individual harvesters (Butler & Coffen-Smout 2017). Nonetheless, it is important to examine the relationship between estimated regions of high bycatch and points where bycatch was empirically recorded, and presented here is a proof-of-concept analysis to validate predictions of bycatch risk against observed records of skate bycatch using the *staRVe* package.

Bycatch risk as predicted from fishery-independent data was included as a spatiotemporal covariate in order to determine the size of its effect on predicting species presence in an at-sea observer dataset. For all three skates (winter skate, thorny skate and smooth skate, and combined), the effect size of bycatch risk was estimated to be greater than 0. These values indicate that the probability of catching a skate increases in areas where bycatch risk is predicted, from fisheries-independent data, to be higher. Notably, observer-derived data for the bottom-trawl fishery does not extend to the regions where bycatch risk is predicted to be highest for two skate species (thorny skate and smooth skate, Figure 2.6). Despite this and the limitations of the at-sea observer dataset, a positive effect of bycatch risk was still observed to predict presence of those species in observed catch. In this analysis, *staRVe* did not incorporate restricted spatial regression to adjust for spatial confounding, where covariates and random effects have a similar spatial structure (Hanks et al. 2015). The unadjusted parameter estimates for bycatch risk are therefore conservative, which increases confidence in the positive effect sizes for bycatch risk that were identified for the thorny skate and smooth skate.

In addition to uncertainties introduced by the limitations of at-sea observer datasets, the degree of uncertainty for the estimation of the bycatch risk covariate effect is difficult to ascertain. Standard errors for bycatch risk predictions were calculated under the assumption that species distributions are independent of each other, which is almost certainly untrue in reality, and which results in estimated standard errors that are too uncertain to avoid criticism. For this reason, this analysis is currently presented as a proof-of-concept to validate bycatch risk predictions.

Another limitation is that of seasonality. This chapter used data from a survey that is conducted annually in the summer, thus I cannot reliably estimate bycatch risk during other months. Several groundfish species on the Scotian Shelf undergo seasonal migrations to deeper waters (Swain et al. 1998, Methratta & Link 2006). While the majority of observed fishing trips occur in May through July (Themelis & den Heyer 2015), the groundfish season is open year-round. Predictions of bycatch hotspots along with observations based on a single season may not fully reflect the annual patterns of bycatch. This caveat may be addressed in regions or jurisdictions in which seasonal surveys are conducted. The availability of comprehensive data for a given fishery or region may improve over time, but likely not until bycatch mitigation becomes a priority for fisheries regulatory agencies.

2.5 Conclusion

Furthering global understanding of the spatiotemporal distribution of bycatch can support conservation efforts for many species at risk and help support economically viable fisheries. Oceanographic processes and their associations with species are non-stationary (Myers 1998), and the waters of the northwest Atlantic around the Scotian Shelf in particular are warming rapidly (Saba et al. 2016). Making use of dynamic tools that incorporate near-real time environmental data will be critical in engaging in ecosystem-based fisheries management in the face of climate change. Many fisheries management bodies employ research surveys to monitor abundance of fish stocks, and these methods provide a framework to assess relative spatial bycatch risk independent of fisheries landings or observer data. While no model is perfect, these frameworks are adaptable to the advancement of statistical techniques and the availability of new data. The methods presented in this chapter can be used to support ongoing efforts to include more dynamic approaches to ecosystem management and may thereby help to ensure the long-term sustainability of fisheries in a changing climate.

Chapter 3 - From policy to practice: Addressing bycatch for species at risk in Canada

3.1 Introduction

3.1.1 Bycatch policy in Canada

Regulatory bodies are increasingly aiming to address bycatch, often in response to a legal mandate to rebuild endangered, threatened and protected species' populations (Holland & Martin 2019, Hutchings et al. 2020). 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 (Bush et al. 2013), and such pressure can help drive management reforms (Schiller & Bailey 2021).

In direct response to ongoing bycatch challenges, the Canadian government introduced the Policy for Managing Bycatch (DFO 2013) under the Sustainable Fisheries Framework, with a goal to address broader and collateral negative impacts of commercial fishing, including incidental bycatch. This policy tool is intended to guide DFO in developing ecosystem-based fisheries management plans with bycatch mitigation as a priority objective (DFO 2013). To date, however, bycatch often remains poorly understood and inadequately addressed in many Integrated Fisheries Management Plans (IFMPs; McDevitt-Irwin et al. 2015, Boudreau et al. 2017). 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 (Babcock et al. 2003, Gavaris et al. 2010, Boudreau et al. 2017). 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 (Gavaris et al. 2010). These factors lead to many fishing trips, and consequently bycatch encounters, remaining unobserved, and estimates of bycatch mortality remain uncertain (Boudreau et al. 2017).

Many non-target species that are impacted by commercial fisheries in Canada have been identified as at-risk to some degree by COSEWIC. While efforts are made to protect COSEWIC species they are typically not the subject of conservation action unless listed for federal protection under the Species at Risk Act (SARA). 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 (Archibald et al. 2020, Hutchings et al. 2020). 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 (Bill C-68, 2019). Although bycatch is not explicitly addressed in the new legislation, there are many non-target groundfish species subject to incidental commercial catch whose populations are well below biomass levels observed prior to the collapse of groundfish (Bundy 2005) and require decisive action (Shackell et al. 2021).

3.1.2 Current strategies, knowledge gaps, and the need for new tools

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) (Cox et al. 2007, Senko et al. 2014, Schram et al. 2019). 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 OECMs (DFO 2020[a]). 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 the spatiotemporal domains of bycatch spatially and over time (Gavaris et al. 2010). Observer coverage within Atlantic Canadian groundfish fleets averages less than 10% (Clark et al. 2015), well below the recommended 50% coverage necessary to make reliable estimates of bycatch (Babcock et al. 2003). In these cases, the most complete and accurate data, especially for affected groundfish, derive from annual scientific bottom trawl surveys.

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 vulnerable by COSEWIC. Although they have declined in some regions by up to 98% from historical abundances (DFO 2017[a,b]), no skate species in Canada has been afforded a proper stock assessment model, and limit reference points (LRPs) are represented by proportions of their long-term mean biomass as proxies (DFO 2018). Skates on the Scotian Shelf are in dire need of proactive, precautionary management strategies to better inform and mitigate bycatch in commercial fisheries. These approach discussed in this chapter will utilize existing scientific survey data and predicted spatial bycatch risk to address this gap. Such an approach can aid fisheries managers in prioritizing bycatch mitigation strategies for vulnerable species as part of Canada's marine conservation objectives. These approaches can be used in conjunction with other sources of information to support MPAs and OECMs aimed at protecting marine biodiversity and species at risk.

3.1.3 Objectives of Chapter 3

In this chapter, I present methodology for assessing the risk to, and conserving, vulnerable species based on bycatch risk predicted from scientific survey data. This method is based on the observation in Chapter 2 and in primary literature that spatial relationships between target and bycatch species can predict patterns of bycatch interactions (Ward et al. 2015, Runnebaum et al. 2020, Stock et al. 2020). 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 (Campbell et al. 2017, Hastings et al. 2017), with a particular focus on data-deficient or rare species where bycatch can't be accurately estimated.

This chapter first applies such a bycatch risk assessment framework to the case of three vulnerable skate species in need of urgent management attention on the Scotian Shelf, using fisheries-independent data sources. From there, the reduction in bycatch risk generated by closing fractions of the fished region was estimated. Finally, this chapter used identified potential closures to estimate the costs to fishing industry that these potential closures might bring about.

3.2 Methods

3.2.1 Study area and species

In late summer every year, DFO conducts an 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 50-500m, and each trawl is conducted at a speed of 3 knots for approximately 30 minutes. In 2018, only the western half of the Scotian Shelf was sampled. This corresponded to NAFO divisions 4X5Z, where the majority of bottom-trawl landings on the Scotian Shelf are caught (Rozalska & Coffen-Smout 2020). In this chapter, data from the years 2015-2019 were used to directly compare to the most recently available commercially-derived fisheries data. Data from bottom-trawl fisheries are highly concentrated on the western portion of the Scotian Shelf, thus the study area covers the western portion 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 (Figure 3.1).

The groundfish community of the Scotian Shelf and surrounding area has been harvested for centuries (Lear 1998). Today, fisheries operate using both fixed (e.g., longlines) and mobile gear types (e.g., bottom trawls). This chapter will focus on bottom-trawl fisheries targeting several groundfish species. The majority of bottom-trawl fishing occurs on the western Scotian Shelf corresponding to NAFO divisions 4X5Z (Rozalska & Coffen-Smout 2020), following the introduction of harvest moratoria on the eastern Scotian Shelf in the 1990s (Bundy 2005). Most landings from these fisheries are comprised of haddock (*Melanogrammus aeglefinus*), pollock (*Pollachius virens*) and cod (*Gadus morhua*), often referred to as the “CHP complex”. Other primary targets include redfish (*Sebastes spp.*), silver hake (*Merluccius bilinearis*) and winter flounder (*Pseudopleuronectes americanus*) (DFO 2021[a]).

Groundfish harvesting by bottom-trawl on the western Scotian Shelf involves a variety of non-target species (Peacock & Anand 2008), including winter, thorny and smooth skates whom COSEWIC has designated as at-risk species (Table 3.1). Bycatch of skates in bottom-trawl fisheries is estimated to be high when fleets target the CHP complex, redfish and flatfishes (DFO 2017[a,b]), although the use of separator grates in the silver hake fishery reduces skate bycatch to negligible levels (Showell et al. 2010). In this chapter, the bycatch risk was assessed for vulnerable skates within 5 primary commercial target species caught by trawl in fleets that do not employ gear modifications (Table 3.1).

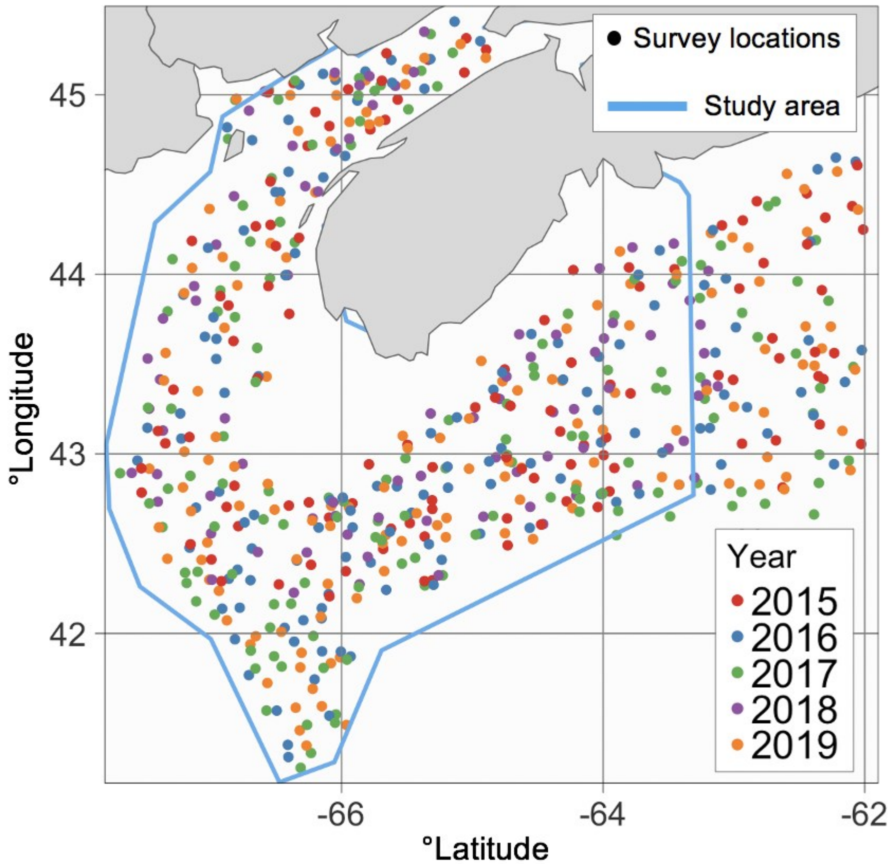

Figure 3.1. Study area. Shown are the locations of each Research Vessel survey tow by year, 2015-2019.

3.2.2 Data

The present study uses RV survey data from the years 2015-2019. 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. I 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 (Figure 3.1). 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.

SST (°C) and depth (m, as a proxy for bottom temperature) were included in species distribution models. These covariates are used as common abiotic factors that predict the distributions of several groundfish (Muetter and Norcross 1999). High-resolution SST data for the years 2015-2019 was extracted from NOAA High-Resolution Blended Analysis of Daily SST (NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, https://psl.noaa.gov/). Mean August SST (°C) was extracted within the study area at a resolution of 0.25° x 0.25° for each year. Depth (m) values were extracted from the NOAA ETOPO1 Global Relief Model raster (Amante and Eakins 2009), which is provided at a resolution of 1 arc-minute x 1 arc-minute (0.0167° x 0.0167°). Environmental data was bilinearly resampled to a common grid of 0.1° x 0.1° for use in species distribution modelling.

In addition to scientific survey and environmental data, I also considered commercial landings of groundfish by bottom trawl fleets, provided by DFO's Maritime Fisheries Information System (MARFIS) database. All bottom-trawl groundfish landings by weight were extracted in the summer months (June-October, inclusive) within the 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 (Methratta & Link 2006, Smith et al. 2015). 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.

3.2.3 Bycatch risk analysis

Bycatch risk for all three skates was calculated within the study area for the years 2015-2019 following the framework from Chapter 2. Recall that 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. Chapter 2 validated that the relative degree of co-occurrence between target and non-target species is predictive of species 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.

All analyses were conducted using R (version 3.6.3, R Core Team 2020). Models for species presence and abundance were fit using the R package *staRVe* (Lawler 2020). Individual species distributions were predicted separately using two-stage generalized linear mixed models ('hurdle' models). The first stage modelled species presence (non-zero) versus absence (zero) using a Bernoulli distribution and log link function. The second stage modelled species abundance (logCPUE) from non-zero catches only, using a Gaussian distribution and identity link function. Environmental covariates SST and depth were specified in the presence stage of the model.

Predictions for presence and abundance were generated over the study area on a 0.1°x 0.1° grid. Local abundance was estimated using the exponential of logCPUE. For each species considered individually, predicted presence probability and abundance were multiplied to estimate local density. Species densities were subsequently scaled between 0-1 to compare relative distributions between all species. For species that are commonly targeted as a complex in bottom trawl fisheries (e.g., cod-haddock-pollock complex, Table 1), the original unscaled densities for all members of the complex were summed together before being scaled (0-1) and treated as a single target. All skate species densities were also first summed and subsequently scaled in order to predict bycatch risk for all three vulnerable skates together against target species.

Bycatch risk (BR) across the study area in each year (t) for each species of skate was calculated from the relative density (D) of the skate multiplied by the relative summed densities of all targets, using the equation from Chapter 2:

$$BR_{Skate,t} = D_{Skate,t} \, x \sum D_{Targets,t} \tag{3.1}$$

Following Eq. 3.1, the resultant values for BR were again scaled between 0-1, where 0 represents low co-occurrence between skates and targets (and thus low bycatch risk), and 1 represent high co-occurrence between skates and targets and consequently high bycatch risk.

3.2.4 Bycatch risk mitigation framework

'Bycatch risk reduction' for the purpose of this study is defined as the percent (%) reduction in the total bycatch risk of a species in a region following a given spatial closure, compared to the same region with no closed areas. The response of bycatch risk reduction to area closures was plotted, where closures were focused precisely on hotspots for each skate species. Potential closure zones at increasing levels of risk reduction were then mapped for each skate species individually and grouped. Finally, costs to industry at increasing levels of risk reduction were approximated by overlaying these zones with spatially referenced commercial landings data and approximating the fraction of landings by weight that would be displaced.

Bycatch risk was calculated for all skates individually and combined between 2015-2019. 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 removed from the grid in steps of 0.05 (e.g., all cells where the bycatch risk value ≥ 0.95 are removed, then all cells where bycatch risk value ≥ 0.90, and so forth) until the highest remaining value was 0.1, after which cells were removed in steps of 0.02. At each step, the sum of remaining cells was recorded to determine percent bycatch risk reduction from the baseline. The difference in approximate area 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 increasing fractions of area closed for each species of skate, individually and together.

Bycatch risk reduction responses were then used to approximate the upper limit of bycatch risk values that would provide a specific level of benefit. 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 benefit were extracted and converted to polygons. These polygons corresponded to the size and geography of the closure that would provide that level of risk reduction.

Spatial polygons representing potential closed areas were mapped for skates at each level of risk 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 risk reduction for each skate individually and together.

3.3 Results

A total of 491 RV survey tows were completed between 2015-2019 across the western Scotian Shelf study area. The number of tows in which each species was present are shown in Table 3.1. Individual species distributions modelled from RV data are shown in Figure 3.2. Each species showed varying levels of abundance across the study area. Environmental covariates had weak predictive strength on species presence (Figure 3.3), however winter flounder exhibited a significant and negative relationship with SST. Bycatch risk within bottom-trawl fisheries was predicted for at-risk skates individually and together, and risk hotspots were identified in different locations for each species of skate (Figure 3.4).

Bycatch risk reduction was expressed as a function of increasing fractions of the study area closed to fishing (Figure 3.5). Each species showed comparable trends in bycatch risk reduction with increasing proportions of area closed to fishing. When winter skate was evaluated individually, intermediate risk reduction required a smaller fraction of area closed when compared to individual species trends. At the lower and upper ends of bycatch risk reduction, trends between skates individually and combined were similar. In all cases, closing only 20% of fishable area resulted in a bycatch risk reduction of at least 50%, however the location of this 20% area varied by species.

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 percent reduction. The percentage of landings by weight that would be displaced from each polygon closure is shown in Figure 3.7. For all analyses, 10% and 25% bycatch risk benefits resulted in less than 1% of landings displaced on average (0.1 $\pm$ 0.05% and 0.58 $\pm$ 0.29%, respectively). Reducing bycatch risk by 25% or less resulted in small but variable displaced landings, depending on the size and location of the polygon with respect to local catch (Figure 3.6). A bycatch risk reduction of 50% in all cases resulted in less than 10% of landings displaced, where average displacement for all cases 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, with mean displaced landings a risk reduction of 75% found to be 59.4 $\pm$ 29.7%.

