Climate-Induced Species Range Projections and the Consequences for Ecosystem Functioning in Canada's Maritimes Region Marine Conservation Network

By

Amy Irvine

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Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

Dedication

In memory of those who supported me in becoming who I am today but are no longer with me: my friends, HeeJin Kim and Brittany Brooks; my uncle, Keith Irvine; and grandparents, David and Audrey Irvine and Lloyd and Louise Janke.

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Abstract

Ensuring the conservation and sustainability of marine ecosystems and the continued provision of ecosystem services are key goals of Canada's framework for its protected seascape sites. With rapid climate change however, the protected seascape sites may become less effective at fulfilling these goals, especially since no consistent and coherent approach exists for adapting marine protected area networks to respond to ongoing and accelerating changes in Canadian marine ecosystems. In this thesis, I project and evaluate the consequences of climate-change induced shifts in marine species compositions for Canada's east coast and for its proposed Scotian Shelf-Bay of Fundy Bioregion marine protected area network. In addition to assessing the effects of changing species distributions on the protected seascape, I develop a novel approach to project the ecological disruption that may be caused by these shifts. Ultimately, future scenarios with higher carbon emissions had larger shifts in species compositions and, subsequently, higher projected ecological disruption than lower emission scenarios. However, the network sites with the largest shifts in species composition did not suffer the highest ecological disruption, indicating the importance of assessing both species and functional change for a fuller understanding of climate change impacts. To ensure representation across the range of changes projected, I developed a "portfolio" of protected seascape sites that I recommend be prioritized for building resiliency and robustness to climate change, while also identifying the sites projected to have the highest ecological disruption and thus, most in need of protection from additional anthropogenic stressors. My results can be used to inform adaptive climate management for this region, and also provide a template for how such strategies can be conceived in terms of their integration into marine protected area design, management, and operation in other parts of the world.

List of Abbreviations Used

AOI – Area of Interest

CGCCA – Corsair/Georges Canyons Conservation Area

CMIP6 – Coupled Model Intercomparison Project Phase 6

COSEWIC - Committee on the Status of Endangered Wildlife in Canada

DFO –Fisheries and Oceans Canada

EBSA – Ecologically and Biologically Significant Area

ECCC – Environment and Climate Change Canada

ECMR – Eastern Canyons Marine Refuge

EDI – Ecological Disruption Index

eDNA – environmental DNA (Deoxyribonucleic acid)

ESM – Earth System Models

FD - Functional Diversity

FE – Functional Entity

FG – Functional Group

FRed – Functional Redundancy

FRic – Functional Richness

FOR – Functional Over-Redundancy

FVul – Functional Vulnerability

GBIF - Global Biodiversity Information Facility

IPCC – International Panel on Climate Change

IUCN – International Union for the Conservation of Nature

JBCA – Jordan Basin Conservation Area

JLMNWA – John Lusby Marsh National Wildlife Area

KDE – Kernel Density

MPA – Marine Protected Area

NCCCA – Northeast Channel Coral Conservation Area

NOAA – National Oceanic and Atmospheric Administration

OBIS - Ocean Biogeographic Information System

OECM – Other Effective area-based Conservation Measure

PCA – Principle Component Analysis

PCoA – Principle Coordinate Analysis

RCP – Representative Concentration Pathway

SDM – Species Distribution Models

SSP – Shared Socioeconomic Pathways

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Chapter 1: Introduction

Climate change has well-known impacts on marine ecosystems, from forcing shifts in regional species compositions (Johnson et al. 2011; Wernberg et al. 2016) to large-scale redistributions of species poleward (Garciá Molinos et al. 2015; IPCC 2022). As it accelerates (Cheng et al. 2019; IPCC 2022), ecosystems are expected to continue changing, with more extreme consequences projected with higher carbon emissions (Garciá Molinos et al. 2015; IPCC 2022). For example, in the Bay of Biscay under a high emissions scenario, there is projected to be a larger proportion of regional species showing range contractions, more climate-immigrant species arriving, and a more extreme species composition shift relative to low-emission scenarios (Le Marchand et al. 2020). The loss of existing species and gain of new species, in combination with other climate change impacts driving these changes (e.g., increased acidification, ocean warming, oxygen loss, etc.), is likely to generate trophic mismatches and new interactions that will ultimately affect ecosystem functions in ways that are difficult – but important – to predict (Nagelkerken and Connell 2015; Pinsky et al. 2020). A major challenge remains how best to assess ecosystem functioning over the coming century (Pinsky et al. 2020).

A high functioning ecosystem is not necessarily the most species-rich *per se* (Tilman et al. 1997), but rather one that can provide goods and services that sustain the ecosystem, upon which marine life and humans depend (e.g., food and fisheries, carbon sequestration, coastal protection, habitat; Reiss et al. 2009; IPCC 2022). The ecological role of each species within an ecosystem is often proxied by its ‘functional group’, such that species that occupy different functional groups (e.g., a top-predator shark relative to an herbivorous sea turtle) play different roles, while species in the same functional group (e.g., mackerel and capelin are both small-bodied forage fish) play similar roles. Therefore, ecosystem functioning can be linked to the diversity of functional groups it contains ('functional diversity') and the number of species within each functional group ('functional redundancy'), with more stable ecosystems having multiple species within each functional group (Hughes et al. 2005; Micheli and Halpern 2005). Yet, it is often only shifts in species diversity that are commonly used as measures of climate-induced change to ecosystems (Hiddink and ter Hofstede 2008; Chase et al. 2019) despite functional diversity likely being a more direct indicator of how the ecosystem will actually respond (Tilman et al. 1997).

The relationship between taxonomic diversity and functional diversity is complex, with functional diversity plateauing at some level of species diversity (Petchey and Gaston 2002; Mouillot et al. 2014). Indeed, tropical ecosystems that are highly biodiverse in fish species, are also largely functionally "over-redundant", with ~35-55% of the roles within these ecosystems containing more species than the average of the number of species in each functional role within that ecosystem (Mouillot et al. 2014). In less speciose ecosystems there are proportionally more functional groups relative to the number of species present, and of those groups, proportionally more groups containing one species in comparison to highly speciose ecosystems (e.g., 2.5x as many FEs but ~4x as many species in Central Indo-Pacific versus tropical Western Atlantic; Mouillot et al. 2014). While high species diversity may provide some insurance against the loss of functional groups following disturbance (Yachi and Loreau 1999), in order to truly understand how an ecosystem functions, or how it may change its functioning into the future, requires some measure of the functional structure and groups it contains (Mouillot et al. 2013). Both species- and functional- diversity metrics are important for understanding the resilience of ecosystems to climate change, and indeed give different insights into how climate change affects the ocean: one looking at how individual species respond, the other aggregating the impacts over the ecosystem as a whole.

My thesis aims to tie these two lenses together to explore how climate change will impact the ecosystems of Canada's Atlantic coast in the Maritimes Region. In particular, I explore how the ecosystems under protection – or proposed for protection – by Marine Protected Areas (MPAs) may change, and consider how the MPA network itself may need to respond. Spatial marine conservation tools such as MPAs have been designated worldwide to protect marine ecosystem structure and diversity. Yet the primary focus, including for the long-term, is on taxonomic diversity (Micheli and Halpern 2005; Government of Canada 2011). Overlooking functional diversity ensures that these protected seascape sites do not encompass how the ecosystem will fundamentally shift in functioning over time. Indeed, temporal changes in species richness within MPAs have often been both positively and negatively associated with changes in functional richness, including declines in functional richness as species richness increases (Micheli and Halpern 2005). This latter outcome could arise if there were few emigrating species, each possibly sole representatives of their functional group, being replaced by higher numbers of immigrating species that are within functional groups already existing within the MPA (i.e. functionally 'redundant'). Such outcomes may consequently have a larger impact on ecosystem functioning than would be predicted from the increase in richness alone.

To ensure protected seascape sites continue to protect, maintain, and restore ecosystem functioning into the future, their design, management, and operation must be adapted to respond to climate change (McLeod et al. 2009; Tittensor et al. 2019). While recommendations exist for how to best account for climate change in spatial marine conservation globally and nationally (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022), Canada is below the average in terms of overall climate integration based on an assessment of climate change in MPA management plans (mean index score of 6.8 compared to global average of 10.9 of 28; O'Regan et al. 2021). As Canada moves towards a national goal of 30% of marine and coastal areas protected by 2030 (Tittensor et al. 2019; DFO 2021a), climate change integration into the upcoming 13 new MPA networks (DFO 2022a) should be considered a priority. In fact, by 2024, a Conservation Network Plan is expected to be completed for the Scotian Shelf-Bay of Fundy bioregion network in DFO's Maritimes Region (termed the "Maritime Conservation Network"; DFO 2022), providing an opportunity to explore climate-adaptive design and management. It is with this context in mind that I undertook my research.

In my thesis, I aim to project how ecosystems on the east coast of Canada will respond to climate change, with the ultimate goal of providing insight on how to best integrate climate change-induced impacts into the Conservation Network Plan for the Maritimes Region. To determine regional ecosystem responses to climate change, I examined (i) shifts in species compositions and (ii) shifts in functional diversity from present day to mid- and end-century under multiple future scenarios, including for each protected seascape site within the region. I used species distribution models (SDMs) and future range projections for >18,000 species globally (Reygondeau *et al.* in prep), which I filtered for species presences in the Maritimes Region, now and in the future. As these models are still being finalized (Reygondeau *et al*. in prep), it is important to note the results in this thesis may change, but overall provide a first look at how marine spatial planning can be adapted with relevant climate change-induced impacts on ecosystem functioning in Canada.

Chapter 2 of my thesis illustrates how species compositions will change into the future, with an examination of the consequences for the Maritimes Region, the Maritime Conservation Network, and select individual species. Chapter 3 focuses on the ecosystem functioning - and disruption of functioning – resulting from these species shifts in the Maritimes Region and each protected seascape site. Finally, Chapter 4 summarizes my results across both Chapter 2 and 3 to provide regionally-specific recommendations for the Maritime Conservation Network based on the combined changes in species and functional diversity into the future.

Chapter 2: Climate-Induced Species Range Shifts and the Consequences for Canada's Maritimes Region Marine Conservation Network

Chapter 2.1: Introduction

The rate of climate change is accelerating (Cheng et al. 2019; IPCC 2022), with a global increase in temperature driven primarily by the accumulation of anthropogenic greenhouse gases (IPCC 2022). The oceans have absorbed more than 90% of this excess heat (Levitus 2005; Gleckler et al. 2016), resulting in rapid warming and consequences for marine organisms at levels from the individual (genetic, phenotypic) to entire communities and ecosystems (Pinsky et al. 2020). A warming ocean affects physiology (e.g. increased metabolic costs; Childress and Seibel 1998; Pörtner 2010; Deutsch et al. 2015) and ultimately can exceed thermal tolerance levels of individuals (Pörtner 2010; IPCC 2022). Beyond this physiological limit, individuals, populations, and species must adapt, move, or become extirpated (Milazzo et al. 2013; Nagelkerken and Munday 2016), resulting in reconfigurations of species compositions within communities that can produce novel assemblages and species interactions. These changes may have cascading effects via novel interspecific interactions (e.g., in foraging, predator avoidance/risk assessment, habitat preference; Lönnstedt et al. 2014; Nagelkerken and Connell 2015; Grady et al. 2019) and even lead to entirely new ecosystem regimes (Johnson et al. 2011; Wernberg et al. 2016). Combined with other warming impacts, this will have profound but difficult to quantify effects on ecosystem functioning (Tilman 1999; Vinebrooke et al. 2004), making projections of shifts in species composition an important first step for understanding future ecosystem dynamics.

In addition to climate change, many other anthropogenic threats are impacting ocean ecosystems (IPBES 2018). In response to these stressors, spatial conservation tools such as Marine Protected Areas (MPAs) have been selected, designed, and managed worldwide to help conserve biodiversity and restore and maintain ecosystem health and services to society (e.g., carbon sequestration, spillover effects for surrounding fisheries; Government of Canada 2011; Hillebrand et al. 2018). In Canada, many forms of marine spatial protection exist (outlined in Bryndum-Bucholz et al. 2022), but MPAs are specifically designated to protect spatially defined areas that are important for one or more priority species or for the whole ecosystem (e.g., nursery grounds, spawning sites, high species diversity, etc.; Government of Canada 2011). An identified "Area of Interest" (AOI) becomes an MPA upon designation by Fisheries and Oceans Canada (DFO), which then manages it under the *Oceans Act* (Minister of Justice 1996; Government of Canada 2011). In MPAs, one or more human activities are prevented or limited, such as oil and gas extraction, mining, dumping, bottom trawls and/or "any activity that disturbs, damages, destroys or removes from the MPA any living organism or any part of its habitat or that is likely to do so" (Government of Canada 2011). Individual MPAs are designated in a coordinated fashion, with the intent of developing comprehensive, resilient, and representative "networks" of protected ecosystems that are cooperatively and adaptively managed to boost their benefits for present and future generations (Government of Canada 2011; DFO 2022a). In addition, Other Effective area-based Conservation Measures (OECMs) in Canada provide positive and sustained long-term conservation of biodiversity, ecosystem functioning and services, cultural, spiritual, socio-economic, and other locally relevant values (ECCC 2022) commonly as a secondary benefit in addition to their stated purpose (e.g., Corsair/Georges Canyons Conservation Area is a restricted bottom fisheries zone with the aim of protecting cold water corals). OECMs that are managed by DFO under the *Fisheries Act* are referred to as Marine Refuges but OECMs can also be managed by other governing bodies (e.g., Indigenous groups, , the military, etc.; DFO 2021a). While MPA networks form the backbone of the protected seascape in Canada, OECMs and other spatial conservation sites (herein collectively termed the "protected seascape") supplement MPAs and will form part of the area to attain the national goal of 30% of marine and coastal areas conserved by 2030 (Tittensor et al. 2019; DFO 2021a).

Although the MPA network is built for resilience to local stressors, protecting spatially defined areas may result in altered effectiveness over time if the original ecosystem dynamics and species assemblages are impacted by climate change, or indeed are no longer within the protected seascape (McLeod et al. 2009; Bruno et al. 2018; Tittensor et al. 2019). As species and habitats shift with climate change, Canada's protected seascape design, management, and operation needs to shift with it (McLeod et al. 2009; Bruno et al. 2018). Yet Canada, in common with many other jurisdictions, has no consistent and coherent approach for adapting and responding to climate-induced changes in habitats and species compositions within its protected seascape (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022). Despite calls for climate-resilient conservation in temperate and polar habitats (Wilson et al. 2020), Canada is ranked low for climate change robustness in its MPA management plans on a global scale (mean index score of 6.8 of 28; O'Regan et al. 2021). Of the 13 planned networks in spatially defined bioregions across Canada, the Scotian Shelf-Bay of Fundy bioregion network in DFO's

Maritimes Region (termed the “Maritime Conservation Network”) has a public timeline for completing its Conservation Network Plan (estimated 2024; DFO 2022); yet even with parts of the Northwest Atlantic region anticipated to warm at a rate almost three times as fast as the global average (Saba et al. 2016), there is no mention of how to integrate climate change effects into this network’s design, management, operation, or adaptation (DFO 2022a). To avoid undermining the efficacy of this protected seascape, it is important to integrate both present and future ocean conditions into the design, management, and on-going development of the Maritime Conservation Network, with an aim to guide protected seascape development nationwide (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022).

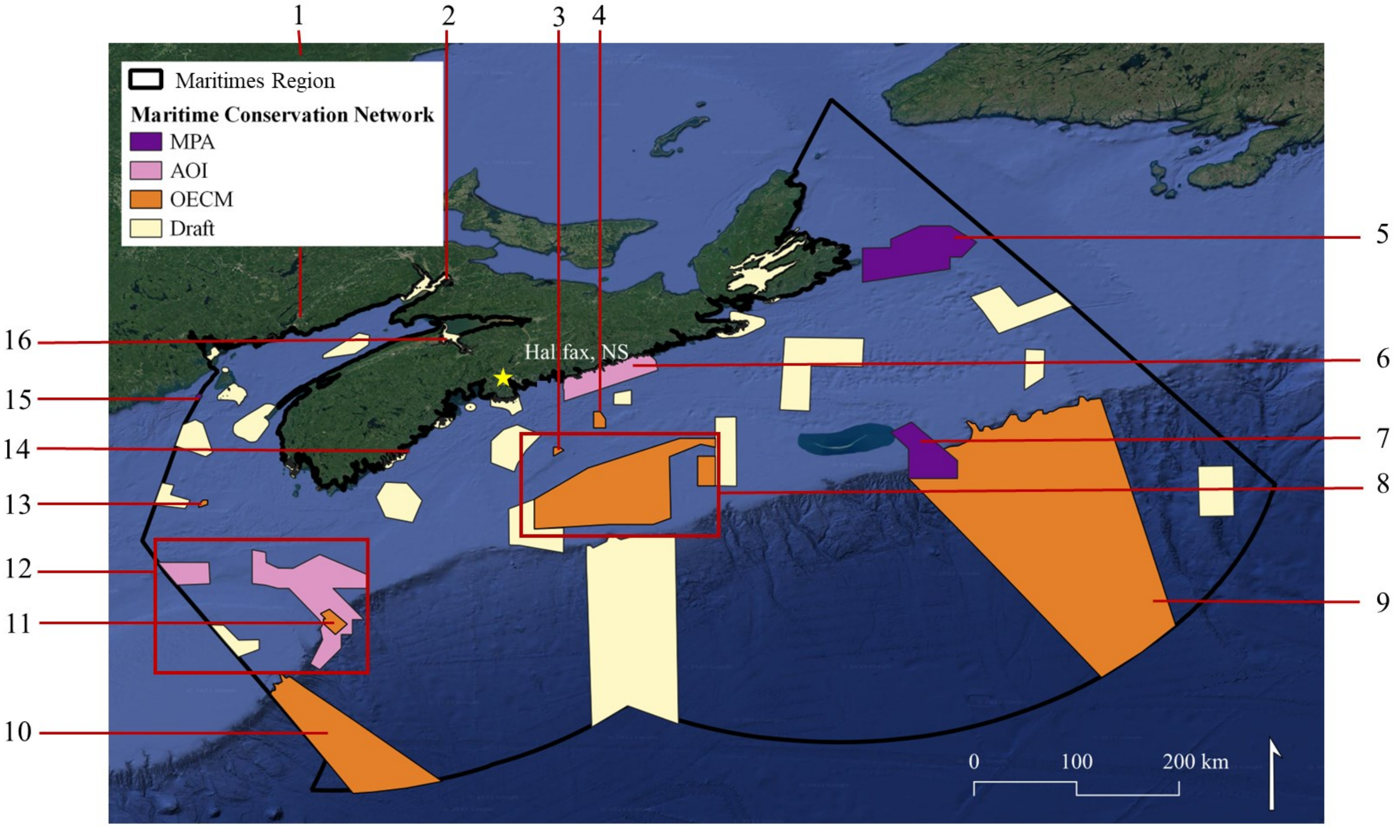
Projecting anticipated changes in species assemblages over the coming century and how they interact with MPA networks and OECMs helps to inform their management and network design. Here I project how the distributions of marine species across numerous taxa on Canada’s eastern coast are likely to change under multiple projections of future climate, and how these changes will affect and interact with the Maritime Conservation Network. To do so, I evaluated marine species that are presently within DFO’s Maritimes Region based on outputs from an ensemble of species distribution models (SDMs). Subsequently, I determined which species were projected to immigrate or emigrate from the Region using the outputs of these models forced by projections from multiple Earth system models (ESMs) under two scenarios, that of high and low emissions (Reygondeau *et al,* in prep.). I then assessed how these range shifts will affect the proportion and composition of species under protection in this region in 2050 and 2099 under each future scenario. I also examined which resident species (i.e.

presently within one or more protected seascape sites) will undergo climate-driven emigration from the network, and which novel species will immigrate into individual MPAs, OECMs, AOIs, and proposed sites for the Maritime Conservation Network. Based on the results of these analyses, I provide recommendations to help guide DFO's Maritimes Region design, management, and monitoring, and provide insight into potential changes within proposed OECMs and AOIs.

Chapter 2.2: Methods

Species Range Projections

To evaluate species distributions presently within and/ or projected to move into DFO's Maritimes Region, an ensemble of global SDMs (Reygondeau *et al*., in prep.) and their future projections were restricted to the study region (Figure 1; Figure 2; ~608,000 km^2). These SDMs initially considered 18,562 species across the globe of marine fish, mammals, reptiles, and lobsters. In total, of the 18,562 species assessed, there were 11,317 fish, 98 marine mammals, 85 reptiles, and 217 lobsters that had sufficient data to construct habitat suitability models (Table A1). For my thesis, I only focused on a subset of species presently found within or projected to move into the region of interest, and a handful of species were manually removed from analyses because they (a) did not have a known location in the water column for restricting future range expansion rates (14 fish sp.; Genus: *Doydixodon* – 1 sp., *Encrasicholina* – 2 spp., *Etmopterus* – 1 spp., *Sardinella* – 2 spp., *Stolephorus* – 2 spp., *Tor* – 1 spp., *Pseudobarbus* – 5 spp.), (b) were a subspecies with the same range as the primary species (Atlantic Hawksbill sea turtle *Eretmochelys imbricata imbricata,* Pacific Hawksbill sea turtle: *Eretmochelys imbricata* *bissa*, Pacific loggerhead sea turtle: *Caretta caretta gigas*, subspecies of the blind lobsters, *Stereomastic sculpta sculpta*), or (c) the future range could not be restricted spatially (12 fish sp.; eight mammal sp.: Common minke whale, *Balaenoptera acutorostrata;* Sei whale, *Balaenoptera borealis*; Blue whale, *Balaenoptera musculus*; Fin whale, *Balaenoptera* physalus; Humpback whale, *Megaptera novaeangliae*; Long-finned pilot whale, *Globicephala melas*; Killer whale, *Orcinus orca*; Sperm whale, *Physeter macrocephalus*). The Gray whale (*Eschrichtius robustus*) was additionally removed as there is reasonable evidence it has been extirpated from the Atlantic Ocean despite sporadic juvenile sightings (Mead and Mitchell 1984; Garrison et al. 2019).



1. Musquash Estuary Marine Protected Area
2. John Lusby Marsh National Wildlife Area (MPA)
3. Sambro Bank Sponge Conservation Area (OECM)
4. Emerald Basin Sponge Conservation Area (OECM)
5. St. Anns Bank Marine Protected Area
6. Eastern Shore Islands Area of Interest
7. The Gully Marine Protected Area
8. Western Emerald Bank Conservation Area (OECM)
9. Eastern Canyons Marine Refuge (OECM)
10. Corsair/Georges Canyons Conservation Area (OECM)
11. Northeast Channel Coral Conservation Area (OECM)
12. Fundian Channel-Browns Bank Area of Interest
13. Jordan Basin Conservation Area (OECM)
14. Kejimkujik Seaside National Park and Historic Site (MPA)
15. Machias Seal Island Migratory Bird Sanctuary (MPA)
16. Boot Island National Wildlife Area (MPA)

Figure 1. Map of the Maritime Conservation Network in the Fisheries and Oceans Canada Maritimes Region, consisting of a) the region outline and b) the existing and proposed conservation sites. Orange is Other Effective area-based Conservation Measures (OECMs), purple is Marine Protected Areas (MPAs, existing and proposed Areas of Interest (AOIs)), and yellow is areas under consideration but undetermined on classification yet.

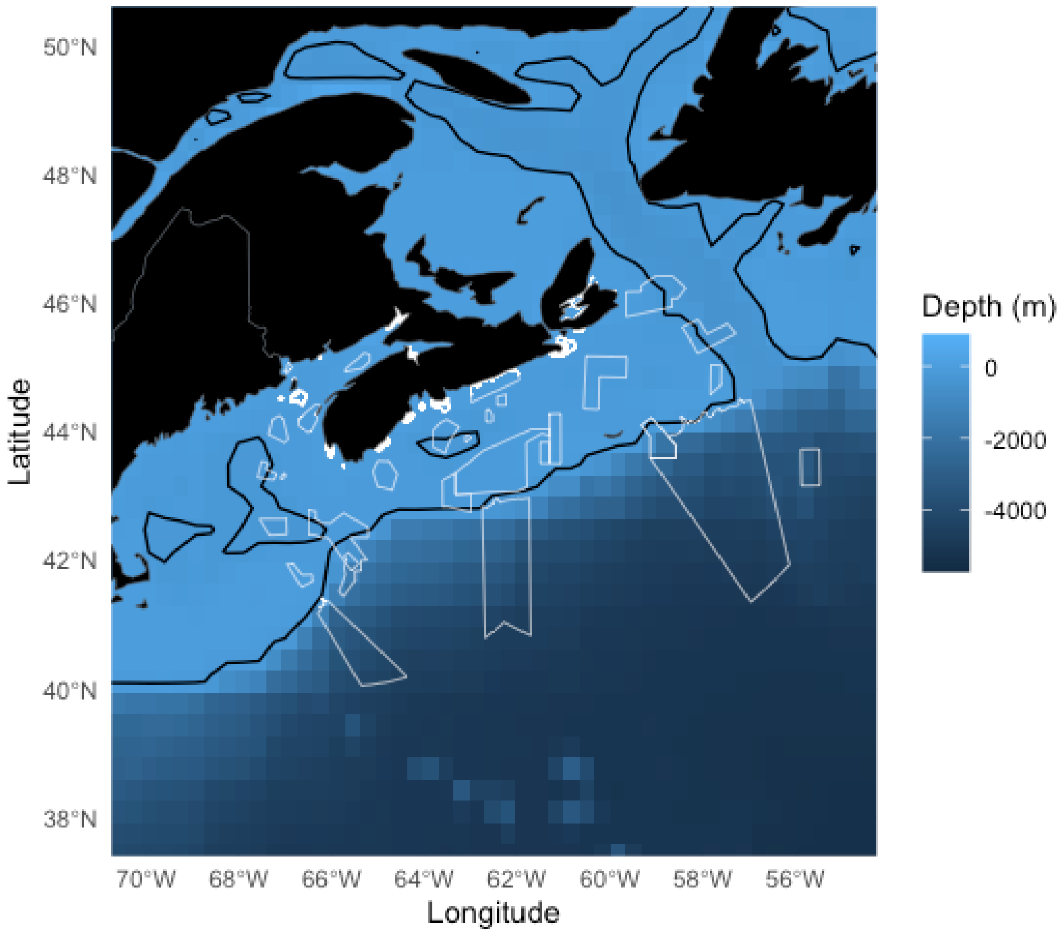


Figure 2. Bathymetry of the Maritime Conservation Network in the Fisheries and Oceans Canada Maritimes Region, consisting of the 200 m depth line in black along the Scotian Shelf and the existing and proposed conservation sites in white.

Full methods for the SDMs can be found in Reygondeau *et al.* (in prep.), but in brief, marine species presence locations worldwide were collected from publicly available databases (SeaLifeBase, Palomares and Pauly 2022; FishBase, Froese and Pauly 2023; International Union for the Conservation of Nature (IUCN) Red List, IUCN 2022; Ocean Biogeographic Information System, OBIS 2023; Global Biodiversity Information Facility, GBIF 2022). Species presences were filtered for outliers using expert range maps when available and only species with sufficient presences were used (minimum seven observations independent of time and space). Each set of species records was then spatially related to a range of environmental predictors (sea surface temperature, salinity, and oxygen; sea bottom temperature, salinity, and oxygen; nitrate, phosphate, silicon dioxide, pH, meridional and zonal current velocity, bathymetric depth, net primary productivity, sea ice concentration, and mixed layer depth) dependent on their positioning within the water column (i.e., pelagic species modelled with surface variables, demersal and benthic species modelled using bottom variables). Each species' distribution was then modelled using 10 approaches that model the species-environment relationship considering this presence-only data (Maxent-Phillips, Generalized Linear Models, General Additive Models, Random Forest, Artificial Neural Network, Bioclim/ Surface Range Envelope, Classification Tree Analysis, Mixture Discriminate Analysis, Multivariate Adaptive Regression Splines, Non-Parametric Probabilistic Ecological Niche; Fortin and Dale 2005).

These individual SDMs each produced maps of relative habitat suitability on a global 55 x 55 km^2 grid, equating to 164,160 equal-area grid cells. The projections were then restricted to their 'native range' in the present day (derived from observations in AquaMaps, Kaschner et al. 2019 and/or expert range maps if available, Reygondeau *et al.* in prep) to prevent range over-estimation relative to observations. A species native range is the environment they are restricted to by both abiotic (i.e., climate, topography) and biotic (i.e., interactions) factors (Guisan et al. 2017). A final ensemble habitat suitability index (HSI) for each grid cell was created using the unweighted average outputs from these SDMs and translated to presence/absence using a species-specific cutoff derived from the receiver operating characteristic (ROC) curve to maximize model classification accuracy (Guisan et al. 2017).

Present-day environmental variables used to construct SDMs, and future environmental variables used to project SDMs, were derived from Earth System Model (ESM) outputs (namely, Geophysical Fluid Dynamics Laboratory, Delworth et al. 2006; Institut Pierre Simon Laplace, Hourdin et al. 2005; Max Planck Institute, Roeckner et al. 2003) from the Coupled Model Intercomparison Project Phase 6 (CMIP6 2019). The period 1996-2015 was used as a present-day baseline, and mid-century (2041-2060) and end-century (2081-2100) for future projections. Given the uncertainties in future emission trajectories and socioeconomic pathways, changes in species ranges were projected under two Shared Socioeconomic Pathway (SSP) Representative Concentration Pathway (RCP) scenario combinations from the CMIP6 scenario matrix, which detail socioeconomic development pathways and the concentrations of greenhouse gases over the coming century, respectively (IPCC 2022). In particular, high mitigation (SSP1-2.6) and high emissions (SSP5-8.5) pathways were used, thus bounding a plausible range of futures and providing contrast among results (IPCC 2022). For future projections, species were limited in their rate of range expansion to literature-derived values to ensure consistency across species and taxa, as the maximum rate of range expansion for each species with climate change is unknown. Therefore, species were limited to a range expansion of 20 km/decade if benthic (80 km in mid-century scenarios, 180 km in end-century scenarios) and 30 km/decade if pelagic (120 km in mid-century scenarios, 270 in end-century scenarios; Table 1; Southward et al. 1995; Burrows et al. 2014; Gabriel Reygondeau, pers. comm), with dispersal barriers considered through each species maximum depth range (Gabriel Reygondeau, pers. comm). As a robustness test, I also evaluated more rapid climate-driven relocation (Table 1; Table A2; 58.5 km/decade if benthic and 85.5 km/decade if pelagic; Poloczanska et al. 2013).

In summary, each species was modelled using ten SDM approaches, three ESMs, and two climate scenarios. Results (i.e., the HSIs) were ensemble-averaged across SDM approaches and ESMs, giving individual species maps in the present day, and projected distributions under two scenarios for mid- and end-century.

Table 1. Climate range expansion per decade in the marine realm from literature reviews.

Distribution	**Shift (km/decade) (mean ± s.e.m)**	**Species**	**Study**
Leading edge	72.0 (± 13.5)	Primarily multi-species (excl. seabirds)	(Poloczanska et al. 2013)
Leading and trailing edge, including centre	30.6 (± 5.2)	Primarily multi-species (excl. seabirds)	(Poloczanska et al. 2013)
Leading edge	20-30 (observed range shifts up to 1980s)	Plankton and intertidal spp.	(Southward et al. 1995; Cheung et al. 2009; Burrows et al. 2014)
	65-130 (extrapolated for 2050 where temperature rises by 2°C, Cheung et al. 2009)	Plankton and intertidal spp.	(Southward et al. 1995; Cheung et al. 2009)

Species Range Shifts and the Maritime Conservation Network

All (>11,000) present and future projected species ranges were intersected with a shapefile of the Maritimes Region to retain only those species already within or projected to be within the region (Figure 1). A shapefile containing 47 existing and proposed network sites, termed collectively “protected seascape sites” (seven MPAs, seven

OECMs (all are Marine Refuges governed under the *Fisheries Act* by DFO), two AOIs, and 31 proposed network sites for potential AOIs or OECMs) in the Maritime Conservation Network (DFO 2021c; Figure 1) was similarly intersected with species ranges to identify those with projected presences within each site in the present-day and under future scenarios. R version 4.2.1 (R Core Team 2022) was used to extract species that spatially overlapped with the network and region, specifically the *sf* (Pebesma 2018) and *tidyverse* (Wickham et al. 2019) packages.

Climate-driven changes in species ranges were evaluated from two perspectives: that of the network and that of the species. From a network perspective, the immigration and emigration of species was determined by analyzing which species were projected to arrive in (climate immigrant) or no longer occur within (climate emigrant) the region or within individual protected seascape sites for both SSP-RCP scenarios. Species with no change in their presence (i.e., staying within the region or within individual sites) were also recorded. Changes in species richness, composition, and dissimilarity were then calculated for each site and for the region as a whole.

From a species perspective, the proportion of each individual species' projected (regional) range that fell within each protected seascape site was assessed and compared across present-day and SSP-RCP scenarios to examine which species were presently the most protected, and how the fraction of their range under protection may shift into the future. In addition, 24 species at risk (Table 2) within the region were highlighted to determine the conservation implications of their range change within protected seascape sites. To determine the potential benefits of emissions mitigation for these species, the proportion of ranges under protection by all (including AOI, proposed) protected seascape sites and all existing network sites was compared in each time-period under high mitigation (SSP1-2.6) and high emissions (SSP5-8.5) scenarios.

Table 2. Proportion of COSEWIC Endangered (END) and Threatened (THR) species ranges within a network site in the present (Pres.) and over time and SSP-RCP scenario with 14 existing network sites (exist) and 47 protected seascape sites combined (exist and proposed). Species were selected based on conservation interest for Canada's east coast. The COSEWIC endangered Deepwater redfish *(Sebastes mentella)*, Porbeagle shark (*Lamna nasus*), White shark (*Carcharodon carcharias*), Bluefin Tuna (*Thunnus thynnus*), Sei whale (*Balaenoptera borealis*), and Blue whale (*Balaenoptera musculus*) were all removed as they did not have a future modelled distribution (Reygendeau et al. *in prep*). The Atlantic salmon endangered Nova Scotia Southern Upland Population was assessed by using the entirety of the modelled Atlantic salmon distribution in the Maritimes Region. The IUCN Red List global status for each selected species is also provided below (LC = Least Concern, NT = Near threatened, VUL = Vulnerable, Crit. END = Critically Endangered).

		Status				Mid-century		End-century	
Taxa	**Species**	**COSEWIC**	**Red List**	**Sites**	**Pres. (%)**	**SSP1 -2.6 (%)**	**SSP5 -8.5 (%)**	**SSP1 -2.6 (%)**	**SSP5 -8.5 (%)**
Fish	Atlantic cod	END	VUL	Exist	34.5	34.9	34.6	33.6	35.2
				Exist and prop.	76.4	74.6	73.8	74.6	71.0
	Atlantic salmon	END (Nova Scotia Southern Upland Pop.)	LC - Global	Exist	22.2	20.0	20.0	21.7	23.3
				Exist and prop.	77.8	75.6	75.6	76.1	76.7
	Acadian redfish	THR	END	Exist	35.2	31.5	32.2	34.3	33.0
				Exist and prop.	76.1	77.1	76.7	75.5	74.8
	Atlantic sturgeon	THR	VUL	Exist	23.1	19.2	20.0	8.3	20.5
				Exist and prop.	76.9	76.9	73.3	79.2	77.3

Taxa	Species	Status COSEWIC	Red List	Sites	Pres. (%)	Mid-century SSP1 -2.6 (%)	SSP5 -8.5 (%)	End-century SSP1 -2.6 (%)	SSP5 -8.5 (%)
	American plaice	THR	END - Global	Exist	34.4	34.6	34.3	34.9	34.5
				Exist and prop.	74.4	71.3	71.4	73.6	67.2
	Cusk	END	LC - Europe	Exist	37.7	36.8	37.7	35.7	34.6
				Exist and prop.	78.3	72.6	72.8	73.9	67.3
	Lumpfish	THR	NT	Exist	32.7	30.6	31.3	31.2	31.8
				Exist and prop.	77.3	75.9	75.0	76.1	71.3
	Roundnose Grenadier	END	END	Exist	39.7	45.9	47.5	34.6	37.1
				Exist and prop.	66.4	59.5	60.0	57.7	54.3
	Northern Wolffish	THR	END	Exist	36.7	37.5	35.2	36.6	33.8
				Exist and prop.	71.6	71.1	68.1	69.5	64.6
	Spotted Wolffish	THR	NT	Exist	33.9	35.2	33.0	32.3	33.3
				Exist and prop.	73.6	71.5	66.0	69.7	64.7
	White Hake	THR	No data	Exist	35.0	34.1	34.4	34.4	34.9
				Exist and prop.	75.6	72.0	72.5	73.4	73.6
	Shortfin Mako	END	VUL - Global	Exist	22.6	26.5	26.1	29.6	36.6
				Exist and prop.	41.9	35.3	43.5	40.7	63.4
	Smooth Skate	END	VUL	Exist	34.6	35.5	26.3	33.3	NA
				Exist and prop.	73.8	69.7	31.6	77.8	NA

		Status				**Mid-century**		**End-century**	
Taxa	**Species**	**COSEWIC**	**Red List**	**Sites**	**Pres. (%)**	**SSP1 -2.6 (%)**	**SSP5 -8.5 (%)**	**SSP1 -2.6 (%)**	**SSP5 -8.5 (%)**
	Winter skate	END	END	Exist	33.6	33.3	34.5	33.0	29.5
				Exist and prop.	74.6	75.0	76.7	76.5	76.8
Mammals	North Atlantic Right whale	END	Crit. END	Exist	34.6	28.9	30.4	30.0	26.3
				Exist and prop.	65.4	71.1	71.7	65.0	26.3
	Northern bottlenose whale	END	NT	Exist	34.8	26.2	26.1	30.8	38.1
				Exist and prop.	66.3	71.4	63.0	63.1	52.4
Reptiles	Leatherback sea turtle	END	VUL	Exist	35.6	32.9	31.5	33.7	33.3
				Exist and prop.	52.2	50.0	49.3	50.0	50.0
	Loggerhead sea turtle	END	VUL	Exist	34.8	32.9	33.8	37.8	32.9
				Exist and prop.	56.3	50.0	50.0	53.1	51.3

Species Dissimilarity

Species dissimilarity was assessed using the Sorensen dissimilarity index (Legendre 2019). This metric was used to determine the percentage difference in community composition between two time (Legendre 2019) points and was calculated as:

$$\beta_{Sørensen} = \frac{(n_{\mathrm{immigrating}} + n_{\mathrm{emigrating}})}{(2 * n_{\mathrm{same}} + n_{\mathrm{immigrating}} + n_{\mathrm{emigrating}})} \qquad (1)$$

where $n_{immigrating}$ is the number of immigrating species, $n_{emigrating}$ the number of emigrating species, and n_{same} the number of species remaining unchanged. I calculated this using the *vegan* (Oksanen et al. 2022) and *labdsv* (Roberts 2019) R packages. Individual protected seascape sites were then ranked by the proportion of immigrating and emigrating species, as well as species dissimilarity for each year and SSP-RCP scenario.

Chapter 2.3: Results

Present Day Regional Species Richness

Of the 11,673 species modelled at the global scale (Table A1), 699 fish, 19 mammals, 5 reptiles, and 2 lobster species were projected to be in the Maritimes Region in the present day (Table 3; Figure 3; Table A3). The average ROC across all models for all species and taxa was 0.75. Present day species richness within the region was projected to be highest along the Scotian Shelf slope (maximum of 461 spp. within a grid cell) and to decline gradually into offshore and rapidly into coastal waters, with the fewest species on Nova Scotia's eastern shore and into Cape Breton (minimum of 139 sp. within a grid cell; Figure 3).

Regional Changes in Species Richness

Relative to the present day, the Maritimes Region was projected to decline in total species richness in all future times and scenarios (Figure 3; Table 3). The largest change in species richness (-119 species) occurred in mid-century under SSP5-8.5 while the smallest change in richness was projected to occur in end-century under SSP5-8.5, when the most immigrations occurred (Table 4). Species emigrations were relatively consistent except in end-century under SSP1-2.6 when the fewest present-day species were projected to emigrate, while the highest number of species immigrations was projected to occur in end-century under SSP5-8.5 (Table 4). The robustness test indicated the same trends with 4-11 additional species immigrations across times and scenarios (Table A2).

When comparing mid-century to end-century, the high emission scenario had ~2x the number of immigrant species and 8x as many emigrants relative to the low emission scenario. Furthermore, changes in species richness were lowest from mid- to end-century under SSP1-2.6 (Table 4). The number of immigrations from mid- to end-century were comparable to the number of immigrations from present day to end-century, indicating a large fraction of climate-driven immigrations occur after mid-century. In contrast, there were substantially fewer emigrating species from mid- to end-century (SSP1-2.6: 5 emigrations, SSP5-8.5: 40) relative to present day to end-century (SSP1-2.6: 141 emigrations, SSP5-8.5: 163), indicating more than three-quarters of emigrating species had left the region by mid-century (Table 4). Of the species immigrating from mid- to end-century (Table 4), 60% were resident species returning to the region after mid-century under SSP1-2.6 (26/43) whereas 47% were resident species returning under SSP5-8.5 (42/89).

Akin to the present day, the highest species richness was projected to occur along the Scotian Shelf slope in all future years and scenarios (Figure 3). In contrast to the present day, however, species richness was projected to decline gradually from the Scotian Shelf slope into coastal waters yet more rapidly into open waters in all future times and scenarios, with the most prominent richness decline occurring into open waters in mid-century under both scenarios (Figure 3).