Table 3.1. Study species and samples 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 (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			**RV Survey Records**
Species		**COSEWIC Status**	**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			**RV Survey Records**
Species or Complex		**COSEWIC Status**	**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**

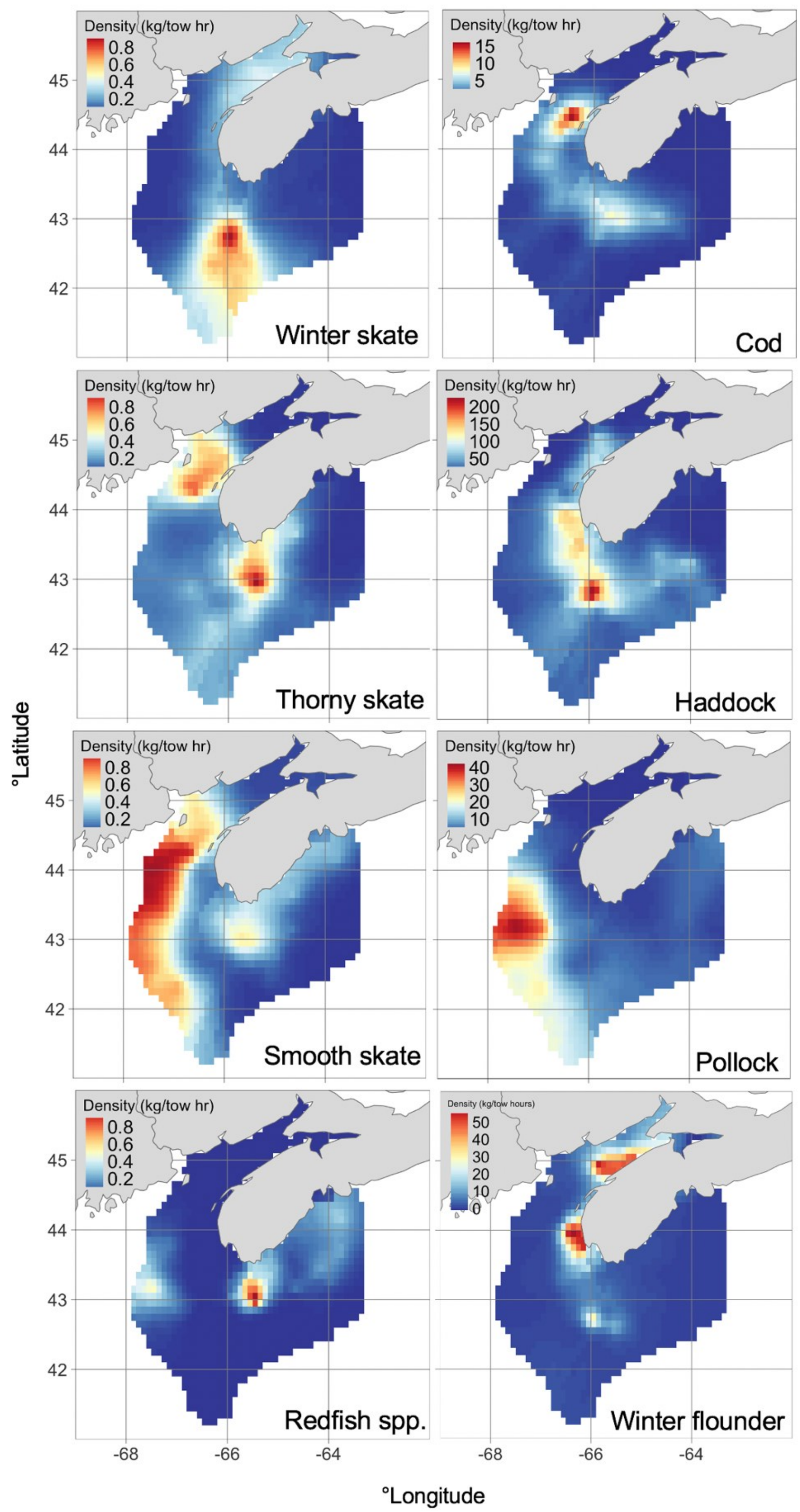

Figure 3.2. Species distributions. Shown are the mean estimated distributions of three at-risk skate species and 5 major bottom-trawl target species for the years 2015-2019.

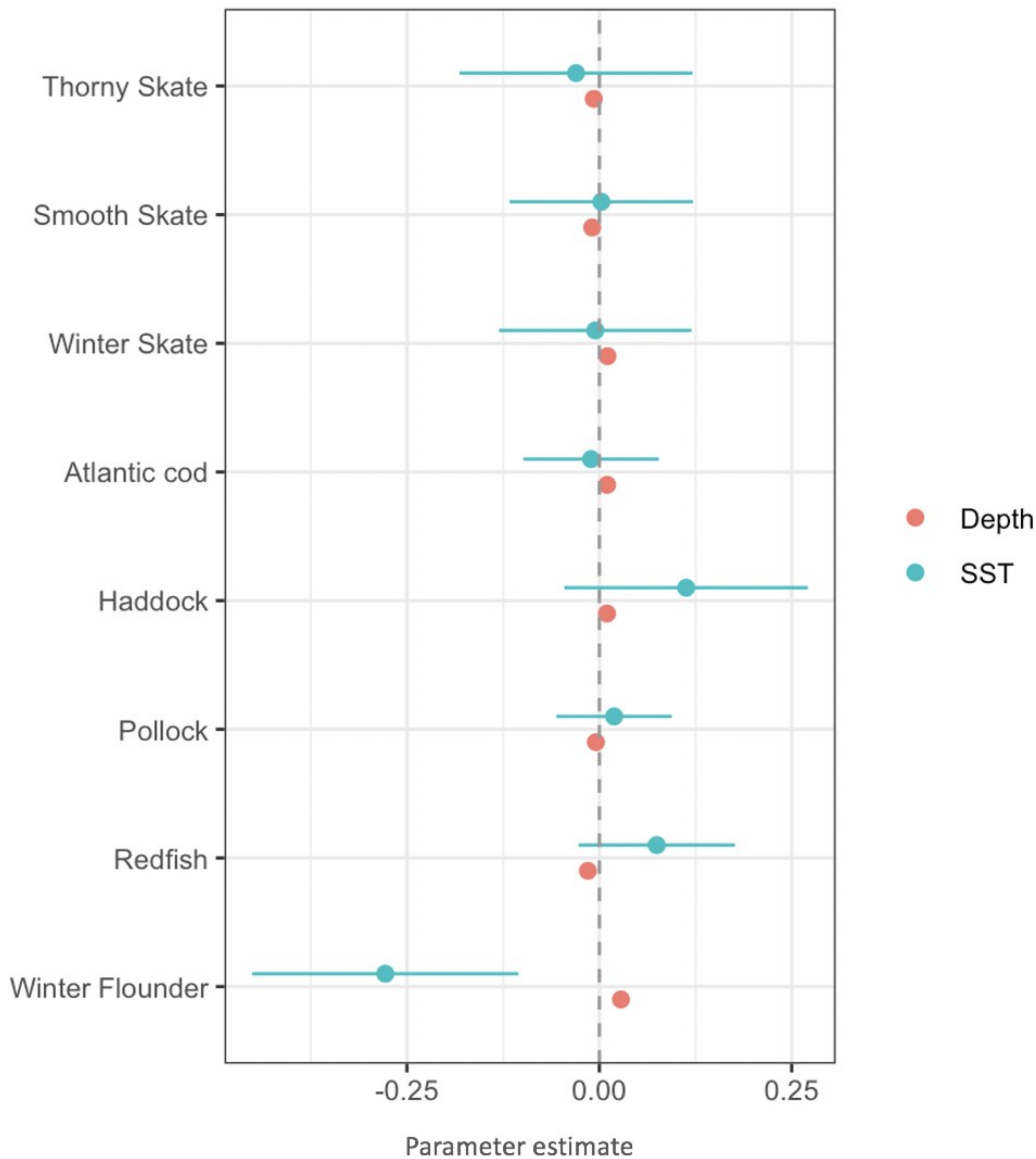

Figure 3.3 Environmental covariates: Shown are point means and 95% confidence intervals for parameter estimates depth (red symbols) and sea surface temperature (SST, blue symbols) in Bernoulli-distributed presence models fit to RV survey data, 2015-2019.

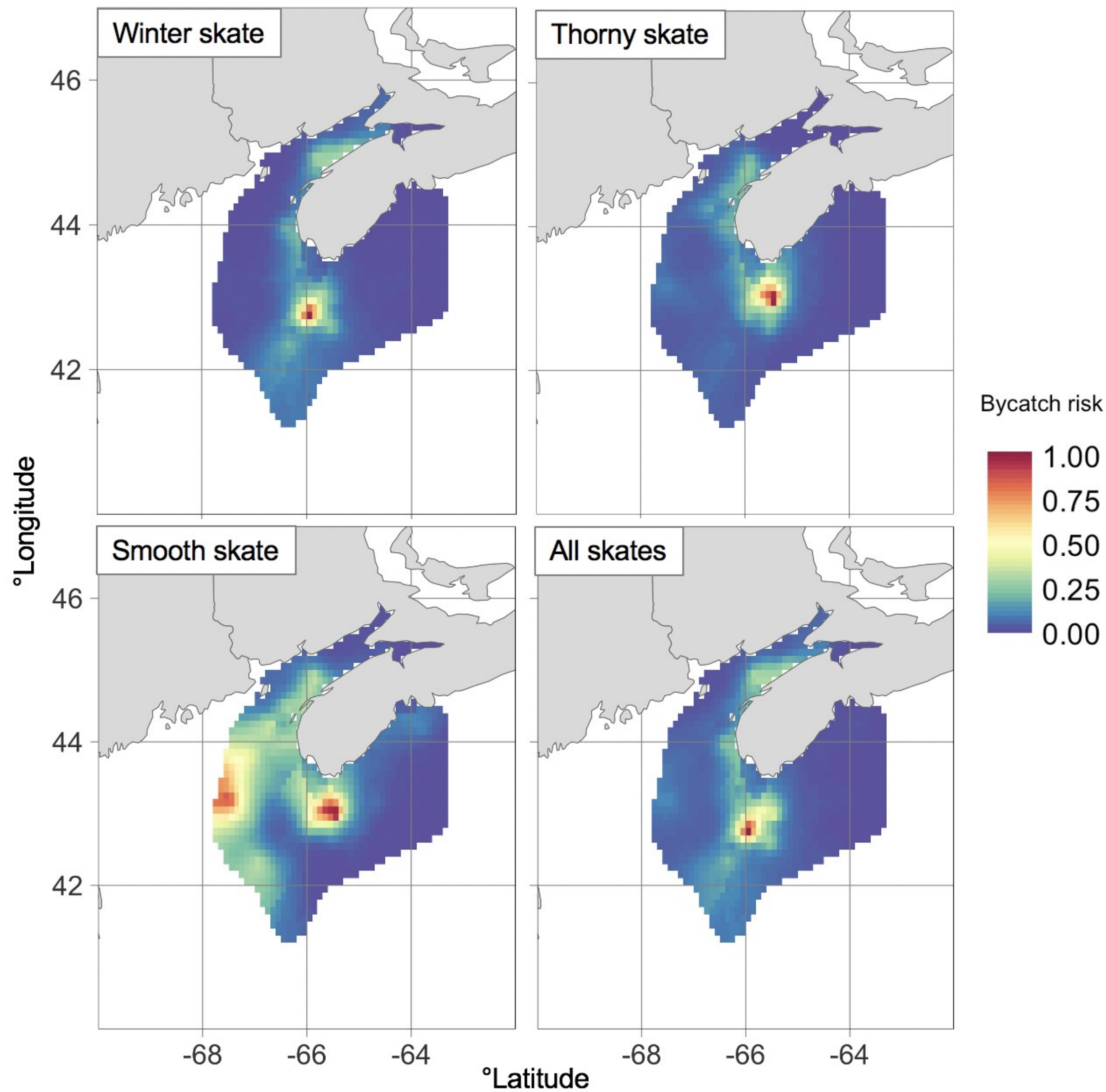

Figure 3.4: Bycatch risk of threatened skates. Shown is the mean relative bycatch risk (2015-2019) within target fisheries' distributions for three at-risk skate species: thorny skate, winter skate and smooth skate. 'Hotspots' (red) indicate a high degree of co-occurrence between the at-risk skate and one or more target fisheries. Low-risk areas (blue) indicate low co-occurrence between at-risk skates and fisheries targets.

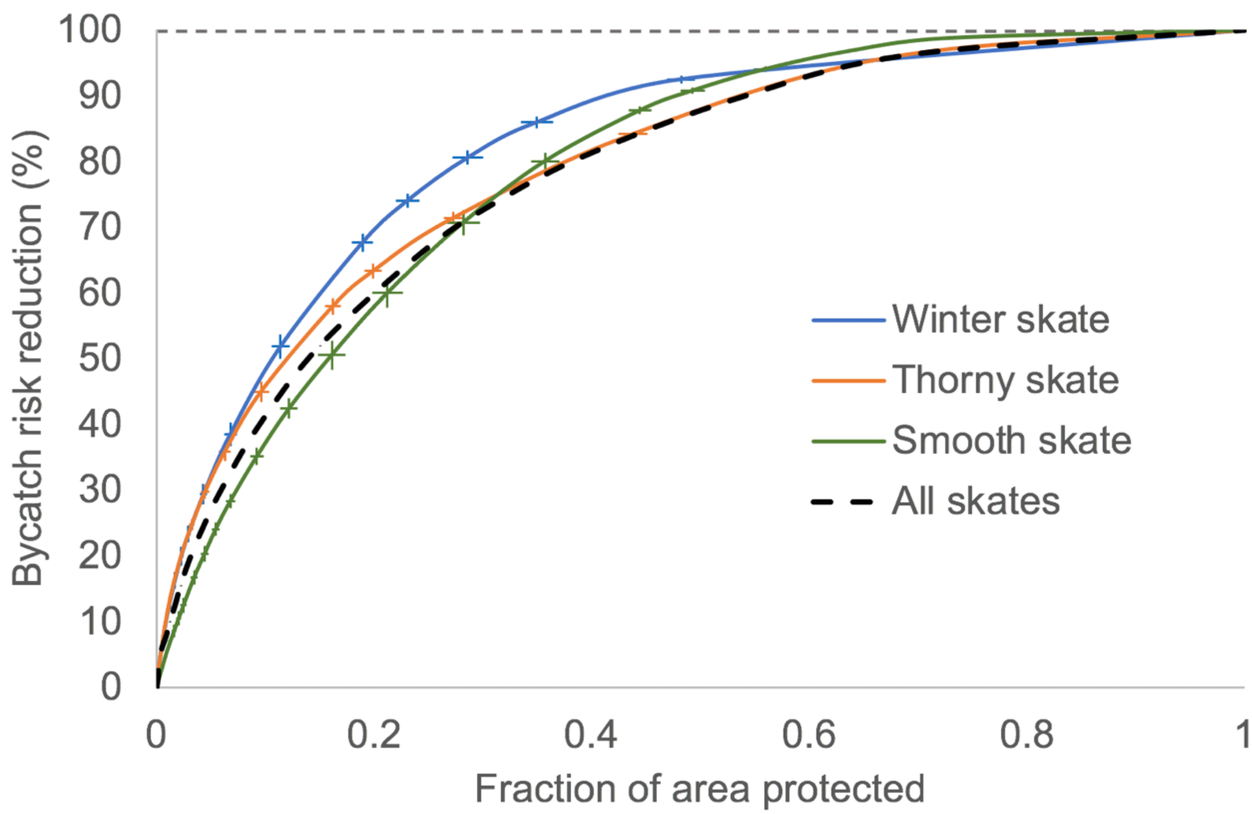

Figure 3.5. Bycatch risk reduction by area closures. Bycatch risk benefit is defined as the percent (%) reduction in sum total bycatch risk across the study area that arises from closing increasing fractions of area across the region (see Fig. 3.5).

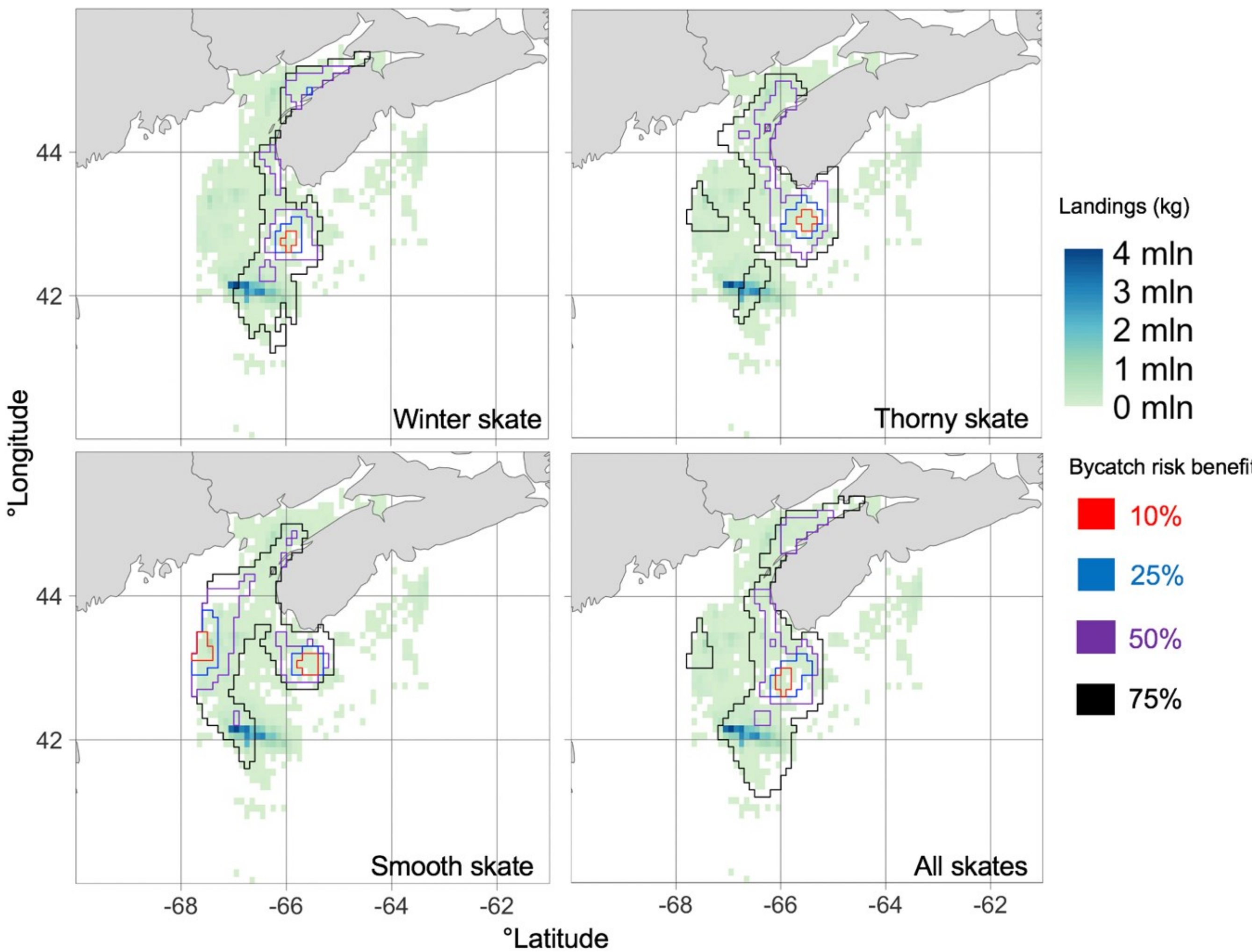

Figure 3.6. Area closures to reduce bycatch risk. Shown are polygons representing potential management areas required to be closed to bottom trawl fisheries in order to reduce bycatch with increasing effectiveness (red= 10% reduction, blue = 25% reduction, purple = 50% reduction, black = 75% reduction). Polygons are overlaid with color-coded total bottom-trawl landings, 2015-2019.

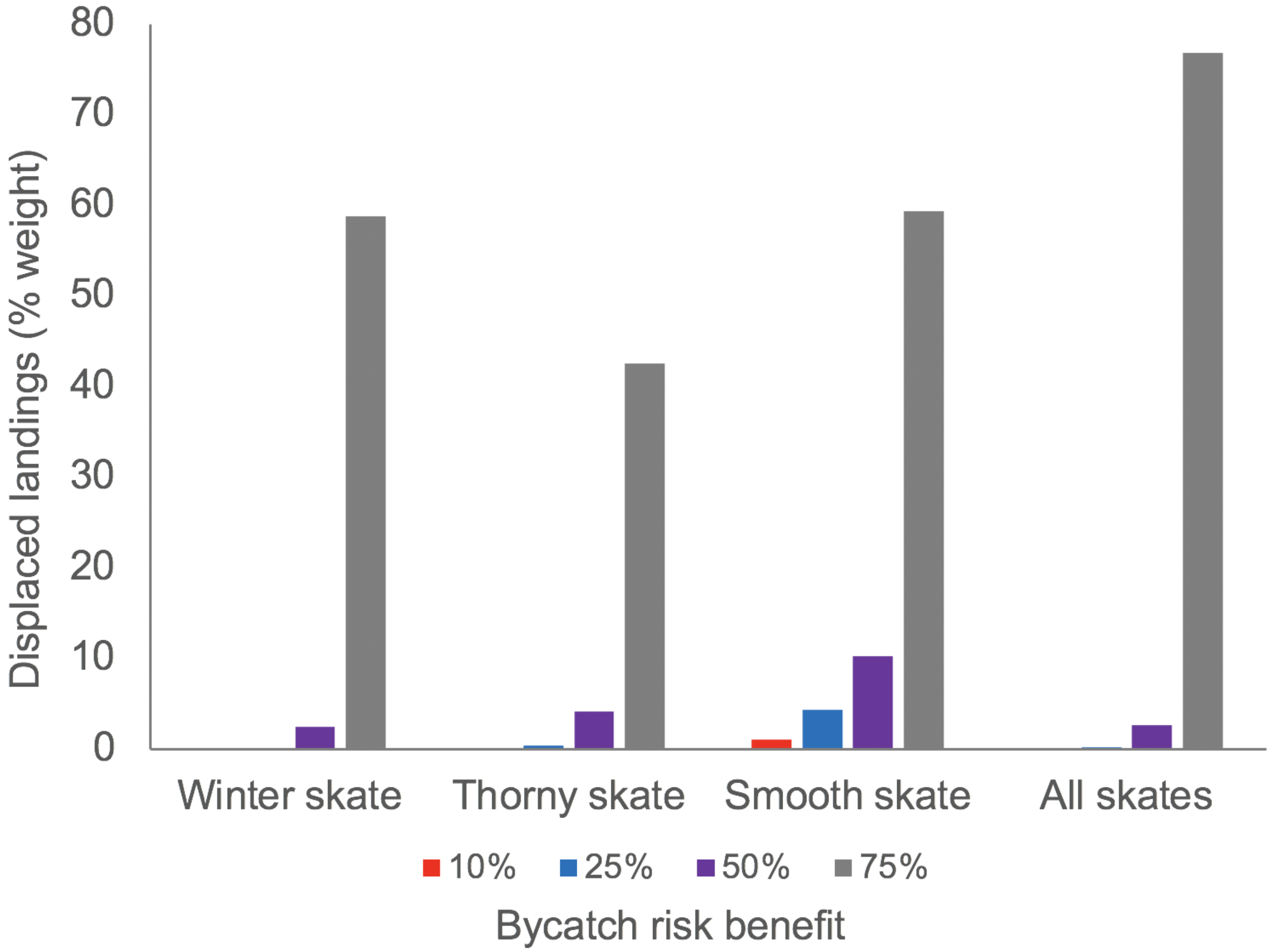

Figure 3.7. Displaced landings. Shown are the percentages of total bottom-trawl landings (kg) within the study area (2015-2019) that would be displaced by closing high-risk areas to achieve increasing thresholds of bycatch risk benefit (red = 10%, blue = 25%, purple = 50%, grey = 75%). Note that the Y-axis maximum is not 100%.

3.4 Discussion

Bycatch in commercial fisheries is a chronic problem with significant implications for sustainable fisheries management. I present here a new approach to address bycatch risk for data-poor species where fisheries-dependent data are insufficient. I modelled the summertime distributions of 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 combined (Figure 3.4). Within the combined distributions of commercial bottom-trawl targets, bycatch risk was highest in the areas of greatest skate abundance (Figure 3.2). Bycatch risk benefit was defined as the percent reduction in sum bycatch risk over the study area following a spatial closure. The response of bycatch risk to increasingly larger area closures showed similar trends for smooth skate, thorny skate and combined skates, whereas when winter skate was considered individually a smaller area size was sufficient to achieve the same level of benefit (Figure 3.5). I mapped potential closure zones to reduce bycatch risk incrementally and overlaid these with spatially referenced bottom-trawl landings from DFO's MARFIS database (Figure 3.6). The impact to fishing industry was approximated by the proportion of landings displaced by closing each zone (Figure 3.7). A bycatch risk benefit of 50% or less in all cases resulted in less than 10% displacement of bottom-trawl landings on the western Scotian Shelf. These 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 bycatch risk mitigation framework presented here can be used not only to identify high-risk areas for bycatch of a given species at risk and approximate industry costs, but also to evaluate whether or not spatial management measures are an appropriate strategy to consider for a given conservation objective. Even at low abundances, if the distribution of the species (and thus bycatch risk) is generally 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 is more concentrated in space 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 reduction versus area closed than other cases (Figure 3.5), as the winter skate is found in more concentrated aggregations within the study area (Figure 3.2). As a species under recent consideration for SARA protection in Canada, it would appear that reducing overall bycatch risk for winter skate by 50% would result in minimal displacement of bottom-trawl landings (2.48%). Fisheries managers may consider applying regulations or closures of some kind to a discrete spatial area near 42.7°N 66.0°W, where mean bycatch risk has been predicted to be high since 2005 (see Chapter 2). The bycatch risk mitigation framework here supports reducing the probability of a bycatch encounter through spatial means that can be continually revised with the availability of new data. This approach makes use of an existing decades-long survey dataset in Atlantic Canada and its application to inform spatial bycatch mitigation measures would cost very little for this or other regions where annual surveys are already budgeted for and conducted for a variety of other scientific pursuits.

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 over-fishing has led to rising levels of market-based sustainability governance of fisheries (Bush et al. 2013). These non-governmental 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 interpretations of sustainable practices (Christian et al. 2013, Le Manach et al. 2020). MSC certifications in Canada are informed by the same data available for the fishery from DFO, and being representative of the best-managed fisheries, this leads to 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 huge amounts of fish (Boudreau et al. 2017). 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 in following the public conscience (Schiller & Bailey 2021), including those to reduce bycatch of non-target species. This framework supports this endeavor at low cost by identifying high-risk regions to avoid, 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, but at a pace slower than other management jurisdictions- at the current rate of improvement, it would take an estimated 37 years to fulfill development of rebuilding plans for all critically depleted stocks (Archibald et al. 2020). Bycatch has been identified as both an ecological and economic concern of commercial fishing industries for decades (Boyce et al. 1996, Crowder & Murawski 1998). Despite this, and the Canadian governments efforts to address bycatch in policy documents (DFO 2013), there remain wide gaps in ability to accurately assess and mitigate bycatch risk in

Canadian fisheries. The most prominent is the availability and accessibility, or lack thereof, of at-sea monitoring data. Only 13% of MSC certified Canadian fisheries employ at-sea observers on 100% of fishing trips. 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 (Boudreau et al. 2017). For these reasons among others, scientists and managers alike have a tenuous 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 come about until bycatch becomes a high priority for Canadian fisheries management, and the status of some fish stocks is dire enough that new tools and approaches must be adopted to mitigate the impacts of bycatch in the interim while catch-monitoring protocols are improved (Archibald et al. 2020, Shackell et al. 2021).

There is a growing catalogue of work developing more adaptive tools to estimate the extent of bycatch using both fisheries-dependent (Stock et al. 2019, Stock et al. 2020) and fisheries-independent data sources (Ward et al. 2015, Hazen et al. 2018, Runnebaum et al. 2020, Chapter 2). 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 (Hazen et al. 2018). 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 (Bennett 2018). 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. (2018) found that areas closed to fishing could be significantly smaller while remaining effective. While fully implementing a similar tool for Canadian fisheries may be impractical at present, the success of EcoCast and support from previous studies makes a strong argument for employing data-driven frameworks to both mitigate relative bycatch risk of vulnerable species and reduce the related financial costs to the fishers. Innovation and adoption of these tools is crucial to help fill in knowledge gaps for data poor species given the urgency, and now legal mandate, to rebuild and recover depleted and endangered stocks in Canadian waters.

The analyses as presented in this chapter do have limitations. I considered data from a longstanding bottom-trawl survey conducted annually in the late summer. For this reason, I 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 (Methratta & Link 2006, Smith et al. 2015), and data from other seasons is currently not available at greater spatiotemporal resolution in this region. To avoid discrepancies related to the catchability of species between different gears (Grieve et al. 2020), it is most likely best to use survey data collected using a similar gear as fishery at hand.

3.5 Conclusion

Bycatch management is one of the most significant unresolved obstacles to sustainable fisheries, globally and in Canada. Though Canada would appear to have strong bycatch-mitigation commitments through the Sustainable Fisheries Framework and Policy on Managing Bycatch (DFO 2013), as well as recent and legally binding updates to the Fisheries Act (Bill C-68, 2019), concrete actions are yet to be taken to systematically confront the problems of bycatch in practice. For example, given the sustained low abundance of many Canadian fish stocks (Hilborn et al. 2020), including Atlantic Canadian groundfish (Shackell et al. 2021), 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, the methods discussed in this paper show promise for using fisheries-independent data as a readily available alternative to predict likely bycatch hotspots. Through identification of high-risk regions of skate bycatch to bottom-trawling, this methodological framework allows managers to approximate costs that may be experienced by the fishing industry at increasing levels of protection. Such tools can help to support the development of spatial bycatch reduction strategies in the absence of adequate fisheries-derived data. Frameworks such as the one presented here can be used in decision making and management of any multi-species commercial fisheries, helping to improve the sustainability of fisheries and resilience of exploited ecosystems worldwide.

Chapter 4 - Conclusions

The primary objective of this thesis was to develop and apply an approach to predict and mitigate bycatch for species-at-risk in Canadian fisheries. Given the persistent low abundances and lack of recovery for many species depleted by fishing, there is a need to fully address bycatch in Canadian fisheries to support population recovery and ecosystem resilience. However, a lack of comprehensive and taxonomically complete catch monitoring often prevents accurate estimation and mitigation of bycatch risks for vulnerable species. Therefore, this thesis aimed to make use of fisheries-independent data to predict the relative spatial patterns of bycatch. To do so, a longstanding scientific bottom-trawl survey was used to model the spatiotemporal presence and abundance of target species, and non-target at-risk skates (Rajidae). This method can provide much-needed information to manage and mitigate bycatch until based on readily available high-quality data.

Chapter 2 described a data-driven method to estimate the spatiotemporal distributions of fisheries bycatch from survey data independent from commercial catch monitoring data. These methods build on some previous observations where relative species overlap was shown to predict bycatch (CITE). Past studies utilized various metrics to measure species distribution overlap, including spatiotemporal ratios between species' abundance (Ward et al. 2015) or habitat suitability indices (Runnebaum et al. 2020). Using a novel statistical package specially developed for the purpose of analyzing spatiotemporally referenced survey data, relative bycatch risk was estimated by the degree of overlap between target species and non-target skates. This was calculated by multiplying the relative (0-1) distributions of target species and skates, where high co-occurrence between the two indicates risk of bycatch. Although weakly significant for some species, depth and sea surface temperature were not found to be predictors of presence probability for of 2 of 3 skate species, and 7 of 10 target species in Chapter 2 (Figure 2.5). In Chapter 3, only winter flounder was significantly impacted by depth (weakly positive) and SST (weakly negative) (Figure 3.3). This finding is consistent with the hypothesis that many groundfish populations may have declined in habitats where they were previously found in high abundance, and remnant populations are now present in more marginal habitats that support lower abundance, where fishing intensity is lower (Shackell et al. 2005). On the other hand, it is possible that the variation in these covariates was not great enough across the study area to detect an effect on species presence. Values for relative bycatch risk were then used in a model to predict species presence in fishing sets from art-sea observer data. This secondary modelling step validated that bycatch risk as estimated from survey data was indeed predictive of the probability of catching skates by bottom-trawl. Therefore, this method may provide fisheries managers with a new tool to assess the risks to a species across space, while avoiding certain limitations associated with commercially-derived catch data. This method makes use of an existing dataset and can be employed at relatively low cost and continually updated as new data become available.

Chapter 3 uses the framework developed and tested in Chapter 2 to evaluate the reduction in bycatch risk that would be expected when employing spatial fisheries closures. Precisely focused closed areas were shown to reduce bycatch risk by up to 50% while closing less than 20% (Figure 3.5) of fishable area and displacing only 10% of bottom-trawl landings by weight (Figure 3.7). Using the framework presented in this thesis to identify bycatch risk hotspots can provide information on spatial management measures in addition to other sources of data. Given that Canada is set to increase the percentage of protected national waters to 25% by 2025 and 30% by 2030 (CITE Press release or news article here), readily available tools and frameworks such as this can aid in reaching conservation targets at low cost and meeting regulatory and market-based demands for sustainable seafood.

The results of this thesis provide both a broader understanding of the spatial distribution of bycatch risks associated with bottom-trawl fisheries, and a means to inform management measures to address bycatch to support the recovery of depleted species. These results are timely given both the updated legal requirements to enact recovery strategies for depleted species in Canada, and an increasing shift towards data-driven and dynamic regulations that move in space and time as species distributions and environmental conditions shift. This thesis also demonstrates the value of using existing but underutilized datasets in addressing present conservation concerns. Annual surveys of the Scotian Shelf have amassed decades of spatiotemporally referenced data on over 500 species or taxa. Given the observation in this thesis and in previous studies (Ward et al. 2015, Runnebaum et al. 2020) that fisheries-independent data can reliably predict commercial catch, making further use of these rich datasets is a promising avenue to support management decisions based on the best available evidence.

4.1 Limitations

A limitation identified throughout this thesis is that of seasonality. Because this thesis used only Scotian Shelf RV surveys conducted annually in late summer, this is the only season for which inferences on relative bycatch risk to skates can be made. Previous studies in areas where at-sea observer data is of higher quality have made use of combinations of fisheries-dependent and fisheries-independent data to cover the entire year. Some species undergo migrations between deeper and shallower waters over the course of a year, with transitions occurring around late autumn and late spring (Methratta & Link 2006, Smith et al. 2015). The entire months of June-October were therefore extracted from the at-sea observer dataset in Chapter 2 to validate bycatch risk predictions for the summer months. This selection assumes that species distributions are relatively consistent in the months between seasonal transitions.

As an additional constraint, this thesis does not account for variation in catchability between species, gear types or fishing practices (scientific or commercial) (Grieve et al. 2020). Further, bycatch of skates also is a significant concern in demersal long-line fisheries for Atlantic halibut (*Hippoglossus hippoglossus)* (DFO 2017[a,b], Hurley et al. 2019). This is not addressed in my thesis, although the methods presented here could be adapted to that problem as well.

Of course, another limitation of this thesis is the degree to which bycatch risk predictions can be validated given the state of the at-sea observer dataset. Because of consistently low observer coverage in bottom-trawl fisheries in combination with DFO's harvester privacy policies, the spatial resolution of observed fishing sets available for analysis is quite coarse. Bycatch risk predictions for NAFO divisions 4VW were not validated in Chapter 2, as at-sea observations in this area were limited and therefore removed from the dataset prior to release to researchers. The temporal aggregation of 10 years of observer data (2005-2009 and 2010-2014) was done to reduce the spatial area affected by DFO's 'rule-of-five' privacy policy (Butler & Coffen-Smout 2017), however this also introduces error into bycatch risk validations. Thus, only a 5-year mean bycatch risk value was validated using 2 time-steps. Nonetheless, it was an important step to verify that predicted bycatch risk did indeed translate into observed bycatch, and although a positive relationship was detected by parameter estimates (Figure 2.8), bycatch risk validation could be improved, and error likely reduced if at-sea observer data was reported at a similar spatial and temporal resolution as annual surveys. This can only be confirmed if improvements to catch-monitoring protocols are made in Canada and privacy regulations are changed.

4.2 Management implications

The results of this thesis have significant implications for the management of vulnerable marine species affected by commercial fishing. The methods developed and tested here can advance managers' ability to estimate, evaluate, monitor and mitigate the risks of bycatch using state-of-the-art analysis techniques and cost-effective sources of available data. The ability to predict the spatial distribution of anthropogenic risks as they change over time can help to identify dynamic closure zones, direct fishing effort towards low-risk areas, and reduce the probability of bycatch encounters for vulnerable species. Such efforts can not only help improve the ecological sustainability of fisheries, but economic viability at the same time. Bycatch imposes economic costs on fish harvesters, such as when bycatch quotas for species-at-risk are prematurely met and fishing grounds closed, or when marketable catch is discarded due to regulatory requirements (Patrick & Beneka 2013). Reducing bycatch encounters can aid in balancing the economic challenges presented by incidental non-target catch and help to meet market demands for sustainable seafood (Pascoe et al. 2010, Bush et al. 2013).

There are several key issues relating to the lack of appropriate assessment tools that this framework can help to address. As has been identified throughout this thesis, this framework is not limited by the lack of catch-monitoring data. In addition to poor observer coverage and incomplete monitoring of non-retained catch, fisheries data are often not as freely available to the public as ecological survey data. Where they are available, it is typically not at the observed scale (such as in this thesis, where observations were aggregated in space and time prior to usage agreements). Furthermore, improving data collection through current catch-monitoring systems will be a logistically and economically challenging task. In Canada the onus of paying for at-sea observers is placed on the fish harvester or licence owner (DFO 2020[b]), and in many areas there is little support to increase oversight and achieve 100% observer coverage in Canadian fisheries (Mangi et al. 2015).