As fish species make up ~95% of the total modelled species in all times and scenarios, the changes in fish richness reflect those in species richness (i.e., reduction in all future scenarios but highest future richness in end-century under SSP5-8.5; Table A3). Mammal richness increased in mid-century and end-century under SSP1-2.6 relative to the present day (Table A3). However, mammal richness decreased slightly in mid-century and remained the same into end-century under SSP5-8.5 (Table A3). The greatest change in mammal richness was ±1 species (Table A4), and both emigrating mammals in mid-century returned by end-century under SSP5-8.5 (Table A5). Reptile richness additionally decreased into all future times and scenarios (Table A3), with a loss of one species occurring between present day to mid-century (Table A4; Table A5). Lobster species had no change in richness in all future times and scenarios relative to present day or mid-century (Table A4).

Table 3. Species richness across the region and for each existing Marine Protected Area (MPA) and Other Effective area-based Conservation Measure (OECM) in the present day relative to mid- and end-century. SSP1-2.6 represents a high mitigation scenario while SSP5-8.5 represents a high emissions scenario. Sites are ordered by conservation type and then by species richness.

Site	**Type**	**Present day**	**Mid-century**		**End-century**	
			SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
Maritimes Region	Region	725	607	606	645	655
Boot Island National Wildlife Area	MPA	157	184	187	170	205
John Lusby Marsh National Wildlife Area	MPA	152	151	163	141	193
Kejimkujik Seaside National Park and Historic Site	MPA	259	375	368	356	388
Machias Seal Island Migratory Bird Sanctuary	MPA	246	312	295	318	351
Musquash Estuary Marine Protected Area	MPA	243	203	207	307	331
St Anns Bank Marine Protected Area	MPA	309	309	319	317	350
The Gully Marine Protected Area	MPA	469	348	350	409	410
Corsair/Georges Canyons Conservation Area	OECM	502	375	376	415	396
Eastern Canyons	OECM	546	425	426	467	465
Emerald Basin Sponge Conservation Area	OECM	184	302	290	285	312
Jordan Basin Conservation Area	OECM	254	337	335	351	355

Site	Type	Present day	Mid-century		End-century	
			SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Northeast Channel Coral Conservation Area	OECM	466	356	355	361	355
Sambro Bank Sponge Conservation Area	OECM	220	342	338	332	353
Western Emerald Bank Conservation Area	OECM	506	421	414	429	425

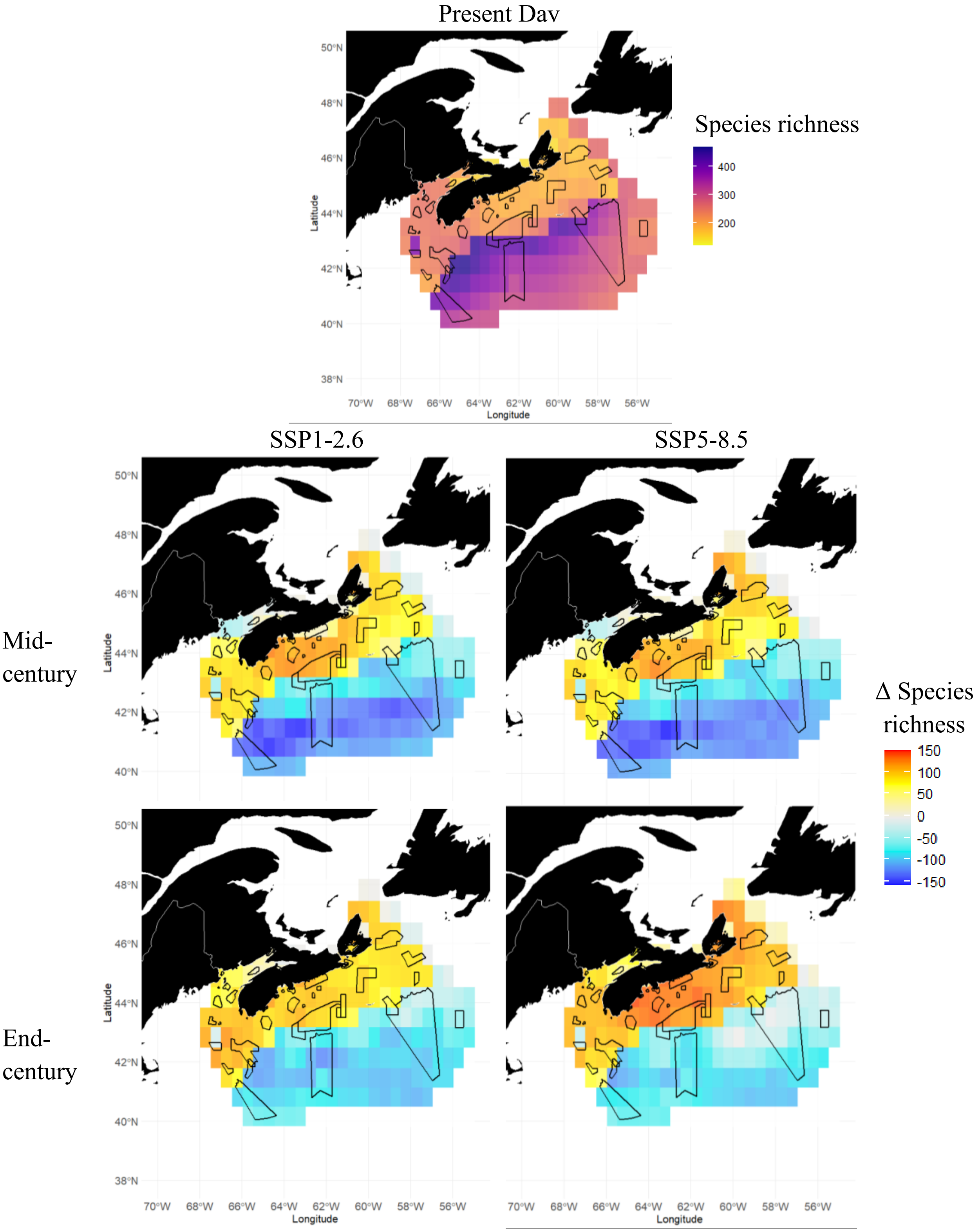


Figure 3. Species richness for the Fisheries and Oceans Canada Maritimes Region. The first row is present day species richness, the second row is mid-century species richness, and the third row is end-century species richness. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

Regional Changes in Taxonomic Dissimilarity

Despite future species richness being highest in end-century under SSP5-8.5, the Maritimes Region is expected to experience the largest species compositional change by this time-period, with 18.4% dissimilarity relative to present day (Table 4; Figure 4). In contrast, the lowest projected regional taxonomic dissimilarity relative to present day was 14.6% and occurred in end-century under SSP1-2.6 (Table 4; Figure 4). Taxonomic dissimilarity was projected to be particularly high along Nova Scotia's eastern shore and in the open waters southeast of Sable Island in all future time-periods and scenarios relative to other parts of the region (Figure 4). Interestingly, while the Scotian Shelf slope was projected to consistently have the highest species richness regardless of year or scenario, it also was projected to consistently have some of the lowest taxonomic dissimilarity, i.e., this speciose region remained relatively taxonomically stable (Figure 4). Additionally, the waters near the Laurentian Channel were projected to have lower taxonomic dissimilarity relative to the rest of the region for all years and scenarios (Figure 4). Generally, inshore waters and offshore waters (as defined by the Scotian Shelf slope; Figure 2) had similar taxonomic dissimilarity, except in end-century under SSP5-8.5 when the inshore waters were projected to experience greater dissimilarity than the offshore waters (Figure 4). Interestingly, while the lowest taxonomic dissimilarity relative to present day occurred in end-century under SSP1-2.6, <4% of taxonomic dissimilarity occurred from mid-century to end-century under SSP1-2.6– this result indicates dissimilarity from mid-century to end-century partially returns the region to its present day species composition (Table 4). Overall, regional taxonomic dissimilarity increased with time for the SSP5-8.5 scenario and but reduced with time under the SSP1-2.6 scenario (Table 4).

Fishes were projected to experience the highest dissimilarity, with the greatest change in composition occurring from the present day to end-century under SSP5-8.5 (Table A4). As lobsters had no changes to species compositions, they had no taxonomic dissimilarity across all times and scenarios (Table A4). Mammals were projected to experience the next lowest taxonomic dissimilarity across both time-periods and scenarios (Table A4). Indeed, mammal taxonomic dissimilarity under SSP1-2.6 occurs entirely by mid-century whereas mammals have the most extreme dissimilarity from mid-century to end-century under SSP5-8.5 (Table A4). Reptile dissimilarity (11.1%) was projected to be the same into all future times relative to present day, and also all occurred from the present day to mid-century (Table A4). A robustness test indicated small increases in taxonomic dissimilarity across times and scenarios for all species (Table A2), fish, and mammals, but had the same dissimilarity for reptiles and lobsters.

Table 4. Taxonomic change within the Fisheries and Oceans Canada Maritimes Region from the future relative to present day or mid-century.

	Present – Mid-century		**Present – End-century**		**Mid-century – End-century**	
	SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
Same	562	558	584	562	600	566
Proportion same as initial community (%)	93.6	93.1	91.5	86.7	94.3	87.3
Immigrating	45	48	61	93	43	89
Proportion of future population that immigrated (%)	7.4	7.9	9.5	14.2	6.7	13.6
Emigrating	163	167	141	163	5	40
Proportion of initial community that emigrated (%)	2.2	23.0	19.4	22.5	1.0	6.7
Change in species richness	-118	-119	-80	-70	38	49
Dissimilarity (%)	15.5	16.0	14.6	18.4	3.8	10.1

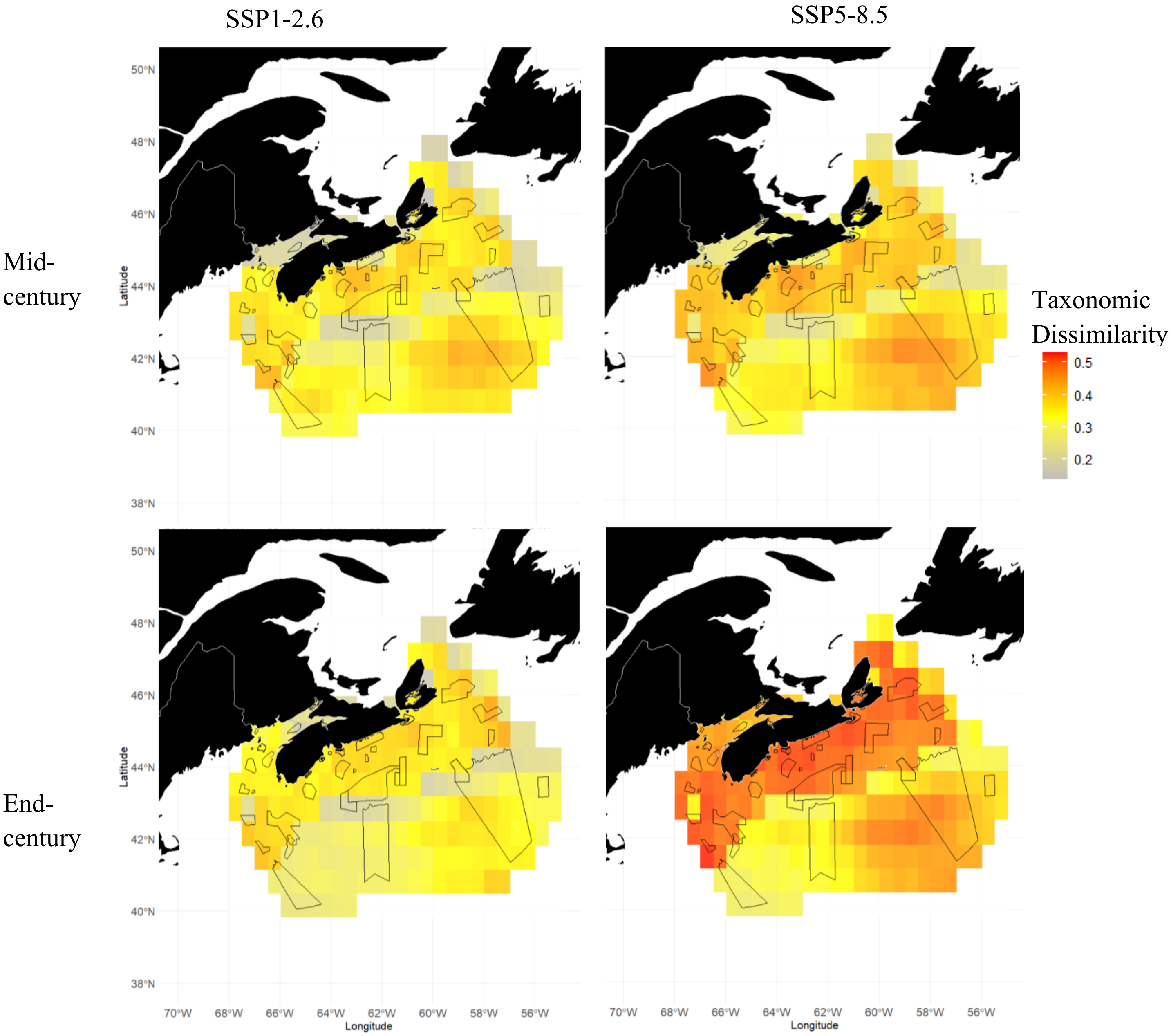


Figure 4. The taxonomic beta-diversity values representing the dissimilarity of species between a future time point relative to present day in the Fisheries and Oceans Canada Maritimes Region. The first row is dissimilarity in mid-century and the second row is dissimilarity in end-century. The columns indicate SSP1-2.6 and SSP5-8.5, respectively.

Present Day Species Richness for All Protected Seascape Sites

Of the existing network sites, the Eastern Canyons Marine Refuge (ECMR), the largest site in the network, was projected to encompass the most present-day species (Table 3), and the most regional fish (~75%) and mammal (~90%) species (Figure 3; Table A3). For reptiles, the Corsair/Georges Canyons Conservation Area (CGCCA) OECM contained all the modelled species for the region (Table A3) while seven existing network sites had 100% of regional lobster species projected within them (Table A3). When including proposed protected seascape sites, the Fundian Channel-Browns Bank AOI was projected to have the most species of all sites (Table A6).

Existing Network Sites Species Richness Changes

Of the existing network sites, the ECMR was projected to remain both the most species rich and to continue to encompass the most fish species (~70% of the regional fish) into the mid- and end-century under both scenarios (Table 3; Figure 5; Table A3). The Western Emerald Bank Conservation Area (WEBCA) encompassed the same number of fish in mid-century under SSP1-2.6. The ECMR was projected to have the highest mammal richness under SSP1-2.6 in mid-century, while the CGCCA was projected to encompass the most mammals in mid-century under SSP5-8.5 and in both end-century scenarios (Table A3). Both the ECMR and CGCCA encompassed the most reptile species in mid-century under SSP1-2.6 and in end-century under SSP5-8.5, but just the CGCCA encompassed the most reptile species in mid-century under SSP5-8.5 while three existing network sites encompassed the most reptiles in end-century under SSP1-2.6 (Table A3). Overall, the ECMR, CGCCA, and WEBCA were projected to encompass the most species across taxa (Table 3; Table A3). In addition, the Gully and St. Anns Bank MPAs and the Northeast Channel Coral Conservation Area (NCCCA) protected all regional lobsters in every future time and scenario (Table A3).

In mid- and end-century under both scenarios, the NCCCA was projected to have the largest proportion of its species emigrate (30-40%; Figure A1.1). Conversely, the existing network sites retaining the largest proportion of resident species were the Kejimkujik Seaside National Park and Historic Site under SSP1-2.6 (~80%) and the St. Anns Bank MPA under SSP5-8.5 (~75%; Figure 5; Figure A2.1). Sambro Bank Sponge Conservation Area received the most immigrating species in mid-century under both scenarios and in end-century under SSP1-2.6, while the Kejimkujik Seaside National Park and Historic Site was projected to have the most species immigrations in end-century under SSP5-8.5 (Figure 5; Figure A3.1). Of these climate-immigrants, 6-9% were regionally novel in the Sambro Bank Sponge Conservation Area and 17% regionally novel for the Kejimkujik Seaside National Park and Historic Site – the remainder existed in the region in present day and shifted their range to overlap with these sites. The ECMR had the largest proportion of regionally novel, climate-immigrant species in mid-century under both scenarios (55-60%) while the CGCCA had the most by end-century under both scenarios (63-67%).

The existing network sites with the largest proportion of their mid-century species protected into end-century was the Musquash Estuary MPA (~99% under SSP1-2.6) and ECMR (~92% under SSP5-8.5). The Musquash Estuary MPA also had the most projected immigrations from mid- to end-century under both scenarios for all taxons collectively; of these immigrants, the majority (93-100%) previously existed in the region at mid-century, indicating primarily within-region movement into this MPA. The CGCCA had the largest proportion of immigrants being regionally novel from mid- to end-century under both scenarios (44-57%).

Trends for fish species generally followed that of all combined species (Figure 3; Figure A1.2 – A3.2). Interestingly, the John Lusby Marsh National Wildlife Area had two mammal species in the present day (Grey seal, *Halichoerus grypus* and Harp seal), both of which were projected to emigrate from this site in mid-century under SSP5-8.5 and were replaced with another regionally resident species (Long beaked common dolphin, *Delphinus capensis*) – a complete shift in its mammal composition (Figure A3.3). For reptiles, the most sites with an immigrating species occurred in end-century under SSP5-8 (nine sites with one immigrating species), primarily the regionally resident Hawksbill sea turtle (*Eretmochelys imbricata*). For lobster species, only the Sambro Bank Sponge Conservation Area had a change in lobster composition with one emigration (Blind lobster sp. *Stereomastis sculpta*; Figure A4.5). All other species trends can be found in the supplementary materials (Figures A1-A4).

In comparison to each existing network site's present-day richness, the Emerald Basin Sponge Conservation Area species richness had the largest proportional increase (1.5-1.7x for all future times and scenarios in this site), while the Gully MPA had the largest proportional decrease in both mid-century scenarios (~0.75x) and the NCCCA in both end-century scenarios (~0.77x; Figure 5; Figure A4.1). From mid- to end-century, the Musquash Estuary MPA had the largest proportional increase in species richness under both scenarios (~1.5x) while the smallest proportional change in species richness was in the Boot Island National Wildlife Area under SSP1-2.6 (~0.92x) and the NCCCA under SSP5-8.5 (~1x). See Figure A4 for full details, and for a breakdown by taxonomic group.

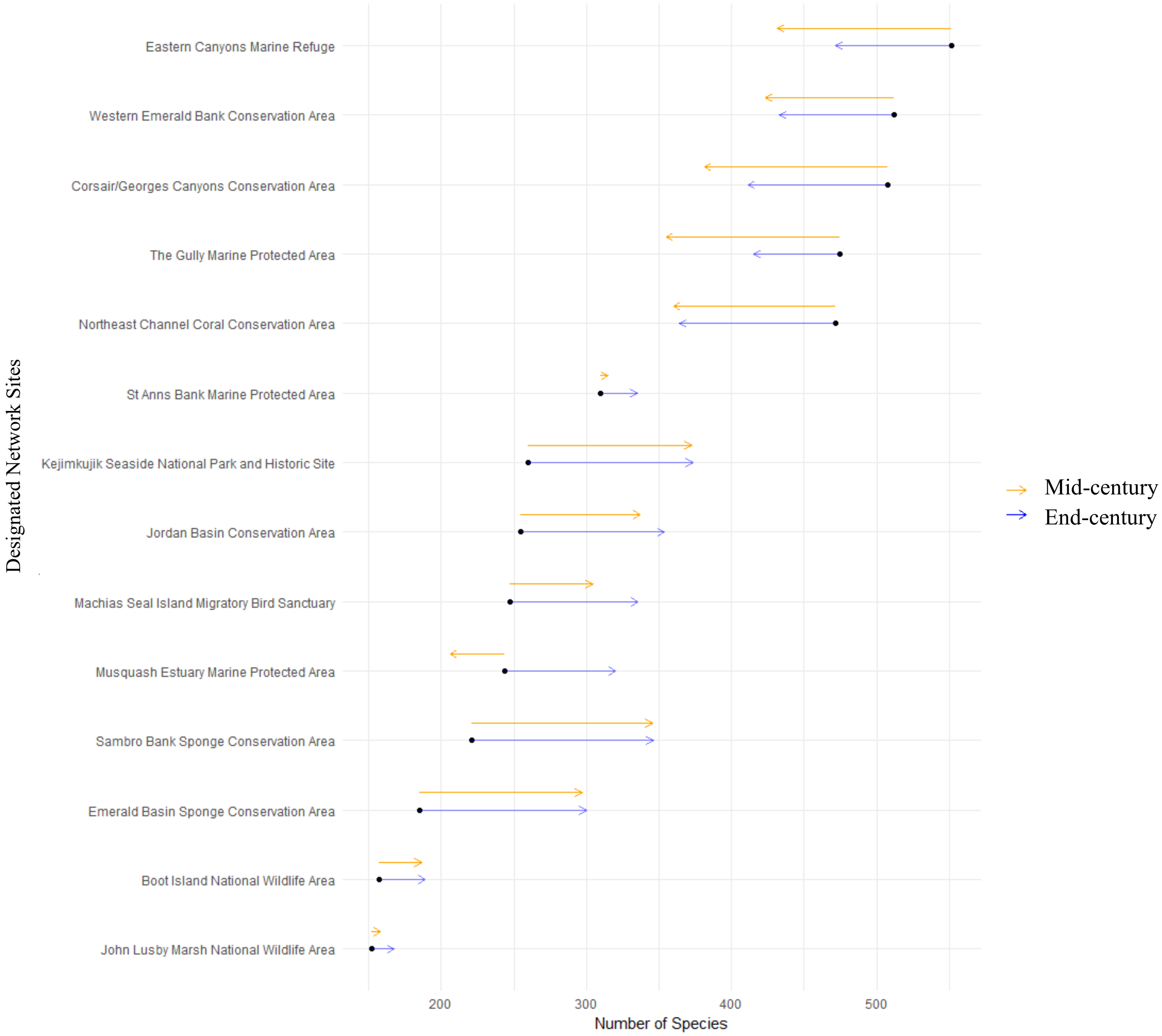


Figure 5. Existing Marine Protected Areas (7) and Other Effective area-based Conservation Measures (7), within the Fisheries and Oceans Canada Maritime Conservation Network ranked by number of species it encompassed overall and the change in species richness into the future. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue arrows, respectively.

Existing Network Site Species Dissimilarity

When compared to present day assemblages, most existing network sites were projected to have higher taxonomic dissimilarity in the SSP5-8.5 scenario relative to the SSP1-2.6 in both future time-periods. This dissimilarity increased with time under the SSP5-8.5 scenario (Figure 4). However, under the SSP1-2.6 scenario, dissimilarity versus present-day was typically lower in end-century than in mid-century. From mid- to end-century all existing network sites had higher taxonomic dissimilarity under the SSP5-8.5 relative to the SSP1-2.6 scenario.

Across all taxa, the existing network site with the highest taxonomic dissimilarity was the Emerald Basin Sponge Conservation Area for all future times and scenarios (~41-48%; Figure A5.1). In contrast, the WEBCA had the lowest taxonomic dissimilarity for all times and scenarios (range: 16.2-19.3%) except in end-century under SSP5-8.5 when the CGCCA had the lowest value (21.2%; Figure A5.1). Similarly, from mid- to end-century, the Emerald Basin Sponge Conservation Area was projected to experience the highest dissimilarity under both scenarios (25-27%) while the WEBCA had the lowest dissimilarity under SSP1-2.6 (5.4%) and ECMR the lowest under SSP5-8.5 (9.2%; Figure A5.1).

Fish species generally followed these trends, with minor differences from mid- to end-century (Figure A5.2). For mammals in end-century, both scenarios had three existing network sites with ≥50% taxonomic dissimilarity, likely due to the inherently low mammalian species richness (Figure A5.3). For reptiles and lobsters, which had 2-3x fewer species than mammals, existing network sites often had 100% or no taxonomic dissimilarity (Figure A5.4). The most existing network sites with 100% reptile taxonomic dissimilarity were projected in end-century under SSP5-8.5 (Figure A5.4). Other taxonomic results can be found in Supplementary materials (Figure A5).

Changes in Species Richness within Proposed Network Sites

Like present day, the Fundian Channel-Browns Bank AOI had a higher species richness than all existing network sites in most future times and scenarios (Table A6). In addition, the Central Scotian Slope, Rise and Abyss proposed site exceeded the existing network sites in species richness in mid-century under SSP5-8.5 (Table A6). For fish, Fundian Channel-Browns Bank AOI was projected to encompass the most species of any existing or proposed sites across all time periods and scenarios (~72% of regional fish; Table A6). Additionally, the Central Scotian Slope, Rise and Abyss, Scotian Gulf, and Fundian Channel-Browns Bank were important for protecting regionally high reptile and lobster species richness across times and scenarios (Table A6).

The Cold Seeps also had a larger proportion of emigrating species than any existing network site relative to present day (mid-century - SSP1-2.6: 38.7%, SSP5-8.5: 42.8%; end-century – SSP1-2.6: 37.9%, SSP5-8.5: 41.6%; Figure A1.1). Select proposed network sites had larger proportions of resident species retained from the present day, which were the Southern Bight in mid-century (86.7% of its initially protected species remained) and Bird Islands in end-century under SSP1-2.6 (84%), while under the SSP5-8.5 scenario, the Bras d'Or Lakes Ecologically and Biologically Significant Area (EBSA) had the largest proportion of present-day species remaining in mid-century (83.6%) and end-century (73.6%; Figure A2.1). Of all protected seascape sites, the LaHave Basin proposed network site had the most immigrating species in most years and scenarios, except in end-century under SSP1-2.6 where both Roseway Bank and Chebogue proposed network sites had higher number of immigrating species (Figure A3.1). Of these immigrating species, 7-13% were regionally novel, climate-immigrants in LaHave Basin and ~7% were novel climate-immigrants for both Roseway Basin and Chebogue.

These trends were generally the same for fish species (Figures A1.2-A3.2). For other taxa, the Eastern Shoal proposed network site was the only site with 100% of its present-day mammal species projected to remain by mid-century under SSP1-2.6 and was projected to retain the largest proportion of present-day mammal species in mid-century under SSP5-8.5 (Figure A2.3). For lobsters, the LaHave Basin proposed network site had one lobster emigration from present day to mid- and end-century under both scenarios (*Stereomastis sculpta*) yet these emigrations occurred from present day to mid-century. For all results by taxonomic group, see Figures A1-A3.

Relative to existing network sites, only one proposed network site (Big Glace Bay) had a greater increase in species richness, but only for mid-century under SSP5-8.5 (1.6x). Two proposed sites had greater reductions in species than existing network sites, the Fundian Channel-Browns Bank AOI in mid-century under both scenarios (~0.72x) and the Cold Seeps proposed network site for end-century under SSP1-2.6 (~0.77x; Figure A4.1). As well, relative to all existing and proposed network sites, projections from mid- to end-century showed the Long Eddy proposed network site to have the largest proportional richness increase (1.5x) under SSP1-2.6 (Figure A4.1). For mammals, there were no existing or proposed network sites that gained mammal richness by mid- or end-century under SSP1-2.6 relative to present day (Figure A4.3). Interestingly, the Sambro Ledges – Prospect proposed network site, which lost mammal species by mid-century, had the highest mammal richness increase from mid- to end-century under SSP1-2.6 (2.3x; Figure A4.3). In end-century under SSP5-8.5, all protected seascape sites (proposed and existing) with non-zero reptile richness in the present day retained at minimum one reptile species, whereas all other times and scenarios had at least one site lose all reptile species (Figure A4.4).

Proposed Network Site Species Dissimilarity

Like existing network sites, all proposed network sites were projected to have higher taxonomic dissimilarity in the SSP5-8.5 relative to the SSP1-2.6 scenario from the present day to mid-century (SSP1-2.6 range: 15.6-39.4%, SSP5-8.5 range: 18.5-42.3%); from the present day to end-century (SSP1-2.6 range: 16.8-38.8%, SSP5-8.5 range: 22.3-45.4%); and from mid- to end-century (SSP1-2.6 range: 4.3-26.0%, SSP5-8.5 range: 9.2-26.1%; Figure A5.1). Most proposed network sites also had higher taxonomic dissimilarity relative to present day under the SSP5-8.5 scenario. In contrast to existing network sites, taxonomic dissimilarity under SSP1-2.6 was less clear – it was higher in end-century than mid-century for 42% of proposed network sites (14/33).

Breaking dissimilarity down by taxonomic group, fish differed somewhat from the total species trends, with a mixed picture for proposed and existing network sites (Figure A5.2). For mammals, from the present day to mid- and end-century under both scenarios there were at least three proposed network sites with ≥50% mammal taxonomic dissimilarity, with as many as nine proposed network sites to have ≥50% dissimilarity in mid-century under SSP5-8.5 (Figure A5.3). Reptiles were the only taxa with 100% dissimilarity to occur in every time period and scenario, primarily due to low reptile richness and few network sites (existing and proposed) containing reptile species (Figure

A5.4). Of the proposed network sites that had reptile species, end-century under SSP5-8.5 had the largest proportion, three-quarters, with 100% dissimilarity (21/28; Figure A5.4). These 21 proposed network sites included 16 sites with no reptiles in present day and one species immigrating, and five sites with all present-day species emigrating and being replaced by a single immigrant species (immigrant sp.: Hawksbill Sea turtle for all sites). Lobsters were the only taxa with no dissimilarity in most proposed network sites (97% with no dissimilarity). Lobster dissimilarity was consistently highest in the LaHave Basin proposed network feature, with 33% dissimilarity in mid- and end-century under both scenarios (Figure A4.5).

Present Day Protection of Species Ranges and Species-at-Risk

As some present-day species' ranges were projected to be primarily outside the region, only those species that were found in a minimum of 5% of the region (10 grid cells of 201) were assessed to determine the proportion of their (regional) range under protection by the network. The fish, mammal, reptile, and lobster species with the largest proportion of their regional range under protection by the existing network sites were the Banded rudderfish (*Seriola zonata*) at 58.8% (Figure A6), Pygmy sperm whale (*Kogia breviceps*) and Striped dolphin (*Stenella coeruleoalba*) at 36.0% (Figure A7-A8), the Leatherback sea turtle (*Dermochelys coriacea*) at 35.6% (Figure A9), and the deep sea lobster sp. *Stereomastis sculpta* at 36.8% (Figure A10), respectively (Table 5; Table A7). In contrast, the species with the smallest proportion of their regional range under protection were the Arctic Char (*Salvelinus alpinus*) and the Bigpored snailfish (*Liparis latifrons*; 10.0%), Dwarf sperm whale (*Kogia sima*; 24.4%), Green Sea turtle (*Chelonia *mydas*; 20.0%), and American Lobster (*Homarus americanus;* 32.1%) respectively (Table 5; Table A7). The proportion of each species regional range protected in the present day would be larger if all protected seascape sites were designated (Table 5; Table A7). The protected seascapes sites (proposed and existing) projected to provide the most protection in present day to a single regional species range were the Fundian Channel-Browns Bank AOI, if designated, which protects 66.7% of the regional range for the Atlantic Angel shark (*Squatina dumeril*), and the ECMR which protects 22.2% of the Pygmy sperm whale regional range, 21.2% of the Leatherback Sea turtle regional range, and 20.0% of the deep sea lobster sp. *Stereomastis sculpta* (Table A8).

Within the Maritimes Region there are 18 modelled species considered to be Threatened or Endangered by COSEWIC, of which 14 are fish, two are mammals, and two are reptiles (Table 2). Existing network sites were projected to collectively protect 22-40% of Threatened or Endangered fish regional ranges (average ~31%), with the Atlantic salmon (*Salmo salar*) the least protected (22%) and the Roundnose Grenadier (*Coryphaenoides rupestris*) the most (~40%; Table 2). For Endangered mammal and reptile species, existing network sites were projected to collectively protect ~35% of each species' regional range (Table 2). By including all protected seascape sites, many of the protected regional ranges for Threatened and Endangered fish become >70%, and Endangered mammals and reptiles increasing to ~66% and ~54%, respectively (Table 2).

Changes in Protection of Species Ranges and Species-at-Risk

On average the proportion of each species' regional range under protection remained close to unchanged for all future times and scenarios, though with huge variation across species (MID26: mean +0.097%, range: -86 to +64% coverage change; MID85: mean +0.88%, range: -67 to +67; END26: mean +0.20%, range: -67 to +72%; END85: mean +0.45%, range: -68 to +81%). Of the species with the largest proportion of their present-day regional range protected by existing network sites, most decrease in range protected with increasing time and carbon emissions (Table 5; Figure A6; Figure A8-A9). Species with the smallest proportion of their regional range under protection were mostly projected to increase in protection with time and scenario (Table 5). However, exceptions exist: for example, the green sea turtle was projected to not be protected by any existing network sites in end-century under SSP1-2.6 (Table 5). The species with the largest and smallest proportion of their regional range protected by existing network sites compared to all protected seascape sites are shown in Table A7. Across all protected seascape sites, the ECMR provided the highest protection for the regional range of a single reptile and lobster species into all future times and scenarios (Table A8). See Table A7 and Table A8 for further taxonomic breakdown.

The 18 modelled species considered Threatened or Endangered by COSEWIC generally decreased in the proportion of their regional range under protection by the existing network sites in most future times and scenarios (11/14 fish, 2/2 mammals, and 2/2 reptiles; Table 2). The three fish species that differed from this trend were the Atlantic cod (*Gadus morhua*), which only decreased the proportion of its regional range under protection in end-century under SSP1-2.6, the Roundnose grenadier, which increased its regional range under protection in mid-century and decreased in end-century, and the Shortfin mako (*Isurus oxyrinchus*), which increased its regional range under protection in all times and scenarios (Table 2). Furthermore, in end-century under

SSP5-8.5, the Endangered Smooth skate (*Malacoraja senta*) was projected to no longer occur in the region (Table 2).

Including all protected seascape sites (proposed and existing), most COSEWIC Threatened or Endangered species had 50-70% of their regional range under protection for both future time-periods and scenarios (Table 2). The lowest protection of regional ranges with all protected seascape sites was on the Shortfin mako in both time-periods under SSP1-2.6 (mid-century: 35.3%, end-century: 40.7%), the Smooth skate (*Malacoraja senta*) in mid- and end-century under SSP5-8.5 (31.6% and 0% respectively), and the North Atlantic Right Whale (*Eubalaena glacialis*) in end-century under SSP5-8.5 (26.3%; Table 2), also the mammal with the least protection during this time and scenario if all protected seascape sites were designated (Table A7). Across all time periods and scenarios, the ECMR contributes the most to the protection of the Endangered Leatherback and Loggerhead sea turtles (Table A8), despite the Leatherback having one of the smallest proportions of its regional range protected relative to the other regional reptile species (~33% in mid-century under SSP1-2.6 and under both scenarios in end-century; Table A7).

Table 5. The species with the largest and smallest proportions of their present and future regional range that is protected by existing network sites (exist) relative to all protected seascape sites (exist and proposed) of the Maritime Conservation Network in the Fisheries and Oceans Canada Maritimes Region. Proportion of regional range protected was assessed into mid- and end-century under SSP1-2.6 (high mitigation) and SSP5-8.5 (high emission) scenarios.

Species	Sites	Present (%)	Mid-century SSP1-2.6 (%)	Mid-century SSP5-8.5 (%)	End-century SSP1-2.6 (%)	End-century SSP5-8.5 (%)
Species with largest proportion of regional range protected in present day						
Banded rudderfish (*Seriola zonata*)	Exist	58.8	26.7	31.8	26.7	NA
	Exist and Prop.	76.5	83.3	81.8	73.3	NA
Pygmy sperm whale (*Kogia breviceps*)	Exist	36.0	38.0	38.0	36.7	36.7
	Exist and Prop.	52.3	53.3	53.7	52.0	64.5
Striped dolphin (*Stenella coeruleoalba*)	Exist	36.0	29.8	24.2	30.8	36.7
	Exist and Prop.	50.0	42.6	33.3	42.3	53.3
Leatherback sea turtle (*Dermochelys coriacea*)	Exist	35.6	32.9	31.5	33.7	33.3
	Exist and Prop.	52.2	50.0	49.3	50.0	50.0
Blind lobster sp. *Stereomastis sculpta*	Exist	36.8	37.0	37.3	36.9	37.9
	Exist and Prop.	52.8	52.1	52.5	52.5	52.6
Species with smallest proportion of regional range protected in present day						
Arctic Char (*Salvelinus alpinus*)	Exist	10.0	0	17.6	13.3	16.7
	Exist and Prop.	0.75	62.5	76.5	86.7	79.2
Bigpored snailfish (*Liparis latifrons*)	Exist	10.0	10.7	13.8	11.1	12.5
	Exist and Prop.	75.0	71.4	72.4	74.1	79.2

Species	**Sites**	**Present (%)**	**Mid-century**		**End-century**	
			SSP1-2.6 (%)	**SSP5-8.5 (%)**	**SSP1-2.6 (%)**	**SSP5-8.5 (%)**
Dwarf sperm whale (*Kogia sima*)	Exist	24.4	27.5	29.1	30.6	35.5
	Exist and Prop.	39.0	42.5	40.0	42.9	57.3
Green sea turtle (*Chelonia mydas*)	Exist	20.0	NA	10.0	NA	33.3
	Exist and Prop.	20.0	NA	10.0	NA	40.0
American Lobster (*Homarus americanus*)	Exist	32.1	33.6	33.0	33.9	36.4
	Exist and Prop.	77.1	76.7	78.9	78.9	75.8

Chapter 2.4: Discussion

Present Day Richness and Protection

I applied an ensemble of species distribution models across four taxa and two scenarios of future change to analyze projected shifts in species composition and coverage for the Maritime Conservation Network. The 725 species projected to be within the region is likely to be an overestimate given that substantially more fish species (699) were projected relative to the number found in bottom trawl surveys (Shackell and Frank 2003; Brown et al. 2005; Clark and Branton 2007; Sherman 2010; Dornelas et al. 2018) and a National Oceanic and Atmospheric Administration (NOAA) pelagic observer program (NOAA 2012) near the region. An estimate of Scotian Shelf fish richness is 164 ± 12 and 172 ± 18, based on the distribution of rare species collected across various shelf samples (i.e., this many species has not been found yet; Shackell and Frank 2003; Ward-Paige and Bundy 2016). However, there are mitigating factors that suggest that these observation-derived values may be underestimates. The higher number of fish species in these regional models likely results from a combination of factors: (1) models projecting ranges beyond which species may commonly occur yet can still physiologically exist, (2) regional surveys primarily occurring no farther offshore than the Scotian Shelf slope and thereby missing the offshore species found in this study (Shackell and Frank 2003; Ward-Paige and Bundy 2016), and (3) rare species within the region being unlikely to be sampled by surveys, as 24% of newly discovered fish species in this region have only been found once since 1971 (Shackell and Frank 2003). Furthermore, as these bottom trawl surveys were primarily focused on groundfish (Brown et al. 2005; Clark and Branton 2007; Sherman 2010), they did not capture many highly mobile and pelagic species, and likely greatly under sample entire parts of the water-column (e.g. mesopelagic communities). Similarly, the NOAA pelagic observer program was limited to large-bodied species identifiable from a distance or those that were commercially important (primarily sharks, tunas, swordfish, turtles, and marine mammals; NOAA 2012). Environmental DNA (eDNA) surveys often finds more taxa at sites than trawl surveys (He et al. 2023). In fact, one regional coastal eDNA study found a rare, subtropical species also projected by this study, the Spotfin butterflyfish *Chaetodon ocellatus* (Table A7; He et al. 2022). For mammals, species richness in this region is comparable to one other study (12-16 species; Kaschner et al. 2011), with 42% of species modelled for present day overlapping with the detections from the NOAA pelagic observer program at the species-level (records also include "Mammalia"; NOAA 2012) and regional eDNA surveys (He et al. 2022). The genera Globicephala, Kogia, and Delphinidae were also detected both in this study and by surveys (NOAA 2012; He et al. 2022). The remaining eight marine mammal species may have been missed due to: rarity of sightings and lack of knowledge (Gervais beaked whale, *Mesoplodon europaeus*; True' beaked whale, *Mesoplodon mirus*; NOAA 2023), surveys occurring in the summer when a species is typically not present (Harp seal; DFO 2022b), or merely because the sampling events and species presences did not co-occur on a specific day/ time (Hooded seal, *Cystophora cristata*; Grey seal, North Atlantic Right Whale, White beaked dolphin, *Lagenorhynchus albirostris*; Northern bottlenose whale, *Hyperoodon ampullatus*). All turtle species modelled for the present day were found in the NOAA pelagic observer program at the species-level (NOAA 2012). Similarly, both lobster species were surveyed with bottom trawls (Ward-Paige and Bundy 2016). Ultimately, adding eDNA as a monitoring tool for the Maritime Conservation Network in addition to observer programs and bottom trawls, and refining ranges in the species distribution models to mitigate the influence of outlying or inaccurate observations, should result in closer agreement between observations and projected species richness in this study.

While this regional model projected more biodiversity relative to 2003 estimates (Shackell and Frank 2003), spatial patterns of richness were consistent with survey data, indicating the highest biodiversity near the Scotian Shelf continental slope (especially the southern shelf slope), high biodiversity near the Gully, and comparatively high biodiversity in the Bay of Fundy and St. Lawrence channel relative to the central Scotian Shelf (Figure 3; Shackell and Frank 2003; Hodge et al. 2022). While I projected the highest biodiversity offshore than coastally (Figure 2; Figure 3), to the best of my knowledge, no publicly available trawl surveys have explored beyond the Scotian Shelf slope to support or refute this finding (Shackell and Frank 2003; Brown et al. 2005; NOAA 2010; Ward-Paige and Bundy 2016). Overall, the richness patterns in this study region may be explained by a variety of mechanisms (e.g., energy-productivity, evolutionary factors; Gray 2001; Shackell and Frank 2003), but support previous suppositions that higher species richness may occur in areas with larger depth ranges (i.e., the Scotian Shelf slope; Shackell and Frank 2003).

Changes in Regional Species Richness and Dissimilarity

These analyses project that future species richness in the Maritimes Region will decrease, with about one-quarter of present-day species projected to leave the region in both future time periods under both scenarios. These results contrast with a global scale assessment of 29 different phyla, where species richness was broadly projected to increase at higher latitudes due to ocean warming by 2100 under mid- and high-emissions as a result of immigrating species expanding their leading range edge faster than the loss of emigrating species (Garciá Molinos et al. 2015; IPCC 2022). However, the global scale assessment was done using only mean annual sea surface temperature (Garciá Molinos et al. 2015), whereas this study accounts for multiple environmental variables. Instead, results here reflect how smaller regional studies tend to vary in species richness future trends versus global scale analyses given that they examine only a subset of species within a larger area (Gruner et al. 2017; Chase et al. 2019). Overall, no other temperate regional studies, to my knowledge, explore projected species richness trends and include the range of taxonomic coverage in this study, or include offshore assessments. One potential explanation for decreasing future richness could be that the rapidly increasing bottom temperature and extreme surface water warming into 2100 under a high-emissions scenario (Saba et al. 2016) is forcing emigrants to shift northwards out of the region due to them being cold-favouring, deep sea and/or boreal species that are no longer physiologically able to tolerate the environment, as was observed west of Scotland (Rijnsdorp et al. 2009; Hoístede et al. 2010), and that this rate of emigration exceeds the immigration rate from more southerly latitudes. Indeed, in my study offshore regions beyond the Scotian Shelf had the greatest species richness loss at all time periods and for all future scenarios (Figure 3). Such a response by present-day species may occur rapidly, as observed in the loss of ~15% of resident species over a decade to the west of Scotland (Hoístede et al. 2010). Alternatively, the regional decline in species richness into mid-century may be because of delays in species immigrations (termed ‘colonization’ or ‘immigration’ lag, Menéndez et al. 2006; Jackson and Sax 2010), as can occur when generalist species, which can tolerate a broad range of environmental conditions, are the primary immigrants ahead of specialists, which relocate more slowly (Menéndez et al. 2006). In this case, new climate-immigrant species may take longer to arrive, which appears to be the case for end-century under SSP5-8.5 which experiences the greatest rate of climate-immigrations.

In contrast, the large flux in species richness that occurred along Nova Scotia’s inshore waters may be due to some species, primarily fish, expanding the leading edge of their range into these warmer waters, likely contributing to increases in species richness (Hiddink and ter Hofstede 2008). As Scotian Shelf waters are projected to have substantial increases in temperature by 2100 under a high-emission scenario (Saba et al. 2016), this area receives the most sub-tropical climate-immigrants. In fact, areas relatively low in species richness, such as along Nova Scotia’s coast, are hypothesized to experience the largest proportional increase in species richness due to “diversity-invasion resistance” whereby lower resident diversity increases survival and settlement ability of invasive species (Stachowicz et al. 2002; Elahi et al. 2015). This pattern was observed in this study (Figure 3).

Regionally, mammals, reptiles, and lobsters have lower species richness relative to fishes, with many having cosmopolitan ranges or wide environmental tolerances (NOAA 2023), resulting in lower overall and proportional change in their species richness (Table A3). No literature was available that projected regional mammal, reptile, and/or lobster richness into mid- or end-century under either the SSP1-2.6 or SSP5-8.5 scenarios. However, marine mammal increases at high latitudes (40° or higher) are projected into mid-century (Whitehead et al. 2008; Kaschner et al. 2011) and end-century (Whitehead et al. 2008) under mid-emission scenarios, with 2-4 immigrations primarily from odontocetes and 0-4 emigrations of pinnipeds, mysticetes, and odontocetes projected for mid-century in the region (Kaschner et al. 2011). I projected one odontocete immigration (False killer whale) and two mysticete emigrations (Atlantic spotted dolphin, Gervais' beaked whale) by mid-century. These differences in mammal projections could arise from the different scenarios or spatial scales and resolutions under consideration. Lobsters were projected to have a net loss in species richness (0 to -2) by 2100 under a mid-emission scenario (Sousa e Silva Boavida-Portugal et al. 2020), which differs from this study as there were no lobster species richness changes, possibly since my study has a finer spatial scale and more environmental variables for the Northwestern Atlantic. Future distributions of marine reptiles are understudied so there are no good points of comparison (Melo-Merino et al. 2020).

Regional taxonomic dissimilarity is expected to be around ~16-18% by mid- and end-century. These numbers represent major ecological changes for this marine region, with communities having approximately one-sixth of their present-day species composition changing. Taxonomic dissimilarity hotspots identified in my study were in coastal waters, especially on the southern edge near the Western Emerald Bank Conservation Area (WEBCA; Figure 1; Figure 4). Importantly, this is an area that overlaps with demersal and lobster fisheries (Hurley et al. 2019; Greenan et al. 2019). Surprisingly high dissimilarity was also projected offshore beyond Sable Island and near the Eastern Canyons Marine Refuge (ECMR; Figure 4). This high offshore dissimilarity may be due to a combination of warming slope waters and the northward shift and retreat of the Gulf Stream and Labrador current respectively by 2100 under high emissions (Saba et al. 2016), allowing for the immigration of more warm-water tolerant species.

Analysis of taxonomic dissimilarity under the high emissions scenario indicated increasing regional community dissimilarity with time (Table 4). These projections match a known trend of higher temperature changes resulting in greater species dissimilarity (Hillebrand et al. 2010; Le Marchand et al. 2020; Hu et al. 2022). Projected taxonomic dissimilarity levels for mid-century under both emission scenarios (15.5%, 16.0%) in this region are lower than off China's coast, which had average rates of 24% and 41% fish species dissimilarity in temperate waters (Hu et al. 2022) but comparable to a global study that modeled over 12,000 species and suggested 10-30% dissimilarity for latitudes 30-50° under SSP5-8.5 into 2100 (Garciá Molinos et al. 2015).

Surprisingly, the end-century had a lower taxonomic dissimilarity than the mid-century relative to present day under SSP1-2.6 despite more immigrating species on average (Table 4). This finding is primarily a result of ~20 fewer emigrations and thus, 20 more present-day species remaining into end-century under SSP1-2.6 (Table 4), as well as the fact that 60% of the immigrations occurring from mid- to end-century are present-day species returning to the region. Thus, the SSP1-2.6 scenario represents a 'bottleneck' of sorts, in which some sort of ecological recovery, or at least reassembly, may become visible by 2100. While studies have indicated marine life can be rebuilt by mid-century with large changes to marine management and reductions in carbon emissions (Duarte et al. 2020; IPCC 2022), this recovery of present-day species into end-century appears unique to this study and suggests strong mitigation of carbon emissions could provide long-term regional ecological benefits.

I appear to be the first or one of few to report on marine mammal, reptile, and lobster species dissimilarity into the future. The trends I observed of low species dissimilarity into the future for mammals and reptiles is likely a result of the large ranges these species have, and while ranges are expected to change by mid-century (Hawkes et al. 2009; Kaschner et al. 2011), they appear likely to remain within this region. The projected net loss of lobster species by 2100 under a mid-emission scenario for this region (Sousa e Silva Boavida-Portugal et al. 2020) would indicate some level of lobster dissimilarity into the future, which is higher than was projected in this study (0%), but again, the finer spatial-resolution and more environmental variables used in this study may distinguish suitable habitat that was missed in other studies.

Despite projected species richness being highest in the end-century under SSP5-8.5, this decade has the highest species dissimilarity, suggesting it is the most fundamentally altered ecosystem. This future ecosystem may therefore have the greatest change in functioning relative to present day, with substantial shifts in species composition and interactions (Vinebrooke et al. 2004; Micheli and Halpern 2005). In fact, species richness may not be the best indicator of climate change impacts as small changes in richness can have significant difference in species substitution (Hillebrand et al. 2010; Dornelas et al. 2014), as I project in end-century under SSP5-8.5. While protecting areas with high biodiversity can be beneficial for ensuring sufficient functional redundancy within an ecosystem to maintain resilience, functioning, and resistance to climate-immigrants (Hughes et al. 2005; McLeod et al. 2009; Elahi et al. 2015), large changes in species composition can result in altered ecosystem functioning due to shifts to entirely new ecosystem regimes (Nagelkerken and Connell 2015; Wernberg et al.

2016). Consequently, it is critical that marine management plans consider the extent of species dissimilarity in addition to changes in species richness when adapting and managing protected seascape sites if the goal is long-term protection of biodiversity (Government of Canada 2011; DFO 2022a).

Present Day Species Richness for All Protected Seascape Sites

The ECMR was projected to have the highest present-day richness (including the most fish and mammal species) of all existing network sites (Table 3; Table A3). This high biodiversity is likely a result of this marine refuge having the largest area relative to other protected seascape sites in the region, in addition to it protecting a naturally unique and biodiverse shelf and canyon habitat (Lacharité and Stanley 2019). While the *in-situ* species diversity within this marine refuge is largely unknown given its depth of >6,000 m (Lacharité and Stanley 2019), shelf and canyon habitats have both been previously shown to have significantly more fish and megafaunal diversity relative to non-canyon sites (Vetter and Dayton 1999; Hodge et al. 2022), likely due to their tidal mixing and predictable productivity (Cox et al. 2018). Other protected seascape sites with large areas, located along the Scotian Shelf, and/or in the southwest of the Maritimes Region near the Fundian Channel also have a high species richness, such as the proposed Fundian Channel-Browns Bank AOI. This proposed AOI likely encompasses high biodiversity due to its location being part offshore and part inshore, potentially protecting regionally cold-tolerant offshore species and warm-water tolerant species carried into the region by the Gulf Stream as warm waters flow in from the south (Saba et al. 2016). These are not species hotspots for reptiles however, which were projected to be most biodiverse within the Corsair/Georges Canyons Conservation Area (CGCCA; Figure 1), possibly a result of turtles staying primarily offshore and near warmer waters (James et al. 2006; Putman et al. 2020). Finally, as regional lobster species are both coastal and deep-sea, network sites that encompassed both shelf/slope habitat and offshore waters protected the most lobster species.

Recommendations for Protected Seascape Site Priorities

To ensure a robust and climate resilience protected seascape off Canada's east coast, both present and projected future ocean conditions must both be considered (Tittensor et al. 2019). One common recommendation is to design protected seascape sites to protect temporary climate refugia (McLeod et al., 2009; Salm et al., 2006; Wilson et al., 2020). Of the existing network sites in the Maritime Conservation Network, the Kejimkujik Seaside National Park and Historic Site and St. Anns Bank MPA were projected to have the largest proportion of resident species across all taxa remain under both time periods and scenarios. The Kejimkujik Seaside National Park and Historic Site is located along Nova Scotia's shore and the St. Anns Bank MPA is by Cape Breton Island, so these areas may be more resilient for resident species and plausible targets for strong management action should protecting climate refugia be a goal.

The WEBCA and CGCCA were projected to experience the lowest species dissimilarity across time periods and scenarios, as well as protecting some of the highest fish, mammal, reptile, and lobster richness. As these two OECMs/Marine Refuges provide bottom protection only (DFO 2021b), the entire water column could be considered for additional management. However, at present, these sites primarily aim to protect specific species groups (groundfish, corals, benthic species/ communities), and do not consider ecosystem productivity and connectivity (DFO 2021b). In particular, the CGCCA was an anomaly among existing network sites with higher dissimilarity in mid- than end-century under both scenarios, higher dissimilarity in mid-century under low relative to high carbon emissions, and the largest proportional decrease in species richness relative to the present day in mid-century under SSP5-8.5 (Figure A5.1).

However, protecting climate refugia alone is not sufficient for long-term conservation of biodiversity (Tittensor et al. 2019), particularly given that even the protected seascape sites with lower levels of richness change still experience substantial taxonomic dissimilarity. Climate-refuge sites may be important for attempting to maintain present-day ecosystems for as long as possible, but are not areas experiencing high climate stress that may be most in need of protection from other anthropogenic pressures (Tittensor et al. 2019). Indeed, ecosystems can be pushed beyond a site-specific threshold or ‘tipping point’ by a critical level of some external condition, beyond which the ecosystem shifts to a new, more stable state (van Nes et al. 2016; Dakos et al. 2019). By prioritizing both temporary climate refugia and areas with a range of future climate change trajectories, the network can “hedge its bets” by protecting ecosystems with various magnitudes of change (Tittensor et al. 2019). To supplement climate-refugia within the Network, management plans could develop some form of adaptive capacity that intensifies protection if those sites are projected and/or observed to experience high levels of ecological change. Sites that could benefit from this include the Emerald Basin Sponge Conservation Area, which is projected to experience the highest taxonomic dissimilarity (>40% dissimilarity; Figure A5.1) and Sambro Bank Sponge Conservation

Area, which was projected to receive the most immigrants across most time periods and scenarios along with other substantial ecological shifts (Figure A3.1). Indeed, the Emerald Basin Sponge Conservation Area was projected to have the largest proportional increase in species richness across all times and scenarios (Figure 5), experience near 50% taxonomic dissimilarity by end-century under SSP5-8.5, and have the highest taxonomic dissimilarity from mid- to end-century under both scenarios (~26%; Figure A5.1) – an extraordinary level of ecological change. Thus, this seascape site may endure remarkable shifts in species composition into all future scenarios, with almost 50% of its species composition shifting should societal trajectories follow a high-emissions pathway. As this conservation area primarily protects benthic sponges from bottom fishing (DFO 2021b), more strict pelagic protection could reduce the likelihood of this site exceeding its ecological tipping point from other anthropogenic pressures (Dakos et al. 2019). By preparing for significant management interventions and adaptive capacity in both climate refuges and nearby sites experiencing large magnitudes of change, a greater level of robustness to an uncertain future is likely (McLeod et al. 2009).

As many of the existing network sites limit bottom fishing and/or aim to protect general habitat and connectivity (DFO 2021b; Parks Canada 2023), adding protection for additional taxonomic groups projected to be most impacted could enhance network robustness. For example, of the existing network sites with >50% mammal dissimilarity, the Northeast Channel Coral Conservation Area (NCCCA) had the most mammal species in present day and was projected to experience up to four immigrations and seven emigrations, maintaining 6-9 mammals into all future times and scenarios (Figure A4.3). Furthermore, with fewer reptile species in the region relative to mammals, 100% reptile dissimilarity was projected to occur in at least three network sites within each time and scenario, but only the NCCCA was projected to lose all reptile richness into mid-century under both scenarios (Figure A4.4). Both mammals and reptiles are particularly susceptible to climate change impacts due to their long-life spans and slow maturation (Sterns 2002; Learmonth et al. 2006; Hawkes et al. 2009) and may thus disproportionately benefit from network protection. A climate-enhanced objective for these sites could be to protect species that emigrate but may ultimately return (Table A5).

As species diversity is a common priority for marine conservation worldwide (Micheli and Halpern 2005; Whitney et al. 2023), protecting seascapes with high species richness into the future can provide benefits without restructuring existing objectives. As the ECMR protects the most species (including ~70% of regional fish species) in both present-day and all future times and scenarios, its objectives could be expanded beyond corals and deep waters (DFO 2021b). With this site also important for mammals in mid-century under SSP1-2.6, along with relatively high reptile richness and 100% lobster species coverage in all future times and scenarios, such taxonomic considerations could be added to enhance ECMR outcomes.

As the Maritime Conservation Network continues to be developed with new proposed network sites and a plan expected for 2024 (DFO 2022a), proactively integrating climate change objectives into the design and management phases of each new site may help to make this region a climate-smart network (Magris et al. 2014; Tittensor et al. 2019). My outputs suggest that the Bird Islands proposed network site could be a priority as a climate-refuge in mid-century under both scenarios as it experiences the lowest species dissimilarity during this period (~17%), and in end-century under SSP1-2.6 when it retains the most resident species (~84%). In addition, the Southern Bight and Bras d'Or Lakes EBSA were projected to retain high numbers of resident species for all scenarios. Finally, the Fundian Channel-Browns Bank AOI had the highest species richness across all future times and scenarios. No proposed network sites exceeded the taxonomic dissimilarity of existing network sites, but LaHave Basin, Roseway Bank, and Chebogue had the highest number of climate immigrants across future time-periods and scenarios. While these proposed network sites may still change throughout the planning process, and we still lack an understanding of how the ecosystem may functionally change due to species composition shifts, integrating potential climate change impacts provides additional information for developing the network.

Present Day Protection of Species Ranges and Species-at-Risk

Models for the present-day ranges of all regional species suggest high network coverage for the Pygmy sperm whale (Table 5; Table A7), despite this species being rare in Atlantic Canada and preferring subtropical waters (NOAA 2023). The Striped dolphin was projected to have as high network coverage as the pygmy sperm whale; however, it is commonly only detected near the Gully MPA, with sightings decreasing since the 1980s (Whitehead 2013). The COSEWIC Endangered Leatherback sea turtle is projected to be the most protected turtle species in the region, which aligns with the Scotian Shelf being critical habitat for this species (James et al. 2006). Protected seascape sites projected to provide the most protection for these three species were the CGCCA and the ECMR, likely a result of their location (i.e., southern/warmer waters, offshore and slope habitat; Figure 1) and size.

Adding proposed network sites enhances protected area coverage for all COSEWIC Threatened and Endangered species (Table 2). The lowest regional protection for such a species was for the Mako shark which, in Atlantic Canada, has low management priority despite severe declines in population (DFO 2020c). Both this study and the management plan for the Fundian Channel-Browns Bank AOI identify it to be very suitable for the Threatened White hake (*Urophycis tenuis*), Endangered Winter skate (*Leucoraja ocellata*), the Endangered Atlantic cod (*Gadus morhua*), and the Endangered Cusk (*Brosme brosme*) (DFO 2020a). As a result, the Fundian Channel-Browns Bank AOI is thought to support some of the highest abundances of these species (DFO 2020a).

Changes in Protection of Species Ranges and Species-at-Risk

On average, the proportion of each present-day species' regional range with coverage increased slightly in all future times and scenarios. However, species with high present-day coverage of their regional ranges mostly decreased in coverage while species with low present-day coverage tended to increase (Table 5; Figure S6; Figure S8-9). These trends could indicate species are following known poleward shifts in distributions given climate-driven changes in temperature and ocean productivity (Sterns 2002; Poloczanska et al. 2013), where species with large regional ranges may have limited thermal headroom requiring them to shift northward where less large-scale protection is in place (Figure 1), whereas species with small regional ranges may have further range expansions into the region as waters warm (Saba et al. 2016). For example, the Harp seal shifted its range northward into mid-century, reducing its regional range under protection, and eventually emigrating from the region by end-century under SSP5-8.5 (Table A5). In contrast, sea turtles (Figure A9) and True's beaked whale appear to retract their ranges southward, with the latter species retracting southward and out of the region by end-century under the high emissions scenario. This pattern could reflect the warming that is projected to occur more rapidly on the Scotian Shelf than surrounding waters by 2100 under the high-emission scenario (Saba et al. 2016), causing environmental conditions to be intolerable for these species and forcing them out of the region/offshore. While these projections are likely to miss key small-scale regional intricacies, an enhanced understanding of potential climate change-induced impacts in relation to site-specific and network-level sites in the Maritime Conservation Network is needed (Bryndum-Buchholz et al. 2022).

For COSEWIC Threatened and Endangered species in the Maritimes Region, the proportion of their regional range under protection also generally decreased (Table 2). In fact, the Smooth skate, a species endemic to the Northwest Atlantic (COSEWIC 2012), is projected to no longer occur in this region by end-century under SSP5-8.5 (Table 2). With the addition of proposed network sites, however, the proportion of this species' range under protection would increase to >70% under the low-emission scenario in mid- and end-century, like most other Threatened or Endangered species, while under high-emissions in mid-century the proportion would decrease beyond the ~50-70% protection which remains for the other species (Table 2). Despite little being known about the habitat of this endemic species and the only known threat being bycatch (COSEWIC 2012), it appears a high priority for the Maritimes Region in proposed network sites, especially in a future with low emissions, as it remains in the region rather than disappears by end-century, as was projected under high emissions (Table 2). The Mako shark was the Endangered species projected to have the smallest proportion of its regional range protected of all Endangered/Threatened species (proposed and existing, one of lowest for existing) under both SSP1-2.6 scenarios and yet, despite Canada contributing little to its overall global protection (DFO 2020c), it is the only regionally Endangered species with an increase in its range under protection across all times and scenarios (Table 2). Of marine mammals, Canada has contributed substantially through numerous protection methods to reduce the population decline of the North Atlantic Right Whale (Meyer-Gutbrod et al. 2018; Davies and Brillant 2019), yet additional conservation proposed network sites may be needed as this species was projected to be the least protected (proposed and present-day) Endangered species in end-century under SSP5-8.5 (Table 2).

As previously noted, marine refuges within the Maritime Conservation Network are primarily focused on protecting benthic species/communities and allow non-bottom contact fishing (DFO 2021b). The ECMR contributes the most to protecting both lobster species in all future time-periods and scenarios (Table A8), yet also benefits both Endangered reptile species (Leatherback and Loggerhead sea turtles) and has a high fish and mammal richness across future years and scenarios (Table A8). As pelagic fishing can have lethal impacts on marine mammals (Garrison 2007) and turtles (Witzell 1999; Garrison et al. 2009; Fossette et al. 2014), restricting additional fishing pressures could help build ecosystem resilience across more species and taxa. While protecting declining species populations from multiple anthropogenic stressors has resulted in population recovery in some circumstances (Lotze et al. 2011), even without full recovery it could delay species emigration/extirpation, as reducing species loss provides resistance against additional stressors (Vinebrooke et al. 2004), buffering the ecosystem from abrupt ecological disturbance and changes in functioning due to climate change.

The Maritime Conservation Network can also be climate-enhanced through increased monitoring of change, particularly for anticipated climate-immigrant and novel species such as those identified here (Tittensor et al. 2019; Wilson et al. 2020). Many techniques are used to monitor for specific species within Canadian protected seascape sites (e.g., underwater remotely operated vehicles, bottom sediment sampling, acoustic recorders; DFO 2019; Abbott et al. 2021), but such monitoring can overlook less abundant and/or cryptic species (Gold et al. 2021) as may be the case with new climate-immigrants. Targeted environmental DNA sampling may help to detect the first appearance of such species (Goldberg et al. 2016; Larson et al. 2020; He et al. 2023). The ECMR (~30 novel climate-immigrants) and CGCCA (29-50 novel climate-immigrants) were projected to receive the most novel species, and hence would benefit from enhanced monitoring for these incursions. Monitoring outcomes (presence/absence of climate-immigrant species) can help guide adaptation for network management and site-specific conservation objectives (Wilson et al. 2020).

Mitigation Benefits

Ultimately, less climate-induced ecological change was projected for the Maritimes Region under the low versus high carbon emission scenario (Figure 4; Table 4; Table A4). Across global studies, high carbon emission scenarios have been projected to have more extreme ecological shifts than low carbon emission scenarios, whether it be in oceanic species composition (Le Marchand et al. 2020; Hu et al. 2022) or ecosystem functioning (Nagelkerken and Connell 2015; IPCC 2022). In addition to high carbon emissions bringing more novel climate-immigrant species in this study (Table 4), they also cause nearly 20% species composition changes across the region, having impacts on all four taxa, particularly by end-century (Table A4). The long-term impacts of high carbon emissions were also apparent, with 10% change in species composition from mid- to end-century under high emissions compared to <4% under low emissions, taxonomic dissimilarity generally increasing with time under the high emission scenario across all protected seascape sites (Figure A5), and fewer resident species returning by end-century relative to the low emission scenario. Therefore, reducing carbon emissions over the next two decades is a priority if marine conservation strategies are to limit changes or rebuild marine life (Duarte et al. 2020), with the tantalizing possibility of also partially restoring present-day assemblages by end-century in such circumstances.

Caveats

This study used global species distributions models and projections that were then filtered for regional ranges. While this method is generally coarse in terms of results when focusing on individual species within a smaller, defined area such as I describe here, it has the advantage that projecting species ranges globally then filtering for the region ensures that ranges were not truncated based on regional environmental variables, a substantial benefit for accuracy in climate-range projections (Guisan et al. 2017). Furthermore, given SDM projections are dependent on environmental conditions without inter-species interactions or dynamic outcomes (Pearson and Dawson 2003), species compositions may depart from these projections if the species cannot tolerate *in situ* biological dynamics and/or if there are delays in species emigration (Tilman 1999; Hillebrand et al. 2018) or immigration (Menéndez et al. 2006; Jackson and Sax 2010). Additionally, while the SDMs were filtered to native ranges using expert range maps when available, presences in the present-day were based on open-access databases (see Methods), which may result in imprecise available habitat in the present day. While I performed an additional manual filtering step to limit these discrepancies, human error could increase (or decrease) the present-day and future range boundaries of some species. Similarly, the projected presences of each species in present-day and the future are sensitive to the species-specific cutoff values derived from the ROC curve. Changes in the ROC curves across all regional species (average: 0.75) could influence which species are present in each time period and consequently, the species richness trends. Finally, as is typical, the models do not account for evolutionary or phenotypic adaptive changes within species (Pearson and Dawson 2003). Therefore, the projections I provide should only be used as guidance for regional patterns of change in species compositions (Pearson and Dawson 2003), and not looked at or used in isolation. An additional note of interpretation for protected seascape sites: sites vary in size, with some being smaller than one 50 km^2 grid cell and hence overrepresented by such a grid cell. Nonetheless, this study stands as a proof-of-concept that can be refined as models are improved in terms of species range accuracy, spatial resolution, or both.

Conclusions

Present day biodiversity within the region and for every protected seascape site was projected to be substantially altered under future climate scenarios (Figure 4; Figure

A5). As a result, the network and each protected area will necessarily need to adapt - including in their conservation objectives - to respond to changes in species composition and ecosystem functioning. Adding consideration of climate-immigrants, emigrants, and changes in protection of species-at-risk can help for developing climate-responsive management plans (Tittensor et al. 2019). The lists of projected climate-immigrants for mid- and end-century under both scenarios may also be of help for anticipating changes and responding through management and monitoring within individual protected seascape sites and the network as a whole. Furthermore, comparison of the two SSP scenarios provides insight into the substantial benefits of emissions mitigation for this region (i.e., lower species dissimilarity associated with lower carbon emissions; long-term benefits of low carbon emissions being the increased return of resident species).

Ultimately, the Maritime Conservation Network is expected to undergo radical ecological change due to a shifting climate. It will experience substantial biodiversity loss by mid-century but may recover some of this species richness by end-century due to climate-driven species immigration. Yet the recovery in species richness arises from novel species arriving, leading to dramatic changes in the assemblages found within the network. These changes will have as-yet unknown impacts on species interactions and ecosystem functioning. Understanding and projecting these changes is the first step towards a more complete integration of climate change into marine conservation networks. This is the focus of my next chapter. Such effects will also propagate through the coupled socio-ecological system and impact individuals and communities reliant on marine ecosystems and their goods and services.

My results not only provide information that can be used to help inform adaptive climate management for the Maritime Conservation Network, but also a template for how such strategies can be conceived in terms of their integration into marine conservation design, management, and operation in other parts of the world. While the Northwest Atlantic is one of the most rapidly changing parts of the global ocean, it is likely that marine conservation networks throughout the world will have to undergo deep changes in their management, operation, and design to attempt to account for a warmer future.

Chapter 3: Altered Ecosystem Functioning Associated with Climate-Induced Shifts in Species Distributions in Canada's Eastern Marine Conservation Network

Chapter 3.1: Introduction

Species ranges are already shifting due to rapid, climate-change induced impacts on global oceanographic conditions (Johnson et al. 2011; Pinsky et al. 2020). Such ecosystem-wide alterations have led, and will increasingly lead, to existing assemblages shifting regimes and transforming into new biological communities, with largely unknown consequences for ecosystem function (Tinta et al. 2016; Nagelkerken et al. 2020), defined as the combined effects of all processes that sustain an ecosystem and which ultimately produce the goods and services on which human society depends (e.g., food and fisheries, carbon sequestration, and coastal protection; Reiss et al. 2009; IPCC 2022). Changes to these foundational processes then propagate through to impact both the marine biological environment and human well-being (Nagelkerken et al. 2020; IPCC 2022). For example, climate change in the North Atlantic has led to mismatches among prey and predators, leading to reduced fish stock recruitment (Asch et al. 2019) and changes in spatial management as the ranges of endangered species follow the distributional shifts of their prey (Meyer-Gutbrod et al. 2018). Ecosystem functioning has also been altered through the introduction and increased abundance of warmer-water species relative to more cold-tolerant species, fostering new trophic dynamics (Fossheim et al. 2015; Pessarrodona et al. 2019).

Yet while there has been numerous studies on projected changes in species distributions over the coming century (e.g., Kaschner et al. 2011; Garciá Molinos et al. 2015; Asch et al. 2018), there are far fewer studies that attempt to evaluate the consequences for ecosystems and ecosystem functioning. Thus, our understanding of the impacts associated with changing species compositions is limited (Hiddink and ter Hofstede 2008; Chase et al. 2019). As each species within an ecosystem fulfills an individual functional role, projecting the loss of existing or gain of new roles as species redistribute may help to understand how the functioning of an ecosystem could be altered with climate change.

Every species has a set of traits, such as body size, diet, and habitat, that encapsulate and define its role in an ecosystem. Ecosystem functioning is then linked to the suite of traits contained within its particular set of species, the sum of which affect its productivity, nutrient flow, stability, invasibility, and other dynamics (Tilman 1999; Gravel et al. 2016). A subset of one or more species with a similar combination of traits can be considered a functional group (FG), the members of which interact with their abiotic and biotic environments in a broadly similar manner (Petchey and Gaston 2002; Naeem et al. 2012). The resilience and functioning of an ecosystem is then determined by the number and type of functional groups, as well as the number of species within each functional group, with ecosystems being more resilient to disturbance if multiple species fill each functional role (‘functional redundancy’; Hughes et al. 2003; Micheli and Halpern 2005). Furthermore, the loss or gain of species within a functional group can alter ecosystem functioning, especially for groups with a single species. For example, when matches or mismatches occur among prey and predators as a result of differentially shifting species ranges, it can impact population dynamics and ecosystem structure (Nagelkerken and Munday 2016); however, a high species richness within prey and predator functional groups may offer functional redundancy to buffer impacts on ecosystem productivity (Yachi and Loreau 1999). The loss of an entire functional group is likely to result in detrimental consequences for ecosystem functioning and resilience (Vinebrooke et al. 2004; Micheli and Halpern 2005), with theoretical models suggesting the removal of some functional groups could have larger scale impacts relative to others (Arreguín-Sánchez and Ruiz-Barreiro 2014). Given these consequences, and as (direct) ecosystem functioning is unmeasurable, assessing how and which functional groups change could be an effective alternative for assessing impacts on ecosystem processes (Tilman et al. 1997).

The diversity of traits, and hence functioning, within an ecological community can be measured through a variety of functional diversity (FD) indices (Table 6, but also, see Table 1 in Magneville et al. 2022; Villéger et al. 2008; Mouillot et al. 2013; Pollock et al. 2020). These metrics describe how species trait values are distributed within multi-dimensional trait space, where each axis is defined by the range of a trait's values or some combination thereof (Pollock et al. 2020). For example, functional richness (FRic) is the volume occupied by all a community's species in multi-dimensional trait space, often measured using a convex hull or other envelope methods (Mouillot et al. 2013; Blonder et al. 2014).

After partitioning species into functional groups, functional redundancy (FRed) can be assessed as the average species richness across each functional group in an assemblage, indicating the assemblage's resilience and redundancy, especially under environmental fluctuations (Yachi and Loreau 1999; Magneville et al. 2022). A functional group is considered 'over-redundant' when it contains more species than the average functional redundancy of the community (Mouillot et al. 2014; Magneville et al.

2022) and functionally vulnerable of the functional group is represented by a single species, indicating to the risk of a loss of FD through the loss of a single species (Table 6; Mouillot et al. 2014; Magneville et al. 2022).

To help understand how species or functional groups in a community are distributed across multiple trait axes, and to reduce correlation among traits, they are frequently visualized and analyzed in a reduced multi-dimensional space through using Principle Component Analysis (PCA), Principle Coordinate Analysis (PCoA), or the Kernel density (KDE) approach (Villéger et al. 2008, 2013; Blonder et al. 2014). When traits are continuous, species can be directly plotted using a PCA (Legendre and Legendre 2012; Buisson et al. 2013), while mixed or categorical traits are first converted into continuous form through computing a distance matrix, commonly through calculating Gower distance (Gower 1967), and then species are plotted with a PCoA (Villéger et al. 2008; Pimiento et al. 2020). Advantages of using PCAs/PCoAs are that they reduce the number of axes to interpret, allowing easier visualization across all traits, and reduce collinearity among traits (Villéger et al. 2008; Legendre and Legendre 2012). The visualization that PCAs/PCoAs provide can also be used to determine which species are clustered in multi-dimensional space, indicating the most appropriate number of species within each functional group (Ladds et al. 2018).

However, when using a convex hull approach (with or without a PCA/PCoA) to calculate functional richness or functional dissimilarity (i.e., changes in functional richness across space or time), only the species with extreme combinations of trait values that may expand or contract the convex hull affect functional richness and dissimilarity. That is, the loss or gain of species within the multi-dimensional boundaries of the convex hull, which can have substantial impacts on ecosystem functioning, are not accounted for, and nor are functional richness 'gaps' within the trait space. To address this "hole" problem, methods have been developed by which KDE can be used on non-normal, rotated, and/or holey data, as well as account for outliers, but this only works with continuous traits and not categorical data (Blonder et al. 2014).

As a final issue, applying a PCA or PCoA, as is common when calculating FRic or FRed indices, creates a set of rotated axes that are unique to the communities studied. For example, species in a tropical environment would differ in the number and variation of trait combinations to species in an Arctic environment and thus vary in their positions within multi-dimensional trait space. Consequently, the trait-space orientation of the principal components that explain the most variation would differ between tropical and Arctic studies. Furthermore, the addition of a singular new species into one of these environments (e.g., a climate-immigrant) would require analyses to reassign species and/or functional groups based on their changed dissimilarity from one another in multi-dimensional space (i.e. to re-run the PCA/PCoA), which could (a) change the species composition of functional groups based on species dissimilarity, and/or (b) bring an entirely new combination of traits yet have no measurable change on FRic or functional dissimilarity if that role is not extreme enough to expand the convex hull. These issues may make analyses inconsistent and incomparable across studies since the distance matrices created do not consider every possible combination of traits across all taxa in all environments.

These issues are not problematic for existing studies as communities remain fixed (i.e. a snapshot in space and time) and the goal is not to compare across regions nor monitor and update over time, and hence all sampled species can be integrated within the initial set used to calculate the PCA/PCoA axes. However, for my study, I needed a metric which was specifically developed with a temporal aspect in mind (i.e. can be updated in the future as the system evolves and be comparable to previous values), and which is standardized and comparable between regions (including those beyond this study) and ecosystems. Thus, I needed an approach which was robust to unexpected species being sampled in the future (e.g. a new, unprojected species arriving in the Maritimes region in several years) and for which FRic and dissimilarity values calculated at future dates or for additional sites produce values which are directly comparable without having to recalculate principal component axes, which can then result in different metric values and indeed different functional group membership. Furthermore, I needed an approach which can be applied to new regions irrespective of taxonomic composition (i.e. is inherently spatially comparable to other parts of the world; note that this also affects trait selection – see Methods for further details).

Table 6. Ecosystem diversity indices derived from the literature (FE = functional entity, FEr = number of functional entities). Functional trait space refers to the multidimensional space species are plotted on, whereby each axis is a trait, and the position of each species is determined by their specific trait values (Magneville et al. 2022). See Introduction of Chapter 3 for more details.

Term	Description	Reference
Functional Richness (FRic)	The volume of trait space occupied by species present in the assemblage.	(Blonder et al. 2014; Magneville et al. 2022)
Functional Vulnerability (FVul)	The proportion of FEs in an assemblage represented by a single species.	(Mouillot et al. 2014; Magneville et al. 2022)
Functional Redundancy (FRed)	The ratio of species richness to functional groups/entities	(Mouillot et al. 2014; Magneville et al. 2022)
Functional over-redundancy (FOR)	Functional groups/entities represented by more species than the FRed.	(Mouillot et al. 2014; Magneville et al. 2022)
Functional specialization (FSp)	The mean distance to the centroid of the functional trait space.	(Mouillot et al. 2013; Pimiento et al. 2020; Magneville et al. 2022)
Functional uniqueness (FUn)	Overall isolation of a species within functional trait space	(Pimiento et al. 2020)
Functionally unique, specialized, and endangered (FUSE)	Combined FUn and FSpe with IUCN extinction threat status	(Pimiento et al. 2020)
Functional evenness (FEve)	The regularity of the distribution and relative abundance of species in functional space for a given community	(Villéger et al. 2008; Mouillot et al. 2013; Magneville et al. 2022)
Functional originality (FOri)	The mean distance to the nearest species in the functional trait space, weighted by abundance if available	(Mouillot et al. 2013; Magneville et al. 2022)
Functional mean pairwise distance (FMPD)	The mean distance between all pairs of species in functional trait space, weighted by abundance if available	(Magneville et al. 2022)
Functional mean nearest neighbour distance (FNND)	The distance to the nearest neighbor within the assemblage in functional trait space, weighted by abundance if available	(Magneville et al. 2022)

For the specific type of study that I wanted to undertake, therefore, there are limitations associated with estimating functional richness and/or dissimilarity using common functional diversity metric estimation approaches. To address this, I develop a simplified approach in which all traits are converted to categorical values and which accounts for the importance of species in the centre as well as on the boundaries of trait space, while also providing a standardized approach that can be directly applied in a comparable way in other regions. Working with a finite set of categorical traits means that, unlike with a convex hull approach, community metrics such as FRic and dissimilarity change with the loss or gain of a 'functional group' with a specific combination of trait values (termed "functional entity", FE; Mouillot et al. 2014) regardless of its position within multi-dimensional space or distance to other FEs. Each species is thus inherently assigned to the FE encompassing its specific combination of trait values, with no site/study-specific clustering or distance matrices necessary. FRic is then the number of FEs with one or more species. Furthermore, the maximum possible number of FEs (i.e. the total number of 'boxes' of unique categorical combinations in multidimensional trait space) remains constant regardless of geographic region or community size. New communities or repeated sampling over time would therefore be consistent with this framework, which could then plausibly be calculated for anywhere in the global marine realm. This provides substantial benefits in terms of being a simple managerial or policy tool which is easily communicated and interpretable (Boyce et al. 2022).

In previous studies, marine ecosystems (primarily fish species) have been spatially compared for differences in functional composition (i.e., functional beta-diversity) at regional (Villéger et al. 2013; Mouillot et al. 2014; Parravicini et al. 2021) and global scales (Stuart-Smith et al. 2013). However, it is also possible to evaluate changes in ecological functioning across time. For example, evaluating the temporal evolution of functional alpha- and beta- diversity may lead to an understanding of how climate change impacts may affect future ecosystem functioning (Buisson et al. 2013; Albouy et al. 2015; Alabia et al. 2020). Functional beta-diversity can be measured with similar indices to taxonomic beta-diversity (e.g., Sorensen dissimilarity index; Baselga 2010; Villéger et al. 2013; Legendre 2019), but instead describes the change in some measure of FD between two communities or time periods (Magneville et al. 2022). What tends to link these functional beta diversity studies is that functional composition shifts, a proxy for shifts in ecosystem functioning, are measured at the whole ecosystem level using summary statistics such as beta FD for some change in an enclosed FRic volume over space/time. By additionally assessing changes in the presence or absence of functional entities themselves, either between sites or across time, I can also provide an understanding of how changing functional entity composition affects ecological functioning, allowing further assessment of potential ecosystem-level impacts of climate change.

Despite FD metrics likely being a more direct indicator of ecosystem functioning than species diversity (Tilman et al. 1997), marine conservation strategies commonly prioritize taxonomic diversity in the designation process (Micheli and Halpern 2005; Whitney et al. 2023). Yet, species richness may remain similar over time with profound shifts in taxonomic beta diversity (Hillebrand et al. 2010; Dornelas et al. 2014), suggesting that regions may undergo large changes in ecosystem functioning, particularly if new functional entities that fulfill different functional roles immigrate or become extirpated, regardless of the amount of change in the number of species. For example, species richness is projected to decline by 10% in parts of the Northwest Atlantic by 2100 relative to present day under both low and high emission scenarios (Chapter 2) , likely a consequence of this region warming 3x faster than the global average (Saba et al. 2016), yet species composition shifts are more substantial under the high emissions scenario, suggesting this postulated future may have larger trophic network reconfigurations and disruption of ecological functioning. Thus, marine conservation strategies should also account for climate change-induced species compositional shifts into the future (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022), as well as integrate both taxonomic diversity and composition priorities with functional ecosystem change assessments (Devictor et al. 2010). This approach is rarely explored (Hidasi-Neto et al. 2019; Alabia et al. 2020) or matched to present day spatial marine management (Naeem et al. 2012; Chapter 2). Yet by doing so, marine conservation networks can account for multiple impacts of ecosystem change and, in combination with evaluating multiple time periods and scenarios, more effectively design and adapt marine conservation to climate change (Tittensor et al. 2019).