This framework cannot just be used for assessment but also to develop cost-effective mitigation tools. Gear modifications have been shown to be effective in reducing bycatch in some fisheries (Showell et al. 2010, Hannah et al. 2012, Larocque et al. 2012). This is not a realistic strategy, however, for all fisheries. For example, a 40mm separator grate used to reduce bycatch in the Scotian Shelf silver hake bottom trawl fishery (Showell et al. 2010) cannot be used in a fishery targeting cod or haddock, as those larger fish would be excluded. Where gear modifications fall short, the most effective way to reduce bycatch is to simply avoid areas where species-at-risk are vulnerable to being caught. Canada's Policy on Managing Bycatch (DFO 2013) recommends the use of spatial and temporal measures as part of a toolbox to reduce interactions with non-target species by identifying regions and times in which to prohibit all or certain gear types. Using a bycatch risk framework allows fisheries managers to predict where these areas and times may be at a greater spatiotemporal resolution than fisheries-derived data can currently provide. It also supports a shift towards ecosystem-based dynamic fisheries management, where high-risk areas can be evaluated as time progresses and regulatory decisions can be made timelines that follow the progression of changing environmental conditions (Maxwell et al. 2015).

4.3 Future directions

The bycatch risk mitigation framework presented here is designed such that it can be applied to any region or fishery where comprehensive biogeographical data are collected and updated as new data become available. There are several avenues of inquiry in Atlantic Canada in which this framework could provide useful information. It could be applied to any number of other species-at-risk, caught in annual surveys and affected by bottom trawl fisheries, such as northern (*Anarhichas denticulatus*) and spotted (*A. minor*) wolffish, both listed as Threatened under SARA, and for whom bycatch is the leading cause of human-induced mortality [DFO 2020[c]]). The framework outlined here could also be applied to annual long-line surveys of the Atlantic halibut fishery and associated bycatch species. These surveys are conducted in cooperation with DFO and fisheries observers cover the entire Scotian Shelf and Southern Grand Banks, where the fishery catches several COSEWIC-assessed species as bycatch (Hurley et al. 2019). Outside of Canada, similar methods can be applied to any fishery where commercial data are limited but where surveys are conducted.

Predictions of relative bycatch risk can also be used to determine the reduction in bycatch risk that may be brought on by implementing an already-planned network of MPAs in Canada. On the western Scotian Shelf, an area of interest has been identified near the Fundian Channel and Brown's Bank for protection, citing the region as important habitat for several species of concern including several skates (DFO 2021[b]). Bycatch hotspots for winter skate within the Atlantic halibut and CHP fisheries were identified near the region proposed for protection (Figures 2.5, 2.6). Employing a method such as this could provide complementary information to other monitoring methods to assess the species-specific benefits of the spatial placement of this protected area, such as the expected reduction of risk attributed to limiting harvesters' access to species-at-risk bycatch hotspots. Under emerging dynamic ocean management strategies, this framework can be used to continually evaluate bycatch risk and quantify shifts in the distribution of bycatch risk over time. Inclusion of environmental covariates relevant to the species of interest can provide insight into which factors drive changes in the spatiotemporal domains of bycatch risk, and the rate at which these changes are occurring.

In conclusion, my primary objective for this work was to contribute to broadening analytical options for spatiotemporal bycatch management, using advanced statistical techniques and available high-quality data sources (such as scientific surveys) for species where commercial data are deficient. It is my hope that frameworks such as the one presented in this thesis can be further built upon by others to aid managers in addressing conservation priorities and informing spatial management, to support sustainable fisheries and functional ecosystems both at home and abroad.

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Appendix A: Chapter 2 Supplemental Figures

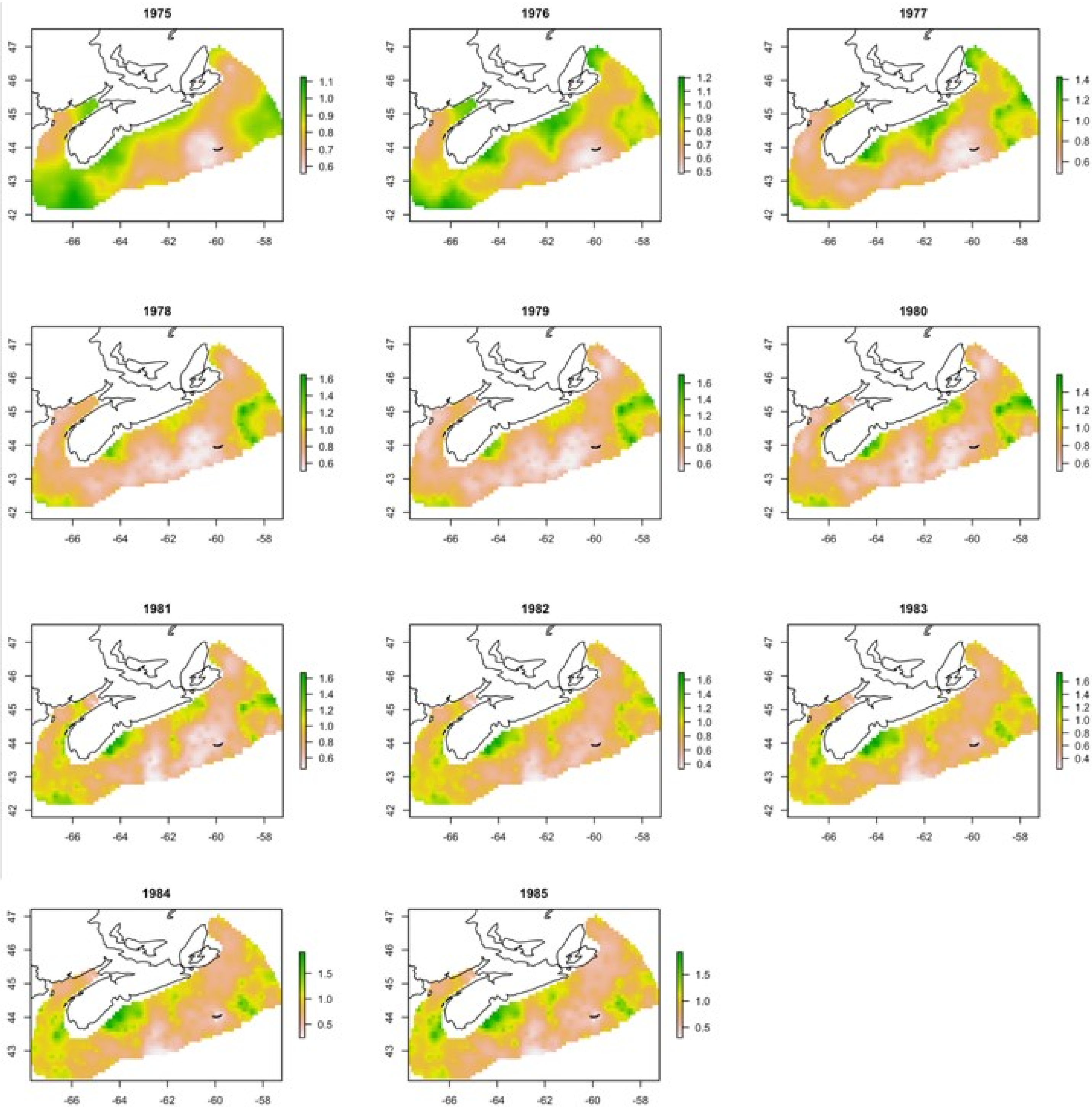

Figure A1: Standard error for historic spatiotemporal distribution for thorny skate. Shown are calculated standard errors for winter skate abundance within the study area for all years in analysis 1. X- and Y-axes indicate degrees (°) longitude and latitude, respectively.

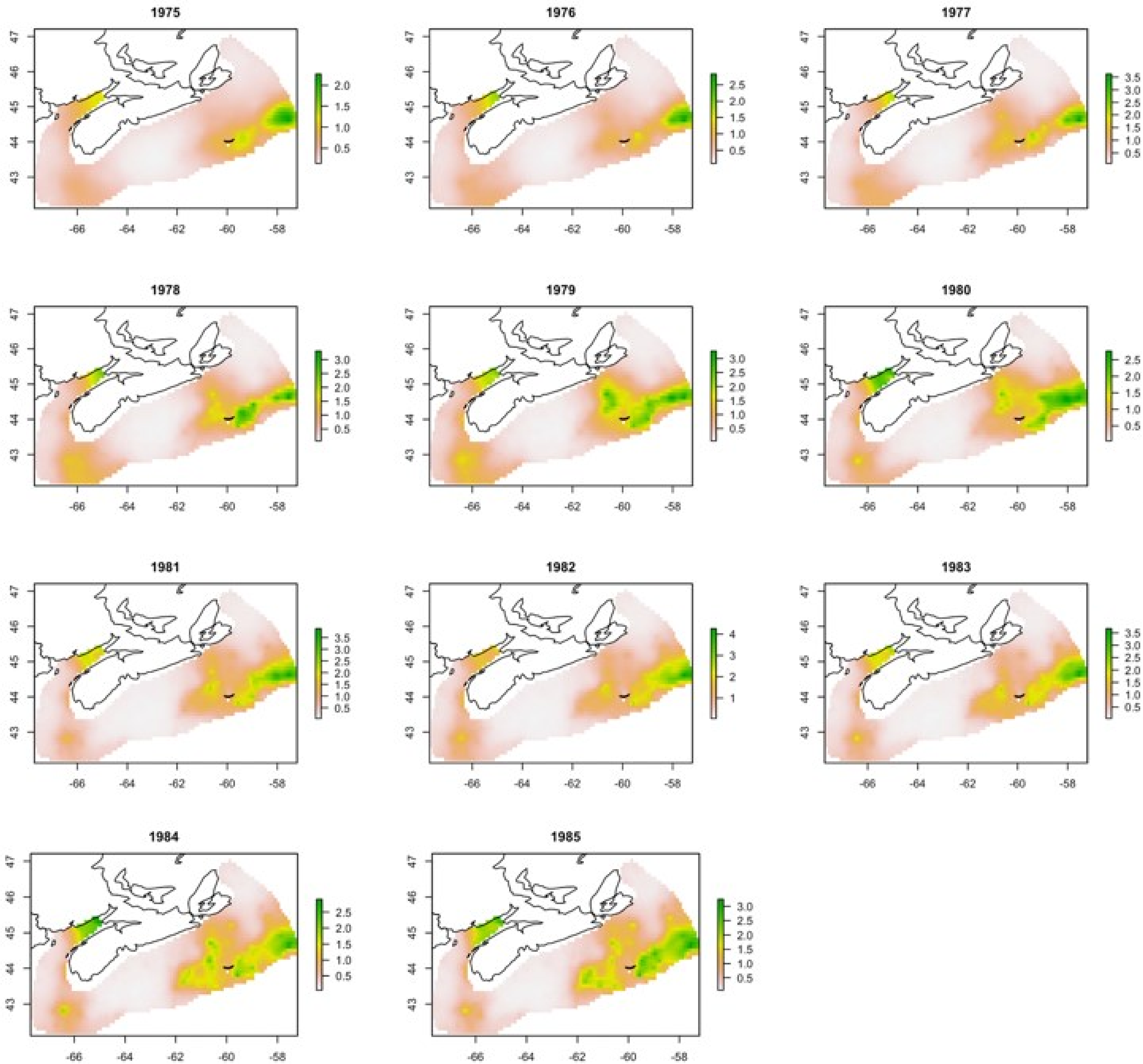

Figure A2: Standard error for historic spatiotemporal distribution for winter skate. Shown are calculated standard errors for winter skate abundance within the study area for all years in analysis 1. X- and Y-axes indicate degrees (°) longitude and latitude, respectively.

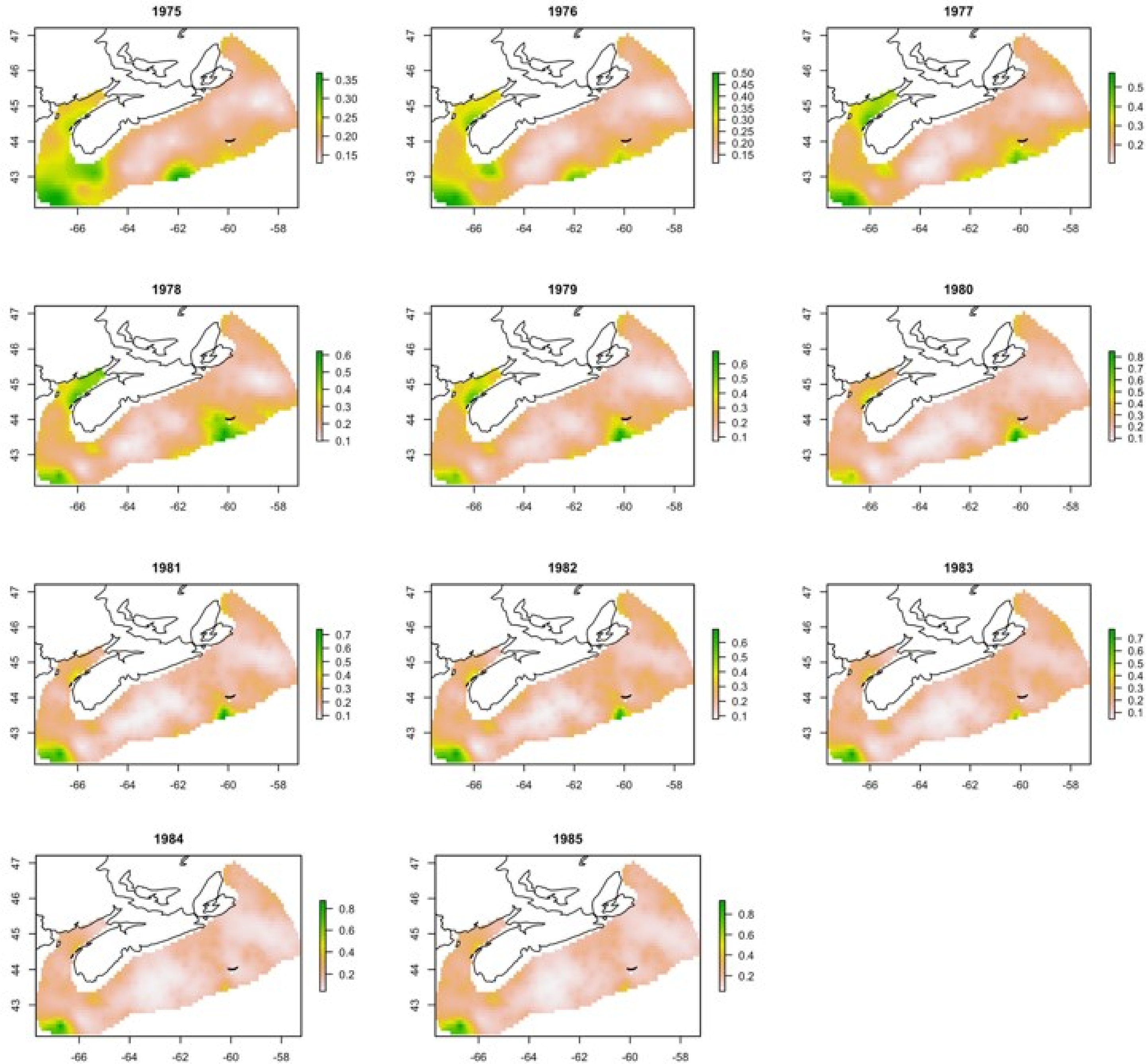

Figure A3: Standard error for historic spatiotemporal distribution for smooth skate. Shown are calculated standard errors for winter skate abundance within the study area for all years in analysis 1. X- and Y-axes indicate degrees (°) longitude and latitude, respectively.

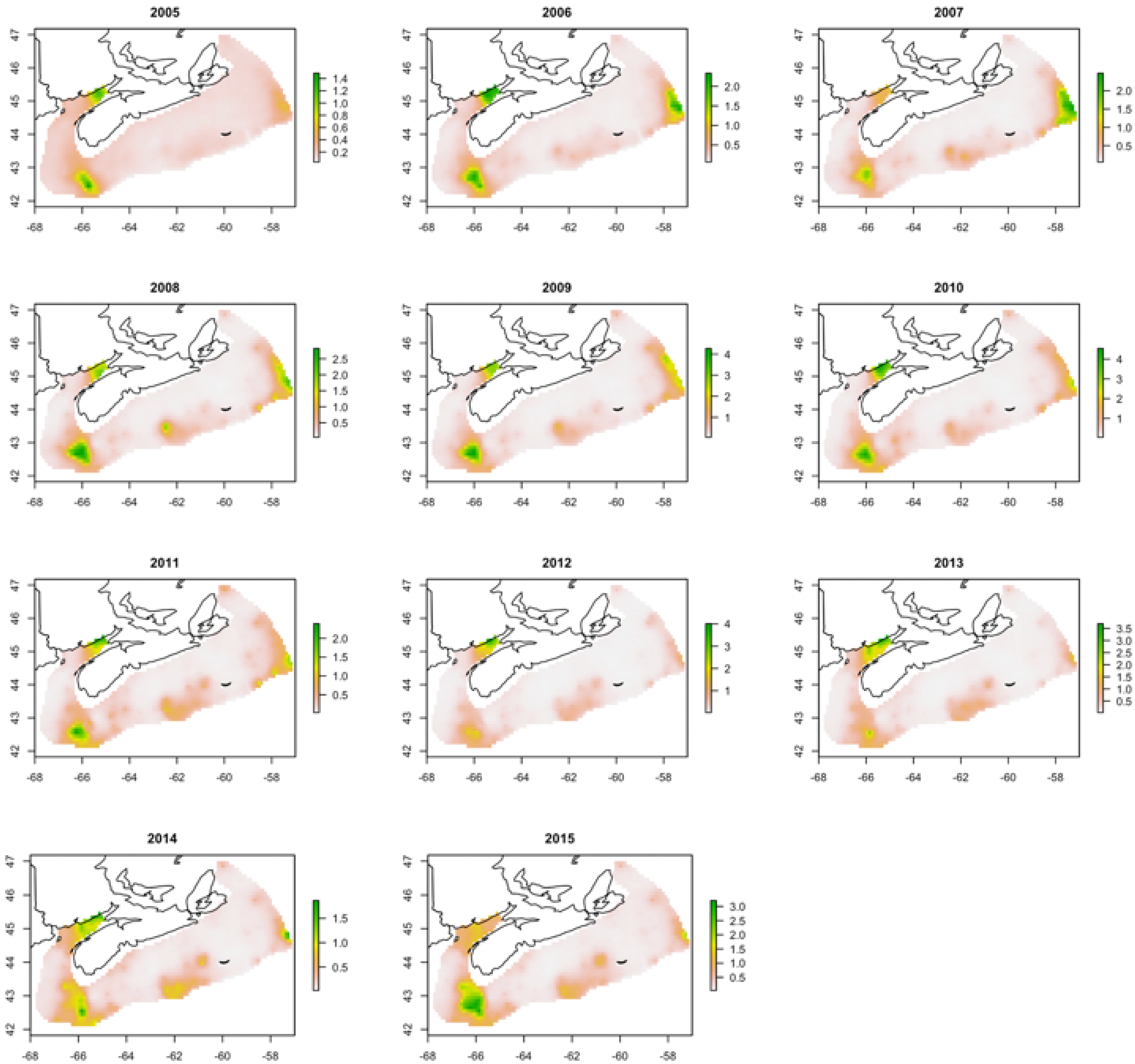

Figure A4: Standard error for present winter skate distribution. Shown are calculated standard errors for winter skate density for 2005-2015.