In Canada, many forms of marine spatial conservation strategies exist (DFO 2020; also see Table 1 in Bryndum-Bucholz et al. 2022). Together, Marine Protected Areas (MPAs) and Other Effective area-based Conservation Measures (OECMs) designated by Fisheries and Oceans Canada (DFO) or other governing bodes (DFO 2021a, 2021b; Bryndum-Buchholz et al. 2022) will be used to attain the national goal of 30% of marine and coastal areas conserved by 2030 (Tittensor et al. 2019; DFO 2021a; ECCC 2023a).

Yet, all these existing and proposed conservation sites would benefit from being updated with an approach for adapting and responding to climate-induced changes in habitats and species compositions (Tittensor et al. 2019; O'Regan et al. 2021). As the Northwest Atlantic may experience some of the largest oceanographic changes globally (Saba et al. 2016) and substantial species compositions shifts (Chapter 2) it represents a good archetype within which to explore whether it is possible to project climate-induced disruptions to ecosystems and how to integrate those projections into management frameworks. In particular, the Scotian Shelf-Bay of Fundy bioregion network in DFO's Maritimes Region (termed the "Maritime Conservation Network"; Figure 1) is one of 13 planned networks in Canada (DFO 2022a) and is likely to encompass many large-scale ecosystem shifts over the coming century. With a public timeline for the completion of its Conservation Network Plan for 2024 (DFO 2022a), assessing and integrating climate change-induced impacts into the Maritime Conservation Network planning phase is prescient.

The assessments of shifting species distributions in the Maritimes Region from this thesis have indicated large changes to the composition of its ecological community (Chapter 2). By mid-century, ~22% of resident species were projected to have emigrated (~165 species, e.g., Polar eelpout *Lycodes turneri*), with entirely new climate immigrant species partly offsetting these richness losses (~45 species, e.g., Northern tonguefish *Symphurus pusillus*; Chapter 2) – with unknown consequences for the ecosystem. The loss of emigrating resident species from protected seascape sites, and the immigration of novel species, each of which has a unique set of ecological traits and roles, will change how the ecosystem functions. If the FEs of emigrating species disappear entirely (i.e.

there are no other species in the FE that remain as residents), then those ecological roles could disappear from the ecosystem. Alternatively, ecological roles may be retained if new, climate-immigrant species bring similar traits (i.e., are from the same FE – ‘continuous trait invaders’; Dukes and Mooney 2004). The disappearance of entire FEs is likely to result in more ecological perturbation than the replacement or addition of species within an existing FE. Novel climate-immigrant species may also bring entirely new functions (i.e., new FEs that do not yet exist – ‘discrete trait invaders’, Dukes and Mooney 2004) to the Maritime Conservation Network and Region, again likely perturbing ecosystem functioning more than immigrating species that build redundancy in an existing FE. By projecting species range shifts in this region under multiple scenarios and future time periods (Chapter 2), and then linking species to changes in FEs and hence to changes in ecosystem functioning, I can then project how Maritime Conservation Network design, designation, and management can be adapted to anticipate and integrate the inevitable climate-change induced shifts that will affect the ecosystems it aims to protect.

Here, I develop a spatial index of projected ecological disruption to evaluate the potential impacts of climate-driven changes in species distributions in the Maritime Conservation Network and Region. By combining projected changes in species distributions with the traits of those species, I project how the loss and gain of functional entities (i.e. changes in functional diversity) are likely to impact ecosystem functioning. Firstly, I project the changing functional diversity of the region as a whole and for each conservation site. Secondly, I develop an ecosystem ‘disruption index’ to evaluate likely impacts on ecosystems and individual network sites. I further examine changes in functional redundancy and functional vulnerability within the region and each network site. Ultimately, I hypothesize that novel combinations of traits (i.e., novel FEs) and losses of existing FEs are more likely to disrupt ecosystems than species replacement within a functionally redundant FE. By quantifying this ‘ecological disruption', I can fill a major knowledge gap by linking changing species ranges to their ecological impacts, to map my findings onto the “real” world of conservation and decision-making (Naeem et al. 2012). Such an approach and index, considering both the functional change in the ecosystem and its implications for marine conservation in a standardized way that can be applied coherently across ocean basins, appears to be a novel functional diversity assessment method. Such information on future changes in ecosystem functioning will provide guidance for designing climate-resilient planning and adaptation within the network and beyond.

Chapter 3.2: Methods

Species Distributions

Present day species ranges for fish (699 sp.), mammals (19 sp.), reptiles (5 sp.), and lobsters (2 sp.) in the Maritimes Region were extracted from AquaX global species distribution models (SDMs) (see Reygondeau et al. in prep; Chapter 2). Species range projections for the region were then extracted for mid-century and end-century under SSP1-2.5 and SSP5-8.5, including potential immigrating and emigrating species. Data were extracted on a 55 km^2 global spatial grid, of which 201 grid cells overlapped with the Maritimes Region (Figure 1; Figure 2). Within this region, 725 species were projected in the present day, 607 in mid-century SSP1-2.5, 606 in mid-century SSP5-8.5, 645 in end-century under SSP1-2.5, and 655 in end-century under SSP5-8.5 (Chapter 2; Figure 2).

Functional Trait Selection

To examine how the set of traits in an ecosystem change over time, it is necessary to select specific traits for analysis. Evaluating and selecting species traits that affect ecosystem functioning is a challenge, necessitating a balance between trait availability (and consistency) across as many species and taxa as possible, and the potential link to ecosystem functioning. Furthermore, and specific to this study, it is important to select traits that can be consistently applied to and remain relevant for other regions. Common traits used to categorize species into functional groups fall into three main categories: topology (i.e., body length, body mass, etc), consumption (i.e., trophic level, diet, etc.), and life history (i.e., fecundity, dispersal ability, etc.; Gravel et al. 2016). While trait data are becoming more readily available (Gravel et al. 2016), there are numerous resources that are either taxonomically restricted (MarLIN 2006; Cleary et al. 2008, 2016; Jones et al. 2009; Brun et al. 2016; Madin et al. 2016; Chapman et al. 2019), not digitized (FIDA: Karen Hunter, pers. comm), regionally restricted (Beukhof et al. 2019), or otherwise incomplete or inconsistent across taxa (e.g., size of a newborn not being relevant for broadcast spawners). Given these challenges, I categorized potential traits into three "tiers" of desirability (justifications in Supplementary Materials, Table B1); following this categorization, I then prioritized traits based on data availability and accessibility, and taxonomic coverage. All traits have been justified in previous studies with some direct link to functional roles within the ecosystem, and thus tiers were created based how regularly each trait appeared in these taxonomically diverse studies (Stuart-Smith et al. 2013; Villéger et al. 2013; Mouillot et al. 2014; Ladds et al. 2018; Pimiento et al. 2020; Salerno et al. 2021; Froese and Pauly 2023; Djeghri et al. 2023), as well as their applicability to the broad taxonomic range in my present study. However, many studies also supplement available trait databases with individual species from the primary literature, imputations, and personal communications (Stuart-Smith et al. 2013; Ladds et al. 2018; Pimiento et al. 2020), making it difficult to use traits without directly open and publicly accessible information across species. To my knowledge, only one marine database has species traits across multiple taxonomic groups on a global scale (i.e., FishBase, Froese and Pauly 2023 / SeaLifeBase, Palomares and Pauly 2022) with consistent data for my 'top tier' of traits. Therefore, trait selection was based on both desirability in terms of directly linking to ecological function, and data availability from this database.

Ultimately, five traits were selected based on their tier ranking and data availability across a large fraction of species within my study, such that each trait covered >50% of species. The final traits I selected were: vertical position in water column, body length (cm), trophic level, diet, and habitat zone (Table 7; See Trait Data Extraction and Cleaning below). I then supplemented these by adding a sixth trait of taxonomic identity (fish, mammal, reptile, or lobster), with the intent that this captures important ecological variation (e.g., in thermoregulatory strategy, physiology, morphology, etc) that is not otherwise captured by the other five traits. This method has also been applied in studies for similar reasons (i.e., used taxonomy groupings such as fish/ invertebrate/autotroph as a proxy for unmeasured traits; Micheli and Halpern 2005; Villamor and Becerro 2012).

As there were limited larval/juvenile life stage data, only adult life stage trait data were included.

Table 7. Traits selected for this study based on defined tiers. The number of categories for each selected trait is in brackets. Explanations for why traits were selected are described in the Appendix B.

Selected Traits	**Categories**	**Definition**
Vertical Position in water column (9)	. Benthopelagic . Pelagic . Pelagic-neritic . Pelagic-oceanic . Bathydemersal . Bathypelagic . Reef-associated . Demersal . Benthic	Zone within the water column which the species lives
Body Length (cm) (13)	. 0.05 (i.e., < 0.05) . 0.5 (i.e., 0.05 - 0.5) . 1 (i.e., 0.51 - 1) . 5 (i.e., 1.1 - 5) . 10 (i.e., 5.1 - 10) . 30 (i.e., 10.1 - 30) . 50 (i.e., 30.1 – 50) . 100 (i.e., 50.1 - 100) . 300 (i.e., 100.1 - 300) . 600 (i.e., 300.1 - 600) . 900 (i.e., 600.1 - 900) . 1200 (i.e., 900.1 - 1200) . >1200	Total length of species (modified from: Micheli and Halpern 2005; Hewitt et al. 2008; Mouillot et al. 2014; Pimiento et al. 2017; Nozarpour et al. 2023)
Trophic Level (4)	. 1-Producers (i.e., 1 – 1.9) . 2-Primary Consumers (i.e., 2 – 2.9) . 3-Secondary Consumers (i.e., 3 – 3.9) . 4-Tertiary Consumers (i.e., 4 – 4.9)	Trophic level of the species
Diet (3)	. "Mainly animals (trophic level 2.8+)" . "Plants/detritus + animals (troph. 2.2-2.79)" . "Mainly plants/ detritus (troph 2-2.19)"	The food group /trophic levels the species feeds on
Habitat Zone (7)	. Oceanic-neritic . Neritic . Oceanic . Oceanic-intertidal/littoral . Neritic-intertidal/littoral . Oceanic-neritic-intertidal/littoral . Intertidal/littoral	Primary species habitat
Taxon (4)	. Fish . Mammals . Reptiles . Lobster	Taxonomic group

Trait Data Extraction and Cleaning

The selected functional traits were extracted for as many species as possible using the ‘rfishbase’ package (Boettiger et al. 2012). In FishBase/ SealifeBase, eight species had multiple values for a single trait based on region-specific stock codes or differing country codes. In such cases, trait values were selected based on the following priority ordering: (1) the North Atlantic if possible and trait data was available for all six traits, or (2) circumpolar data, or (3) any ocean basin with available data. FishBase/SeaLifeBase also reported multiple categories of habitat zoning (i.e., distance from shore), with some species found in multiple zones (e.g., intertidal, neritic, and oceanic). Some of the FishBase/SealifeBase zones also overlapped (e.g., supralittoral, littoral, intertidal are all within the littoral zone) and thus, species in at least one of the littoral, supralittoral, sublittoral, or intertidal zone categories were synthesized into a single littoral category. I then created one habitat zone category that encompassed all seven possible combinations of oceanic, neritic, and/or littoral habitat zones (Table 7). The two continuous traits (body length, trophic level) were converted into categorical data to follow the standardized approach described in the Introduction. Correlation among traits was assessed using a chi-square test and Cramer’s V for nominal variables.

For the length trait, the value used was maximum male tail length (TL), except for reptiles which were consistently measured with maximum male carapace length and had no conversion to TL (Froese and Pauly 2023); maximum male tail length and maximum male carapace length were merged into one “length” variable. When maximum male tail length was unavailable, lengths were supplemented first with (1) maximum female tail length, or if unavailable then with (2) standard length (SL) or fin length (FL) converted to tail length (TL) using the species-specific equations in the 'length_length' function in rfishbase (Boettiger et al. 2012; Froese and Pauly 2023). Occasionally there was more than one species-specific conversion option, in which case I prioritized using the conversion constant in order: (1) Northwest Atlantic region, (2) had the most information filled in for that species, (3) had a reference, or (4) was an average of all constants if each had all the same information (e.g., Frigate tuna *Auxis thazard*). One fish species did not have a length type identified (*Histiobranchus bathybius*) and was hence imported directly from the literature (Karmovskaya and Merrett 1998). Lengths were then divided into categories based on an evaluation and modification of the literature to account for the variety of taxa I considered and to encompass the range of trait space plausibly available for such a diverse biological community (i.e, from <0.05 to 1200< cm; Micheli and Halpern 2005; Hewitt et al. 2008; Mouillot et al. 2014; Pimiento et al. 2017; Nozarpour et al. 2023).

As there were fewer species within the mammals (21), reptiles (5), and lobsters (2), where possible missing trait information was manually imported from the literature. For mammals, data on diets (2 sp.), habitat zone (1 sp.) and tail length (1 sp.) were extracted from NOAA (2023). For lobsters, one length was manually imported from the primary literature (Briones-Fourzán et al. 2021). That same lobster species (Blind lobster sp. *Stereomastis sculpta*) had no habitat zone but was described on SeaLifeBase as "deep-sea", which did not fall into any of the habitat zone categories and was therefore manually input to be part of the "oceanic" habitat zone. Once traits were extracted for all species of interest, they were filtered to only retain species with complete data across all six traits. Following this process, each time-period and scenarios had, on average, ~44% of taxa complete with trait data and retained for the analysis (Table B2).

Calculating Functional Indices

Spatially-gridded lists of species and their associated traits were used to calculate functional diversity indices for individual grid cells, protected seascape sites, and the entire region for each time period and scenario using the ‘mFD’ package (Magneville et al. 2022). Given the key goals outlined previously, all traits were converted to categorical variables to create an understandable, consistent, and easily applicable index for measuring ‘ecological disruption’ across all taxa and at any scale (Table 7). Categorizing traits created a finite pool of potential functional entities (i.e., discrete combinations of categorical values for each trait; Mouillot et al. 2014) on all geographical and temporal scales.

Species were grouped into functional entities based on their traits. These functional entities were then used to calculate functional diversity metrics including functional-richness, redundancy/over-redundancy, vulnerability, and dissimilarity (Table 6). While my focus was on functional entity dissimilarity (i.e. functional beta-diversity), FRic provides an alternative perspective on ecosystem change. This metric was simply the number of FEs containing one or more species. Functional redundancy (FRed), the average number of species across all FEs in an assemblage, and functional over-redundancy (FOR), the proportion of FEs with more species than the community’s functional redundancy, were used to determine which FEs were most speciose and may be more resilient to climate change impacts. Functional vulnerability (FVul) was calculated by determining the number of FEs with only a single species, as these FEs are likely to be more vulnerable to disturbance as there is no buffer in terms of fulfilling an ecological role should that single species emigrate or be extirpated.

Finally, I created an “ecological disruption index” (EDI) using an adaptation of the Sorensen dissimilarity index for functional entities (Baselga 2010; see Figure 1 in Villéger et al. 2013; Legendre 2019). This index describes the difference in FE composition (i.e. beta-diversity of FEs) between two time-points or scenarios and was calculated as:

$$\text{EDI} = \frac{(n_{\text{immigrating}} + n_{\text{emigrating}})}{(2 * n_{\text{same}} + n_{\text{immigrating}} + n_{\text{emigrating}})} \quad (2)$$

where $n_{\text{immigrating}}$ is the number of immigrating FEs, $n_{\text{emigrating}}$ is the number of emigrating FEs, and n_{same} is the number of FEs remaining unchanged across two time points. The EDI has a value between zero and one, where zero represents no change in functional entities over time, and 1 represents complete FE composition change.

Assessing the change in individual FEs is also useful for knowing which FEs are expected to immigrate, emigrate, and remain similar across time and scenario. After EDI values were calculated, protected seascape sites were then ranked by projected ecological disruption, as well as the number of immigrating and emigrating FEs for each year and SSP-RCP scenario.

Chapter 3.3: Results

Present Day Regional Functional Entity Richness

In the region in present day there are 136 FEs of a total possible 39,312 FEs globally (all combinations across the six traits; Table 7). Correlation revealed the strongest associations (>0.4) between vertical position in the water column/taxa (0.75), taxa/diet (0.48), trophic level/diet (0.42), and trophic level/body length (0.41). The greatest number of species within an FE was 22 (FE 1; Table 8). Of the 136 FEs, ~66% were functionally vulnerable with one species representing the entity and 24% were functionally over-redundant with more species in them than the region's FRed (i.e. average species across all FEs; Table 9). Across the region, FVul was normally distributed around 0.68 (Figure B1) while the FRed distribution ranged from 1.6-2.2 (Figure B2). FRic was greatest along the Scotian Shelf slope down to Browns Bank, and into the Fundian Channel, and decreased gradually towards the shore and more rapidly offshore (regional range: 38-97 FEs; Figure 6). Regions inshore of the Scotian Shelf had higher FRic and FVul, and lower FRed than those offshore (Table 9).

Table 8. Top 12 Functional Entities (FEs) for the Fisheries and Oceans Canada Maritime Region, where FE # indicates descending order of species richness and the # of Sp. is the range of species richness in each FE across present and future time periods and scenarios. In sum, these FEs contain one third of species from the Maritime Region across present day and future time periods and scenarios.

FE #	Vert. Pos.	Diet	Habitat Zone	Body Length Bin (cm)	Trophic Level Bin	Taxon	# of Sp.	Example
1	Demersal	mainly animals (troph. 2.8 and up)	oceanic	30	3	Fish	22-23	Pale eelpout (*Lycodes pallidus*)
2	Bathydemersal	mainly animals (troph. 2.8 and up)	oceanic	50	3	Fish	9-11	Carapine grenadier (*Coryphaenoides carapinus*)
3	Demersal	mainly animals (troph. 2.8 and up)	oceanic	100	3	Fish	10	Shorthorn sculpin (*Myoxocephalus Scorpius*)
4	Bathydemersal	mainly animals (troph. 2.8 and up)	oceanic	100	3	Fish	8-10	Abyssal halosaur (*Halosauropsis macrochir*)
5	Bathypelagic	mainly animals (troph. 2.8 and up)	oceanic	10	3	Fish	5-9	Winged lanternfish (*Lampanyctus alatus*)
6	Demersal	mainly animals (troph. 2.8 and up)	oceanic	300	3	Fish	7-9	Winter skate (*Leucoraja ocellata*)
7	Bathydemersal	mainly animals (troph. 2.8 and up)	oceanic	30	3	Fish	7-8	Sar’s wolfeel (*Lycenchelys sarsii*)

FE #	Vert. Pos.	Diet	Habitat Zone	Body Length Bin (cm)	Trophic Level Bin	Taxon	# of Sp.	Example
8	Pelagic-oceanic	mainly animals (troph. 2.8 and up)	oceanic	600	4	Fish	5-8	Swordfish (*Xiphias gladius*)
9	Pelagic-oceanic	mainly animals (troph. 2.8 and up)	oceanic	300	4	Fish	5-7	Skipjack tuna (*Katsuwonus pelamis*)
10	Bathypelagic	mainly animals (troph. 2.8 and up)	oceanic	100	3	Fish	6-7	Blackfin sorcerer (*Nettastoma melanura*)
11	Demersal	mainly animals (troph. 2.8 and up)	oceanic	100	4	Fish	3-7	Silver hake (*Merluccius bilinearis*)
12	Bathypelagic	mainly animals (troph. 2.8 and up)	oceanic	30	3	Fish	5-6	Kroyer's deep-sea angler fish (*Ceratias holboelli*)

Regional Change in Functional Entities

FRic was projected to reduce for all future times and scenarios relative to the present day, with the highest future FRic in the end-century under SSP1-2.6 (Table 9). Hotspots of increases in FRic occurred throughout the region, with increases proportional to present day richness occurring primarily inshore (Figure B3). Coinciding with this decrease in FEs was a small change in FVul (increase) and FRed (decrease) in most times and scenarios into the future relative to present day (Table 9). The exception to this trend was in the end-century under SSP5-8.5 when FVul had the lowest value of all times and scenarios (Table 9). Interestingly, the future time-period and scenario with the greatest functional vulnerability and lowest FRed was the mid-century under SSP1-2.6 (Table 9).

Relative to the present day, the end-century under SSP5-8.5 was projected to have the most immigrating FEs (10), of which 90% were functionally vulnerable (Table 10), and 40% of which were projected to have already immigrated by mid-century (Figure 6). The majority of FE immigrations into the Maritimes Region occurred from mid-century to end-century rather than present day to mid-century under both scenarios (Table 10). The FEs projected to immigrate were primarily reef-associated, bottom-associated (demersal, benthopelagic), or a subset of pelagic, primarily with a body size binned 100-1200< cm, a diet of mainly animals, habitat zone of oceanic and/or neritic, and trophic level 3-4 or 4-5 (i.e. top pelagic predators). The immigrating FE that contained the most novel species (2 sp.) across times and scenarios was reef-associated fishes with a diet of mainly animals (troph. 2.8 and up), oceanic habitat zone, a body size between 300-600 cm and trophic level of 4-5. (Dusky shark *Carcharhinus obscurus*, Bull shark *Carcharhinus leucas*). One of the 10 immigrating FEs at the end-century under SSP5-8.5 was a mammal that was the sole representative of its FE (Bryde's whale *Balaenoptera* *brydei*) while another FE was the only littoral-associated immigrating FE (Red cornetfish *Fistularia petimba*) in this time and scenario. The majority of these immigrating FEs occur inshore of the Scotian Shelf, where a net increase in FEs appears primarily near the Eastern Shore Islands AOI and northwards (Figure 6; Figure B3). Inshore waters were projected to gain 5-14 FEs (9/14 from outside region), while offshore waters were projected to gain 11-14 FEs (7/14 from outside of region).

The most projected FE emigrations (17) relative to the present day was also for the end-century under SSP5-8.5, of which 94.1% were functionally vulnerable (Table 10) and 76.5% had emigrated by mid-century (13/17). Of these emigrations, one reptile and one mammal FE emigrated (reptile: Kemp's ridley turtle *Lepidochelys kempii*, mammal: Harp seal *Pagophilus groenlandicus*) while the remainder were primarily fish associated with benthic, deep water or pelagic habitats, with a diet of mainly animals, an oceanic or neritic habitat zone, a body size of 50-900 cm, and a trophic level of 3-4 or 4-5; one FE emigration contained a fish species of trophic level 2 (Atlantic menhaden *Brevoortia tyrannus*). As a result of these emigrations, the region was projected to experience the highest net negative change in FRic in the deep waters offshore of the Scotian Shelf in most times and scenarios (Figure 6). The exception was the end-century under SSP5-8.5 when the offshore waters were projected to have almost no change in FRic and instead, with hotspots of FRic increases relative to present day (Figure 6; Figure B3). In all times and scenarios, the waters offshore of Sable Island and along the Scotian Shelf slope consistently had some of the highest negative changes in FRic (Figure 6; Figure B3). Interestingly, the fewest emigrations relative to present day were in the end-century under SSP1-2.6 (Table 10); thus, most emigrations from the Maritimes Region occurred from present day to mid-century under both scenarios, with only one and four emigrations expected from mid-century to end-century under SSP1-2.6 and SSP5-8.5, respectively. The offshore had the most emigrations across every time period and scenario relative to the inshore (Table 10).

The mid-century under SSP1-2.6 had the largest proportion of FEs remaining the same relative to present day (~97%) while end-century under SSP1-2.6 had the most overall present-day species remaining (Table 10). Of these FEs remaining into the mid-century under SSP1-2.6, FE 19 gained two species, FE 9 gained one species (Table 8), and two other FEs gained one species, increasing their functional over-redundance. This time-period and scenario also lost four fish species in FE 5 (Table 8) and 18 FEs lost 1-3 species. From mid-century to end-century under SSP1-2.6, two resident FEs that had emigrated by mid-century had returned by the end-century, both of which were a result of the present-day species returning.

Table 9. Functional diversity indices across all times and scenarios for the Fisheries and Oceans Canada Maritimes Region and each existing protected seascape site, where functional richness (FRic) is the number of functional entities present, functional redundancy (FRed) is the average number of species within each functional entity present, and functional vulnerability (FVul) is the number of functional entities represented by a single species in each time period and scenario.

Site	**Type**	**Func. Index**	**Present**	**Mid-century**		**End-century**	
				SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
Maritimes Region	Region	FRic	136	128	124	132	129
		FRed.	2.28	2.14	2.16	2.20	2.19
		FVul (%)	66.2 (90/136)	68.0 (87/128)	67.7 (84/124)	66.7 (88/132)	65.9 (85/129)
Maritimes Region (inshore)	Sub-region	FRic	128	121	117	126	123
		FRed.	2.24	2.10	2.14	2.15	2.13
		FVul (%)	66.4 (85/128)	68.6 (83/121)	66.7 (78/117)	67.5 (85/126)	65.9 (81/123)
Maritimes Region (offshore)	Sub-region	FRic	112	105	103	109	106
		FRed.	2.26	2.20	2.19	2.14	2.19
		FVul (%)	62.5 (70/112)	61.6 (69/105)	70.0 (69/103)	65.1 (71/109)	65.1 (69/106)
Boot Island National Wildlife Area	MPA	FRic	56	56	53	55	56
		FRed	1.98	2.02	2.02	1.89	1.96
		FVul (%)	66.1 (37/56)	69.6 (39/56)	67.9 (36/53)	70.9 (39/55)	67.9 (38/56)
John Lusby Marsh National Wildlife Area	MPA	FRic	52	52	53	53	60
		FRed	2.08	1.87	1.81	1.72	1.83
		FVul (%)	65.4 (34/52)	75.0 (39/52)	77.4 (41/53)	77.4 (41/53)	75.0 (45/60)
Kejimkujik Seaside National Park and Historic Site	MPA	FRic	91	91	83	89	91
		FRed	1.76	1.98	2.01	1.93	1.92
		FVul (%)	70.3 (64/91)	68.1 (62/91)	63.9 (53/83)	67.4 (60/89)	69.2 (63/91)

				Mid-century		**End-century**	
Site	**Type**	**Func. Index**	**Present**	**SSP1-2.6**	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
Machias Seal Island Migratory Bird Sanctuary	MPA	FRic	84	79	74	81	86
		FRed	1.82	2.00	1.96	1.93	1.90
		FVul (%)	67.9 (57/84)	64.6 (51/79)	63.5 (47/74)	65.4 (53/81)	70.9 (61/86)
Musquash Estuary	MPA	FRic	87	73	72	84	78
		FRed	1.78	1.79	1.81	1.85	1.94
		FVul (%)	70.1 (61/87)	69.9 (51/73)	70.8 (51/72)	69.0 (58/84)	67.9 (53/78)
St Anns Bank	MPA	FRic	83	80	81	83	87
		FRed	1.98	1.93	1.93	1.88	1.87
		FVul (%)	65.1 (54/83)	65.0 (52/80)	65.4 (53/81)	66.3 (55/83)	72.4 (63/87)
The Gully	MPA	FRic	101	81	81	86	87
		FRed	2.15	2.06	2.04	2.15	2.15
		FVul (%)	67.3 (68/101)	65.4 (53/81)	64.2 (52/81)	66.3 (57/86)	65.5 (57/87)
Corsair/ Georges Canyons Conservation Area	OECM	FRic	96	80	83	89	82
		FRed	1.98	1.86	1.80	1.85	1.80
		FVul (%)	67.7 (65/96)	67.5 (54/80)	71.1 (59/83)	68.5 (61/89)	69.5 (57/82)
Eastern Canyons	OECM	FRic	103	93	88	95	94
		FRed	2.28	2.12	2.20	2.15	2.18
		FVul (%)	64.1 (66/103)	67.7 (63/93)	64.8 (57/88)	64.2 (61/95)	66.0 (62/94)
Emerald Basin Sponge Conservation Area	OECM	FRic	72	77	71	74	74
		FRed	1.76	1.86	1.86	1.84	1.89
			69.4	67.5	64.8	66.2	67.6

Site	Type	Func. Index	Present	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
		FVul (%)	(50/72)	(52/77)	(46/71)	(49/74)	(50/74)
Jordan Basin Conservation Area	OECM	FRic	84	83	81	85	79
		FRed	1.86	2.00	1.98	1.96	1.99
		FVul (%)	65.5 (55/84)	65.1 (54/83)	65.4 (53/81)	67.1 (57/85)	65.8 (52/79)
Northeast Channel Coral Conservation Area	OECM	FRic	90	84	84	88	81
		FRed	2.10	2.00	1.98	1.95	1.96
		FVul (%)	66.7 (60/90)	69.0 (58/84)	69.0 (58/84)	68.2 (60/88)	65.4 (53/81)
Sambro Bank Sponge Conservation Area	OECM	FRic	80	81	79	82	84
		FRed	1.82	1.93	1.97	1.89	1.88
		FVul (%)	68.8 (55/80)	66.7 (54/81)	63.3 (50/79)	67.1 (55/82)	70.2 (59/84)
Western Emerald Bank Conservation Area	OECM	FRic	107	94	90	98	93
		FRed	2.19	2.10	2.09	2.05	2.10
		FVul (%)	67.3 (72/107)	69.1 (65/94)	67.8 (61/90)	68.4 (67/98)	65.6 (61/93)

Table 10. Change in functional entities (FEs) for the Fisheries and Oceans Canada Maritime Region and each existing protected seascape feature comparing the number of immigrating (Immig.), emigrating (Emig.) and the same FEs between each time and scenario. Sites are ordered by conservation type and alphabetically.

Site	Type	Func. Change	Present - Mid-century		Present – End-century		Mid-century – End-century	
			SSP1 -2.6	SSP1 -8.5	SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5 -8.5
Maritimes Region	Region	Same	124	120	126	119	127	120
		Immig.	4	4	6	10	5	9
		Emig.	12	16	10	17	1	4
Maritimes Region (inshore)	Sub-region	Same	116	111	117	109	120	112
		Immig.	5	6	9	14	6	11
		Emig.	12	17	11	19	1	5
Maritimes Region (offshore)	Sub-region	Same	94	92	96	92	102	98
		Immig.	11	11	13	14	7	8
		Emig.	18	20	16	20	3	5
Boot Island National Wildlife Area	MPA	Same	49	45	48	41	53	48
		Immig.	7	8	7	15	2	8
		Emig.	7	11	8	15	3	5
John Lusby Marsh National Wildlife Area	MPA	Same	43	42	44	41	52	46
		Immig.	9	11	9	19	1	14
		Emig.	9	10	8	11	0	7
Kejimkujik Seaside National Park and Historic Site	MPA	Same	75	69	76	70	87	80
		Immig.	16	14	13	21	2	11
		Emig.	16	22	15	21	4	3
Machias Seal Island Migratory Bird Sanctuary	MPA	Same	63	60	64	62	77	67
		Immig.	16	14	17	24	4	19
		Emig.	21	24	20	22	2	7
Musquash Estuary	MPA	Same	69	65	69	61	73	62
		Immig.	4	7	15	17	11	16
		Emig.	18	22	18	26	0	10
St Anns Bank	MPA	Same	72	73	73	70	78	75
		Immig.	8	8	10	17	5	12
		Emig.	11	10	10	13	2	6
The Gully	MPA	Same	77	77	80	76	76	76
		Immig.	4	4	6	11	10	11
		Emig.	24	24	21	25	5	5
	OECM	Same	77	80	83	78	77	74

Site	Type	Func. Change	Present - Mid-century		Present – End-century		Mid-century – End-century	
			SSP1 -2.6	SSP1 -8.5	SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5 -8.5
Corsair/ Georges Canyons Conservation Area		Immig.	3	3	6	4	12	8
		Emig.	19	16	13	18	3	9
Eastern Canyons	OECM	Same	87	82	85	79	88	84
		Immig.	6	6	10	15	7	10
		Emig.	16	21	18	24	5	4
Emerald Basin Sponge Conservation Area	OECM	Same	59	58	60	52	72	63
		Immig.	18	13	14	22	2	11
		Emig.	13	14	12	20	5	8
Jordan Basin Conservation Area	OECM	Same	64	61	66	53	82	69
		Immig.	19	20	19	26	3	10
		Emig.	20	23	18	31	1	12
Northeast Channel Coral Conservation Area	OECM	Same	71	72	74	68	79	74
		Immig.	13	12	14	13	9	7
		Emig.	19	18	16	22	5	10
Sambro Bank Sponge Conservation Area	OECM	Same	64	61	65	59	75	73
		Immig.	17	18	17	25	7	11
		Emig.	16	19	15	21	6	6
Western Emerald Bank Conservation Area	OECM	Same	89	84	92	82	91	83
		Immig.	5	6	6	11	7	10
		Emig.	18	23	15	25	3	7

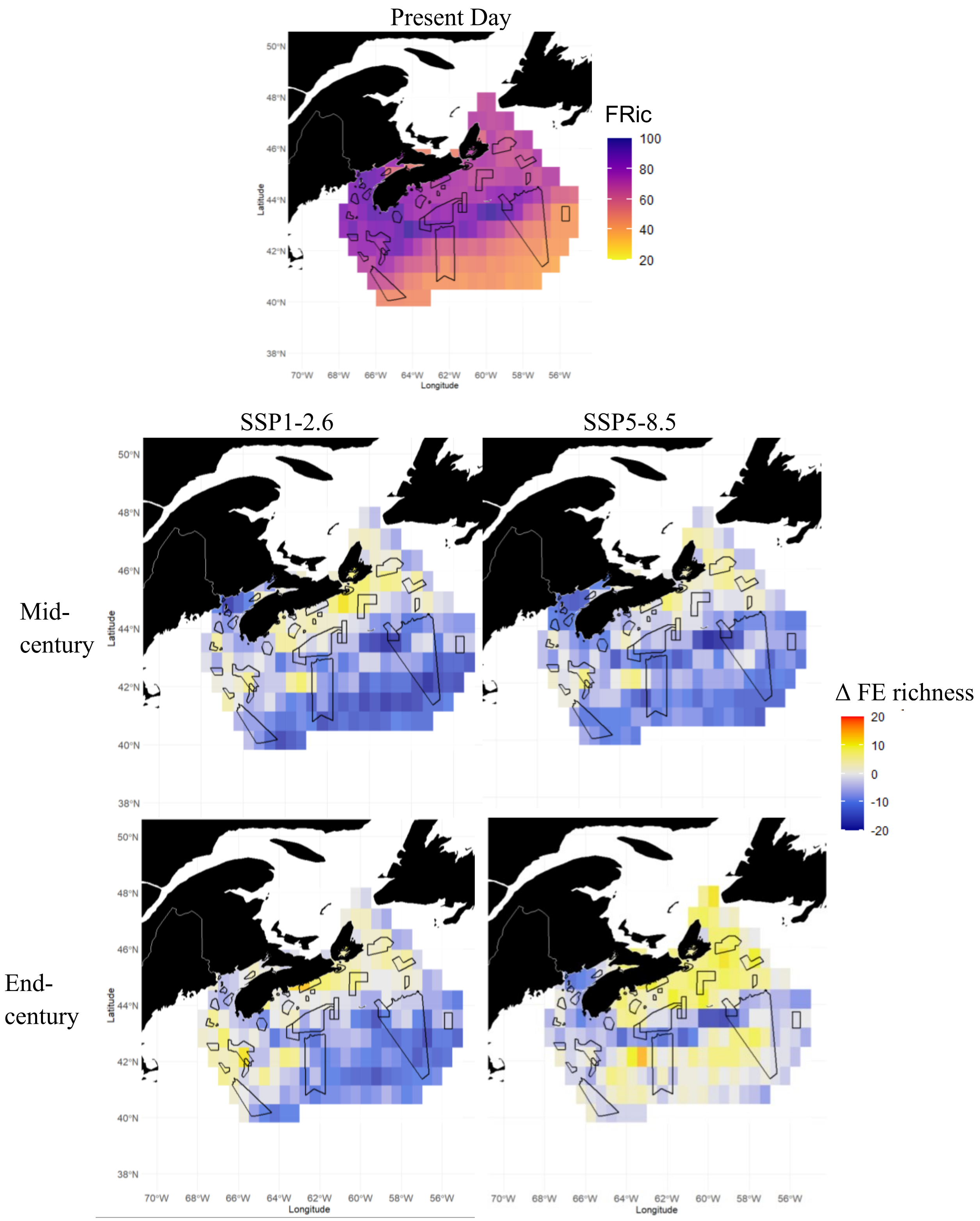


Figure 6. Functional Entity (FE) richness for the Fisheries and Oceans Canada Maritimes Region. The first row is present day FE richness, the second row is the change in FE richness from present day to mid-century, and the third row is the change in FE richness from present day to end-century. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

Regional Ecological Disruption

The highest value of the regional ecological disruption index relative to present day was 0.1, projected at the end-century under SSP5-8.5 (Figure 7), with the majority of that disruption occurring in the first half of this century (0.08; Table 11). Interestingly, ecological disruption was projected to be similar in mid-century and end-century under SSP1-2.6, with end-century being slightly lower; thus, the ecosystem actually regained some of its original functional composition over the latter part of the century (Table 11). When the region was split into inshore and offshore subregions, both subregions had higher ecological disruption than the entirety of the Maritimes Region. In a similar manner to the region as a whole, the majority of the ecological disruption into end-century under SSP5-8.5 for both subregions occurred from present day to mid-century rather than mid-century to end-century (Table 11).

Overall, the most ecological disruption was projected in the offshore waters beyond the Scotian Shelf (Table 11), with especially high disruption south of Sable Island and into the Eastern Canyons in all time periods and scenarios (max: 0.42 in a grid cell; Figure 7). The least amount of ecological disruption was consistently projected along the Scotian Shelf slope in all times and scenarios, with other areas of low ecological disruption along the Northeastern shelf and in the Bay of Fundy (Figure 7). Generally, the distribution of EDIs across the region was skewed left to lower values (highest point: ~0.20; Figure 8). However, by end-century under SSP5-8.5, Nova Scotia's inshore waters, in particular the Northeastern shelf and Bay of Fundy, were projected to experience substantially more ecological disruption than in other times and scenarios (Figure 7), centring the distribution of EDI values at ~0.30 (Figure 8).

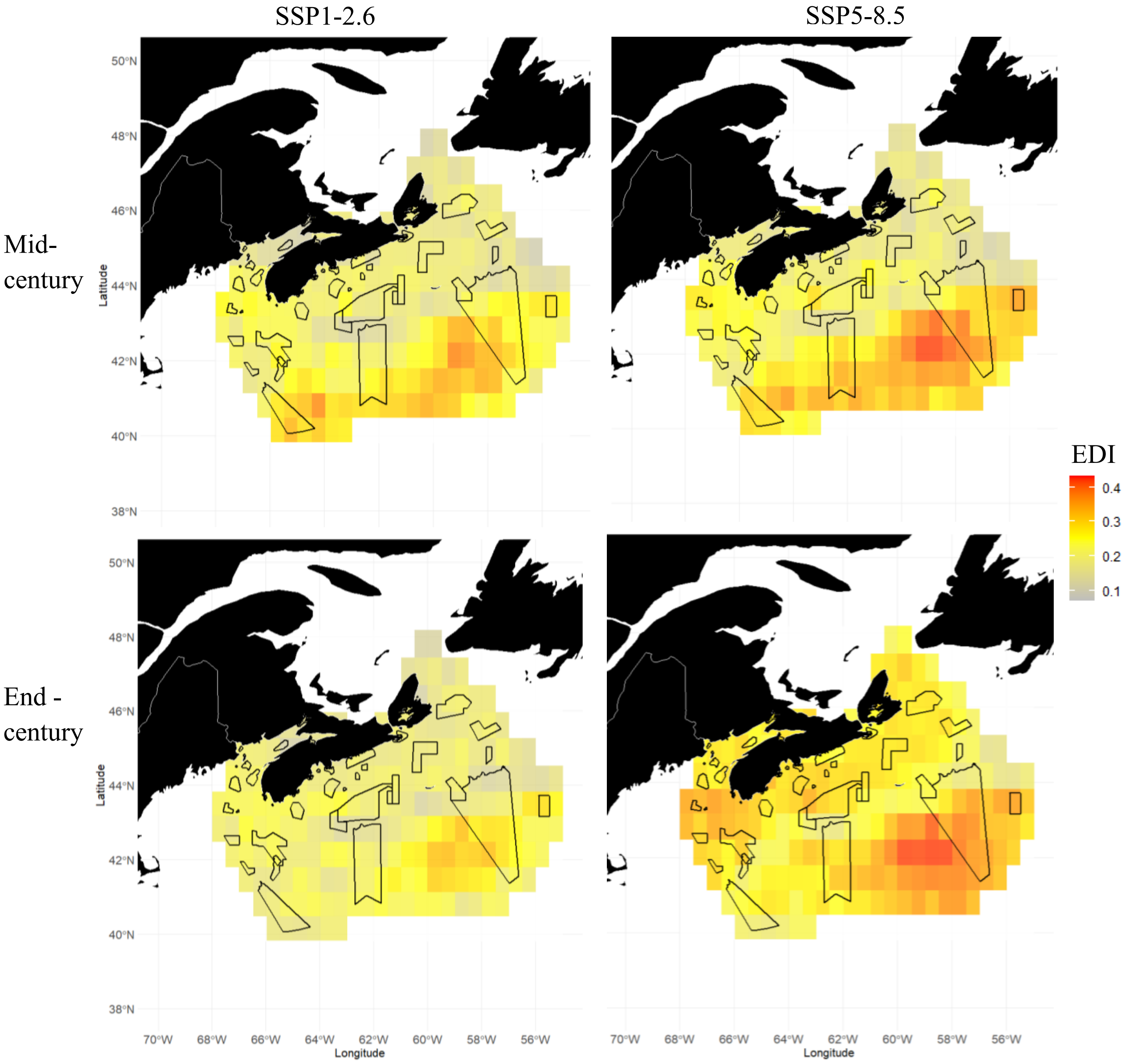


Figure 7. Projected ecological disruption (EDI) for the Fisheries and Oceans Canada Maritimes Region. Top row: ecological disruption from present day to mid-century. Bottom row: disruption from present day to end-century. Columns indicate SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions) scenarios, respectively.

Table 11. The Ecological Disruption Index (EDI) for the Fisheries and Oceans Canada Maritime Region and each existing protected seascape feature comparing across each time period and scenario. Sites are ordered by conservation type and alphabetically.

Site	Type	Present - Mid-century		Present – End-century		Mid-century – End-century	
		SSP1 -2.6	SSP1- 8.5	SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5 -8.5
Maritimes Region	Region	0.06	0.08	0.06	0.10	0.02	0.05
Maritimes Region (inshore)	Sub-region	0.07	0.09	0.08	0.13	0.03	0.07
Maritimes Region (offshore)	Sub-region	0.13	0.14	0.13	0.16	0.05	0.06
Boot Island National Wildlife Area	MPA	0.12	0.17	0.14	0.27	0.05	0.12
John Lusby Marsh National Wildlife Area	MPA	0.17	0.20	0.16	0.27	0.01	0.19
Kejimkujik Seaside National Park and Historic Site	MPA	0.18	0.21	0.16	0.23	0.03	0.08
Machias Seal Island Migratory Bird Sanctuary	MPA	0.23	0.24	0.22	0.27	0.04	0.16
Musquash Estuary	MPA	0.14	0.18	0.19	0.26	0.07	0.17
St Anns Bank	MPA	0.12	0.11	0.12	0.18	0.04	0.11
The Gully	MPA	0.15	0.15	0.14	0.19	0.09	0.10
Corsair/ Georges Canyons	OECM	0.12	0.11	0.10	0.12	0.09	0.10

Site	Type	Present - Mid-century		Present – End-century		Mid-century – End-century	
		SSP1 -2.6	SSP1-8.5	SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5 -8.5
Conservation Area							
Eastern Canyons	OECM	0.11	0.14	0.14	0.20	0.06	0.08
Emerald Basin Sponge Conservation Area	OECM	0.21	0.19	0.18	0.29	0.05	0.13
Jordan Basin Conservation Area	OECM	0.23	0.26	0.22	0.35	0.02	0.14
Northeast Channel Coral Conservation Area	OECM	0.18	0.17	0.17	0.20	0.08	0.10
Sambro Bank Sponge Conservation Area	OECM	0.20	0.23	0.20	0.28	0.08	0.10
Western Emerald Bank Conservation Area	OECM	0.11	0.15	0.10	0.18	0.05	0.09

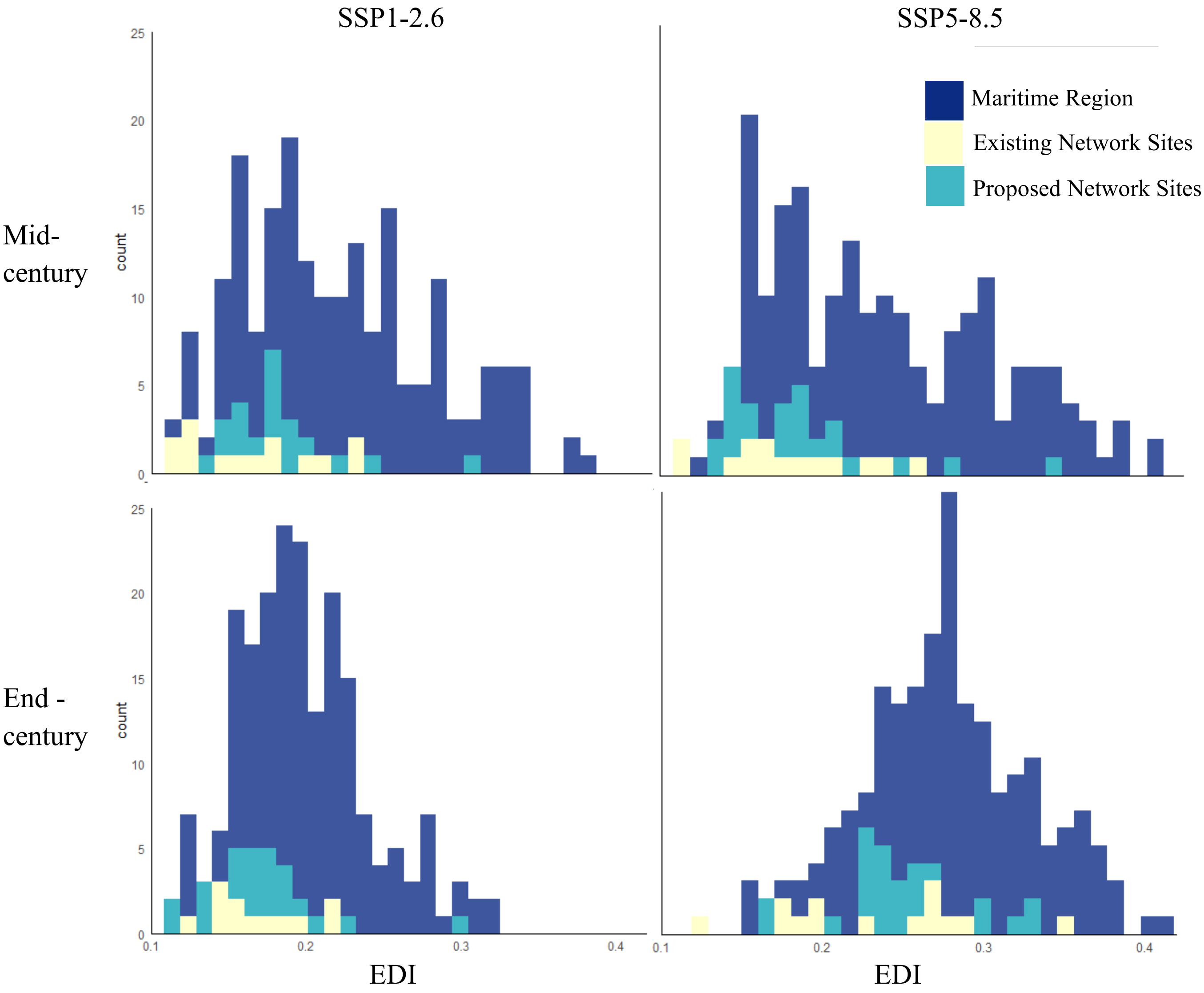


Figure 8. The distribution of the Ecological Disruption Index (EDI), as calculated for each of the 201 grid cells across the Fisheries and Oceans Canada Scotian Shelf-Bay of Fundy Bioregion relative to all existing sites in the Maritime Conservation Network (Marine Protected Areas: 7; Other Effective area-based Conservation Measures: 7) and proposed network sites (areas of interest: 2; proposed: 31). The first row is the EDI from present day to mid-century and the second row is the EDI from present day to end-century. Columns indicate SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions) scenarios, respectively.

Present Day Functional Entity Richness for All Protected Seascape Sites

Across existing network sites, the Western Emerald Bank Conservation Area (WEBCA), one of the top three largest existing network sites and located near the Scotian Shelf slope, had the highest FRic. The John Lusby Marsh National Wildlife Area (JLMNWA), one of the smallest MPAs in the network and located in the Bay of Fundy (Figure 1), had the lowest FRic (52 FEs; Table 9; Figure 9). FRed and FVul were similar across existing network sites and ranged from 1.7 – 2.3 (average: 1.97) and 64-70% (average: 67%), respectively. The Eastern Canyons Marine Refuge, the largest of all existing network sites and located offshore (Figure 1), had the greatest FRed (and lowest FVul), the inshore Emerald Basin Sponge Conservation Area had the lowest FRed, and the inshore Kejimkujik Seaside National Park and Historic Site had the highest FVul (Table 9).

When including the proposed network sites, the Fundian Channel-Browns Bank AOI, the second largest protected seascape site, had the highest FRic, and the Cold Seeps proposed network site had the lowest FRic of all protected seascape sites (proposed and existing; Table B3; Figure B5). The highest overall FVul was in the North of Emerald Sea Pen proposed site while the Fundian Channel-Browns Bank AOI had the lowest FVul (Table B3). The Fundian Channel-Browns Bank AOI additionally had the highest FRed of all proposed sites while the lowest FRed of all protected seascape sites was in the Bon Portage Island proposed site (Figure B5).

Existing Network Sites Change in Functional Entities

The existing network site with the highest FRic in all future times and scenarios was the WEBCA (Table 9; Figure 9). This Marine Refuge also retained the most resident FEs across each time and scenario (Table 10). Like the present day, the JLMNWA was projected to continue having the lowest FRic across all scenarios, except the end-century under SSP5-8.5 where another one of the smallest protected seascape sites, Boot Island National Wildlife Area, was projected to have the lowest FRic (Table 9).

The existing network site projected to have the most immigrating FEs relative to present day was the Jordan Basin Conservation Area, located in the Fundian Channel, with 19-26 FE immigrants across times and scenarios (Table 10). Of these immigrating FEs, up to 15% were novel to the region, depending on scenario and time period. The Corsair/Georges Canyons Conservation Area (CGCCA), the third largest existing network site, located offshore and in the southern part of the Region, was projected to have the fewest immigrating FEs across times and scenarios, of which up to one was novel to the region. The sites with the most emigrating FEs across most times and scenarios was the Gully MPA (located off Cape Breton Island, Figure 1), except for the end-century under SSP5-8.5 when the Jordan Basin Conservation Area had the most FE emigrations (Table 10). All other comparisons of FE immigration and emigration can be found in Table 10.

Across all times, scenarios, and existing network sites, FRed averaged ~1.9 (Figure B2), and the FVul ranged from 60-79% (Table 9; Figure B1). The existing network site with the highest FRed was the Eastern Canyons Marine Refuge across all times and scenarios, but also The Gully MPA in the end-century under SSP1-2.6 (Table 9). During the times when these existing network sites had the highest FRed, FOR was relatively consistent (~23-27%), but higher in the Gully MPA at the end-century under SSP1-2.6. The existing network site with the lowest FVul varied by time and scenario. The JLMNWA had the highest FVul for all future times and scenarios (Table 9). Despite the WEBCA encompassing the most resident FEs across all time-periods and scenarios (Table 10), this Marine Refuge only had the largest proportion of these FEs from present day in end-century under SSP1-2.6 (Figure B4). In all other time-periods and scenarios, the CGCCA had the largest proportion of its encompassed FEs be from present day (>95%; Figure B4). The existing seascape sites with the smallest proportion of resident species relative to present day were the Emerald Basin Sponge Conservation Area in mid-century under SSP1-2.6 (~77%), and the Jordan Basin Conservation Area in the remaining times and scenarios (~67-78%; Figure B4).

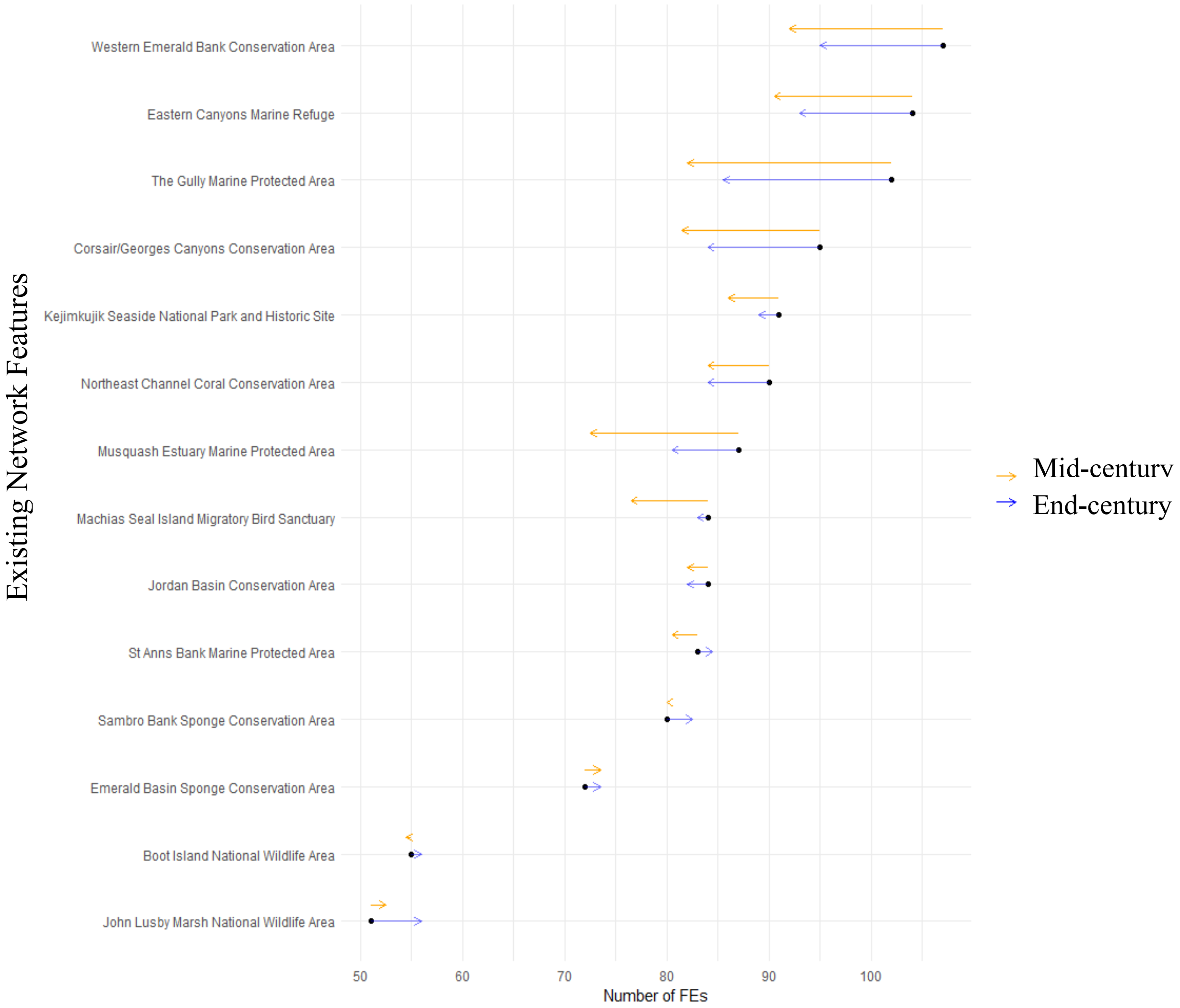


Figure 9. Marine Protected Areas (n = 7) and Other Effective area-based Conservation Measures (n = 7) within the Fisheries and Oceans Canada Maritime Conservation Network ranked by overall number of functional entities (FEs) protected. The change in the number of FEs within each site by mid- and end-century (averaged across high and low emissions scenarios) is indicated by orange and blue arrows, respectively.

Ecological Disruption of Existing Network Sites

The EDI within each protected seascape site was highest for the end-century under SSP5-8.5 relative to present day for all sites, except the Corsair/Georges Canyons Conservation Area, which had its highest EDI value in mid-century under SSP1-2.6 (Table 11). The individual site with the highest EDI across most times was the Jordan Basin Conservation Area (range: 0.23-0.35), but for the end-century under SSP1-2.6, the Machias Seal Island Migratory Bird Sanctuary had the highest EDI. In contrast, the CGCCA had the lowest EDI under SSP5-8.5 (~0.11), while the Eastern Canyons Marine Refuge (0.11) and WEBCA (0.10) had a lower EDI in mid- and end-century under SSP1-2.6, respectively. Of note is that the EDI from mid- to end-century under SSP1-2.6 was much lower than mid- to end-century under SSP5-8.5 for most existing network sites (Table 11).

Changes in Functional Entities within Proposed Network Sites

The Fundian Channel-Browns Bank AOI had the highest FRic and the Cold Seeps proposed site had the lowest FRic of all protected seascape sites for all future time-periods and scenarios (Table B3; Figure B5). The Cold Seeps proposed site was also projected to encompass the smallest proportion of present-day resident FEs in mid-century and end-century under SSP1-2.6 (72-74%; Figure B4). The highest numbers of immigrating FEs were found in proposed sites, with Bras d'Or Lakes EBSA and Western Jordan Basin having the most for mid-century, and Chebogue and Southern Bight, and Pearl Island having the most for end-century under SSP1-2.6 and SSP5-8.5 respectively (Table B4). Furthermore, the Bon Portage proposed site had the most FE emigrations across most times and scenarios, coming second to the Gully MPA only in mid-century under SSP1-2.6 (Table B4). In mid-century under SSP5-8.5 the Eastern Shoal proposed site had the fewest emigrations while end-century under SSP1-2.6 the Bird Islands had the fewest (Table B4). Existing network sites had the fewest emigrations in the other times and scenarios (Table 10).

Across all designated and proposed protected seascape sites, the FVul and FRed were relatively consistent (FVul range: 60-78%, Figure B1; FRed range: ~1.6-2.2, Figure B2; Table B3). In addition to the Bird Islands having some of the fewest emigrations, it also had on of the highest FVul in mid-century under SSP1-2.6 and end-century under SSP5-8.5 (Table B3). All other proposed site functional indices and changes can be found in Table B3 and Table B4.

Proposed Network Sites Ecological Disruption

Across almost all proposed network sites, ecological disruption was projected to be highest at the end of the century under SSP5-8.5 relative to present day (Table B5). The only exception was the Cold Seeps which experienced the highest ecological disruption by mid-century under SSP5-8.5 (Table B5). The Cold Seeps proposed site also had the highest ecological disruption of all sites in mid-century under both scenarios and end-century under SSP1-2.6 relative to present day (Table B5); this result suggests that this site will be among the most perturbed in terms of functionality. Comparing ecological disruption from mid- to end-century across both proposed and designated sites revealed similar trends as previously (SSP1-2.6 EDI range: 0.01 - 0.10; SSP5-8.5 EDI range: 0.08 - 0.21), with Horse Mussels Reefs proposed site having the highest EDI under SSP5-8.5 and Brier Island having one of the lowest EDIs under SSP1-2.6.

Chapter 3.4: Discussion

Present Day FE Richness and Protection

To assess how ecosystem functioning in the Maritime Conservation Network may be impacted by climate change, I linked species traits to projected future ranges under two climate change scenarios from an ensemble of species distribution models. This is the first study to collectively project Northwest Atlantic functional diversity for fish, mammals, reptiles, and lobsters. The 310 species with trait data (Table B2) projected to be resident to the Maritimes Region were categorized into 136 different FEs, of which one third of species were within 12 FEs (Table 8). This skewed distribution of species within FEs indicates a high functional over-redundance for some FEs – and high functional vulnerability for other FEs - across the region (Mouillot et al. 2014).

As fish dominated species richness, and likely represent an overestimate of true species richness levels (Brown et al. 2005; Ward-Paige and Bundy 2016; Bundy et al. 2017, but see discussion in previous chapter on under-sampling), functional diversity measures are consequently also likely overestimations. With this study including multiple taxonomic groups, the results here are not comparable to other literature yet, which tends to focus on specific taxa and use individual traits for each. However, regional functional diversity assessments have been conducted at a coarser resolution. Long-term bottom-trawl survey datasets of fish and invertebrates on the Scotian Shelf found 185 species, of which 113 were fish that were classified into nine fish functional groups and 72 were invertebrates classified into six invertebrate functional groups (Bundy et al. 2017), a less resolved set of FGs/FEs than in this study. Furthermore, since most DFO surveys occur on the Scotian Shelf and focus on benthic and demersal species (Shackell and Frank 2003; Ward-Paige and Bundy 2016; Bundy et al. 2017), the inclusion of offshore, nearshore, mid-water, and open-ocean areas likely would have resulted in new functional groups in Bundy et al. (2017), dependent on which traits were assessed, but ultimately increasing functional diversity.

A study of invertebrate species and functional richness on the Flemish Cap found 285 invertebrate taxa which were organized into ~45 functional groups (Murillo et al. 2020), suggesting again that spatially restricted studies in the region are under sampling both species and functional richness. The variation in invertebrate taxonomic and functional richness between inshore (Bundy et al. 2017) and offshore (Murillo et al. 2020) illustrates how it is not possible to distinguish between true differences in functional diversity and those attributed to different trait combinations, as highlighted in the rationale for choosing the approach that I did (see Methods). Thus, assessing both inshore and offshore habitat is one of several potential explanation for my higher-than-expected projections for functional richness in the Maritimes Region, supported by the fact that 50% of the most functionally redundant FEs projected for this region included bathypelagic or bathydemersal fish species that would inhabit deeper, mid-water, and offshore waters (Table 8). Further, functional richness will increase with the inclusion of more taxa that were not assessed for this study region (e.g., bivalves, crabs, corals, etc.).

Spatial patterns of regional functional richness were generally comparable to those from the long-term bottom-trawl survey study (Bundy et al. 2017; note: this study spatially interpolated functional group diversity patterns for the region from fish and invertebrate biomass tows). In both studies, the inshore generally had high functional richness, with hotspots near Sable Island, in the southwest of the region near Browns Bank, the Bay of Fundy, and near the Shelf slope (Figure 6; Bundy et al. 2017). These hotspots of functional richness coincide with circulation patterns such as water flowing into the Bay of Fundy and back southwards towards the Fundian Channel/Browns Bank (Sutcliffe Jr. et al. 1976; Smith et al. 1978), indicating that the high functional richness here may derive from the inclusion of the northern range extent of species in warm water FEs. High functional richness near the Scotian Shelf slope (Figure 6) is likely a result of more functionally unique species occupying heterogeneous habitat (Shackell and Frank 2003). In contrast to this study, the bottom-trawl survey found a consistent trend of high functional richness along the Northeastern shelf and low values east of Browns Bank and north and east of the Gully (Bundy et al. 2017), whereas functional richness in this study was highest along the shelf slope (Figure 6). The discrepancies between these functional richness hotspots may be a result of the bottom-trawl surveys capturing more benthic and demersal species that congregate in specific basins (Bundy et al. 2017) while my study considers fishes, mammals, reptiles, and lobsters throughout the water column, including pelagic species, as well as a more discrete classification of species into a higher number of FEs. Furthermore, functional richness discrepancies may arise as the bottom-trawl survey results were spatially extrapolated for the entire Shelf rather than being empirically sampled at all locations (Bundy et al. 2017).

Regardless of time-period or scenario, 12 FEs contained about one third of species in the region (Table 8). These FEs were higher-trophic level (3-4 and 4-5) fishes with a diet composed primarily of animals (which themselves are at trophic levels 2.8≤), with body lengths ranging from 10-600 cm, and living in a range of water column positions including 6/12 FEs in deep water (Table 8). While these specific trait combinations were not used within other studies, bottom trawl survey data collected for finfish from 1970-2014 had the greatest over-redundancy of fish species in a benthivorous, benthic, small body size (<31 cm) category (25 sp., Bundy et al. 2017): this matches what I found for FE 1, which contained the most species (22 sp., Table 8). Given Bundy et al. (2017) categorized body size into fewer categories (small (<31 cm); medium (30-80 cm); large (80< cm)) relative to this study (Table 7), it is likely FE 1 would have more species than Bundy et al. (2017) were body size ranges more similar. In addition, an assessment of species from FE 1 that overlap with finfish from the trawl surveys indicated 54% of projected fish species in FE 1 were not found in those surveys (Bundy et al. 2017). Given that the region represents physiologically suitable habitat for these species, this variation between observations and projections suggests there may be species yet to be surveyed in other functional groups as well, bringing additional combinations of traits in the Maritimes Region.

Previous functional diversity studies for this region classified species into far fewer FEs (range: 6-9; Bundy 2005; Shackell et al. 2012; Bundy et al. 2017) than this study (136). As a result, research to date considered no functional groups for this region to be vulnerable. In contrast, I find 90 functionally vulnerable FEs that provide unique combinations of traits (and likely functioning) to the region but are represented by few species (Table 9). This result suggests that the resolution of classification into FGs/FEs affects the level of functional redundancy and vulnerability detected. Indeed, it is difficult to compare functional redundancy and vulnerability across studies as trait combinations defining FGs/FEs vary, again illuminating the need for a consistent approach. Generally, functional redundancy in this region has been identified to be larger (~7-13) in other studies relative to this one (~2; Table 9; Bundy 2005; Shackell et al. 2012; Bundy et al. 2017), likely another product of the FG/FE classification scheme. The functional redundancy I observed was more consistent with another large-scale functional diversity study in the tropics (Mouillot et al. 2014) that considered ~6,300 species divided into 646 FEs (a maximum of 5,670 unique combinations of traits); Mouillot et al. 2014). Mouillot et al. (2014) provided an equation linking species richness and FRed, which when applied in this region suggests a functional redundancy of ~2.9; a higher but comparable redundancy to my study, but still much lower than suggested from the regional bottom trawl survey functional diversity analyses. In tropical marine ecosystems, regions with fewer species tended to have higher functional vulnerability and lower over-redundancy (Mouillot et al. 2014), and as temperate regions have fewer species than tropical regions (Garciá Molinos et al. 2015), it is unsurprising that vulnerability was higher and redundancy and over-redundancy were lower in the Maritimes Region's temperate waters than in the tropical western Atlantic (Table 9; Mouillot et al. 2014).

Regional Changes in FE Richness and Ecological Disruption

Functional richness decreased slightly across the region, both inshore and offshore, for all future time-periods and scenarios (Figure 6; Table 9). Offshore waters were projected to experience the most immigrating and emigrating FEs (Table 10) and, as a result of also having the lowest functional richness (Figure 6), had the highest ecological disruption (range: 0.13-0.16) relative to the region as a whole and coastal waters (range: 0.06-0.13; Figure 7). High levels of change in offshore community composition have also been found in Greenland over the past two decades, with greater borealization of the community at depths of 350-1000 m relative to inshore waters (Emblemsvåg et al. 2022). Similarly, the offshore waters in the Maritimes Region may have a high ecological disruption because FE ranges of species that can tolerate inshore and offshore waters may be contracting and shifting further offshore, with some shifting outside or northward of the Maritimes Region, due to bottom temperatures on the Scotian Shelf and along the slope projected to increase (Saba et al. 2016). This is supported as ~75% and ~60% of FE immigrations into offshore waters were from the shelf in the mid-century and end-century respectively, and nearly all emigrating FEs had oceanic habitat zones and could move further offshore. These inshore species are then replaced with species presently existing inshore or new FEs that are more tolerant to warm water. Additionally, some warm-water species immigrated into regional offshore waters but did not introduce a new FE (e.g., Fringed flounder *Etropus crossotus*).

With warming becoming very high on the Shelf by the end of the century under a high-emissions scenario (Saba et al. 2016), ecological disruption in coastal waters was projected to become as impacted as offshore waters by the end-century under SSP5-8.5 (EDI: 0.13; Figure 7). Overall, the highest ecological disruption was projected for the end-century under the SSP5-8.5 scenario (EDI for the region, inshore, and offshore range: 0.10 – 0.16) but as the majority of change in FEs happened by the mid-century under SSP5-8.5 (Table 10), most of the projected ecological disruption will occur by mid-century (Table 11; Figure 7). To the best of my knowledge, this is the first study that assesses both coastal and offshore ‘ecological disruption’ over time and provides evidence that temperate offshore waters may experience higher ecological disruption than coastal communities by mid-century (Figure 7).

Generally, for inshore waters there was higher functional richness, less change in functional richness (Figure 6), and lower ecological disruption (Figure 7). This is reflected in a marine Arctic study where areas of high present day functional richness also had low functional dissimilarity by end-century (Alabia et al. 2020). Areas of particularly low functional change and ecological disruption were projected near the Fundian Channel and Browns Bank, and along the Northeastern shelf (Figure 6; Figure 7), suggesting that these areas are likely to see lower levels of ecological change from climate-driven shifts in species assemblages. As there is inflow of southern, warmer waters into the Bay of Fundy (Sutcliffe Jr. et al. 1976; Smith et al. 1978; Saba et al. 2016), this region receives high numbers of species immigrations which bring up to 26 new FEs to the Fundian Channel and Browns Bank; however, many immigrating species slot into existing FEs and hence simply add redundancy to those FEs rather than bringing new functioning entirely.

The continental slope adjacent to the Scotian Shelf had high functional richness and low ecological disruption despite a reduction in functional richness for all time-periods and scenarios (Figure 6; Figure 7). As these areas contain highly heterogeneous habitat supporting a variety of species including forage fish, predators, and rare/depleted species (Shackell and Frank 2003; Horsman and Shackell 2009), this habitat may be beneficial for sustaining existing FEs into the future, as few FEs immigrated. Such findings emphasize the importance of considering functional redundancy alongside functional richness to determine consequences for ecological functioning, much like assessing changes in species compositions in combination with species richness (Vinebrooke et al. 2004; Micheli and Halpern 2005).

Together with decreases in functional richness, the region was projected to have minor decreases in functional redundancy and increases in vulnerability across most times and scenarios relative to the present day (Table 9). Reduced functional redundancy occurred due to species emigrating from existing, redundant FEs in the present day. While ultimately functional richness decreased - resulting from all species emigrating from an FE – proportionally there was a larger number of remaining FEs vulnerable in the future relative to present day, thus increasing the functional vulnerability. Ultimately, there are fewer regionally vulnerable FEs in the future than in the present day, but with the reduction of functional richness overall, emigrating species that either extirpate an FE or make an FE vulnerable appear to be driving these shifts. These findings are consistent with the literature, which suggest disturbances such as climate change are projected to decrease functional richness (Buisson et al. 2013; Alabia et al. 2020), and, while functional vulnerability projections are limited, past extinction events have led to increases in megafauna functional vulnerability (Pimiento et al. 2017). The decrease in functional redundancy and increase in functional vulnerability is likely a result of the waters in the Maritimes Region expected to experience climate-induced warming almost 3x that of the global average (Saba et al. 2016), resulting in many of the resident FEs losing species and become more vulnerable to extinction. Interestingly, the strongest warming under high emissions and end-century (Saba et al. 2016) coincided with the lowest future functional vulnerability (fewest vulnerable FEs) across the region, inshore, and offshore. This outcome is because this time-period and scenario had the most vulnerable FEs becoming extirpated from the region, and hence is somewhat misleading on its own without considering declines in functional richness.

Additionally, some novel but vulnerable FEs immigrated to the region, possibly also influencing the regional functional vulnerability and redundancy. With ≤10 FE immigrations across all times and scenarios, ninety 90% of these FEs were functionally vulnerable. These immigrations may come from select species expanding their ranges into this region from more functionally diverse warmer waters (Stuart-Smith et al. 2013; Edie et al. 2018). While immigrating FEs contribute to ecological disruption, bringing new functions and hence a potential for critical disturbance to the ecosystem, they also moderately offset FE losses (4-10 immigrating FEs; 10-17 emigrating), reinforcing the ecological stability of the region with greater functional richness.

The general pattern among projected changes in FEs within the region suggested bottom-associated, deep water, and pelagic fish of small-mid body size were replaced with bottom-associated, deep water, pelagic, and reef-associated FEs of mid-large body size. The immigration of functionally unique bottom-associated species follows northward range shift patterns in the northern Atlantic (Fossheim et al. 2015), with the species in temperate FEs able to tolerate the incoming warm water conditions and being generalizable enough to feed on both benthic and pelagic food chains (Kortsch et al. 2015; Emblemsvåg et al. 2022). In addition, while most immigrating and emigrating FEs were fish, for the end-century under SSP5-8.5, the range of the Bryde’s whale was projected to extend into this region and two vulnerable FEs containing the Kemp ridley sea turtle and the Harp seal were lost and not replaced. The immigration of reef-associated FEs and the Bryde's whale is likely a result of poleward range expansions (Schlaff et al. 2014; Pinsky et al. 2020).

Implications of Ecological Disruption in the Maritimes Region

Two objectives of the Maritimes Region Network Plan include (1) protecting representative ecosystems and habitat types and (2) helping to maintain ecosystem structure, functioning, and resilience in the bioregion (DFO 2022a). The EDI provides a novel, ecosystem-based metric to evaluate whether these objectives can be fulfilled under climate change. By defining areas across a range of projected disruption, a "portfolio" of sites that could be protected based on this range of future disruption was created, as is recommended for marine conservation in the global ocean (Tittensor et al. 2019). While the region as a whole had an EDI ≤0.10, hotspots of ecological disruption were visible (Figure 7). Indeed, across all times and scenarios, individual grid cells in the Maritimes Region had a large range of EDI (0.10-0.42), indicating that there were hotspots that experienced dramatic shifts in functioning primarily due to regionally resident FEs shifting distributions. While other approaches have functional beta-diversity at similar spatial scales (Alabia et al. 2020; Hu et al. 2022), none appear to have assessed one measure across the whole study region.

Shifts in functional entities and hence ecosystem functioning, regardless of whether they arise from climate-immigrant FEs or shifts in distributions or emigrations of resident FEs, are likely to cause greater disruption to the ecosystem than species with similar functional roles immigrating, emigrating, or moving. Following the Canadian MPA network pursuit of protecting "naturally functioning" ecosystems (Government of

Canada 2011), the EDI for existing (0.10-0.35) and proposed (0.11-0.34) network sites predominately represented the lower half of the regional range in EDI (Figure 8). Thus, present sites do not reflect the range of forecasted change in ecosystem function in the region; this may be appropriate for protecting naturally functioning ecosystems, but does not fit within a paradigm of a protected seascape bracketing a range of future change (Tittensor et al., 2019). Additionally, while existing and proposed network sites provide a relatively good representation of the region's functional vulnerability (Figure B1), they are skewed towards protecting ecosystems with higher functional redundancy (Figure B2; Tittensor et al. 2019). In fact, the broadest reflection of regional EDI from all protected seascape sites (existing and proposed) was at end-century under SSP5-8.5 (region: 0.16-0.42; designated: 0.12-0.35; proposed: 0.17-0.33; Figure 8), further illustrating how with time and a higher emission scenario, the region will experience a more homogenous disruption across all its waters. These results also highlight the utility of the EDI for projecting long-term ecological representation, an important measure for protecting, maintaining, and restoring Canada's ecosystem integrity (Government of Canada 2011), especially in response to climate change.

Policy Recommendations

Integrating the projected impacts of climate change into spatial marine conservation strategies is needed to ensure the resiliency and robustness of present and future marine networks (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022). However, climate change-induced impacts vary in magnitudes. Climate refugia protect ecosystems experiencing low levels of change, contributing to ecosystem resilience and the ability to rebound following disturbances (Tittensor et al. 2019; Wilson et al. 2020), yet overlook sites that may be most in need of protection. Considering sites of high (or indeed low, or any) ecological disruption represents a new frontier for marine conservation. The present struggle to incorporate climate change impacts into conservation networks arises from several challenges, including limited capacity and resources, and a lack of data layers of future change to integrate (Tittensor et al. 2019). Consequently, at present, network planning and design does not consider how changes in dissimilarity of assemblages may affect ecological functioning, goods, and services. There is thus a need to develop new strategies for sites facing ecological disruption due to climate change that may be near some critical threshold of disruption (Dakos et al. 2019; Tittensor et al. 2019). Additionally, marine conservation networks aim to be representative (Government of Canada 2011; DFO 2022a), and thus, MPA guidelines should reconsider protecting only "naturally functioning" ecosystems to include sites with multiple future trajectories to ensure representation remains into the future (Tittensor et al. 2019). Uncertain futures imply a need to develop a "portfolio" of sites requiring protection, with that portfolio not just representative of present-day and future biodiversity, but also of present-day and future functioning. Approaches and indices such as those developed in this Chapter are needed to help inform the latter of these.

Protecting climate refugia is part of the portfolio; integrating areas of relatively low ecological change with the aim of giving species more ability and time to adapt to the changing conditions (McLeod et al. 2009; Wilson et al. 2020). To date, existing network sites predominately represent areas of low ecological disruption, with the Eastern Canyons Marine Refuge (ECMR), Corsair/Georges Canyons Conservation Area

(CGCCA), and Western Emerald Bank Conservation Area (WEBCA) projected to experience the lowest EDI into all future times and scenarios (EDI: 0.10-0.12). The CGCCA also had the fewest FEs projected to immigrate including only one climate-immigrant FE by the end-century and contained the largest proportion of FEs remaining resident (>96%) across all future times and scenarios (Table 10; Figure B4). This finding suggests that functional climate refugia may be over-represented in the network as it stands.

Another climate refugia approach could be to protect sites with the highest functional richness and high functional redundancy/ low functional vulnerability into the future, which may provide a natural buffer to climate-disturbances for functional roles through high diversity and redundancy, respectively. The WEBCA has the highest functional richness across all existing network sites, in addition to having one of the highest functional redundancies alongside the ECMR (Table 9; Figure 9). The ECMR and WEBCA also have some of the lowest functional vulnerability by the end-century. As these sites (WEBCA, ECMR, CGCCA) consistently appear as forms of climate refugia for FEs in various futures outcomes, it suggests that they are core sites to act as functional climate refugia within the region, and their conservation objectives could be updated to indicate their importance for ecosystem resilience and robustness to climate-induced disturbance. My study was based on the entire community (at least, as many species as I could find traits for), meaning that these measures reflect changes in the whole ecosystem. Increasing protection to include the entire water column in these three Marine Refuges, which provide bottom protection only (DFO 2021b), could help ensure these sites truly act as refugia for the FEs they contain.

Hotspots of ecological disruption identify where climate change and shifting species may have disproportionate impacts on ecological functioning (Figure 7). In the Maritime Conservation Network, the Jordan Basin Conservation Area (JBCA) generally had the highest functional disruption (range: 0.21-0.35; Figure 1; Table 11), with the Machias Seal Island Migratory Bird Sanctuary (MSIMBS) slightly higher in end-century under SSP1-2.6 (range: 0.22-0.27). The JBCA also had the most immigrating FEs of the existing network sites across all times and scenarios (Table 10). Given both these sites are located on the western part of the Scotian Shelf near the Fundian Channel where climate-immigrant FEs are likely to be shifting into the region, it is surprising that just 0-15% of the JBCA immigrations were novel to the region, suggesting resident FEs may be moving into this site as a refuge. However, while the JBCA may be an important site for resident FEs in the future, every FE contributes uniquely to ecosystem functioning and thus are expected to equally perturb an ecosystem on arrival irrespective of whether they are regionally resident. Both the JBCA and MSIMBS aim to protect a single general taxon (i.e., cold water corals and seabirds, respectively; (DFO 2021b; ECCC 2023b) and thus could become management priorities for monitoring for incoming species (in the JBCA) and changes in species composition (in the MSIMBS).

Areas with low functional richness may also be more vulnerable to ecological disruption as the loss or gain of a single FE may proportionally have a larger impact on ecosystem functioning; this outcome was projected in regional offshore waters with low functional richness (Figure 6) and high ecological disruption (Figure 7). Therefore, the low functional richness in the JLMNWA Park and Boot Island National Wildlife Area relative to the region and other network sites may indicate a vulnerability to ecological change. These two sites were also projected to have the fewest FE emigrations of present-day species in most future times and scenarios (Table 10), with the former having the highest functional vulnerability in all future times and scenarios (Table 9). While high diversity is generally preferred within network sites (Government of Canada 2011), it remains unknown how shifts in the distributions of individual FEs will specifically affect ecosystem functioning. As these National Wildlife Areas both primarily focus on the protection of birds and their habitat (ECCC 2023c), biodiversity assessments across marine taxa should be completed to determine present-day species assemblages and functioning, relative to these projections. Doing so would establish a baseline of functioning prior to the loss/gain of FEs in the future to aid ongoing monitoring of these potentially fragile ecosystems.

With the Maritime Conservation Network Plan expected to be complete for 2024 (DFO 2022a), assessments of how climate change may impact future protected areas can also be used to inform marine conservation planning (Bryndum-Buchholz et al. 2022). Generally, proposed network sites also primarily protect areas of low ecological disruption; however, select sites provide greater representation across the range of regional EDI values (Figure 8). The Cold Seeps proposed site was projected to have the highest ecological disruption of all existing and proposed sites (EDI: 0.30-0.34; Table B5) across times and scenarios. With ~1/3 of its present-day functional composition changing by mid-century, the functional diversity and plausibly functioning of this ecosystem will be permanently altered. Were this site to be pushed over its critical threshold of disruption (Dakos et al. 2019), beyond which it can rebound, it may be a climate-driven regime shift, whereby its reduced stability would allow for increased invasibility and potentially lead to ecosystem collapse (Tilman 1999). Thus, I recommend the Cold Seeps, located along the Shelf slope, be added to the portfolio of sites in need of protection as a top priority - to reduce additional anthropogenic stressors in this region through strong regulation (i.e., ideally designated as an MPA) by mid-century. Its high susceptibility to ecological disruption is likely a result of also having the lowest functional richness (Figure B5) and proportionally the fewest resident FEs remaining in mid-century under SSP5-8.5 (most emigrations during this time and scenario) and end-century under SSP1-2.6 (Table B4). With high ecological disruption projected in the next 20 years under both scenarios (Table 11), development and growth of the Maritime Conservation Network using pre-defined proposed sites should reflect this urgency.

As the current framework for marine conservation in Canada focuses on protecting areas of comparatively higher diversity (Government of Canada 2011), proposed network sites with high functional richness and redundancy could supplement the climate refugia in the Maritimes Region to build additional resilience within the network. For example, the Fundian Channel-Browns Bank AOI could be designated as a climate refuge as it has the highest functional richness of all protected seascape sites in present day and the future (Table B3; Figure B5) and comparatively low ecological disruption (0.11-0.19), with >85% of its protected FEs remaining resident in all future times and scenarios (Table B4). Additionally, this site was projected to have the highest functional redundancy of all protected seascape sites in mid-century under SSP1-2.6 with a high functional over-redundancy, making it a top contender for protection going forward (Table B3). The Misaine Bank and Laurentian Channel proposed site could also play a role in mitigating climate-induced impacts as it had the lowest functional vulnerability and one of the lowest EDI of all protected seascape sites across most future times and scenarios (Table B5) and thus, may have a reduced likelihood of FEs becoming extirpated. Given the protection of "naturally functioning" ecosystems is a guiding principle for MPA development (Government of Canada 2011), these sites may best retain present-day ecosystem functioning into the future.