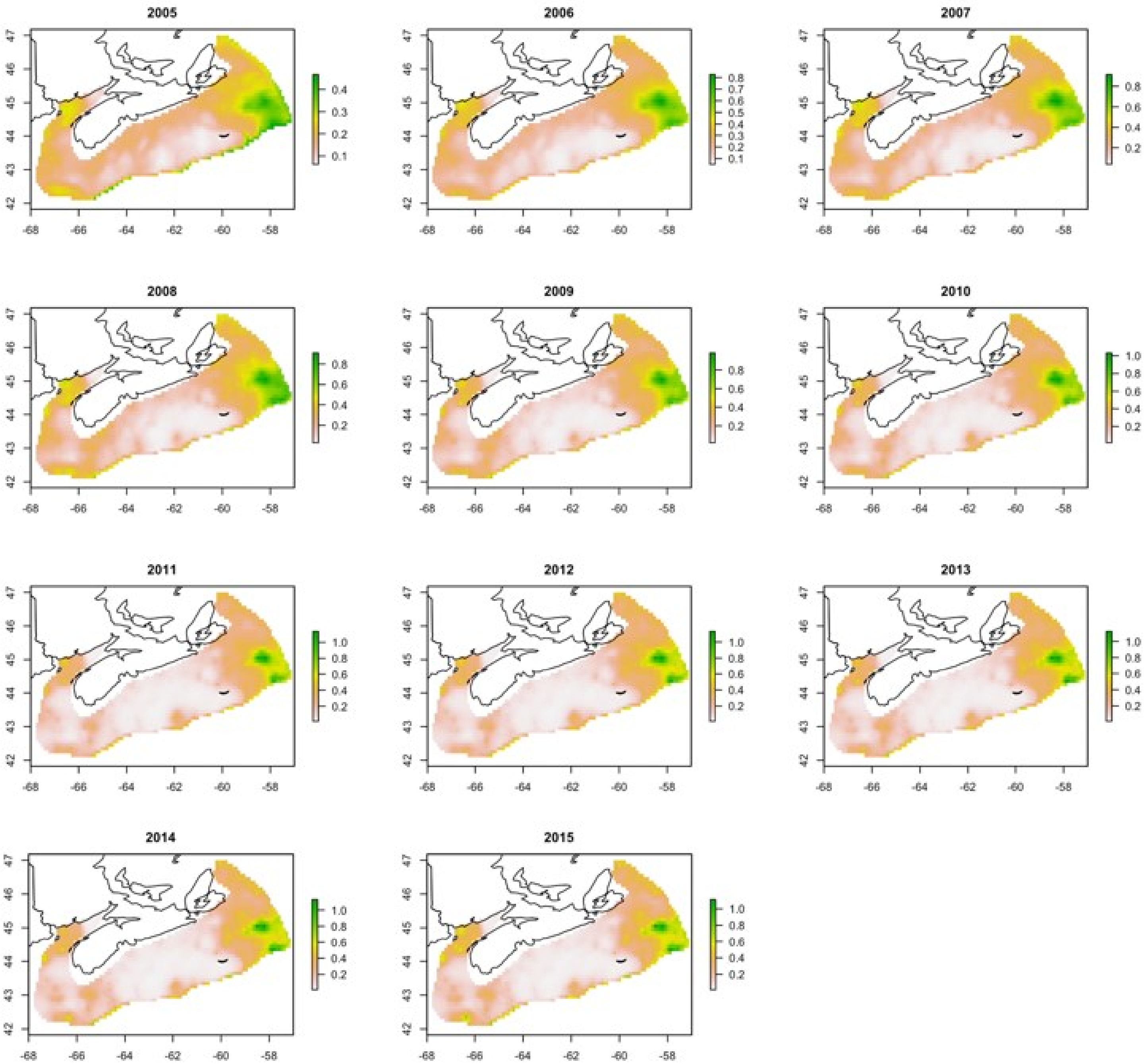

Figure A5: Standard error for present thorny skate distribution. Shown are calculated standard errors for thorny skate density for 2005-2015.

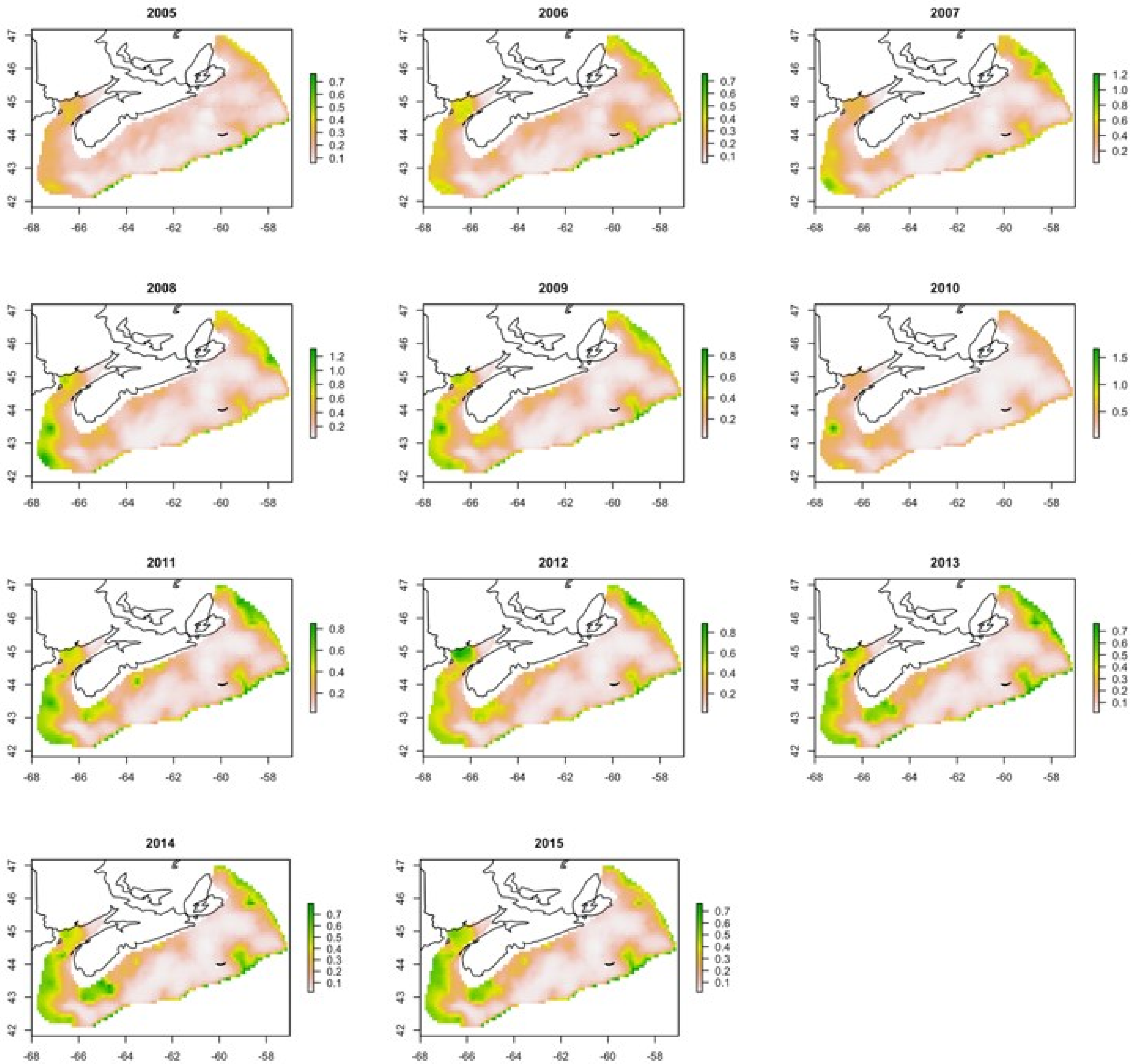

Figure A6: Standard error for present smooth skate distribution. Shown are calculated standard errors for smooth skate density for 2005-2015.

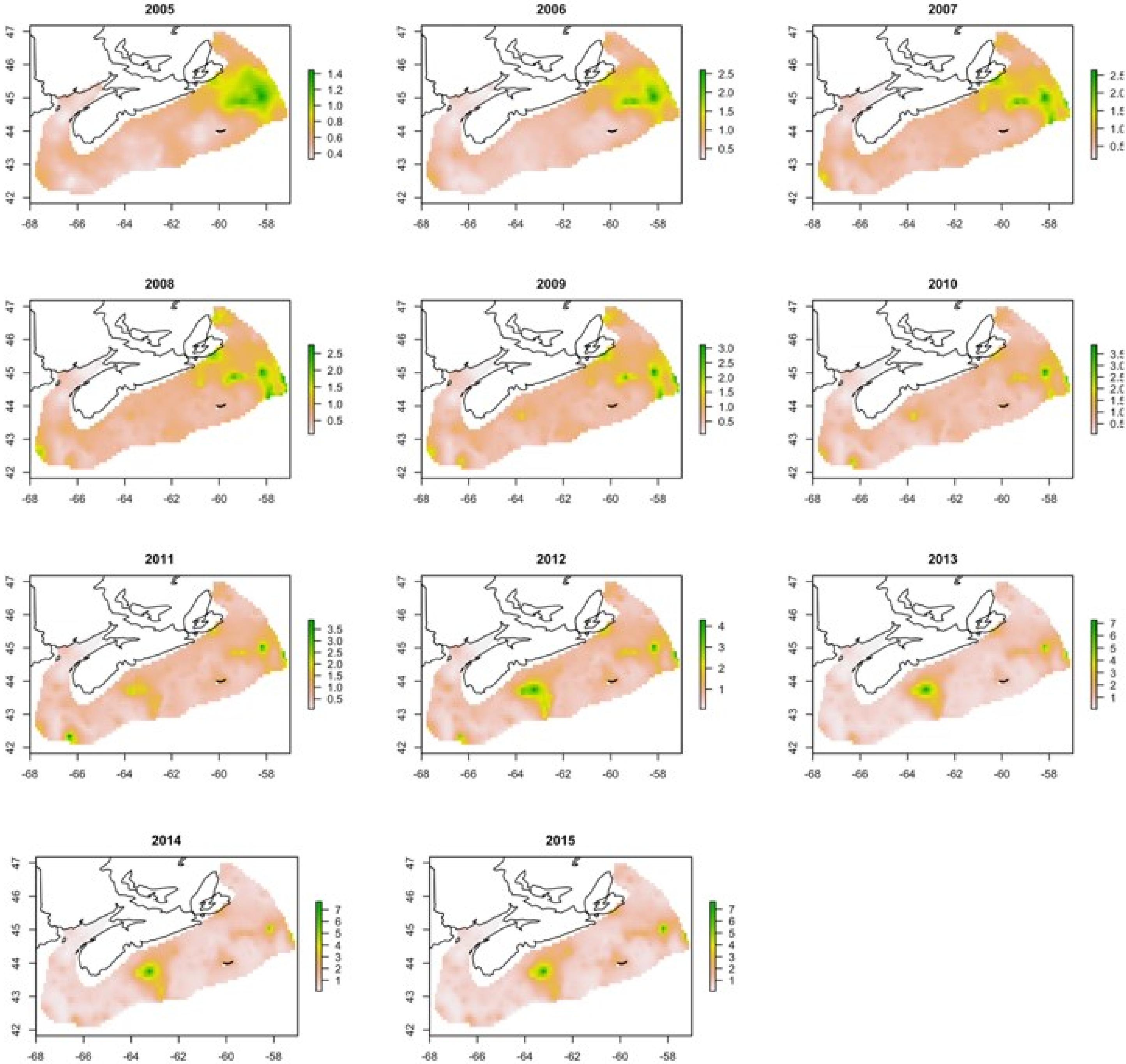

Figure A7: Standard error for present American plaice distribution. Shown are calculated standard errors for American plaice density for 2005-2015.

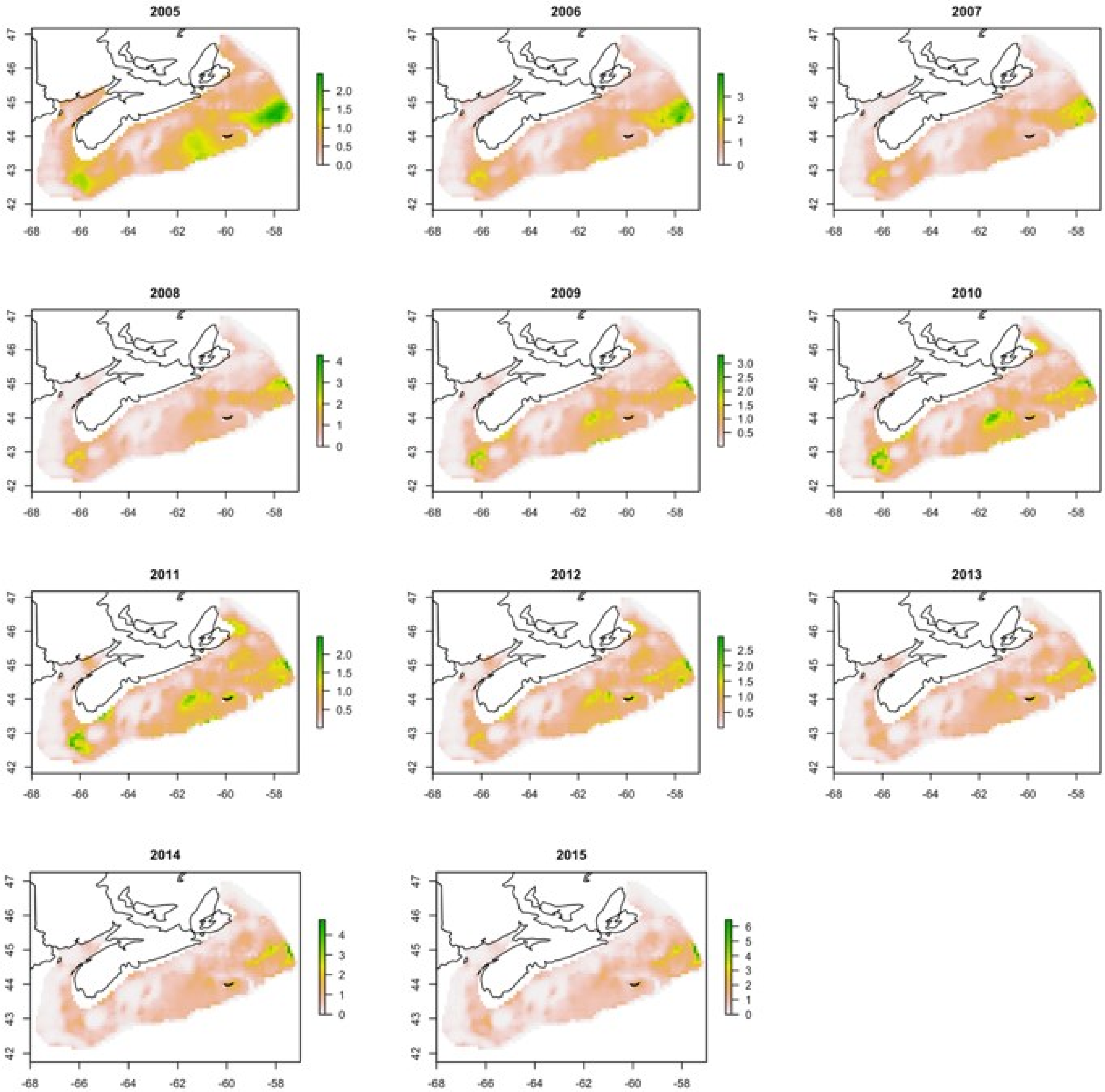

Figure A8: Standard error for present yellowtail flounder distribution. Shown are calculated standard errors for yellowtail flounder density for 2005-2015.

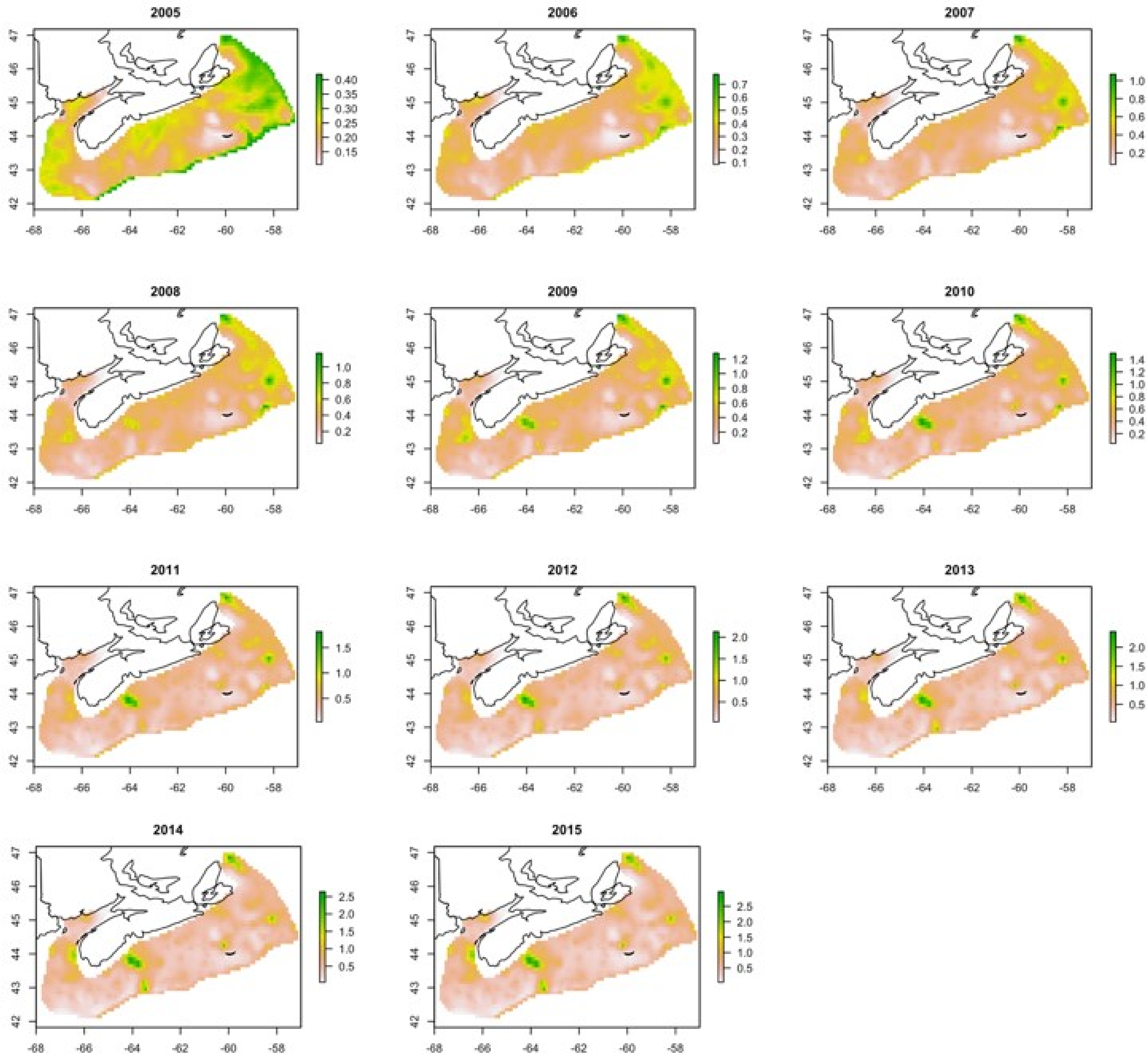

Figure A9: Standard error for present witch flounder distribution. Shown are calculated standard errors for witch flounder density for 2005-2015.