In terms of site-specific conservation objectives in the Maritime Network Plan (DFO 2022a), specific functional roles could also be prioritized for protection. I suggest the management plan for the Cold Seeps could therefore integrate a focus on the primarily bottom-associated and deep water FEs. For future sites designated on the Scotian Shelf, I recommend the prioritization of protection for the range of reef- and bottom-associated FEs immigrating from outside the region and from offshore waters, as areas experiencing an influx of these FEs may suffer proportionally more disturbance in functioning relative to areas with FEs that presently exist within the region.

Mitigation Benefits

Climate change has a range of impacts on the ocean (Poloczanska et al. 2013; IPCC 2022), with large community shifts anticipated by mid- and end-century (Le Marchand et al. 2020; Chapter 2). Yet, mitigation of climate change impacts is both possible and desirable through the reduction of carbon emissions, bringing the future towards an SSP1-2.6 scenario (Duarte et al. 2020; IPCC 2022). The projected impacts of climate change in the Maritimes Region suggest that an SSP5-8.5 future will have higher ecological disruption than SSP1-2.6 into mid- and end-century (Figure 7), with the majority of protected seascape sites having higher functional richness (Table 9; Table

B3), a larger proportion of their encompassed FEs remaining residents (Table 10; Table B4), and lower ecological disruption under SSP1-2.6 (Table 11; Table B5). Other temperate and Arctic regions have similarly found greater climate change-induced impacts on ecosystem functioning under a high relative to low carbon emission scenario (Buisson et al. 2013; Alabia et al. 2020). However, most functional change in this study occurred from present day to mid-century for the region and for protected seascape sites, with relatively less change from mid- to end-century under both scenarios (Table 10; Table B4). As larger shifts in species distributions are projected to occur from present day to mid-century, (Le Marchand et al. 2020; Chapter 2), reducing carbon emissions imminently would have substantial benefits for limiting species range shifts and changes to present day ecosystem functioning. Additionally, ecological disruption from mid- to end-century is more extreme in the SSP5-8.5 scenario than the SSP1-2.6 scenario for the region, and for each protected seascape site (SSP1-2.6 EDI <0.10; SSP5-8.5 EDI <0.20; Table 11; Table B5), indicating a reduction of carbon emissions, even past mid-century, can greatly reduce future climate change impacts (Figure 7). While the tipping point of these ecosystems is unknown (Dakos et al. 2019), an EDI represents a metric of their risk level. With the Northwest Atlantic having experienced a complete trophic level restructuring after the cod collapse and subsequent ecosystem regime shift, having drastic ecological and economic consequences (Frank et al. 2005), this outcome could surely be mitigated in the Maritimes Region through reduced emission and the associated lower ecological disruption.

Caveats

By using global species distribution models then subsequently filtering for present and future regional species and functional entities, this study may overlook small-scale or high-resolution environmental trends influencing local species. However, using global models and filtering regionally avoids truncating each species' niche, allowing for better future niche projections under climate change (Guisan et al. 2017). Additionally, due to the inherent limitations in trait databases, <50% of the species projected to be present now and into each future time and scenario were able to be assessed in this Chapter (Table B2). As many marine species are poorly studied (Mora et al. 2011), trait imputations are sometimes used to fill in missing trait data, yet can also be problematic (e.g., impute specific traits only, Thorson et al. 2023; maximum of 25% of data should be imputed, Ladds et al. 2018). By not imputing traits in this study, the trait data were more limited, but the functional trait accuracy was only limited by human data recording error (Palomares and Pauly 2022; Froese and Pauly 2023). Furthermore, the range of taxa integrated into this study was broader than most others (Villéger et al. 2013; Mouillot et al. 2014; Hu et al. 2022). Similarly, this study did not weigh functional entities by species abundances due to a lack of biomass or abundance information for the vast majority of species, as well as for all marine taxa projected to arrive the region. As each functional group may contribute to ecosystem functioning in proportion to their abundance within the ecosystem (Villéger et al. 2008), a change in a functional group with a high biomass of species may have a substantially larger impact on ecosystem functioning than a group with low biomass (Dukes and Mooney 2004; Villéger et al. 2008). The next step would be to link the spatial patterns found for the Maritime Region with existing biomass projections for Canada's Exclusive Economic Zone (EEZ) using the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP; Tittensor et al. 2018; Bryndum-Buchholz et al. 2020) to determine how the trends compare, especially as temperate regions are expected to undergo biomass loss by the 2090s under both SSP1-2.6 and SSP5-8.5 . Nonetheless, this is an unavoidable limitation, is unlikely to be resolved in the future due to a lack of abundance projections for many species, and is a common approach when studying functional diversity (Mouillot et al. 2014; Pimiento et al. 2020; Alabia et al. 2020).

My analyses assessed fish, mammals, reptiles, and lobsters. Including additional taxa may result in differences in functional diversity patterns. However, as these are relatively well-studied taxa, including others may result in a greater proportion of species without traits as more deep-sea and understudied species would be included, thus possibly increasing the need for imputations and resulting in low coverage for individual taxa. As well, most invertebrates (except lobsters) were not in this study; given regional invertebrate species richness is less but comparable to fish species richness, as was sampled from bottom trawls (Ward-Paige and Bundy 2016; Bundy et al. 2017), their inclusion could drive different richness patterns. Ultimately, as with many biological studies, these results are biased towards well-known species. However, the majority of other functional diversity studies only consider a single taxon (Villéger et al. 2013; Mouillot et al. 2014; Ladds et al. 2018; Salerno et al. 2021; Hu et al. 2022) and the range of species included here is reasonably broad in comparison.

Finally, the methodology that I developed does not use a PCA/PCoA for the reasons given in the Introduction. While my method enables greater consistency across studies, it does not account for potential correlations among trait variables. It is important to note that while traits may be correlated, they still contain unique information and are not correlated at extremely high levels (>0.9). Furthermore, traits that have higher levels of correlation in this region may have lower levels of correlation elsewhere; furthermore, correlations are likely to decrease when other taxa are included. As well, species interactions are not included in SDMs, which are instead dependent on environmental variables (Pearson and Dawson 2003). As a result, the EDI may differ from *in situ* ecosystems that fundamentally contain synergistic and antagonistic effects beyond what these models considered. Yet, the creation of this new standardized, expandable, and comparable index that can be broadly applied warrants these compromises, and I acknowledge these limitations.

Conclusion

Functional diversity, and hence ecological functioning, in the Maritimes Region will be impacted as species distributions shift from climate change (Chapter 2), with more profound changes under high carbon emission scenarios. Contrasting patterns within the Maritimes Region indicate that coastal and offshore waters will have drastically different futures, with shelf waters projected to have relatively low ecological disruption and offshore waters relatively high disruption. Consequently, conservation objectives for both existing and proposed protected seascape sites should consider integrating future changes in ecological functioning as well as species composition (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022). My study aims to assist in this process by projecting the relative magnitude of site-specific ecological change they will undergo. It also identifies the relative ecological change likely to be experienced by proposed network sites. With the mix of increased temperate and sub-tropical FEs in this region, arising from primarily bottom-associated, deep water, and pelagic fish of small-mid body size being replaced with generalist demersal/bathydemersal FEs or reef-associated FEs with mid-large body size, sites projected to experience the greatest functional change could also monitor for changes in these specific FEs and the ecological consequences that their arrival will engender. The Maritime Network Plan aims to have site-specific, climate-smart objectives by 2024 (DFO 2022a), and I recommend that these include how to maintain ecological resilience as well as account for individual species changes.

Linking changes in species ranges to their ecological roles through trait compositions is necessary for understanding ecosystem functioning (Reiss et al. 2009) yet in general studies hitherto are not comparable. My approach can universally incorporate all taxa and spatial scales into one functional diversity analysis. In addition to categorizing every possible FE (i.e., combination of traits) across all taxa, it also provides a direct understanding of which FEs are changing into the future regardless of their position within multidimensional space, with the assumption that any change in FE can disrupt how an ecosystem presently functions. With a major limitation for functional diversity analyses being inconsistent trait use across studies that inhibits comparisons across regions (Villéger et al. 2008), this functional diversity approach can be used on both regional and global scales to explore a comparable functional trait space. Projected changes in ecosystem functioning provide a foundation for understanding the consequences of species range shifts resulting from climate change, and can identify projected hotspots of low and high ecological disruption, with the associated management consequences that these entail. The integration of climate change consequences into spatial marine conservation needs to include both ecological and species-levels impacts to ensure truly climate-responsive and representative management at regional and global scales.

Chapter 4: Conclusion

Implications and Conservation Priorities

My thesis illustrates the importance of assessing metrics of changes in both functional diversity and taxonomic diversity to understand multiple facets of climate change impacts on ecosystems and protected seascapes. While other studies primarily focus on how climate change affects taxonomic richness and diversity, and/or functional metrics of fish communities (Mouillot et al. 2014; Villéger et al. 2017; Hu et al. 2022), this study is the first, to my knowledge, that assesses climate-induced impacts across entire taxa (rather than parts of taxa, i.e., megafauna, Pimiento et al. 2017) and across metrics of taxonomic dissimilarity, functional diversity, and ecosystem disruption. I additionally apply diversity metrics consistently across taxa and spatial-scales to create a universal measure of projected ecological disruption - the first of its kind. In doing so, I determined that future scenarios with high carbon emissions were generally associated with both high taxonomic dissimilarity (Table 4; Figure 4) and ecological disruption (Table 11; Figure 7), indicating profound consequences for ecosystem functioning in the Maritimes Region off Canada's east coast. This finding contributes to the evidence that carbon emission mitigation is imperative to limit climate change impacts on marine ecosystems, and to the less well-explored knowledge base of climate impacts on ecosystem functioning (Duarte et al. 2020; IPCC 2022).

Across the Maritimes Region, 725 present-day species were filtered down to 310 species with traits, then categorized into 136 unique functional entities (FEs), each with unique combinations of traits. The highest present-day species and functional richness were found along the Scotian Shelf slope, indicating the importance of protecting shelf and canyon habitat to support a wide variety of functionally and taxonomically diverse species (Cox et al. 2018; Hodge et al. 2022). Beyond this, however, trends in taxonomic relative to functional diversity varied, with the inshore projected to have lower taxonomic diversity (Figure 3) but higher functional diversity (Figure 6) relative to offshore waters, separated by the Scotian Shelf (Figure 2). In other words, there were fewer species across more FEs in inshore waters while offshore waters had more species within few FEs. Such variation in these diversity metrics could indicate that inshore waters favour a wider variety of functional roles rather than many competitors using the same resources (Edie et al. 2018). In offshore waters, speculatively, it could be vice versa - a lower variety but greater abundance and stability of resources to support higher taxonomic diversity but lower functional diversity. Alternatively, species in inshore FEs may have "hitchhiked on refugia", whereby FEs with low functional redundancy possibly exist by surviving in areas more resistant to environmental change (Edie et al. 2018). This latter explanation may also be true in the Maritimes Region as two-thirds of inshore FEs were also functionally vulnerable in present-day (Table 9). Ultimately, the inclusion of a wider variety of taxa may alter these differing species and functional richness trends.

Both taxonomic and functional diversity decreased into all future time periods and scenarios (Table 3; Table 9). Despite future species richness being highest in end-century under SSP5-8.5, this time-period and scenario had the most species and FE immigrations and consequently the highest taxonomic dissimilarity and ecological disruption (Figure 4; Figure 7). In contrast, end-century under SSP1-2.6 had the lowest taxonomic dissimilarity and ecological disruption, having the fewest species and FEs to emigrate (Table 4; Table 10; Table 11). In both scenarios, most of the ecological change occurred by mid-century

(Table 4; Table 10), with climate change-induced impacts exacerbated under SSP5-8.5 and alleviated under SSP1-2.6 with time. In the long-term under SSP1-2.6, some species and FEs that had emigrated by mid-century were projected to return to the region by end-century; under SSP5-8.5, fewer species and no FEs were projected to return by end-century. Collectively, these results indicate serious urgency behind carbon emissions reduction if the marine conservation goal is to limit ecological change or rebuild marine life (Duarte et al. 2020). It would also be beneficial for protected seascape sites, particularly prior to mid-century, to limit other anthropogenic stressors on present-day species to the greatest extent possible, as they experience some of their largest ecological change in the next 25 years (Tittensor et al. 2019).

My thesis also provides a perspective on the offshore waters within the Maritimes Region, an area beyond the Scotian Shelf that is often missed as most data comes from bottom trawls along the Scotian Shelf or Gulf of Maine (Shackell and Frank 2003; Brown et al. 2005; Clark and Branton 2007; Sherman 2010; Dornelas et al. 2018). For all future times and scenarios, taxonomic diversity was positively associated with functional diversity, and followed known gradients of higher diversity (taxonomic and functional) at shallower depths (Costello and Chaudhary 2017) and warmer temperatures (Tittensor et al. 2010; Stuart-Smith et al. 2013) relative to deeper depths and colder temperatures. In combination with lower taxonomic and functional diversity, the offshore also had the most immigrating and emigrating FEs and consequently the highest ecosystem disruption (up to 0.42 across the region; Table 11; Figure 7). This study is one of few to find more ecological change occurring in offshore relative to inshore waters, possibly resulting from more extreme temperate and sub-tropical fish immigrations to the community at depths of

350-1000 m relative to inshore waters (Emblemsvåg et al. 2022). Indeed, the region followed a tropicalization trend with primarily bottom-associated, deep water, and pelagic fish of small-mid body size being replaced with less diverse demersal/bathydemersal FEs with mid-large body size.

With climate change projected to alter future taxonomic and functional diversity in the Maritimes Region, Canada's framework for MPAs (Government of Canada 2011) and marine conservation targets (DFO 2021a) could be enhanced through integrating considerations of anticipated future ecological shifts. Given the current goals for marine conservation in Canada are to conserve biodiversity, ecosystem function, and habitats in the long-term for their continued provision of ecosystem services (Government of Canada 2011), understanding how long-term marine ecosystem protection can be most efficiently provided is valuable. My thesis identified a 'portfolio' of protected seascape sites that best protected both present and future ecosystems within the Maritimes Region, identified from existing and proposed network sites. Of the existing network sites, the Eastern Canyons Marine Refuge (ECMR), Corsair/Georges Canyons Conservation Area (CGCCA), and Western Emerald Bank Conservation Area (WEBCA) had the highest taxonomic and functional diversity, with high proportions of present-day species and FEs remaining into the future in these sites (Table 3-4; Table 9-10; Table A3; Figure A2). These three sites are the largest existing network sites and are located offshore (ECMR, WEBCA) and central Scotian Shelf (CGCCA; Figure 1). To increase protection of taxonomic and functional diversity, the Fundian Channel-Browns Bank AOI, the second largest site of all existing and proposed sites, would be beneficial to designate. Despite this AOI being ~1/2 the size of the ECMR, it retained the highest functional diversity of all sites across all future times and scenarios and had the highest taxonomic diversity in 2099 (both scenarios; Table A6). Ultimately, the largest four protected seascape sites provide the most benefit for present and future diversity, generally protecting large proportions of species ranges (Table S8). While none of these sites are large relative to those designated on a global scale (Davies et al. 2017), my findings support the need for large protected areas that conserve more taxonomically and functionally diverse species in the present and future.

Disruptions to present-day ecosystems are inevitable (Figure 7; Hoegh-Guldberg and Bruno 2010). Thus, marine conservation networks should protect areas with a range of climate trajectories rather than only climate refugia, as sites experiencing the most change may have a greater need for a reduction in additional pressures (Tittensor et al. 2019). Of existing protected seascape sites, the Emerald Basin Sponge Conservation Area (EBSCA) was projected to experience the largest shift in taxonomic composition into all future times and scenarios (41-48% of assemblage differs; Figure A5.1). However, across all existing sites, the highest ecological disruption occurred in the Jordan Basin Conservation Area (0.22-0.35) and the Machias Seal Island Migratory Bird Sanctuary (end-century, SSP1-2.6: 0.22; Table 11). Yet of all protected seascape sites, including proposed sites, the offshore Cold Seeps had the highest ecological disruption in most times and scenarios (Table B5). Given the sites with the highest taxonomic dissimilarity and ecosystem disruption differed, the species shifting within the EBSCA must have had more similar functioning whereas species changing in the Jordan Basin Conservation Area and Cold Seeps were more functionally distinct. The implication is that, while species diversity and taxonomic compositional shifts are important, there may be a larger ecosystem-wide impact from the replacement of present-day functional roles with functional different species, including those novel to the region. It also identifies the fact that changes in taxonomic diversity do not necessarily map to those in functioning. My study is also the first to assume that, regardless of their position in trait space, every new functional entity bringing a new ecosystem role will bring the same measure of ecosystem disruption. Other studies assume that only those FGs or FEs at the fringes of trait space are important in this aspect. As has been suggested for species (Petchey and Gaston 2002), providing the same weight of disruption to every FE is not because all FEs are similar, but rather because each FE brings a similarly different function.

Final Thoughts

Climate change is altering our marine ecosystems, and I find that its continued acceleration will lead to more drastic shifts in ecosystem functioning (Figure 7). While carbon emissions mitigation can reduce these projected impacts (Figure 4; Figure 7), adapting the protected seascape design, objectives and targets, management, monitoring, and overall framework to respond and adapt to the various climate change trajectories is a necessary first step for the Maritimes Region. Existing protected seascape sites will not only be acting as climate refuges into the future, but also as hotspots for ecosystem disruption and taxonomic composition shifts (Table 11; Figure A5). Yet, more protected seascape sites are needed, in particular those that can increase regional representativity by protecting regionally resident species and FEs, and the incoming, novel species and FEs that will most perturb the ecosystems. Generally, protected seascape sites located in the southwest in the region near the Fundian Channel are projected to have high species and functional diversity in the present and future. Those located in offshore waters (i.e., beyond the Scotian Shelf; Figure 2) will have the most ecosystem disruption and protect regionally resident species as they relocate from inshore to offshore. Those located inshore will gain more regionally novel species and functional entities. Ultimately, depending on the goal of the regional conservation network, designation could be prioritized for proposed sites based on these broad regional trends.

Creating understandable and interpretable projections of climate change impacts on marine ecosystems is important not only for understanding the extent of its impact, but also for identifying and implementing proactive and climate-adaptive responses necessary for a dynamic future (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022). Yet, biodiversity and ecosystem functioning research has rarely been integrated with marine conservation tools and decision-making (Naeem et al. 2012). This thesis is an example of how functioning, via the ecological disruption index, can be assessed and applied in a meaningful and relevant manner for climate change integration into regional marine conservation. With its metrics being universally applicable across all taxa and comparable across spatial scales, its relevance goes beyond Canada’s Maritimes Region. As climate change works on a global scale and has no boundaries, ensuring its integration into marine conservation can be beneficial both long-term and worldwide.

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Appendix A – Chapter 2 Supplementary Tables and Figures

Table A1. Taxonomic class and number of species with ranges assessed and those with presence data used within the AquaX species distribution model (SDM). Species removed from analyses but had a SDM include three subspecies of reptiles (Hawksbill sea turtle Atlantic and Pacific subspecies, respectively, which were projected with same range at species-level: *Eretmochelys imbricata imbricata, Eretmochelys imbricata bissa*, Pacific loggerhead sea turtle subspecies projected with same range at species-level: *Caretta caretta gigas*), and one subspecies of lobster (*Stereomastis sculpta sculpta*).

Taxonomic Group	Class	Number Orders	Number of species	Number of species with SDM	Percentage of species with SDMs (%)
Fish	Actinopterygii	38	16,714	10,266	61.4
	Cephalaspidomorphi	1	10	7	70.0
	Elasmobranchii	10	1,194	953	79.8
	Holocephali	1	56	43	76.8
	Myxini	1	82	47	57.3
	Sarcopterygii	1	2	1	50.0
Mammals	Mammalia	3	133	98	72.9
Reptile	Reptilia	4	99	85	85.9
Lobster	Malacostraca	1	272	217	79.8
Total	**9**	**60**	**18,562**	**11,673**	**62.9**

Table A2. Robustness test for species richness relative to each taxonomic group for the Fisheries and Oceans Canada Maritimes Region. The climate range expansion was increased for benthic species (from 80 to 234 km by mid-century; 180 to 342 km by end-century), and pelagic species (from 120 to 526.5 km by mid-century; 270 to 769.5 km by end-century), following 58.5 km/decade if benthic and 85.5 km/decade if pelagic (Poloczanska et al. 2013).

Site	**Metric**	**Taxa/ Func. Change**	**Present Day**	**Mid-century**		**End-century**	
				SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
Maritimes Region	Richness	Total	725	610	614	652	666
		Fish	699	584	588	626	639
		Mammals	19	20	20	20	21
		Reptiles	5	4	4	4	4
		Lobsters	2	2	2	2	2
	Change in species	Same		562	559	584	562
		Immigrating		48	55	68	104
		Emigrating		163	166	141	163
		Change in species richness		-115	-111	-73	-59
		Dissimiliarity (%)		15.7	16.4	15.0	19.0

Table A3. Species richness relative to each taxonomic group for the region and each existing network site presently in the Maritime Conservation Network plan within the Maritimes Region off Canada's east coast.

Site	Type	Species	Present Day	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Maritimes Region	Region	Total	725	607	606	645	655
		Fish	699	581	582	619	630
		Mammals	19	20	18	20	19
		Reptiles	5	4	4	4	4
		Lobsters	2	2	2	2	2
Boot Island National Wildlife Area	MPA	Total	157	184	187	170	205
		Fish	153	181	184	166	201
		Mammals	3	2	2	3	2
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Corsair/Georges Canyons Conservation Area	OECM	Total	502	375	376	415	396
		Fish	479	358	357	395	376
		Mammals	16	12	13	15	14
		Reptiles	5	3	4	3	4
		Lobsters	2	2	2	2	2
Eastern Canyons	OECM	Total	546	425	426	467	465
		Fish	523	406	409	449	447
		Mammals	17	14	12	13	12
		Reptiles	4	3	3	3	4
		Lobsters	2	2	2	2	2
Emerald Basin Sponge Conservation Area	OECM	Total	184	302	290	285	312
		Fish	173	297	282	278	302
		Mammals	10	3	6	6	8
		Reptiles	0	1	1	0	1
		Lobsters	1	1	1	1	1
John Lusby Marsh National Wildlife Area	MPA	Total	152	151	163	141	193
		Fish	149	148	161	138	188
		Mammals	2	2	1	2	3
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Jordan Basin Conservation Area	OECM	Total	254	337	335	351	355
		Fish	239	331	327	345	346
		Mammals	12	5	6	5	7

Site	Type	Species	Present Day	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
		Reptiles	2	0	1	0	1
		Lobsters	1	1	1	1	1
Kejimkujik Seaside National Park and Historic Site	MPA	Total	259	375	368	356	388
		Fish	246	369	362	349	379
		Mammals	11	5	5	6	7
		Reptiles	1	0	0	0	1
		Lobsters	1	1	1	1	1
Machias Seal Island Migratory Bird Sanctuary	MPA	Total	246	312	295	318	351
		Fish	235	306	290	313	343
		Mammals	10	5	4	4	6
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Musquash Estuary	MPA	Total	243	203	207	307	331
		Fish	232	196	200	300	325
		Mammals	10	6	6	6	4
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Northeast Channel Coral Conservation Area	OECM	Total	466	356	355	361	355
		Fish	450	346	346	350	342
		Mammals	11	8	7	6	9
		Reptiles	3	0	0	3	2
		Lobsters	2	2	2	2	2
Sambro Bank Sponge Conservation Area	OECM	Total	220	342	338	332	353
		Fish	208	335	331	321	342
		Mammals	10	5	5	9	9
		Reptiles	0	1	1	1	1
		Lobsters	2	1	1	1	1
St. Anns Bank	MPA	Total	309	309	319	317	350
		Fish	296	297	308	305	340
		Mammals	11	10	9	10	8
		Reptiles	0	0	0	0	0
		Lobsters	2	2	2	2	2
The Gully	MPA	Total	469	348	350	409	410
		Fish	449	335	339	397	396
		Mammals	14	10	8	8	11
		Reptiles	4	1	1	2	1

Site	Type	Species	Present Day	Mid-century SSP1-2.6	Mid-century SSP5-8.5	End-century SSP1-2.6	End-century SSP5-8.5
		Lobsters	2	2	2	2	2
Western Emerald Bank Conservation Area	OECM	Total	506	421	414	429	425
		Fish	485	406	403	411	411
		Mammals	15	11	8	13	11
		Reptiles	4	2	1	3	1
		Lobsters	2	2	2	2	2

Table A4. Change in species in the Fisheries and Oceans Canada Maritimes Region for each taxonomic group from mid-and end-century to present day and end-century relative to mid-century.

Taxa	Taxonomic Change	Present - Mid-century		Present - End-century		Mid-century – End-century	
		SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5-8.5
Fish	Same	537	535	559	539	576	544
	Proportion same as initial community (%)	92.4	91.9	90.3	85.6	93.1	86.3
	Immigrating	44	47	60	91	43	86
	Proportion of future population that immigrated (%)	7.6	8.1	9.7	14.4	6.9	13.7
	Emigrating	162	164	140	160	5	38
	Proportion of initial community that emigrated (%)	23.2	23.5	20.0	22.9	1.0	6.5
	Change in species richness	-118	-117	-80	-69	38	48
	Dissimilarity (%)	16.1	16.5	15.2	18.9	4.0	10.2
Mammals	Same	19	17	19	17	20	16
	Proportion same as initial community (%)	95.0	94.4	95.0	89.5	100	84.2
	Immigrating	1	1	1	2	0	3
	Proportion of future population that immigrated (%)	5.0	5.6	5.0	10.5	0	15.8
	Emigrating	0	2	0	2	0	2
	Proportion of initial community that emigrated (%)	0	10.5	0	10.5	0	11.1
	Change in species richness	1	-1	1	0	0	1
	Dissimilarity (%)	2.6	8.1	2.6	10.5	0	13.5
Reptiles	Same	4	4	4	4	4	4
	Proportion same as initial community (%)	100	100	100	100	100	100

Taxa	Taxonomic Change	Present - Mid-century		Present - End-century		Mid-century – End-century	
		SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5 -8.5	SSP1 -2.6	SSP5-8.5
	Immigrating	0	0	0	0	0	0
	Proportion of future population that immigrated (%)	0	0	0	0	0	0
	Emigrating	1	1	1	1	0	0
	Proportion of initial community that emigrated (%)	20.0	20.0	20.0	20.0	0	0
	Change in species richness	-1	-1	-1	-1	0	0
	Dissimilarity (%)	11.1	11.1	11.1	11.1	0	0
Lobster	Same	2	2	2	2	2	2
	Proportion same as initial community (%)	100	100	100	100	100	100
	Immigrating	0	0	0	0	0	0
	Proportion of future population that immigrated (%)	0	0	0	0	0	0
	Emigrating	0	0	0	0	0	0
	Proportion of initial community that emigrated (%)	0	0	0	0	0	0
	Change in species richness	0	0	0	0	0	0
	Dissimilarity (%)	0	0	0	0	0	0

Table A5. Mammal and reptile species projected to immigrate (imm.) and emigrate (em.) into the Maritime Conservation Network plan within the Maritimes Region off Canada's east coast across mid-century and end-century under SSP1-2.6 and SSP5-8.5.

Species	**Shift**	**Present – Mid-century**		**Present – End-century**		**Mid-century – End-century**	
		SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**	**SSP 1-2.6**	**SSP5 -8.5**
Mammals	Imm.	False killer whale (*Pseudorca crassidens*)	False killer whale	False killer whale	False killer whale Eden's whale (*Balaenoptera edeni*)	NA	Atlantic spotted dolphin Gervais' beaked whale (*Mesoplodon europaeus*) Eden's whale
	Em.	NA	Atlantic spotted dolphin (*Stenella frontalis*) Gervais' beaked whale	NA	Harp seal (*Pagophilus groenlandicus*) True's beaked whale (*Mesoplodon mirus*)	NA	Harp seal True's beaked whale
Reptiles	Imm.	NA	NA	NA	NA	NA	NA
	Em.	Kemp's ridley sea turtle (*Lepidochelys kempii*)	Kemp's ridley sea turtle	Kemp's ridley sea turtle	Kemp's ridley sea turtle	NA	NA

Table A6. Species richness relative to each taxonomic group for each proposed network site in the Fisheries and Oceans Canada Maritimes Region off Canada's east coast.

Site	Type	Species	Present Day	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Big Glace Bay	TBD	Total	178	271	286	273	300
		Fish	167	262	277	264	293
		Mammals	10	8	8	8	6
		Reptiles	0	0	0	0	0
		Lobsters	1	1	1	1	1
Bird Islands	TBD	Total	143	149	155	146	173
		Fish	133	140	146	138	167
		Mammals	9	8	8	7	5
		Reptiles	0	0	0	0	0
		Lobsters	1	1	1	1	1
Bon Portage Island	TBD	Total	243	328	322	347	353
		Fish	230	323	317	342	348
		Mammals	11	4	4	4	4
		Reptiles	1	0	0	0	1
		Lobsters	1	1	1	1	0
Bras d'Or Lakes EBSA	TBD	Total	200	312	311	300	335
		Fish	189	303	302	291	327
		Mammals	10	8	8	8	7
		Reptiles	0	0	0	0	0
		Lobsters	1	1	1	1	1
Brier Island	TBD	Total	263	334	330	347	376
		Fish	251	328	324	341	367
		Mammals	11	5	5	5	7
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Canso Ledges - Sugar Harbour Islands	TBD	Total	206	318	307	303	335
		Fish	194	309	299	294	327
		Mammals	11	8	7	8	7
		Reptiles	0	0	0	0	0
		Lobsters	1	1	1	1	1
Central Scotian Slope, Rise and Abyss	TBD	Total	542	424	429	457	443
		Fish	520	407	413	437	423
		Mammals	16	12	11	15	14
		Reptiles	4	3	3	3	4

Site	Type	Species	Present Day	Mid-century SSP1-2.6	Mid-century SSP5-8.5	End-century SSP1-2.6	End-century SSP5-8.5
		Lobsters	2	2	2	2	2
Chebogue	TBD	Total	257	350	340	368	372
		Fish	243	345	335	363	365
		Mammals	11	4	4	4	6
		Reptiles	2	0	0	0	1
		Lobsters	1	1	1	1	0
Chignecto Bay	TBD	Total	219	198	213	232	286
		Fish	210	194	210	227	279
		Mammals	8	3	2	4	5
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Cold Seeps	TBD	Total	269	205	200	206	225
		Fish	251	194	190	194	211
		Mammals	13	7	6	8	10
		Reptiles	4	3	3	3	3
		Lobsters	1	1	1	1	1
Eastern Shoal	TBD	Total	178	254	255	259	279
		Fish	168	244	245	250	270
		Mammals	9	9	9	8	7
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Eastern Shore Islands	AOI	Total	224	354	345	336	366
		Fish	213	345	335	327	356
		Mammals	10	7	8	8	8
		Reptiles	0	1	1	0	1
		Lobsters	1	1	1	1	1
Fundian Channel-Browns Bank	AOI	Total	591	422	428	478	475
		Fish	569	410	416	463	459
		Mammals	16	9	9	10	12
		Reptiles	4	1	1	3	2
		Lobsters	2	2	2	2	2
Georges Bank	TBD	Total	280	348	345	372	359
		Fish	264	341	336	363	346
		Mammals	12	5	7	5	9
		Reptiles	2	0	0	2	2
		Lobsters	2	2	2	2	2

Site	Type	Species	Present Day	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Head Harbour, West Isles and The Passages	TBD	Total	256	218	218	330	345
		Fish	245	212	212	323	339
		Mammals	10	5	5	6	4
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Horse Mussel Reefs	TBD	Total	242	225	223	290	312
		Fish	231	218	217	283	306
		Mammals	10	6	5	6	4
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
LaHave Basin	TBD	Total	232	357	356	347	371
		Fish	220	349	348	335	360
		Mammals	10	6	6	10	9
		Reptiles	0	1	1	1	1
		Lobsters	2	1	1	1	1
LaHave Islands	TBD	Total	223	340	332	315	357
		Fish	212	333	326	307	349
		Mammals	10	5	4	7	6
		Reptiles	0	1	1	0	1
		Lobsters	1	1	1	1	1
Long Eddy	TBD	Total	251	207	213	316	335
		Fish	240	201	207	309	329
		Mammals	10	5	5	6	4
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Middle Bank-Canso Bank	TBD	Total	221	317	311	313	332
		Fish	209	308	303	304	322
		Mammals	11	8	7	8	8
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Misaine Bank and Laurentian Channel	TBD	Total	319	289	296	314	328
		Fish	305	277	284	303	315
		Mammals	12	10	10	9	10
		Reptiles	0	0	0	0	1
		Lobsters	2	2	2	2	2
	TBD	Total	220	339	336	324	361

Site	Type	Species	Present Day	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
North of Emerald Basin Sea Pen Field		Fish	209	330	327	315	351
		Mammals	10	7	8	8	8
		Reptiles	0	1	0	0	1
		Lobsters	1	1	1	1	1
Northern Gulf of Maine	TBD	Total	274	350	346	365	388
		Fish	259	343	338	359	378
		Mammals	12	6	6	5	8
		Reptiles	2	0	1	0	1
		Lobsters	1	1	1	1	1
Pearl Island	TBD	Total	234	354	347	331	369
		Fish	222	347	340	323	360
		Mammals	11	5	5	7	7
		Reptiles	0	1	1	0	1
		Lobsters	1	1	1	1	1
Point Michaud and Basque Islands	TBD	Total	178	219	233	265	297
		Fish	167	210	225	257	290
		Mammals	10	8	7	7	6
		Reptiles	0	0	0	0	0
		Lobsters	1	1	1	1	1
Port Joli and Surrounding Areas	TBD	Total	274	390	380	375	404
		Fish	261	384	374	368	395
		Mammals	11	5	5	6	7
		Reptiles	1	0	0	0	1
		Lobsters	1	1	1	1	1
Roseway Bank	TBD	Total	323	400	399	407	428
		Fish	307	391	391	396	418
		Mammals	13	8	7	8	8
		Reptiles	2	0	0	2	1
		Lobsters	1	1	1	1	1
Sable Island Bank	TBD	Total	266	338	340	344	376
		Fish	252	328	330	331	362
		Mammals	11	7	7	9	11
		Reptiles	1	1	1	2	1
		Lobsters	2	2	2	2	2
	TBD	Total	207	322	319	305	346
		Fish	196	316	313	295	335

Site	Type	Species	Present Day	Mid-century SSP1-2.6	Mid-century SSP5-8.5	End-century SSP1-2.6	End-century SSP5-8.5
Sambro Ledges - Prospect		Mammals	10	4	4	9	9
		Reptiles	0	1	1	0	1
		Lobsters	1	1	1	1	1
Scotian Gulf	TBD	Total	460	389	389	391	411
		Fish	442	377	379	379	399
		Mammals	12	9	7	7	9
		Reptiles	4	1	1	3	1
		Lobsters	2	2	2	2	2
South Grand Manan	TBD	Total	282	337	332	357	385
		Fish	270	331	325	350	376
		Mammals	11	5	6	6	7
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Southern Bight	TBD	Total	224	251	246	321	346
		Fish	215	244	240	313	339
		Mammals	8	6	5	7	5
		Reptiles	0	0	0	0	1
		Lobsters	1	1	1	1	1
Western Jordan Basin	TBD	Total	252	335	339	349	354
		Fish	237	329	330	342	345
		Mammals	12	5	7	6	7
		Reptiles	2	0	1	0	1
		Lobsters	1	1	1	1	1

Table A7. The species in the Fisheries and Oceans Canada Maritimes Region with the largest and smallest proportion (Prop.) of their regional range protected by existing network sites (Exist) and all protected seascape sites combined (Exist and proposed).

Taxa	Prop.	Type	Present	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Fish	Highest	Exist	Banded rudderfish (*Seriola zonata*)	Channel scabbardfish (*Evoxymetopon taeniatus*)	Pygmy pipehore (*Amphelikturus dendriticus*); Spotted tinselfish (*Xenolepidichthys dalgleishi*)	Spotted tinselfish; Carlsbergs dreamer (*Oneirodes carlsbergi*)	Bristletooth conger (*Xenomystax bidentatus*)
			58.5	62.5	63.6	61.5	80.0
		Exist and Prop.	Longwing spinyfish (*Diretmoides pauciradiatus*); Spotfin butterfly fish (*Chaetodon ocellatus*); Atlantic thread herring (*Opisthonema oglinum*)	*Bathygadus favosus*; Gulf snailfish (*Liparis coheni*)	Hickory shad (*Alosa mediocris*)	Little tunny (*Euthynnus alletteratus*); Nurse shark (*Ginglymostoma cirratum*), Striped killifish (*Fundulus majalis*)	Nurse shark
			100	100	96.0	100	100
	Lowest	Exist	Arctic Char (*Salvelinus alpinus*); Bigpored snailfish (*Liparis latifrons*)	Roughtail stingray (*Bathytoshia centroura*)	*Paraliparis stehmanni*	Atlantic sturgeon (*Acipenser oxyrinchus*)	Brook trout (*Salvelinus fontinalis*)

Taxa	Prop.	Type	Present	Mid-century		End-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
			10.0	7.7	11.1	8.3	5.0
		Exist and Prop.	Hollowsnout grenadier (*Coelorinchus caelorhincus*)	Roundscale spearfish (*Tetrapturus georgii*)	*Lophiodes beroe*	Deep-sea anglerfish sp. *Oneirodes schmidti*	Deepsea sole (*Embassichthys bathybius*)
			23.1	16.7	20.0	8.3	20.0
Mammals	Highest	Exist	Pygmy sperm whale (*Kogia breviceps*); Striped dolphin (*Stenella coeruleoalba*)	Pygmy sperm whale	Hooded seal (*Cystophora cristata*)	Hooded seal	Bryde's whale (*Balaenoptera edeni*)
			36.0	38.0	39.4	42.6	39.7
		Exist and Prop.	Harp seal (*Pagophilus groenlandicus*)	Grey seal (*Halichoerus grypus*)	Grey seal	Atlantic white-sided dolphin (*Lagenorhynchus acutus*)	Bryde's whale
			76.7	79.5	93.3	78.7	74.5
	Lowest	Exist	Dwarf sperm whale (*Kogia sima*)	Harp seal	True's beaked whale (*Mesoplodon mirus*)	Short-finned pilot whale (*Globicephala macrorhynchus*)	Gervais' beaked whale (*Mesoplodon europaeus*)
			24.4	17.1	23.5	19.0	24.2
		Exist and Prop.	Dwarf sperm whale	Atlantic spotted dolphin	Striped dolphin	Short-finned pilot whale	North Atlantic right whale

Taxa	**Prop.**	**Type**	**Present**	**Mid-century**		**End-century**	
				SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
				(*Stenella frontalis*)			(*Eubalaena glacialis*)
			39.0	31.3	33.3	33.3	26.3
Reptiles	Highest	Exist	Leatherback sea turtle (*Dermochelys coriacea*)	Hawksbill sea turtle (*Eretmochelys imbricata*)	Hawksbill sea turtle	Hawksbill sea turtle	Hawksbill sea turtle
			35.6	37.2	36.8	38.3	35.3
		Exist and Prop.	Kemp's ridley sea turtle (*Lepidochelys kempii*)	Hawksbill sea turtle	Hawksbill sea turtle	Hawksbill sea turtle	Hawksbill sea turtle
			59.2	54.9	56.1	55.7	63.5
	Lowest	Exist	Green sea turtle (*Chelonia mydas*)	Green sea turtle; Leatherback Sea turtle	Green sea turtle	Leatherback sea turtle	Green sea turtle; Leatherback Sea turtle
			20.0	32.9	10.0	33.7	33.3
		Exist and Prop.	Green sea turtle	Green sea turtle; Leatherback sea turtle	Green sea turtle	Leatherback sea turtle	Green sea turtle
			20.0	50.0	10.0	50.0	40.0
Lobsters	Highest	Exist	Blind lobster sp. *Stereomastis sculpta*	*Stereomastis sculpta*	*Stereomastis sculpta*	*Stereomastis sculpta*	*Stereomastis sculpta*
			36.8	37.0	37.3	36.9	37.9

Taxa	**Prop.**	**Type**	**Present**	**Mid-century**		**End-century**	
				SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
		Exist and Prop.	American Lobster (*Homarus americanus*)	American Lobster	American Lobster	American Lobster	American Lobster
			77.1	76.7	76.5	78.9	75.8
	Lowest	Exist	American Lobster	American Lobster	American Lobster	American Lobster	American Lobster
			32.1	33.6	33.0	33.9	75.8
		Exist and Prop.	*Stereomastis sculpta*	*Stereomastis sculpta*	*Stereomastis sculpta*	*Stereomastis sculpta*	*Stereomastis sculpta*
			52.8	52.1	52.5	52.5	52.6

Table A8. The protected seascape sites (proposed and existing) of the Maritime Conservation Network that provided the most protection of the regional range of a single species across taxa.