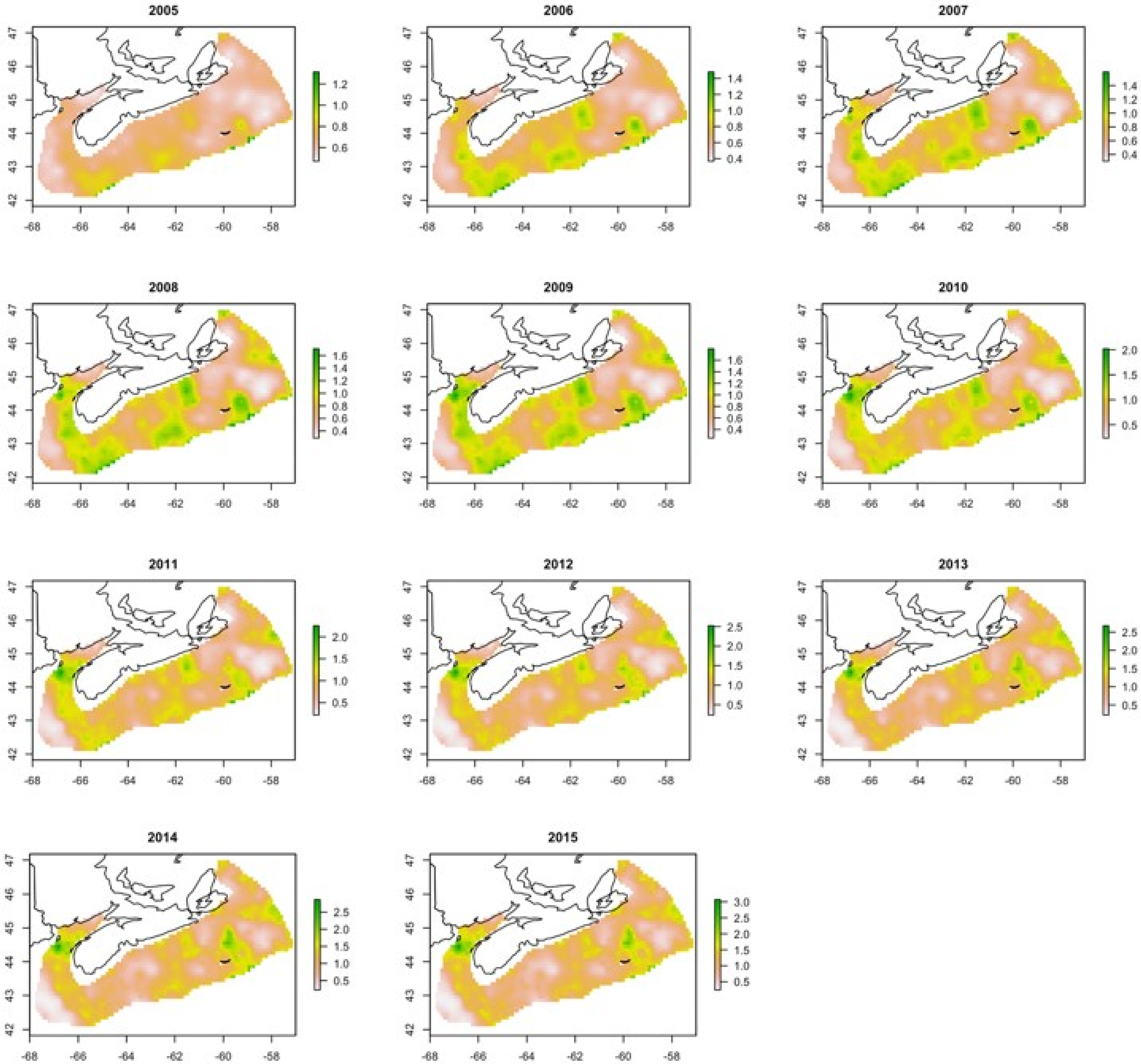

Figure A10: Standard error for present Atlantic halibut distribution. Shown are calculated standard errors for Atlantic halibut density for 2005-2015.

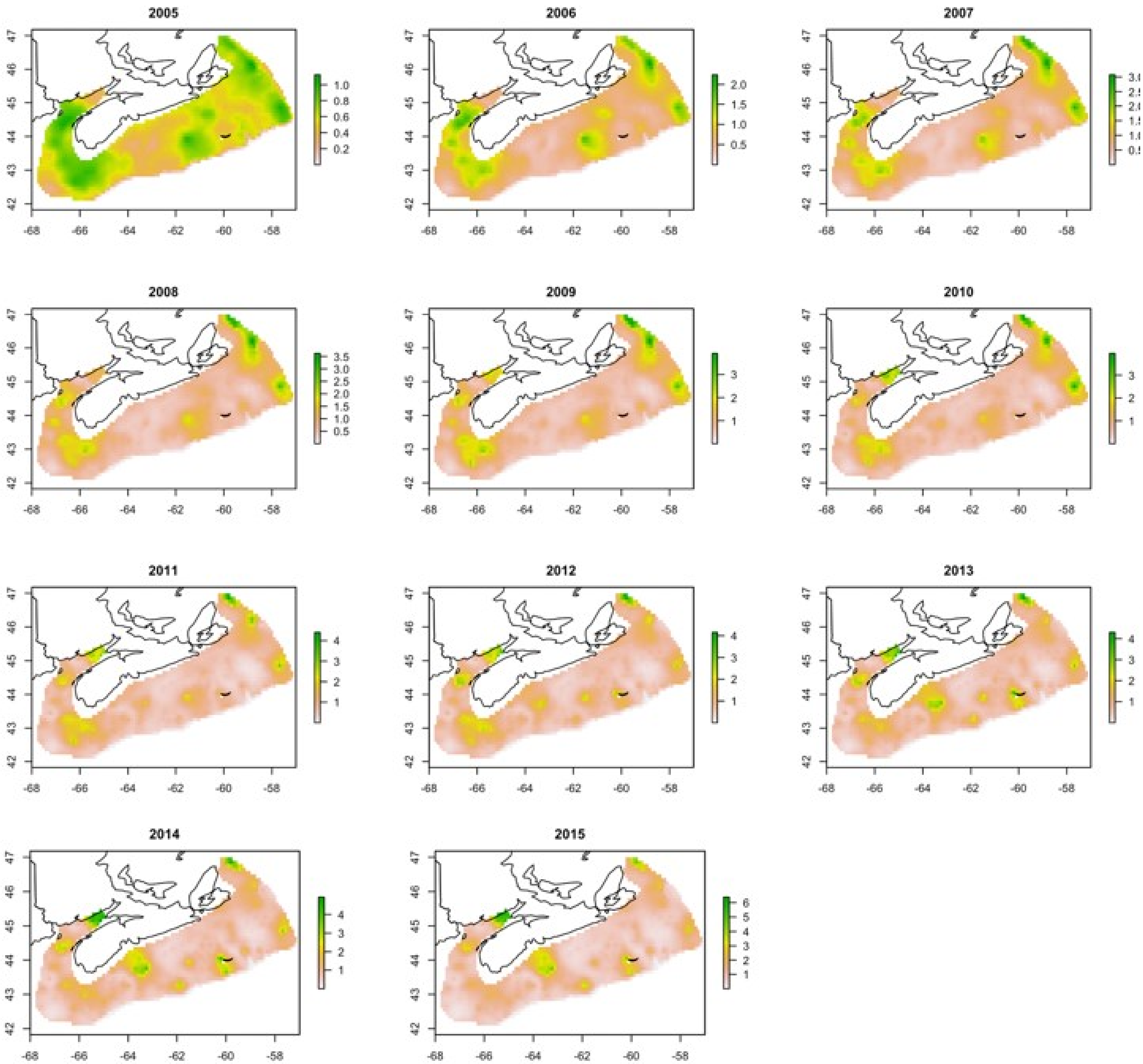

Figure A11: Standard error for present Atlantic cod distribution. Shown are calculated standard errors for Atlantic cod density for 2005-2015.

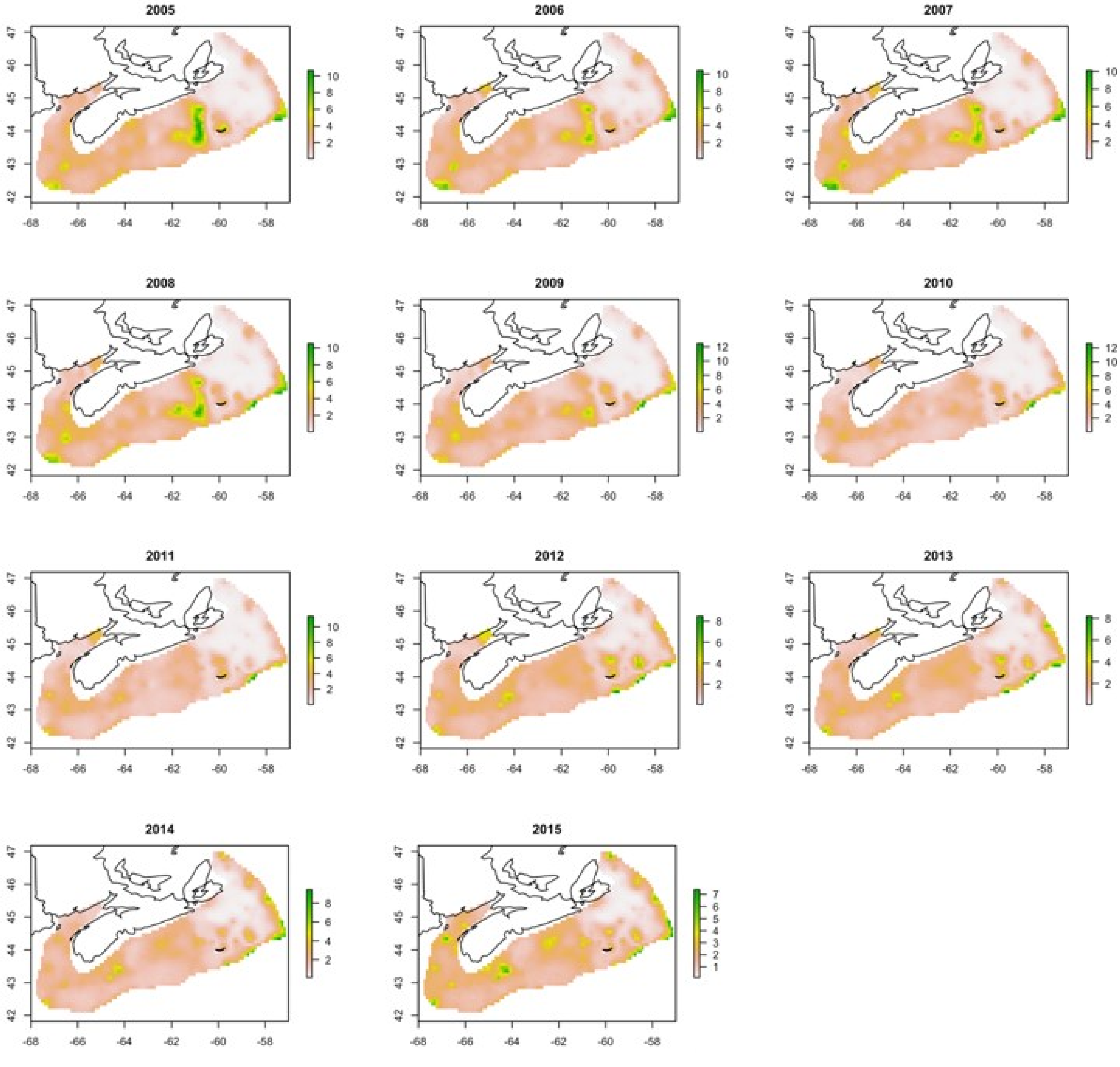

Figure A12: Standard error for present haddock distribution. Shown are calculated standard errors for haddock density for 2005-2015.

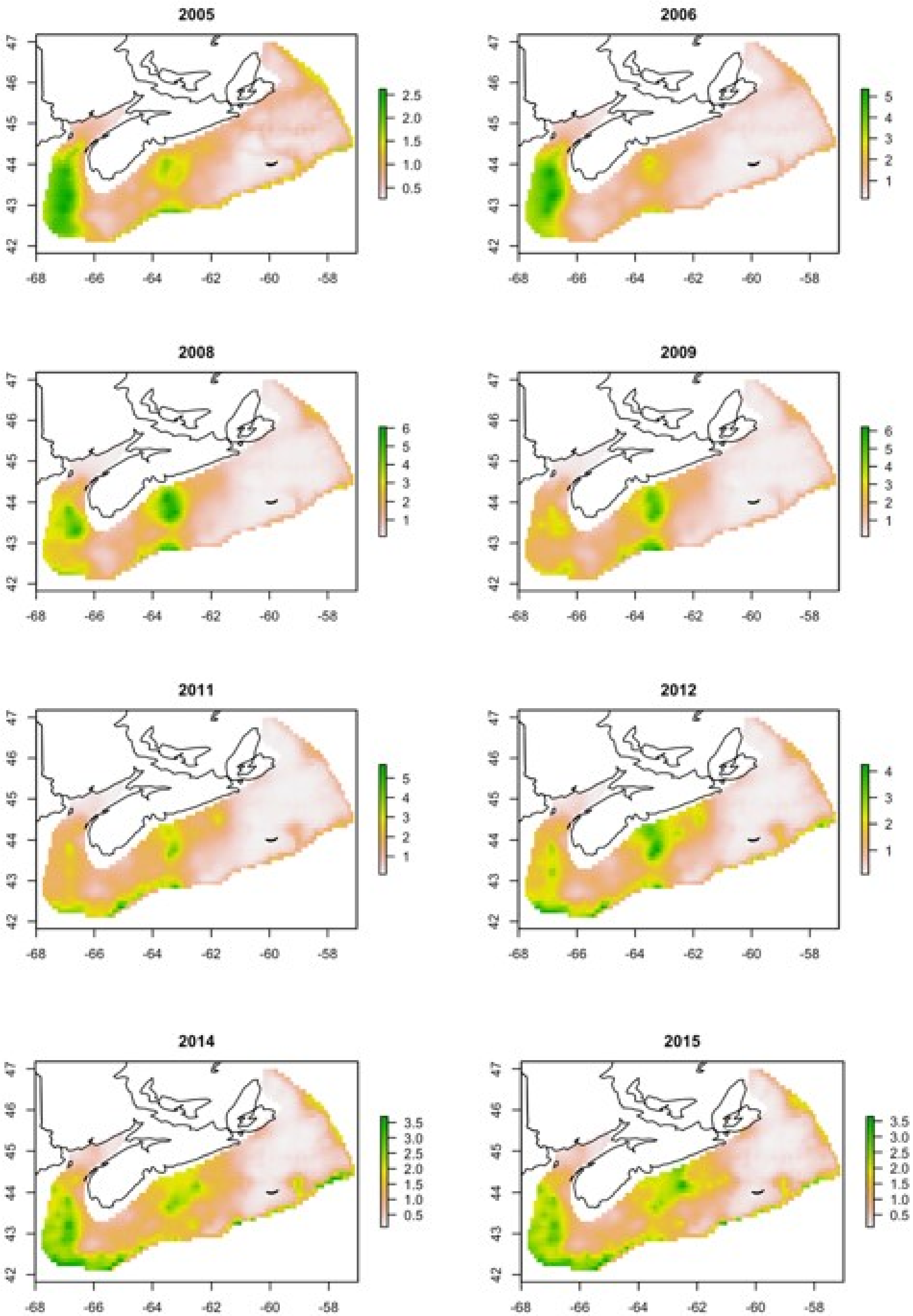

Figure A13: Standard error for present pollock distribution. Shown are calculated standard errors for pollock density for 2005-2015.