Taxa	**Scenario**	**Site**	**Species**	**Proportion protected (%)**
Fish	Present	Fundian Channel-Browns Bank AOI	Atlantic Angel shark (*Squatina dumeril*)	66.7
	Mid-century SSP1-2.6	Fundian Channel-Browns Bank AOI	Gulf snailfish (*Liparis coheni*)	53.3
	Mid-century SSP5-8.5	Eastern Canyons Marine Refuge	Lanternfish sp. *Nannobrachium lineatum*	60.0
	End-century SSP1-2.6	Corsair/Georges Canyons Conservation Area	Carlsbergs dreamer (*Oneirodes carlsbergi*)	61.5
	End-century SSP5-8.5	Corsair/Georges Canyons Conservation Area	Bristletooth conger (*Xenomystax bidentatus*)	80.0
Mammals	Present	Eastern Canyons Marine Refuge	Pygmy sperm whale (*Kogia breviceps*)	22.2
	Mid-century SSP1-2.6	Eastern Canyons Marine Refuge	Pygmy sperm whale	21.7
	Mid-century SSP5-8.5	St. Anns Bank MPA	Atlantic white-sided dolphin (*Lagenorhynchus acutus*)	37.5

Taxa	Scenario	Site	Species	Proportion protected (%)
	End-century SSP1-2.6	Corsair/Georges Canyons Conservation Area	Gervais' beaked whale (*Mesoplodon europaeus*)	38.9
	End-century SSP5-8.5	Eastern Shoal and Misaine Bank and Laurentian Channel	White-beaked dolphin (*Lagenorhynchus albirostris*)	50.0
Reptiles	Present	Eastern Canyons Marine Refuge	Leatherback sea turtle (*Dermochelys coriacea*)	21.2
	Mid-century SSP1-2.6	Eastern Canyons Marine Refuge	Leatherback sea turtle	23.7
	Mid-century SSP5-8.5	Eastern Canyons Marine Refuge	Leatherback sea turtle	23.3
	End-century SSP1-2.6	Eastern Canyons Marine Refuge	Loggerhead sea turtle (*Caretta caretta*)	22.4
	End-century SSP5-8.5	Eastern Canyons Marine Refuge	Leatherback sea turtle	24.1
Lobster	Present	Eastern Canyons Marine Refuge	Blind lobster sp. *Stereomastis sculpta*	20.0
	Mid-century SSP1-2.6	Eastern Canyons Marine Refuge	Blind lobster sp. *Stereomastis sculpta*	21.0

Taxa	Scenario	Site	Species	Proportion protected (%)
	Mid-century SSP5-8.5	Eastern Canyons Marine Refuge	*Stereomastis sculpta*	21.2
	End-century SSP1-2.6	Eastern Canyons Marine Refuge	*Stereomastis sculpta*	20.5
	End-century SSP5-8.5	Eastern Canyons Marine Refuge	*Stereomastis sculpta*	21.6

Figure A1. The average proportion of present-day species that emigrated from each protected seascape site (existing and proposed) in the the Fisheries and Oceans Canada Maritime Conservation Network. Plots consider (1) all species, (2) fish, (3) mammals, and (4) reptiles (sites with reptile occurrences). Protected seascape sites are ranked from highest to lowest proportion of emigrants occurring in the end-century for each taxa grouping. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue dots, respectively.

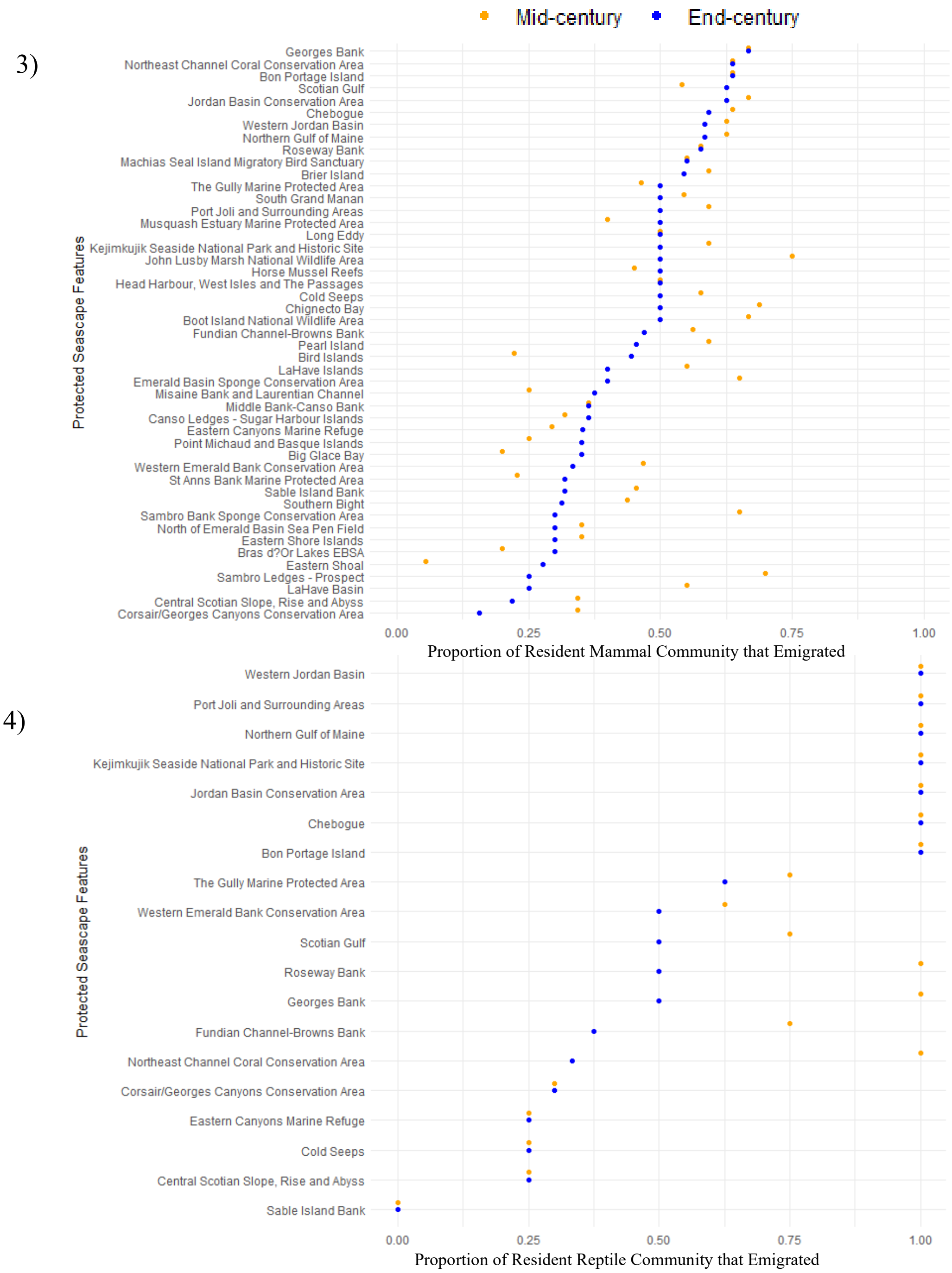


Figure A1. Continued.

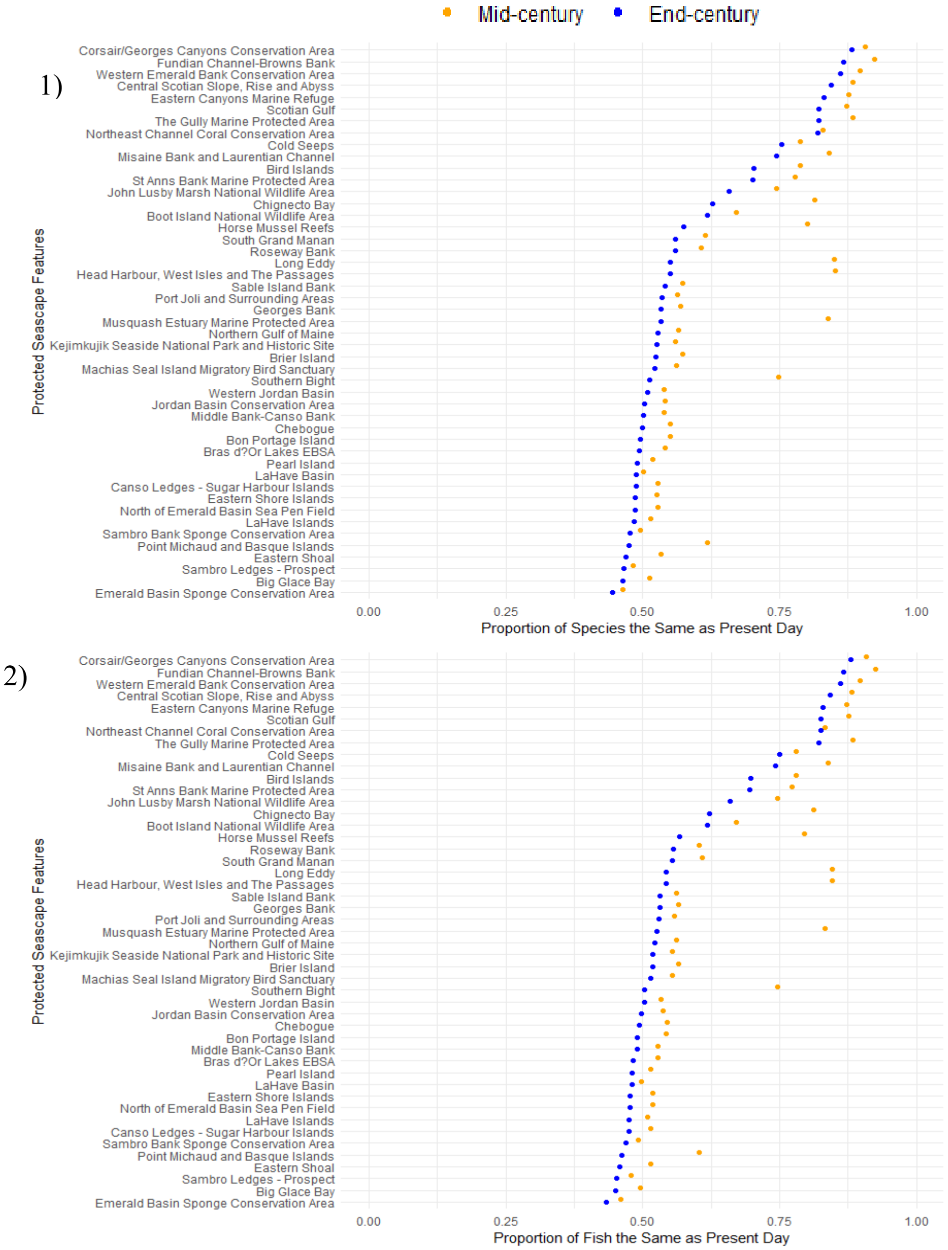
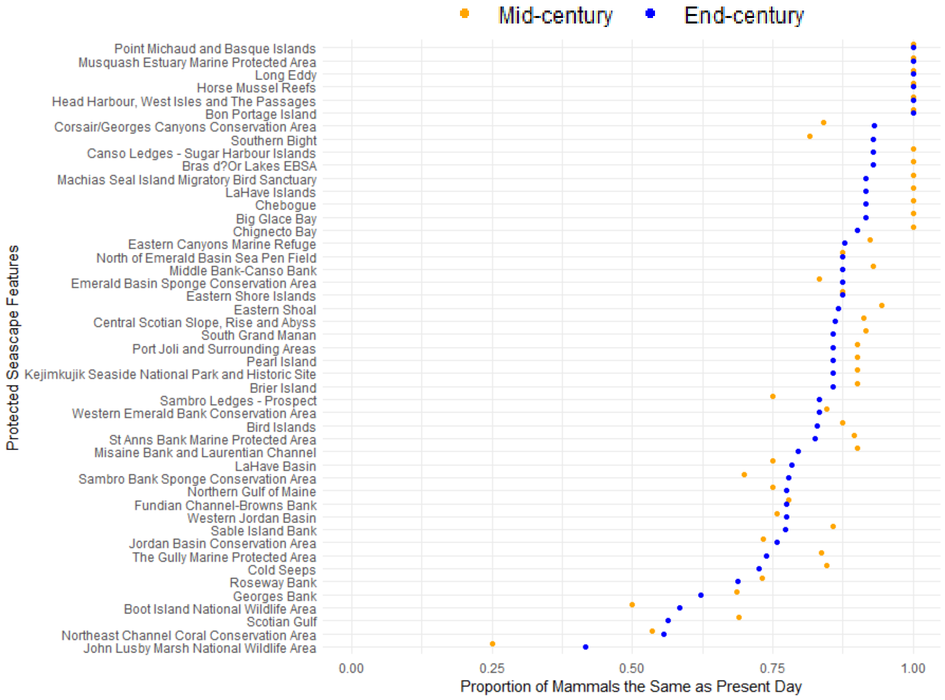


Figure A2. The average proportion of future species that were the same as present day for each protected seascape site (existing and proposed) in the Fisheries and Oceans Canada Maritime Conservation Network. Plots consider (1) all species, (2) fish, (3) mammals, and (4) reptiles (sites with reptile occurrences). Protected seascape sites are ranked from highest to lowest proportions of remaining residents in the end-century for each taxa grouping. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue dots, respectively.

3)



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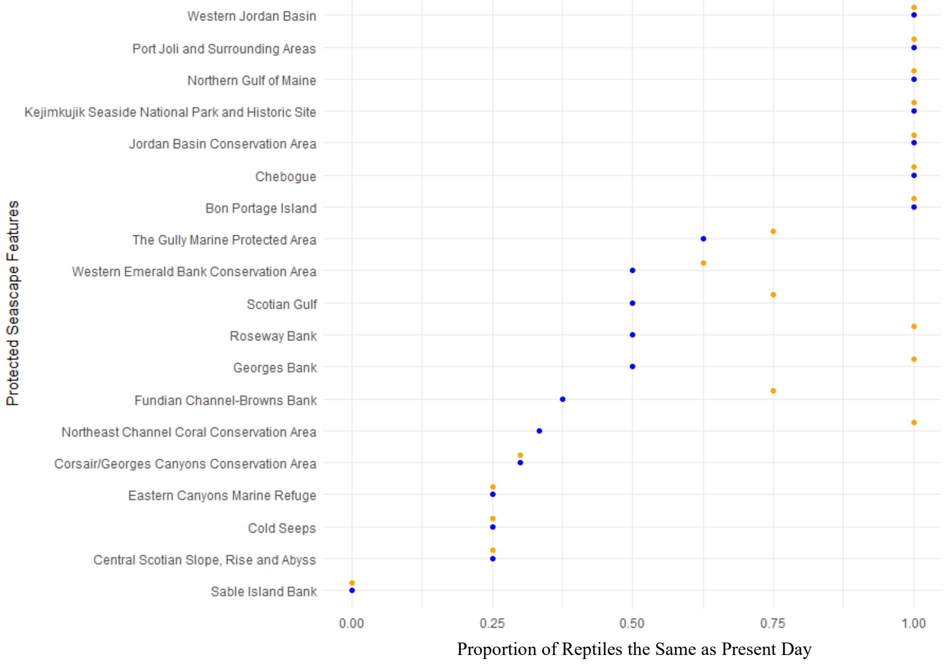

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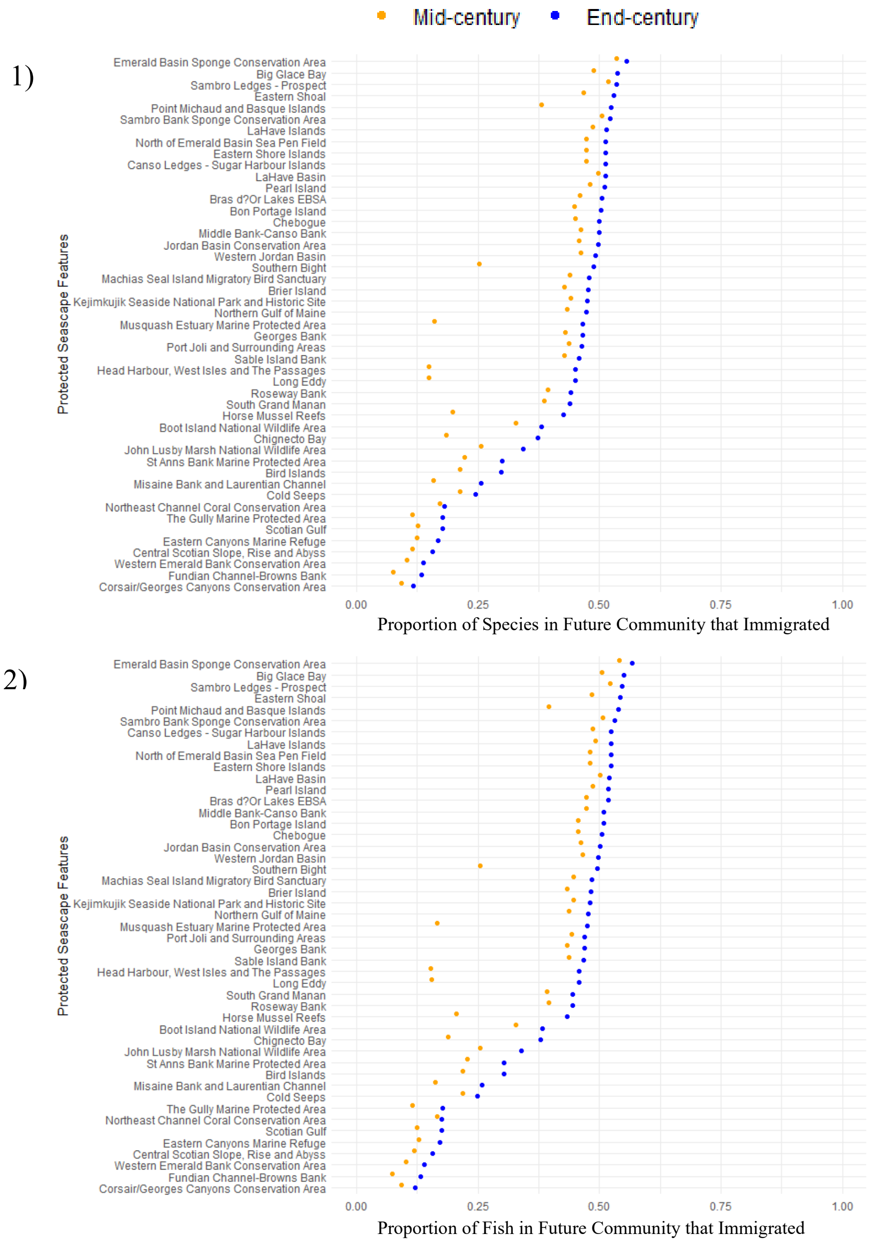


Figure A3. The average proportion of immigrants represented in projected future species populations within each protected seascape site (existing and proposed) in the the Fisheries and Oceans Canada Maritime Conservation Network. Plots consider (1) all species, (2) fish, (3) mammals, and (4) reptiles (sites with reptile occurrences). Protected seascape sites are ranked from highest to lowest proportion of immigrants protected in the end-century for each taxa grouping. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue dots, respectively.

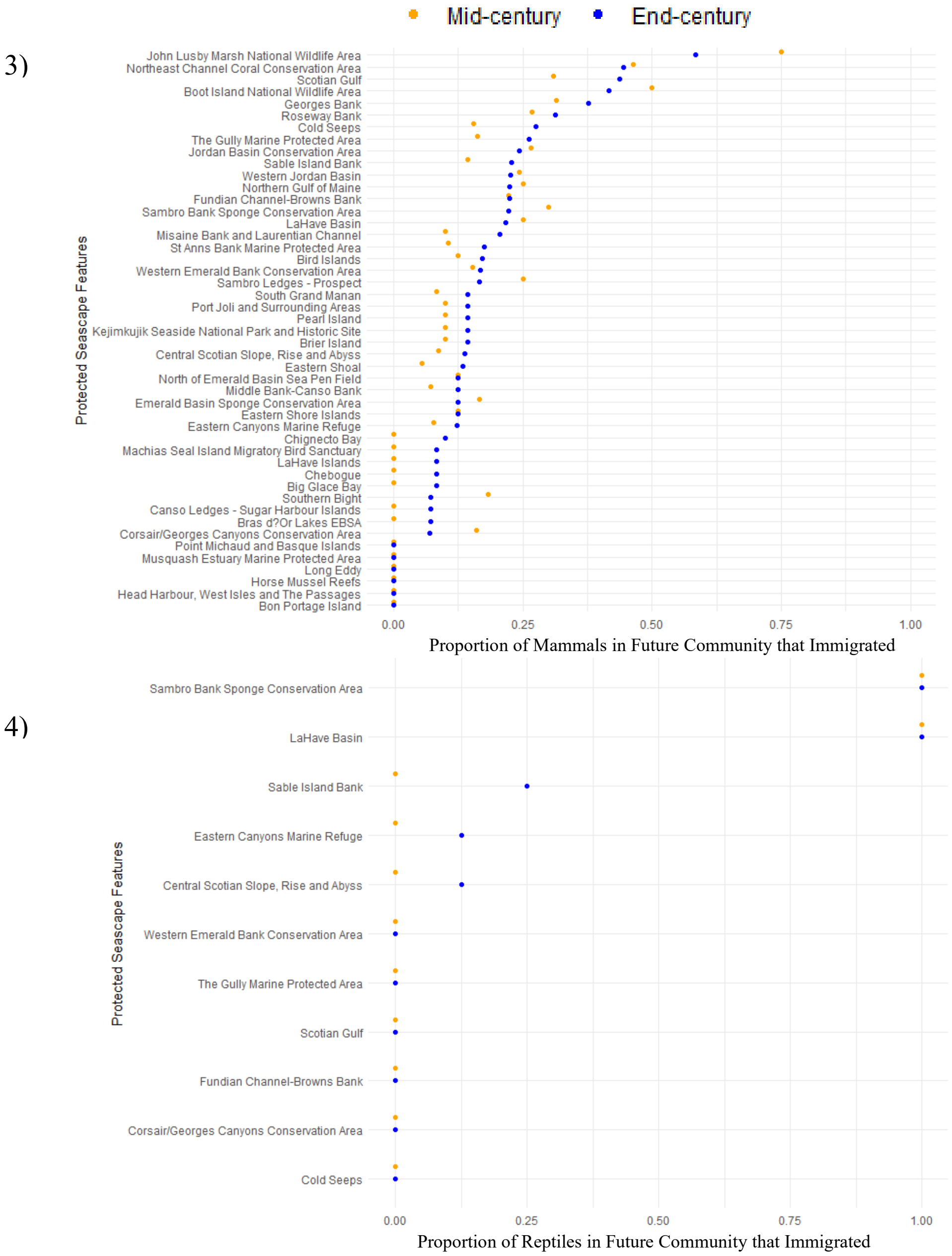


Figure A3. Continued.

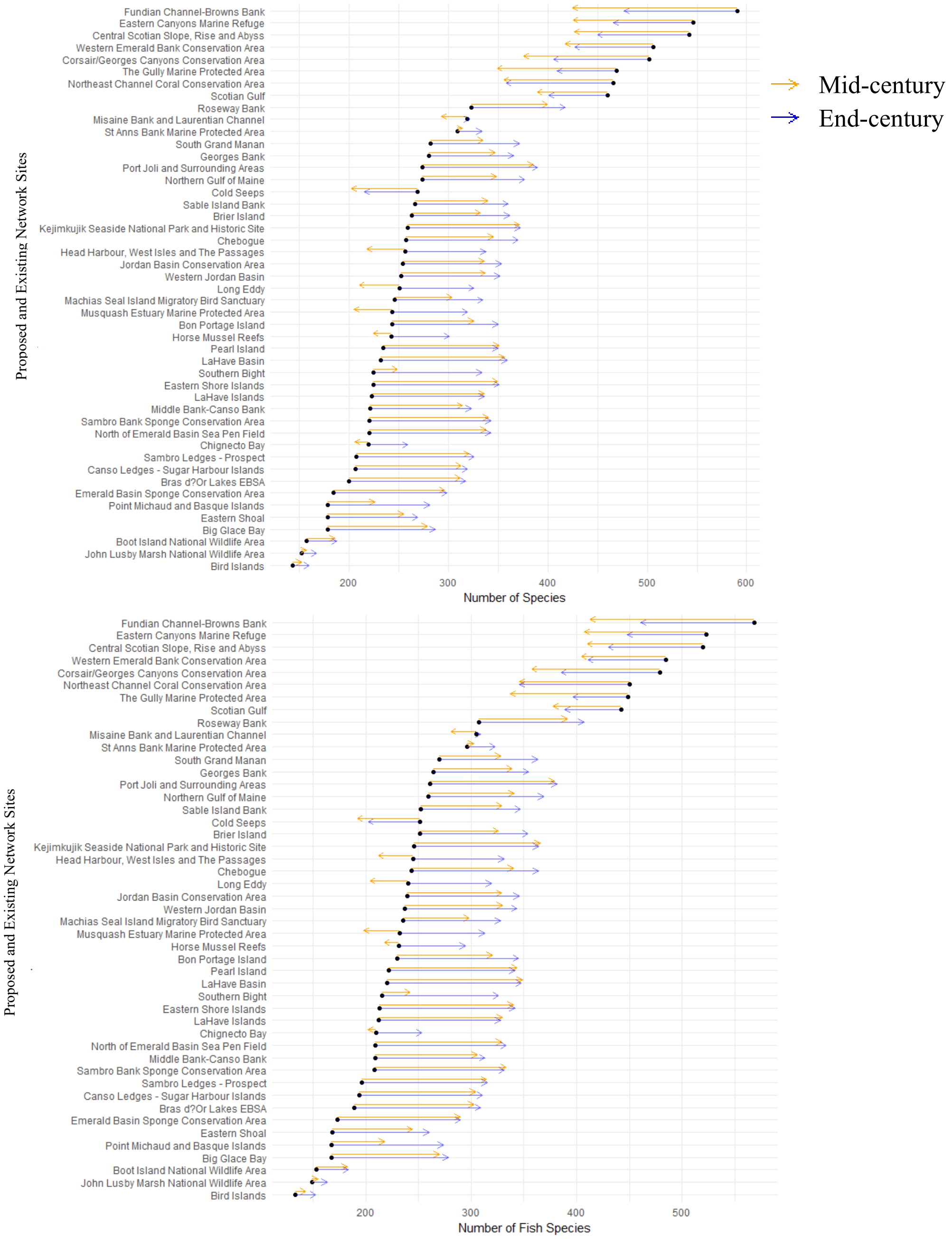
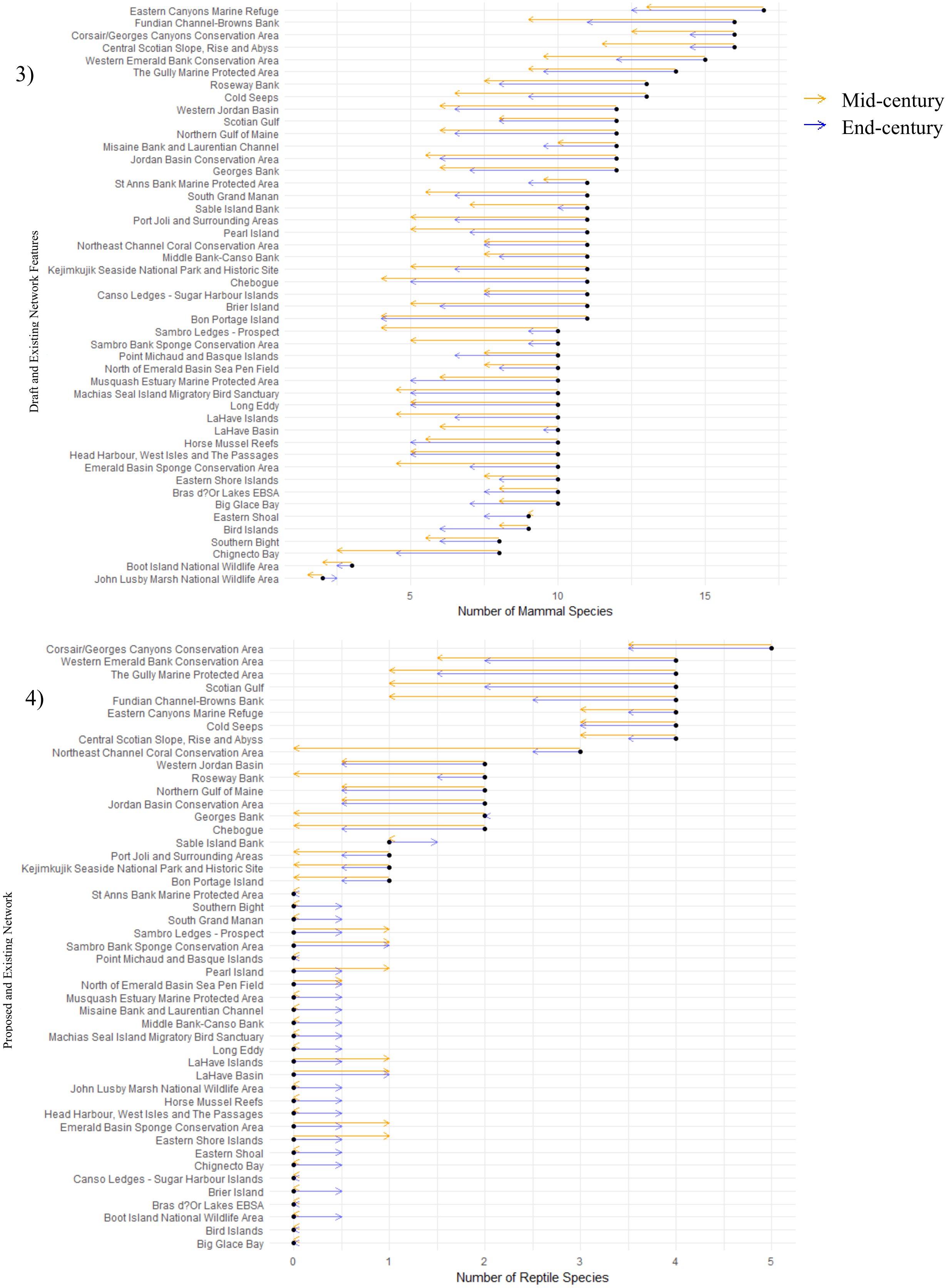


Figure A4. The change in species richness occurring for each protected seascape site (existing and proposed) in the Fisheries and Oceans Canada Maritime Conservation Network. Plots consider (1) all species, (2) fish, (3) mammals, (4) reptiles (sites with reptile occurrences), and (5) Lobsters. Protected seascape sites are ranked from highest to lowest for present day species richness. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue arrows, respectively.



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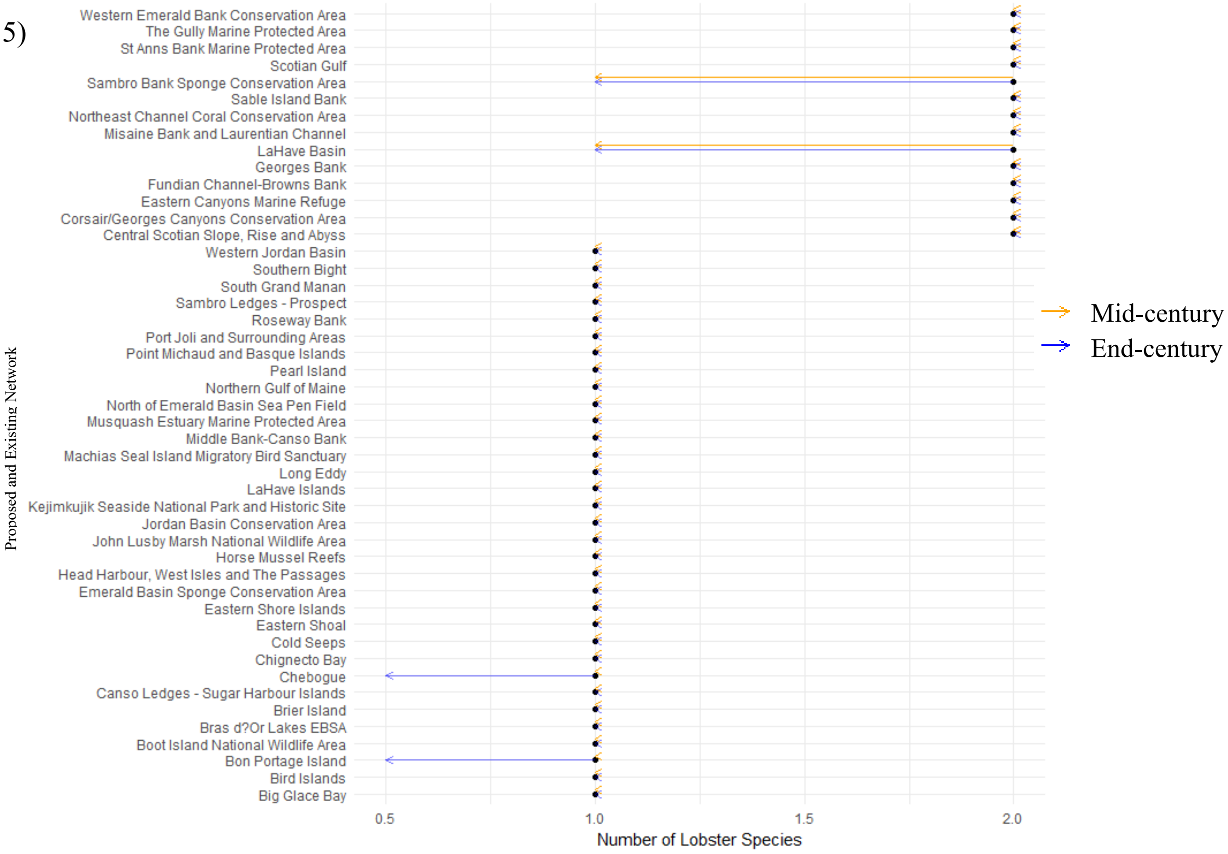

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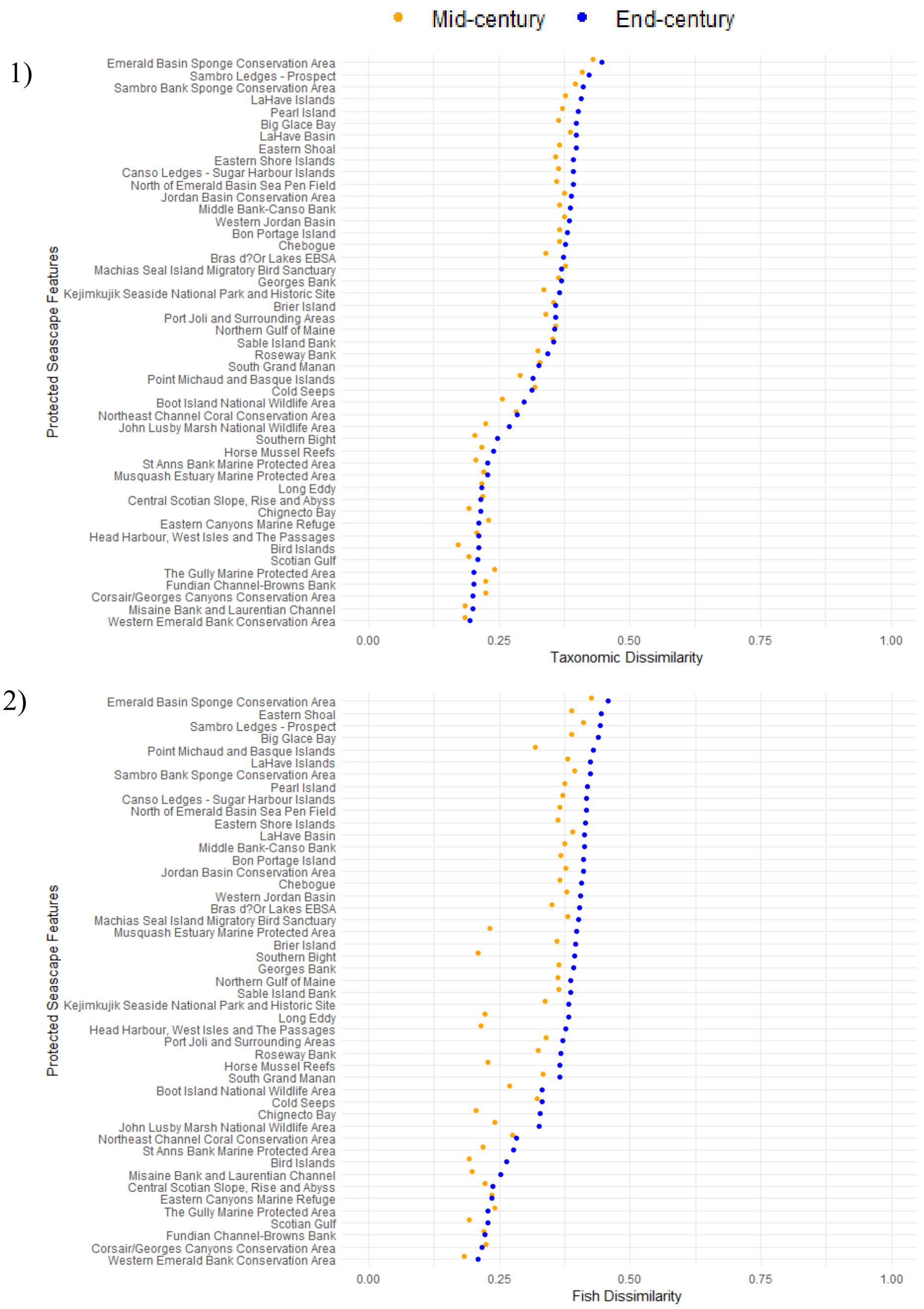

Figure A5. Taxonomic dissimilarity occurring for each protected seascape site (existing and proposed) in the the Fisheries and Oceans Canada Maritime Conservation Network. Plots consider (1) all species, (2) fish, (3) mammals, and (4) reptiles (sites with reptile occurrences). Protected seascape sites are ranked from highest to lowest for end-century dissimilarity. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue arrows, respectively.