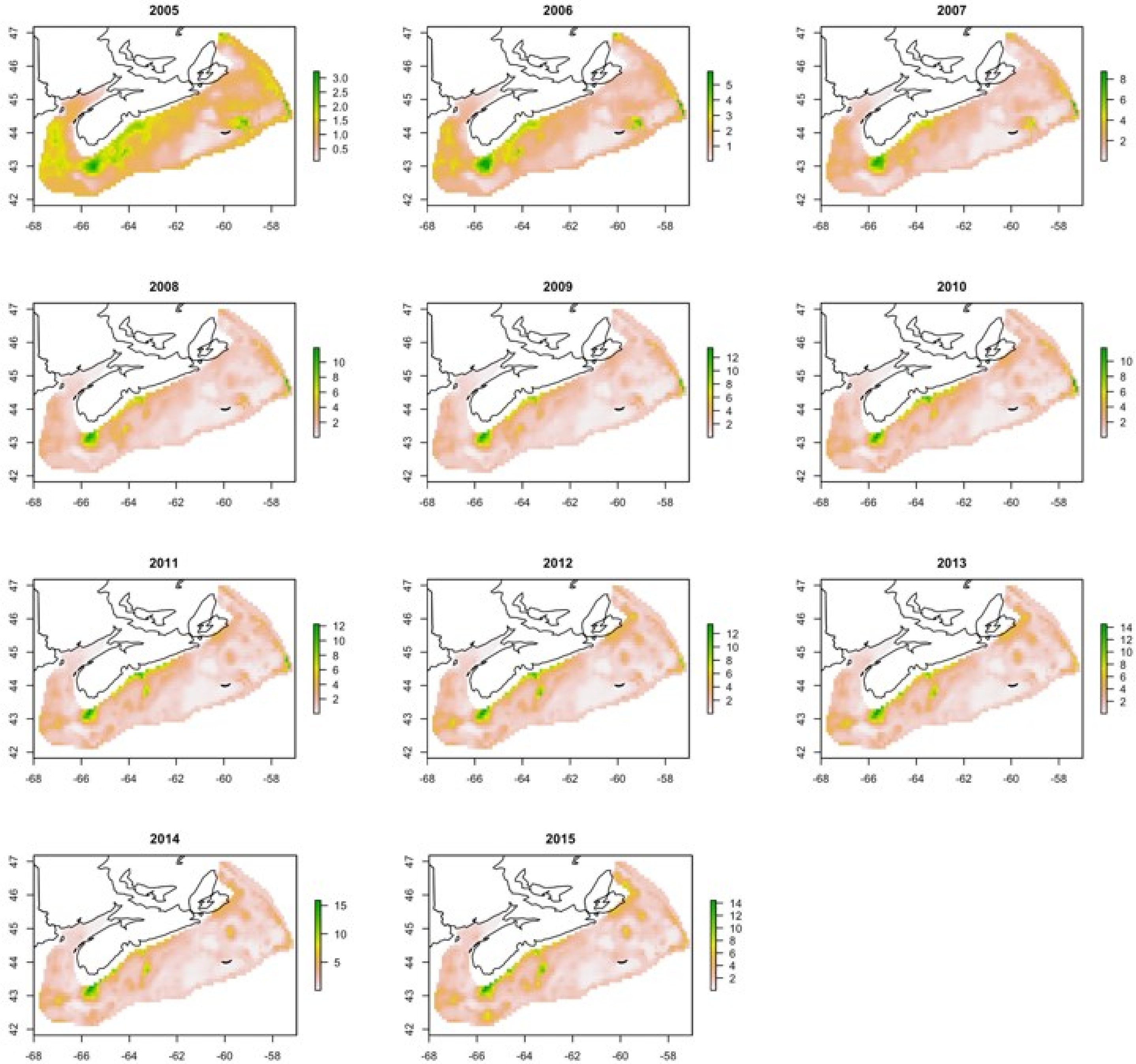

Figure A14: Standard error for present redfish distribution. Shown are calculated standard errors for redfish density for 2005-2015.

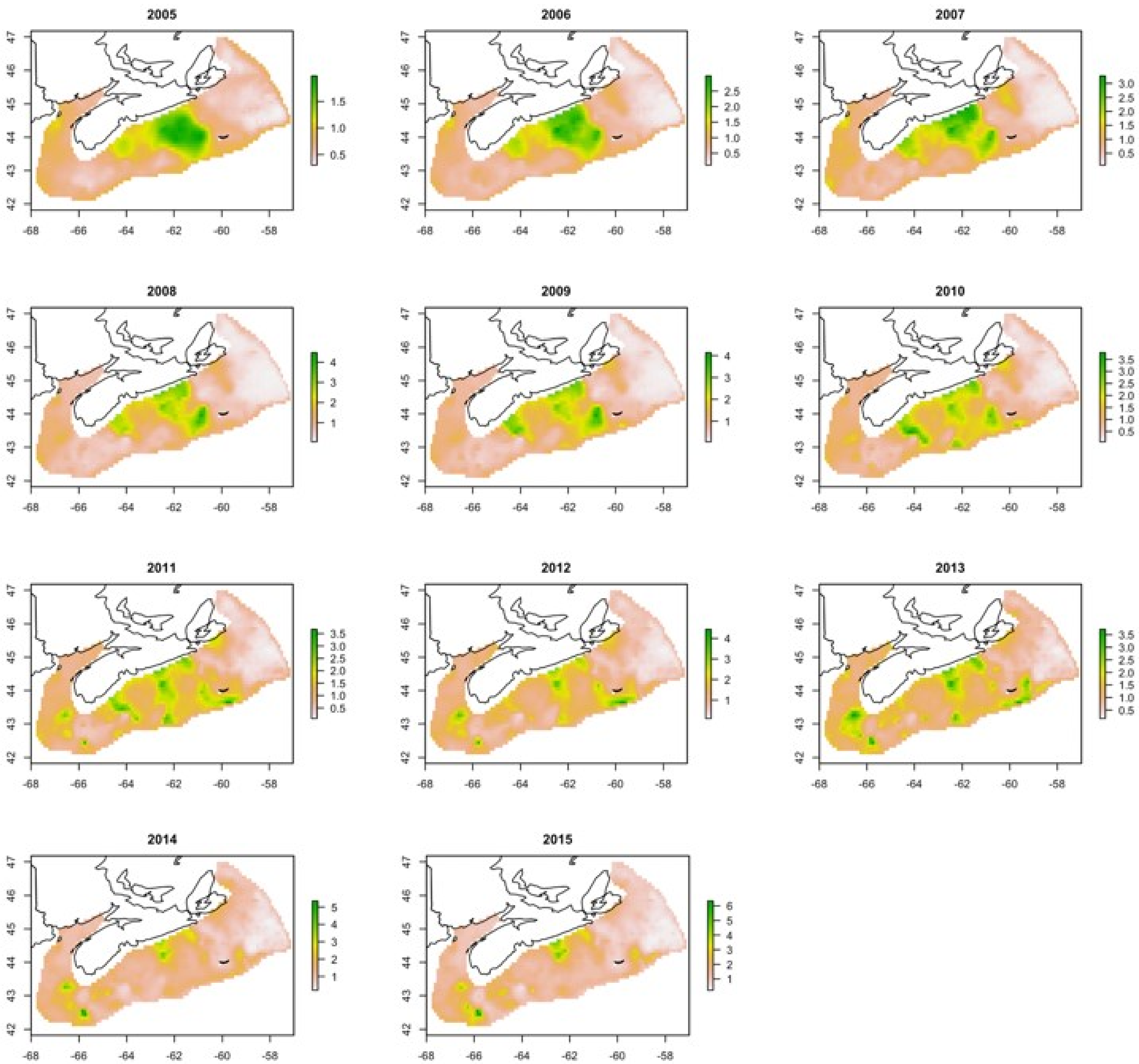

Figure A15: Standard error for present silver hake distribution. Shown are calculated standard errors for silver hake density for 2005-2015.

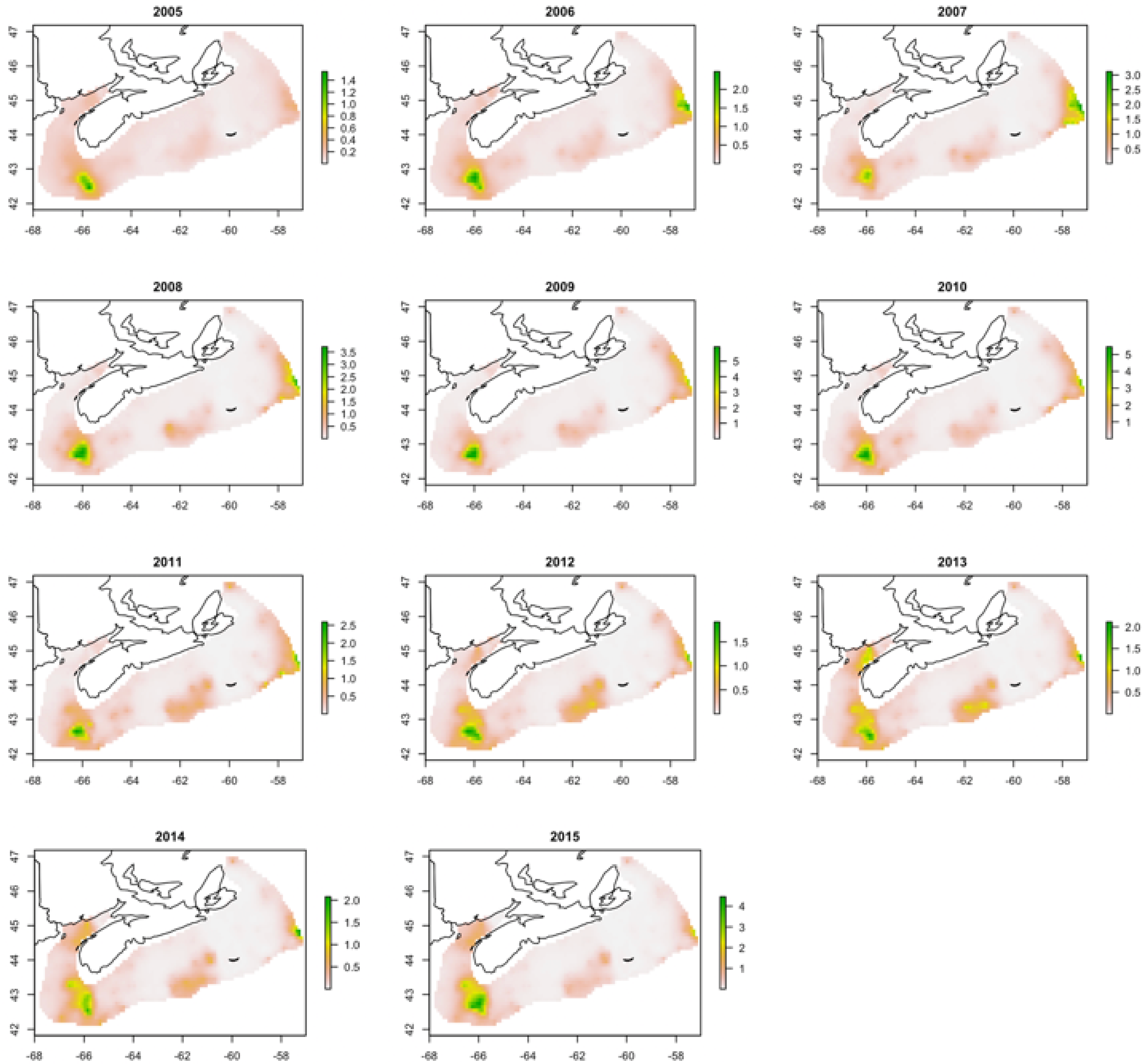

Figure A16: Standard error of estimated bycatch risk for winter skate. Shown is the calculated standard error for bycatch risk maps from non-scaled species distribution predictions, 2005-2015

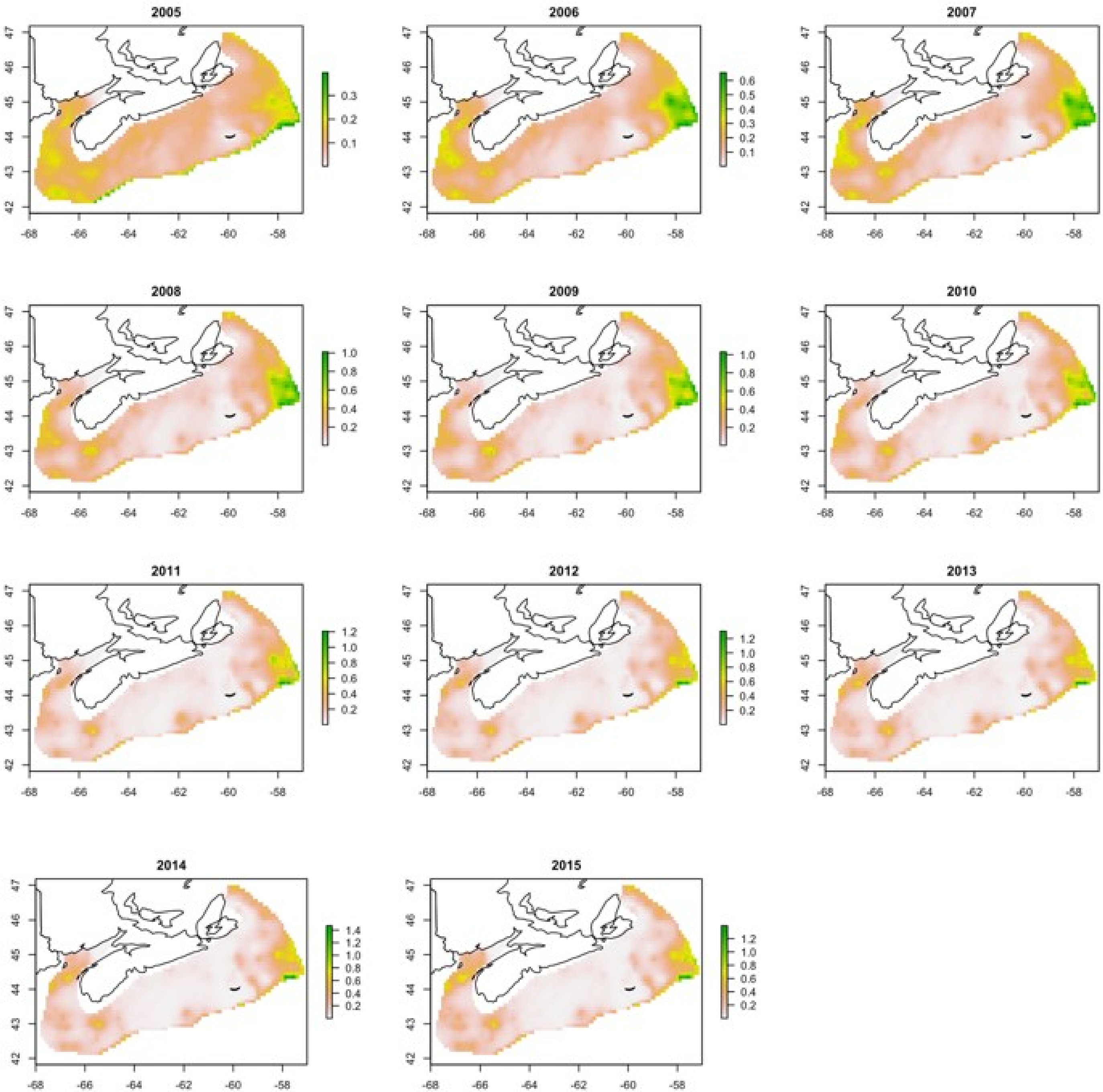

Figure A17: Standard error of estimated bycatch risk for thorny skate. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015

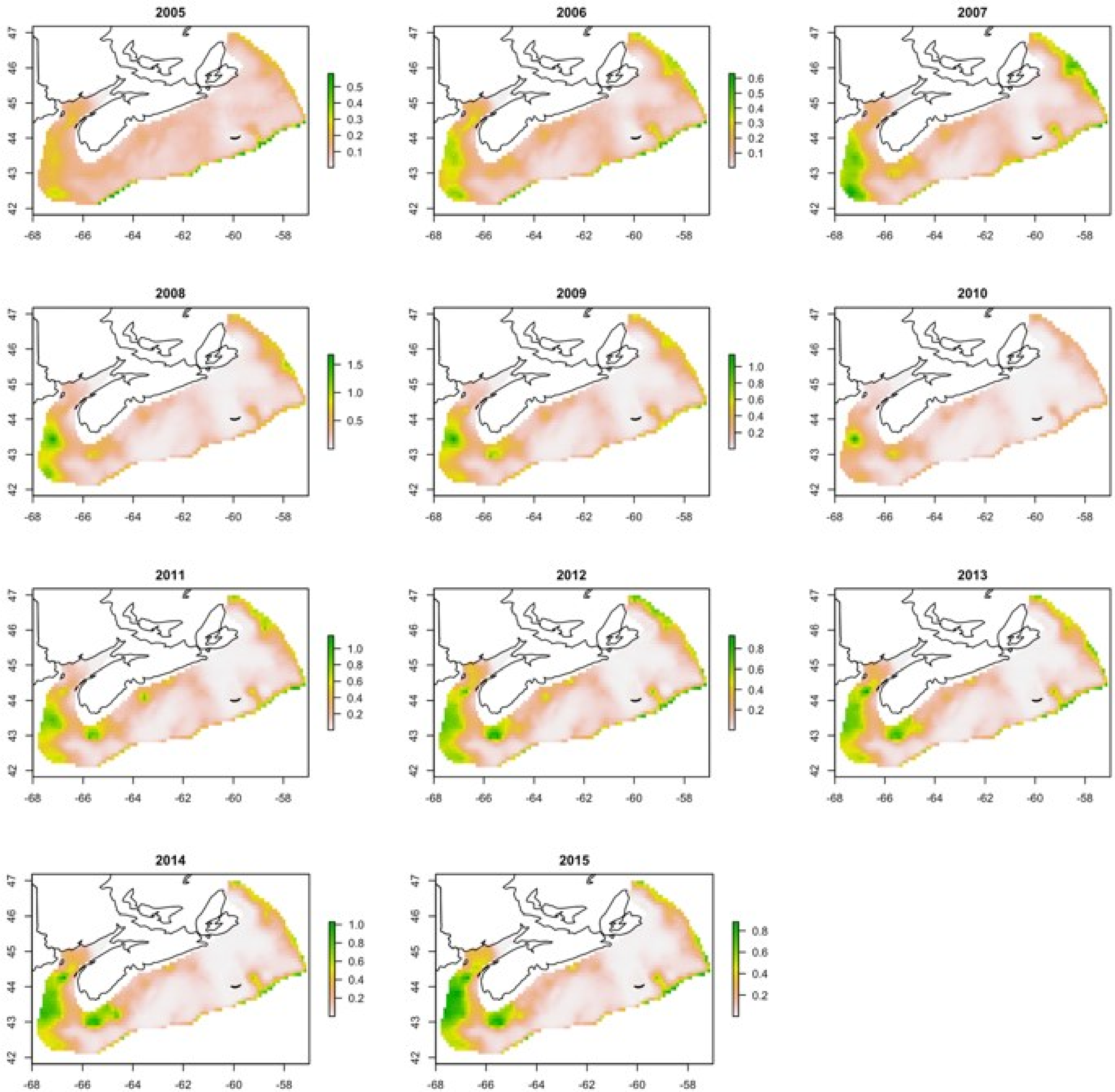

Figure A18: Standard error of estimated bycatch risk for smooth skate. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015

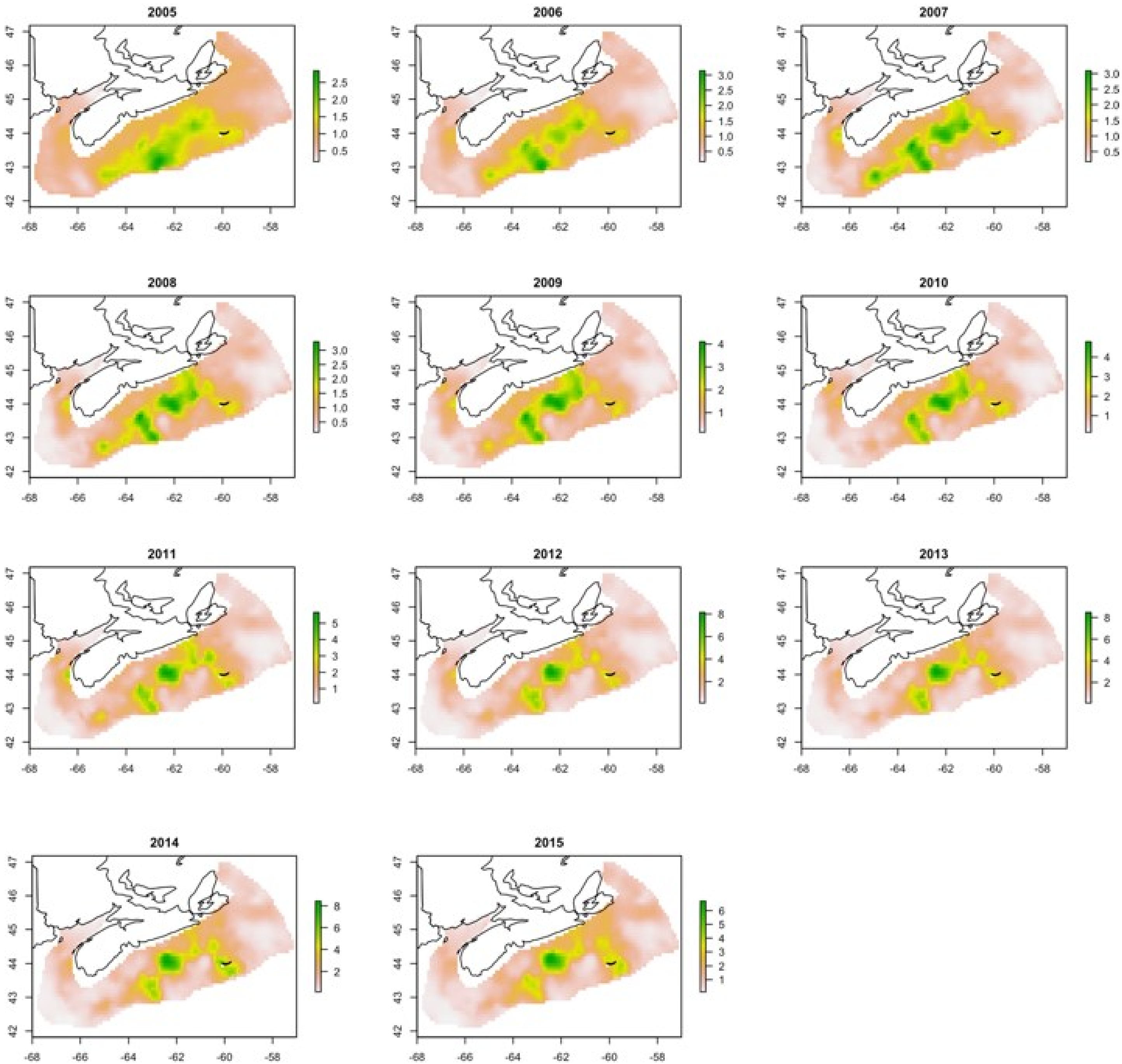

Figure A19: Standard error of estimated bycatch risk for Atlantic halibut. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015

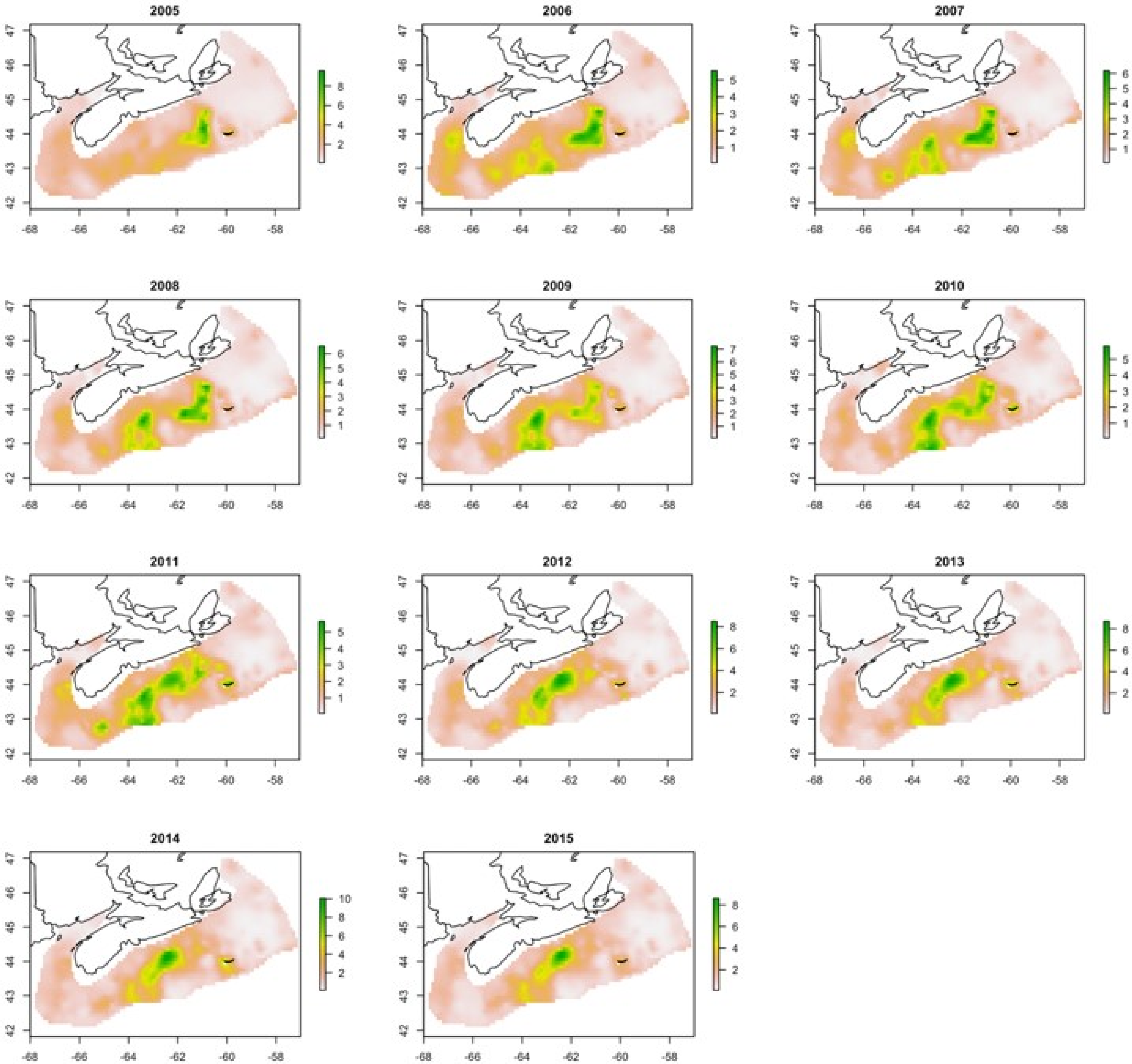

Figure A20: Standard error of estimated bycatch risk for the cod-haddock-pollock complex. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015

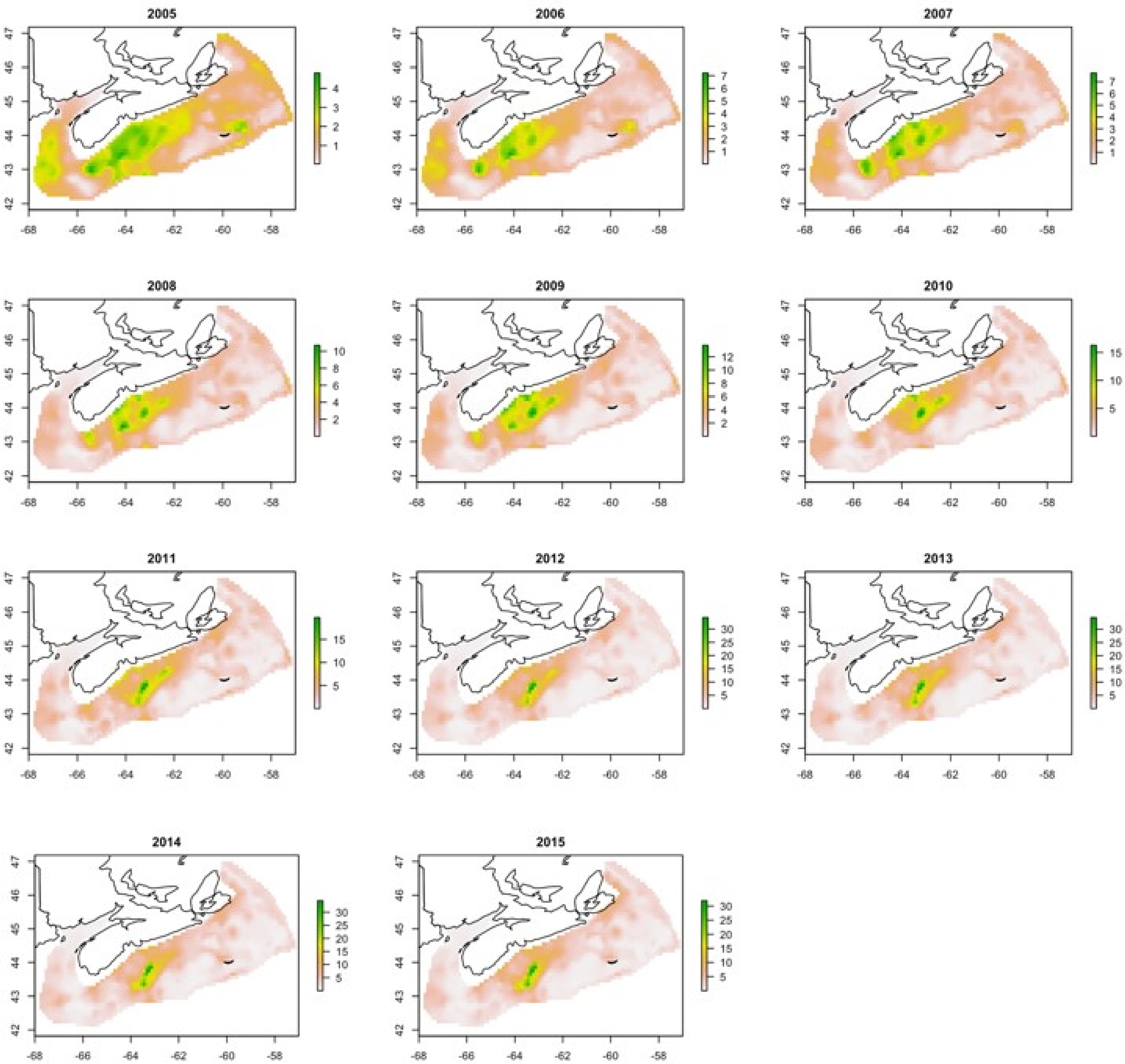

Figure A21: Standard error of estimated bycatch risk for redfish spp. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015

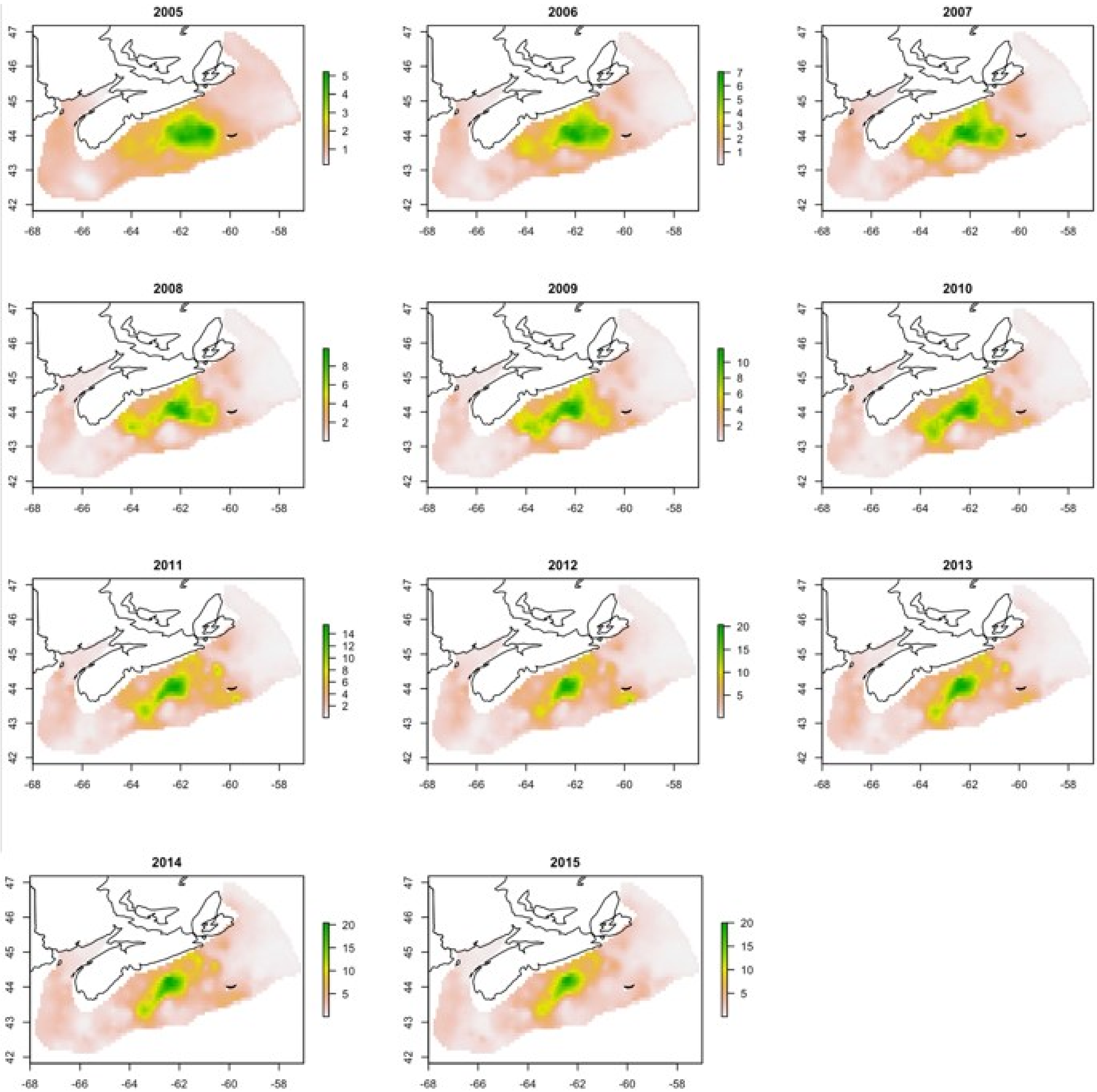

Figure A22: Standard error of estimated bycatch risk for silver hake. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015

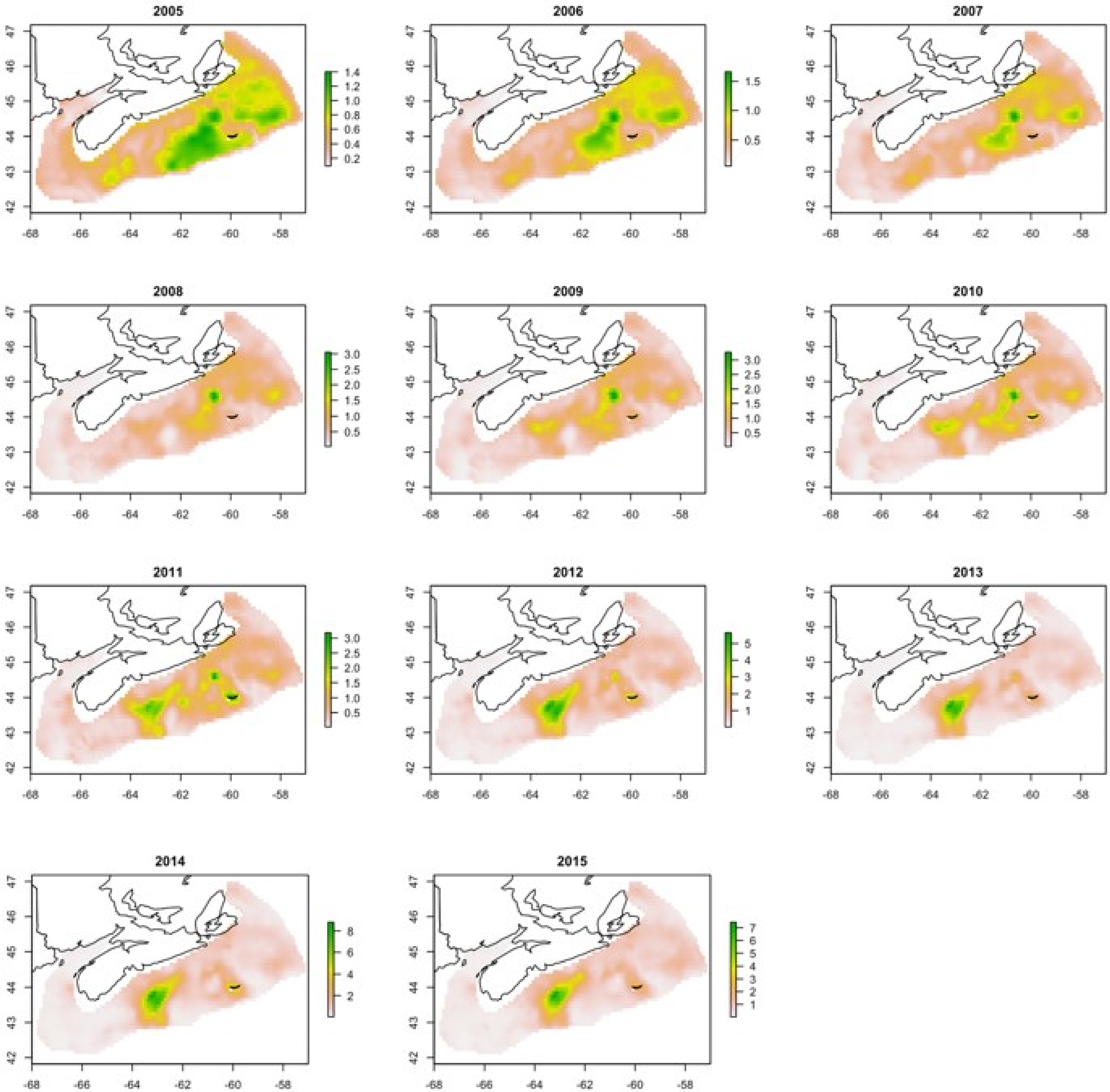

Figure A23: Standard error of estimated bycatch risk for flatfishes. Shown is the calculated standard error for bycatch risk maps from unscaled species distribution predictions, 2005-2015