3)

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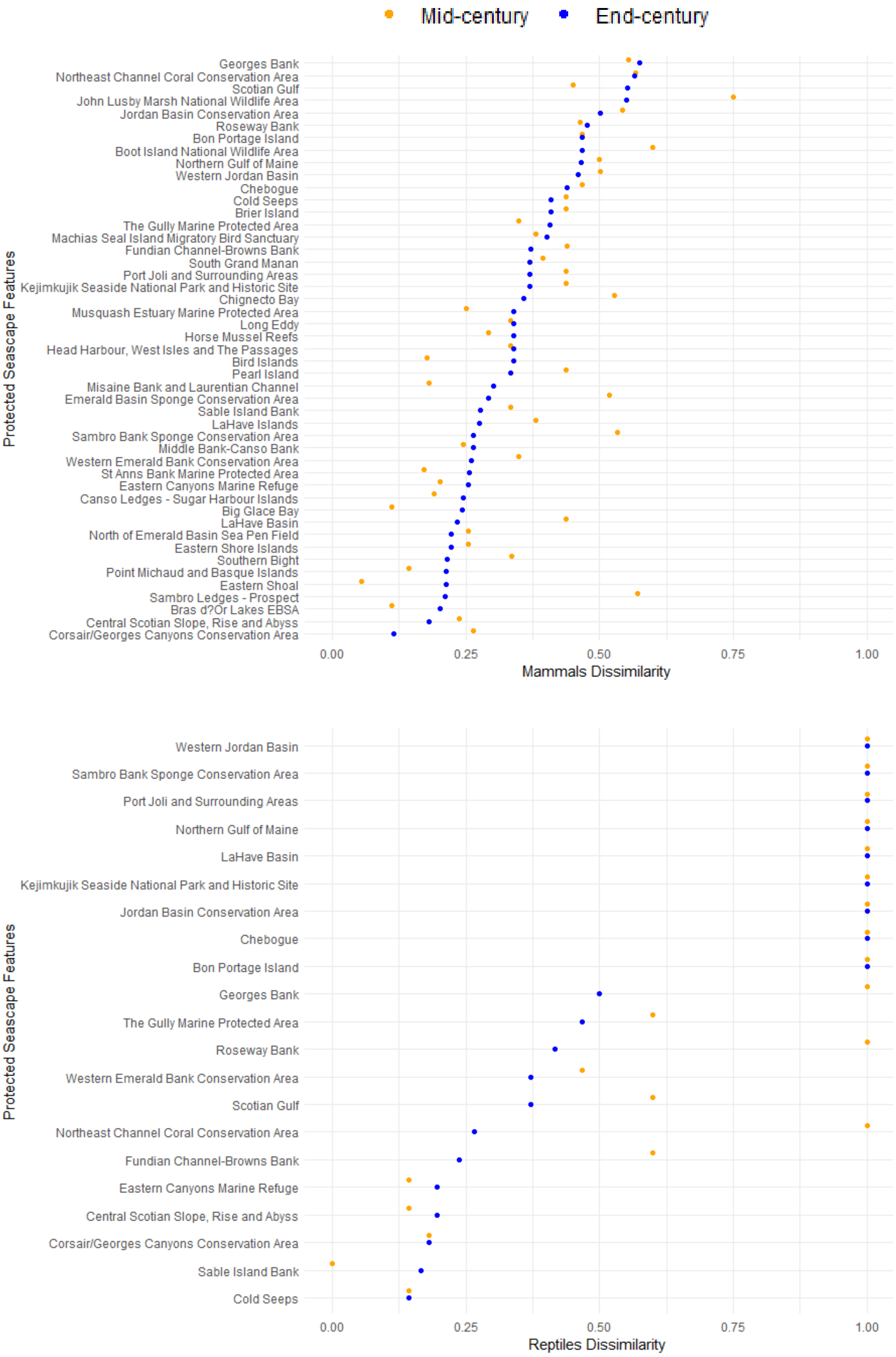

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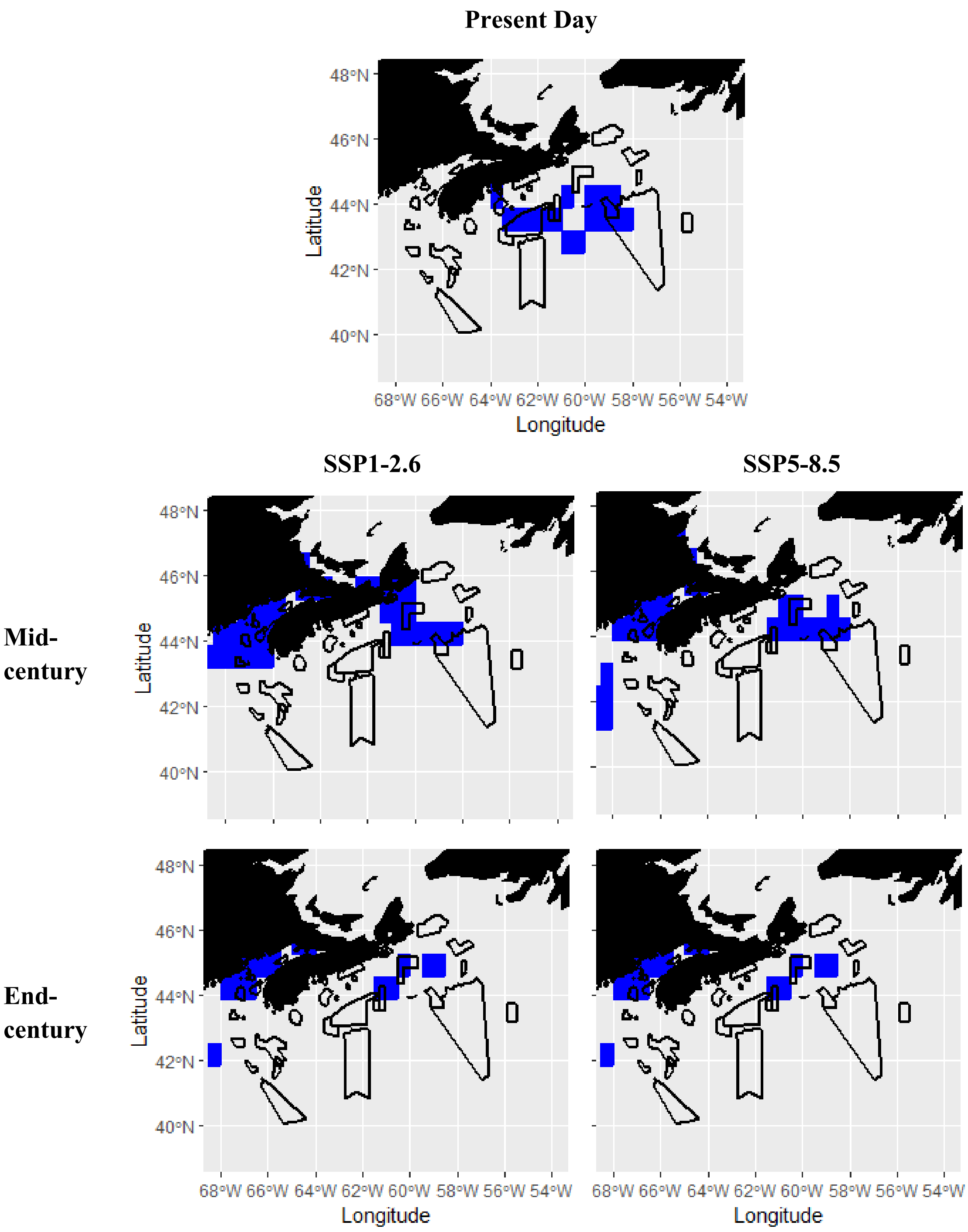

Figure A6. Banded rudderfish (*Seriola zonata*) presences nearby and within the Fisheries and Oceans Canada Maritimes Region indicating presence overlap with the protected seascape sites in the Maritime Conservation Network. The first row is present day, the second row is mid-century, and the third row is end-century Banded rudderfish presences. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

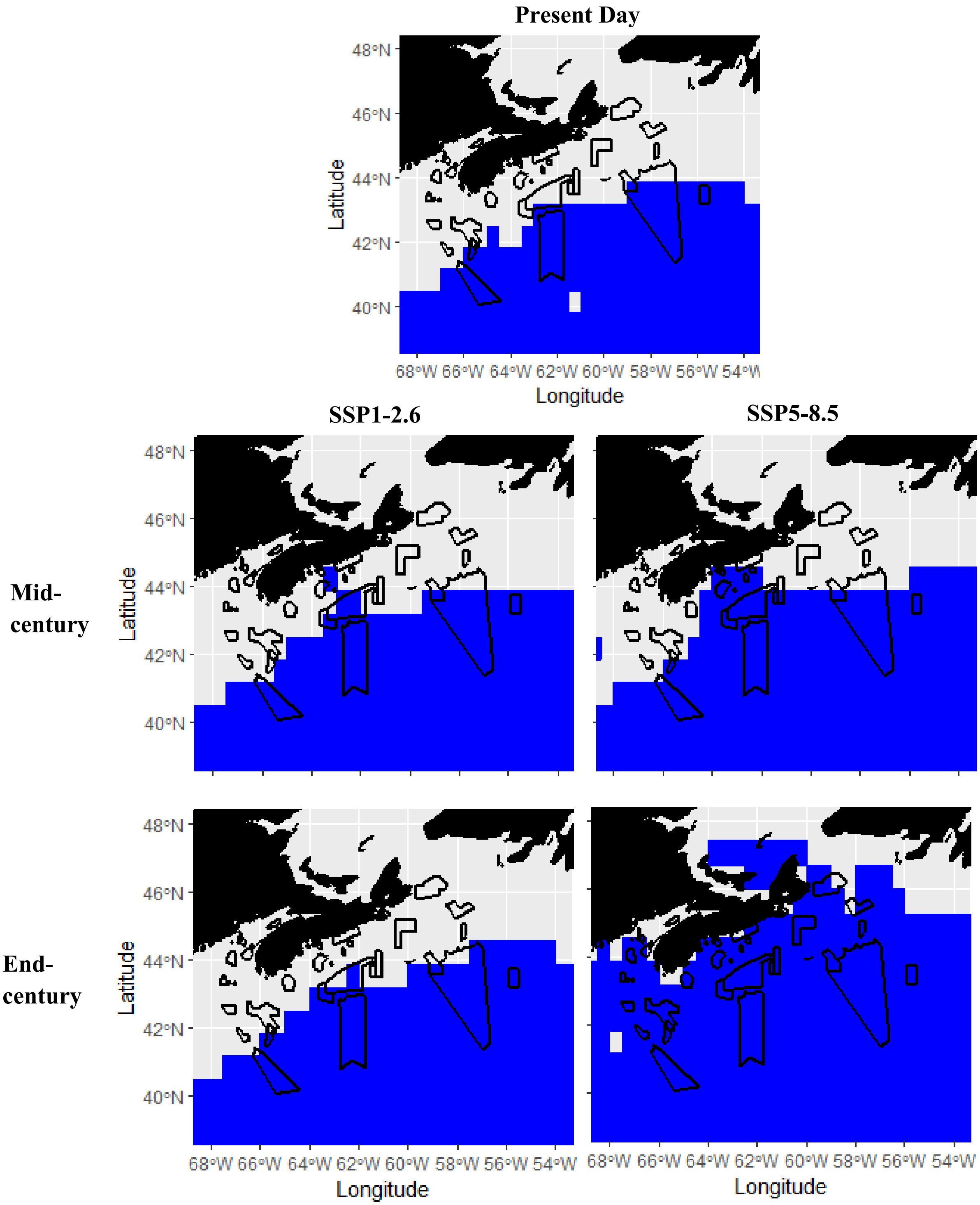

Figure A7. Pygmy sperm whale (*Kogia breviceps*) presences nearby and within the Fisheries and Oceans Canada Maritimes Region indicating presence overlap with the protected seascape sites in the Maritime Conservation Network. The first row is present day, the second row is mid-century, and the third row is end-century Pygmy sperm whale presences. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

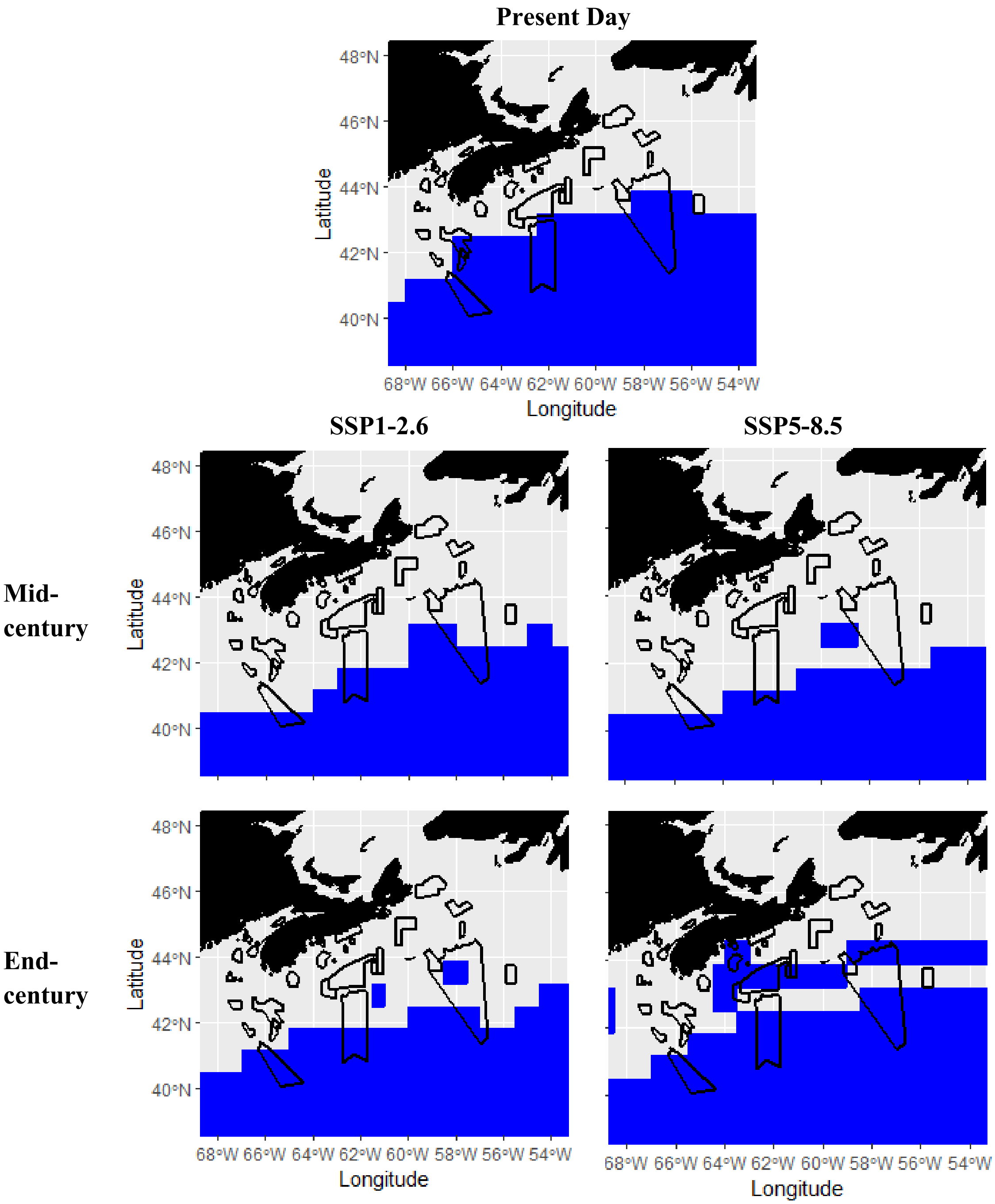

Figure A8. Striped dolphin (*Stenella coeruleoalba*) presences nearby and within the Fisheries and Oceans Canada Maritimes Region indicating presence overlap with the protected seascape sites in the Maritime Conservation Network. The first row is present day, the second row is mid-century, and the third row is end-century Striped dolphin presences. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

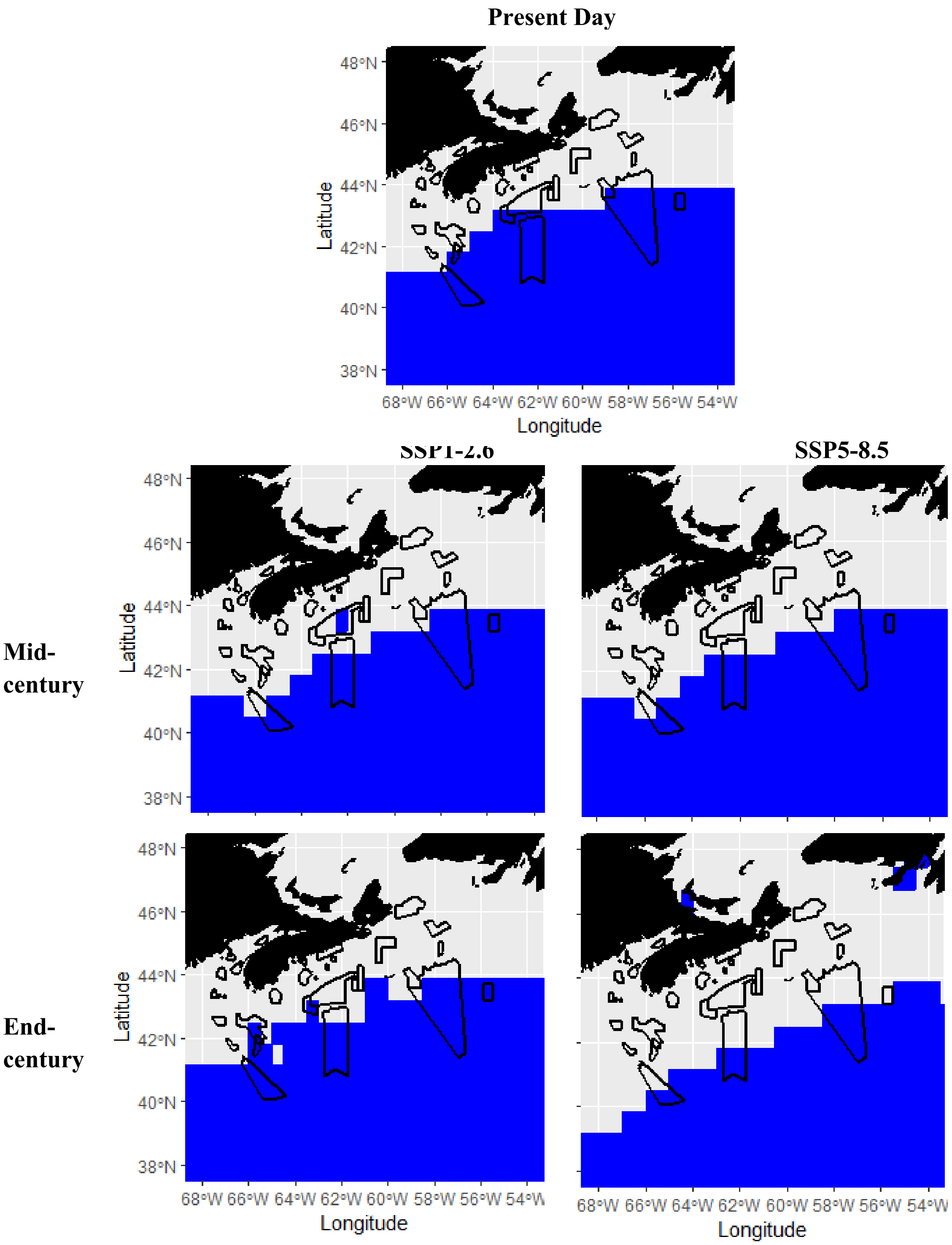

Figure A9. Leatherback sea turtle (*Dermochelys coriacea*) presences nearby and within the Fisheries and Oceans Canada Maritimes Region indicating presence overlap with the protected seascape sites in the Maritime Conservation Network. The first row is present day, the second row is mid-century, and the third row is end-century Leatherback sea turtle presences. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

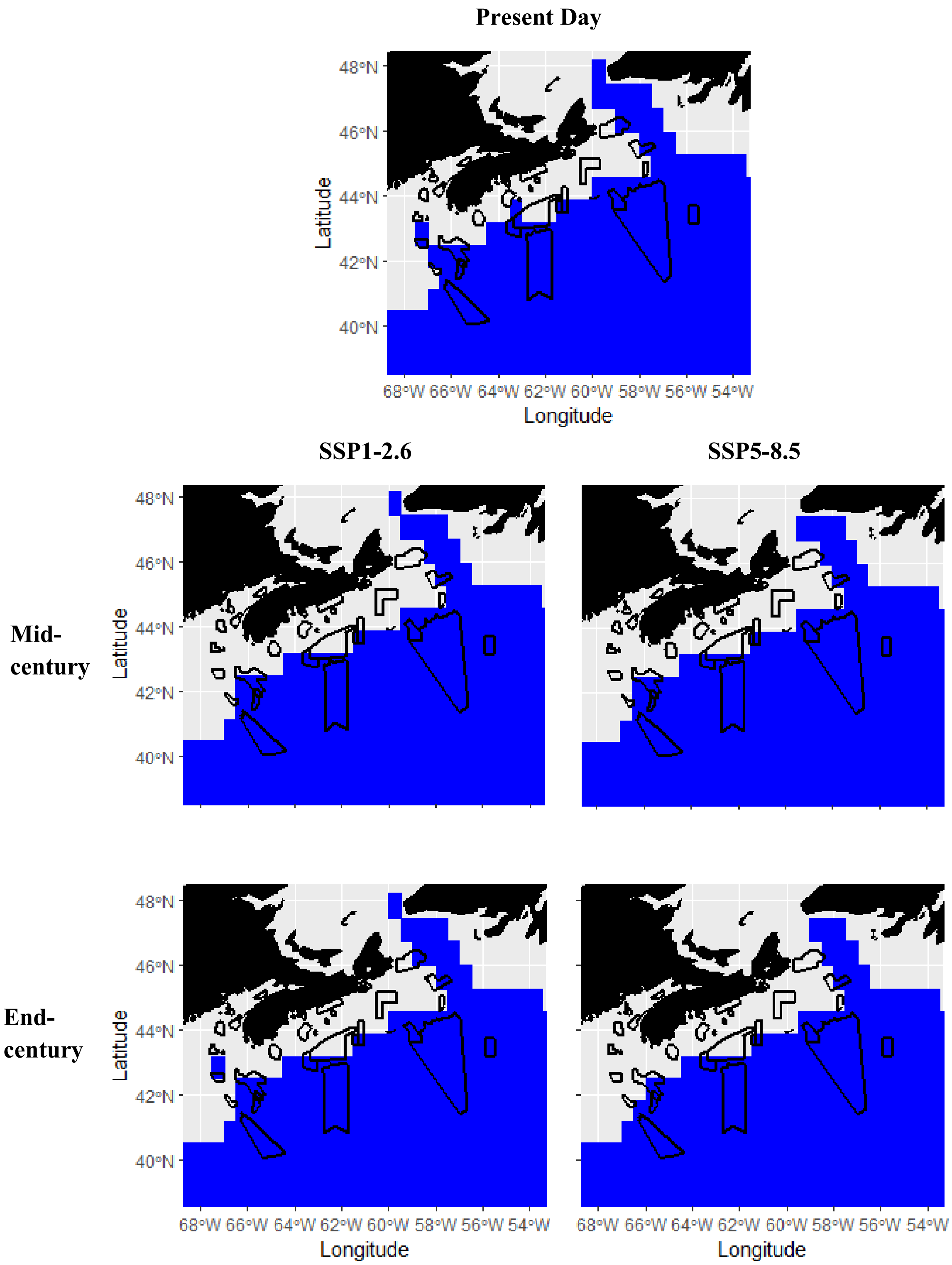

Figure A10. Blind lobster sp. *Stereomastis sculpta* presences nearby and within the Fisheries and Oceans Canada Maritimes Region indicating presence overlap with the protected seascape sites in the Maritime Conservation Network. The first row is present day, the second row is mid-century, and the third row is end-century *Stereomastis sculpta* presences. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

Appendix B - Chapter 3 Supplementary Tables and Figures

Trait Explanations:
Each species has a specific role within an ecosystem defined by its combination of traits. This trait combination determines the other species they may interact with (predation, position in water column) and aspects that affect their ecological role (reproductive mode, max reported age; Reiss et al., 2009). For example, a large bodied, carnivorous, pelagic, and long-lived white shark has a top-down influence on the ecosystem, whereas a small-bodied, planktivorous, pelagic, and short-lived mackerel may act as a main prey source. Here I describe three tiers of traits for assessing functional richness and functional beta diversity of an ecosystem across time and scenarios. See Table B1 for trait explanations.

For all traits, I considered the adult stage only.

Table B1. Tiers of trait desirability based on usage across scientific literature for various taxa, whereby higher tiers are used more across taxa (MarLIN 2006; Cleary et al. 2008; Jones et al. 2009; Stuart-Smith et al. 2013; Villéger et al. 2013; Mouillot et al. 2014; Brun et al. 2016; Madin et al. 2016; Ladds et al. 2018; Beukhof et al. 2019; Chapman et al. 2019; Pimiento et al. 2020; Salerno et al. 2021; Froese and Pauly 2023; Djeghri et al. 2023).

Trait	**Role in Ecosystem Functioning**	**Trait Type**	**Units**
Tier 1			
Trophic level	Trophic interactions and population control (Villéger et al. 2017); energy flow/nutrient cycling (Villéger et al. 2017). Trophic level is a continuous variable that can rank and compare species across and within feeding modes.	Continuous	Dimensionless
Maximum body length	Relates to metabolic rate and energy demand, growth rate, fecundity, and mortality rate (Brown et al. 2007); limits predation pressure as species must fit the mouth gap of its predator (Karpouzi and Stergiou 2003); intraspecific competitive advantages (Munday et al. 2001).	Continuous	cm
Diet	Determines how and which populations the species regulates at lower trophic levels (Gravel et al. 2016; Villéger et al. 2017); nutrient cycling in the food web (Villéger et al. 2017).	Categorical	(1) Herbivorous-detritivorous (turf/filamentous algae) (2) Macroalgae herbivorous, (3) Invertivorous targeting sessile invertebrates, (4) Invertivourous targeting mobile inverts, (5) Planktivorous, (6) Piscivorous, (7) Omnivourous, (8) Carnivorous

Trait	Role in Ecosystem Functioning	Trait Type	Units
Reproductive Mode	Indicates species' fitness and resiliency to shifts in ocean conditions within the community (Villéger et al. 2017); population recovery/ turnover.	Categorical	(1) Asexual, (2) Asexual and/or sexual, (3) Broadcast spawning, (4) External fertilization with parental care, (5) Oviparous, (6) Ovoviviparious, (7) Viviparious (parental), (8) Viviparious (no care),
Vertical position in water column	Trophic interactions (predation, competition); vertical movement of nutrients (Munday et al. 2001; Villéger et al. 2017).	Categorical	(1) Attached to substrate, (2) Infaunal (3) Reef-associated, (4) Benthic, (5) Bathypelagic, (6) Benthopelagic, (7) Bathydemersal, (8) Demersal, (9) Epipelagic, (10) Mesopelagic, (11) Pleustonic (rest on surface)
Tier 2			
Age at maturity	When they can begin contributing to ecosystem adaptation and resiliency through reproduction (Villéger et al. 2017); energy demand required for the species to reproduce (Villéger et al. 2017); tolerance to changes in environmental conditions (Higham 1995).	Continuous	Years
Length at maturity	Energy demand for reproduction (Higham 1995; Villéger et al. 2017); life-history strategy; resiliency within an ecosystem (Higham 1995).	Continuous	Cm
Mean fecundity	Annual reproduction investment and reproductive energy demands (Villéger et	Continuous	Count

Trait	Role in Ecosystem Functioning	Trait Type	Units
	al. 2017); rates of population recovery, growth, and stability within an ecosystem, especially after a disturbance (Higham 1995; Ladds et al. 2018).		
Max reported age	Life-history strategy / resiliency to rapid shifts in ecosystem functioning (Higham 1995); how rapid the population turnover rate can be (Ladds et al. 2018).	Continuous	Years
Adult mobility	Habitat use and resources available to them (Villéger et al. 2017); nutrient cycling within and across ecosystems (Villéger et al. 2017); indicates ability to capture prey and prey preference, migratory patterns, and swimming performance/ capabilities within an ecosystem (Higham 2007; Villéger et al. 2017; Ladds et al. 2018).	Categorical	(1) Sessile (or territorial), (2) Roving, (3) Highly mobile or migratory
Grouping size/ Sociality	Intraspecific and interspecific behaviour of a species within an ecosystem; can have multiple purposes affecting trophic interactions, such as being used as a defense from predators (Higham 1995; Tyack 2009; Villéger et al. 2017) or a formation of a social community (Tyack 2009).	Categorical	(1) Solitary, (2) Colonial, (3) Schooling/aggregated, (4) Gregarious/social, (5) Unknown
Habitat zone	Defines which trophic interactions may occur within that ecosystem based on the preferred location of the species; nutrient transport across and within	Categorical	(1) Coastal, (2) Neritic, (3) Oceanic

Trait	**Role in Ecosystem Functioning**	**Trait Type**	**Units**
	ecosystems (Villéger et al. 2017).		
Tier 3			
Maximum adult mass	Metabolism and energy demand (Akin and Winemiller 2008; Villéger et al. 2017); trophic level position within an ecosystem (Akin and Winemiller 2008; Villéger et al. 2017). Body mass may allow for more accurate trophic level comparisons of species than body length (Villéger et al. 2017).	Continuous	Grams (g)
Terrestriality	Habitat use (Pimiento et al. 2020); nutrient transfer across ecosystems (Bouchard and Bjorndal 2000; Pimiento et al. 2020). Species able to exploit multiple habitats appear to be at increased risk of extinction (Pimiento et al. 2020).	Categorical	(1) Land associated, (2) Freshwater associated (migrate between marine/fresh, enter estuaries, brackish) (3) None
Movement method	**E**xtent of nutrient movement within and across ecosystems (Villéger et al. 2017); movement method may alter the physical features of the environment.	Categorical	(1) Burrower, (2) Byssus (attachment mucus), (3) Crawler, (4) Rafter/drifter, (5) Swimmer, (6) Tube-builder, (7) Motionless, (8) Not found
Diel activity pattern	Trophic interactions and habitat use (Stuart-Smith et al. 2013; Villéger et al. 2017); behaviour restricted by light sensitivities for prey/predator detection (Stuart-Smith et al. 2013; Villéger et al. 2017).	Categorical	(1) Diurnal, (2) Nocturnal, (3) No pattern, (4) Not found

Table B2. Proportion of species with trait data for those from the species distribution models for the Fisheries and Oceans Canada Maritimes Region across each taxon, time period, and scenario.

Time	Scenario	Fish	Mammals	Reptiles	Lobster	Total
Present		284/699	19/19	5/5	2/2	310/725 42.8%
Mid-century	SSP1-2.6	248/581	20/20	4/4	2/2	274/607 45.1%
	SSP5-8.5	244/582	18/18	4/4	2/2	268/606 44.2%
End-of-century	SSP1-2.6	264/619	20/20	4/4	2/2	290/645 45.0%
		257/630	19/19	4/4	2/2	282/655 43.1%
Average		41.7%	100%	100%	100%	43.9%

Table B3. Functional diversity indices across all times and scenarios for each proposed protected seascape feature, where functional richness (FRic) is the number of functional entities present, functional redundancy (FRed) is the average number of species within each functional entity present, and functional vulnerability (FVul) is the number of functional entities represented by a single species in each time period and scenario. Sites are ordered alphabetically.

Site	**Type**	**Func. Index**	**Present**	**Mid-century**		**End-of-century**	
				SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
Big Glace Bay	TBD	FRic	71	73	76	73	80
		FRed.	1.87	1.85	1.82	1.82	1.74
		FVul (%)	67.6 (48/71)	68.5 (50/73)	67.1 (51/76)	68.5 (50/73)	72.5 (58/80)
Bird Islands	TBD	FRic	58	56	54	57	56
		FRed	1.84	1.79	1.78	1.74	1.75
		FVul (%)	67.2 (39/58)	75.0 (42/56)	72.2 (39/54)	77.2 (44/57)	78.6 (44/56)
Bon Portage Island	TBD	FRic	89	82	78	84	81
		FRed	1.71	1.96	2.00	1.96	1.95
		FVul (%)	67.1 (62/89)	64.1 (55/82)	67.9 (50/78)	69.1 (57/84)	67.1 (56/81)
Bras d'Or Lakes EBSA	TBD	FRic	74	84	78	80	87
		FRed.	1.88	1.85	1.91	1.85	1.79
		FVul (%)	67.6 (50/74)	69.0 (58/84)	64.1 (50/78)	70.0 (56/80)	72.4 (63/87)
Brier Island	TBD	FRic	90	83	79	85	87
		FRed	1.77	1.96	1.95	1.92	1.94
		FVul (%)	68.9 (62/90)	65.1 (54/83)	64.6 (51/79)	67.1 (57/85)	67.8 (59/87)
Canso Ledges - Sugar Harbour Islands	TBD	FRic	74	85	80	82	86
		FRed	1.91	1.79	1.81	1.79	1.77
		FVul (%)	66.2 (49/74)	70.6 (60/85)	70.0 (56/80)	70.7 (58/82)	75.6 (65/86)
Central Scotian	TBD	FRic	95	89	86	96	92
		FRed.	2.25	2.00	2.02	2.02	2.04
			64.2	66.3	67.4	68.8	67.4

Site	Type	Func. Index	Present	Mid-century		End-of-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Slope, Rise and Abyss		FVul (%)	(61/95)	(59/89)	(58/86)	(66/96)	(62/92)
Chebogue	TBD	FRic	90	85	84	88	85
		FRed.	1.76	2.00	1.96	1.94	1.94
		FVul (%)	70.0 (63/90)	65.9 (56/85)	66.7 (56/84)	69.3 (61/88)	68.2 (58/85)
Chignecto Bay	TBD	FRic	77	69	70	77	83
		FRed	1.88	1.78	1.76	1.68	1.78
		FVul (%)	67.5 (52/77)	71.0 (49/69)	74.3 (52/70)	75.3 (58/77)	73.5 (61/83)
Cold Seeps	TBD	FRic	48	41	40	43	47
		FRed	1.81	1.73	1.75	1.65	1.68
		FVul (%)	68.8 (33/48)	70.7 (29/41)	65.0 (26/40)	74.4 (32/43)	66.0 (31/47)
Eastern Shoal	TBD	FRic	67	68	69	69	72
		FRed.	1.76	1.78	1.75	1.74	1.74
		FVul (%)	67.2 (45/67)	67.6 (46/68)	68.1 (47/69)	65.2 (45/69)	70.8 (51/72)
Eastern Shore Islands	AOI	FRic	83	91	85	88	90
		FRed	1.81	1.88	1.88	1.83	1.81
		FVul (%)	69.9 (58/83)	68.1 (62/91)	69.4 (59/85)	69.3 (61/88)	71.1 (64/90)
Fundian Channel-Browns Bank	AOI	FRic	108	95	94	104	99
		FRed	2.27	2.11	2.07	2.12	2.15
		FVul (%)	63.0 (68/108)	65.3 (62/95)	67.0 (63/94)	64.4 (67/104)	61.6 (61/99)
Georges Bank	TBD	FRic	82	84	83	90	84
		FRed.	1.95	1.90	1.87	1.90	1.88
		FVul (%)	64.6 (53/82)	69.0 (58/84)	67.5 (56/83)	68.9 (62/90)	66.7 (56/84)
Head Harbour, West Isles and The Passages	TBD	FRic	91	73	75	87	81
		FRed	1.76	1.86	1.81	1.87	1.91
		FVul (%)	69.2 (63/91)	69.9 (51/73)	72.0 (54/75)	69.0 (60/87)	69.1 (56/81)

Site	Type	Func. Index	Present	Mid-century		End-of-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
Horse Mussel Reefs	TBD	FRic	85	77	73	88	78
		FRed	1.80	1.81	1.85	1.78	1.90
		FVul (%)	69.4 (59/85)	70.1 (54/77)	67.1 (49/73)	70.5 (62/88)	67.9 (53/78)
LaHave Basin	TBD	FRic	82	85	82	86	88
		FRed.	1.85	1.98	2.01	1.92	1.93
		FVul (%)	69.5 (57/82)	68.2 (58/85)	64.6 (53/82)	66.3 (57/86)	68.2 (60/88)
LaHave Islands	TBD	FRic	78	83	76	80	87
		FRed	1.88	1.98	1.99	1.90	1.87
		FVul (%)	64.1 (50/78)	67.5 (56/83)	63.2 (48/76)	65.0 (52/80)	69.0 (60/87)
Long Eddy	TBD	FRic	89	71	75	85	78
		FRed	1.75	1.83	1.76	1.85	1.94
		FVul (%)	69.7 (62/89)	70.4 (50/71)	73.3 (55/75)	69.4 (59/85)	67.9 (53/78)
Middle Bank-Canso Bank	TBD	FRic	74	79	76	78	84
		FRed.	1.99	1.90	1.95	1.90	1.82
		FVul (%)	63.5 (47/74)	68.4 (54/79)	65.8 (50/76)	67.9 (53/78)	75.0 (63/84)
Misaine Bank and Laurentian Channel	TBD	FRic	83	74	75	78	83
		FRed	2.02	1.95	1.96	1.97	1.84
		FVul (%)	63.9 (53/83)	63.5 (47/74)	60.0 (45/75)	62.8 (49/78)	71.1 (59/83)
North of Emerald Basin Sea Pen Field	TBD	FRic	82	89	84	89	91
		FRed	1.79	1.85	1.87	1.78	1.78
		FVul (%)	73.2 (60/82)	68.5 (61/89)	67.9 (57/84)	69.7 (62/89)	72.5 (66/91)
Northern Gulf of Maine	TBD	FRic	90	86	84	87	88
		FRed	1.88	2.01	1.99	2.03	1.99
		FVul (%)	67.8 (61/90)	66.3 (57/86)	66.7 (56/84)	64.4 (56/87)	69.3 (61/88)
Pearl Island	TBD	FRic	80	85	79	83	89
		FRed	1.91	1.96	1.99	1.88	1.89

Site	Type	Func. Index	Present	Mid-century		End-of-century	
				SSP1-2.6	SSP5-8.5	SSP1-2.6	SSP5-8.5
		FVul (%)	65.0 (52/80)	68.2 (58/85)	64.6 (51/79)	66.3 (55/83)	69.7 (62/89)
Point Michaud and Basque Islands	TBD	FRic	70	77	73	74	76
		FRed	1.80	1.62	1.66	1.76	1.76
		FVul (%)	71.4 (50/70)	74.0 (57/77)	75.3 (55/73)	71.6 (53/74)	73.7 (56/76)
Port Joli and Surrounding Areas	TBD	FRic	70	77	73	74	76
		FRed	1.78	2.01	1.98	1.95	1.96
		FVul (%)	69.9 (65/70)	66.3 (61/77)	65.5 (57/73)	68.1 (62/74)	68.8 (64/76)
Roseway Bank	TBD	FRic	98	93	90	97	95
		FRed	1.90	2.05	2.07	1.99	2.04
		FVul (%)	68.4 (67/98)	65.6 (61/93)	65.6 (59/90)	69.1 (67/97)	66.3 (63/95)
Sable Island Bank	TBD	FRic	82	80	79	83	86
		FRed	2.01	1.94	2.03	1.94	1.97
		FVul (%)	65.9 (54/82)	66.2 (53/80)	64.6 (51/79)	67.5 (56/83)	69.8 (60/86)
Sambro Ledges - Prospect	TBD	FRic	77	79	74	80	83
		FRed	1.83	1.91	1.96	1.81	1.90
		FVul (%)	68.8 (53/77)	67.1 (53/79)	63.5 (47/74)	66.2 (53/80)	69.9 (58/83)
Scotian Gulf	TBD	FRic	99	89	85	88	88
		FRed	2.08	2.03	2.07	2.08	2.14
		FVul (%)	65.7 (65/99)	68.5 (61/89)	65.9 (56/85)	67.0 (59/88)	62. (55/88)
South Grand Manan	TBD	FRic	92	85	83	88	89
		FRed	1.83	1.98	1.92	1.93	1.97
		FVul (%)	67.4 (62/92)	65.9 (56/85)	65.1 (54/83)	68.2 (60/88)	68.5 (61/89)
Southern Bight	TBD	FRic	78	79	77	89	85
		FRed	1.90	1.95	1.88	1.83	1.85
			67.9	68.4	72.7	70.8	69.4

Site	**Type**	**Func. Index**	**Present**	**Mid-century**		**End-of-century**	
				SSP1-2.6	**SSP5-8.5**	**SSP1-2.6**	**SSP5-8.5**
		FVul (%)	(53/78)	(54/79)	(56/77)	(63/89)	(59/85)
Western Jordan Basin	TBD	FRic	83	82	80	83	80
		FRed	1.87	1.98	2.00	2.01	1.96
		FVul (%)	65.1 (54/83)	64.6 (53/82)	66.2 (53/80)	65.1 (54/83)	67.5 (54/80)

Table B4. Change in functional entities (FEs) for the proposed protected seascape features in the Fisheries and Oceans Canada Maritime Region, comparing the number of immigrating (Immig.), emigrating (Emig.) and the same FEs between each time and scenario. Sites are ordered alphabetically.

Site	Type	Func. Change	Present – Mid-century		Present – End-century		Mid-century - End-century	
			SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5
Big Glace Bay	TBD	Same	59	62	60	56	72	67
		Immig.	14	14	13	24	1	13
		Emig.	12	9	11	15	1	9
Bird Islands	TBD	Same	50	48	51	41	55	45
		Immig.	6	6	6	15	2	11
		Emig.	8	10	7	17	1	9
Bon Portage Island	TBD	Same	66	64	67	58	82	68
		Immig.	16	14	17	23	2	13
		Emig.	23	25	22	31	0	10
Bras d'Or Lakes EBSA	TBD	Same	65	65	64	61	80	70
		Immig.	19	13	16	26	0	17
		Emig.	9	9	10	13	4	8
Brier Island	TBD	Same	68	67	70	66	83	71
		Immig.	15	12	15	21	2	16
		Emig.	22	23	20	24	0	8
Canso Ledges - Sugar Harbour Islands	TBD	Same	66	64	65	61	81	72
		Immig.	19	16	17	25	1	14
		Emig.	8	10	9	13	4	8
Central Scotian Slope, Rise and Abyss	TBD	Same	79	77	83	78	89	81
		Immig.	10	9	13	14	7	11
		Emig.	16	18	12	17	0	5
Chebogue	TBD	Same	67	66	69	61	83	74
		Immig.	18	18	19	24	5	11
		Emig.	23	24	21	29	2	10
Chignecto Bay	TBD	Same	65	62	66	61	69	64
		Immig.	4	8	11	22	8	19
		Emig.	12	15	11	16	0	6
Cold Seeps	TBD	Same	31	29	32	32	38	39
		Immig.	10	11	11	15	5	8
		Emig.	17	19	16	16	3	1
	TBD	Same	58	59	57	55	65	64

Site	**Type**	**Func. Change**	**Present – Mid-century**		**Present – End-century**		**Mid-century - End-century**	
			SSP1-2.6	**SSP1-8.5**	**SSP1-2.6**	**SSP1-8.5**	**SSP1-2.6**	**SSP1-8.5**
Eastern Shoal		Immig.	10	10	12	17	4	8
		Emig.	9	8	10	12	3	5
Eastern Shore Islands	AOI	Same	73	72	74	67	85	77
		Immig.	18	13	14	23	3	13
		Emig.	10	11	9	16	6	8
Fundian Channel-Browns Bank	AOI	Same	88	87	94	84	95	88
		Immig.	7	7	10	15	9	11
		Emig.	20	21	14	24	0	6
Georges Bank	TBD	Same	69	67	72	63	83	76
		Immig.	15	16	18	21	7	8
		Emig.	13	15	10	19	1	7
Head Harbour, West Isles and The Passages	TBD	Same	69	68	72	63	73	64
		Immig.	4	7	15	18	14	17
		Emig.	22	23	19	28	0	11
Horse Mussel Reefs	TBD	Same	70	65	71	57	77	60
		Immig.	7	8	17	21	11	18
		Emig.	15	20	14	28	0	13
LaHave Basin	TBD	Same	67	64	68	63	78	77
		Immig.	18	18	18	25	8	11
		Emig.	15	18	14	19	7	5
LaHave Islands	TBD	Same	66	63	65	61	76	70
		Immig.	17	13	15	26	4	17
		Emig.	12	15	13	17	7	6
Long Eddy	TBD	Same	67	67	70	61	70	64
		Immig.	4	8	15	17	15	14
		Emig.	22	22	19	28	1	11
Middle Bank-Canso Bank	TBD	Same	63	59	63	59	76	72
		Immig.	16	17	15	25	2	12
		Emig.	11	15	11	15	3	4
Misaine Bank and Laurentian Channel	TBD	Same	70	69	69	69	72	72
		Immig.	4	6	9	14	6	11
		Emig.	13	14	14	14	2	3

Site	Type	Func. Change	Present – Mid-century		Present – End-century		Mid-century - End-century	
			SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5
North of Emerald Basin Sea Pen Field	TBD	Same	73	71	73	67	85	77
		Immig.	16	13	16	24	4	14
		Emig.	9	11	9	15	4	7
Northern Gulf of Maine	TBD	Same	69	65	70	65	84	76
		Immig.	17	19	17	23	3	12
		Emig.	21	25	20	25	2	8
Pearl Island	TBD	Same	67	64	67	62	78	74
		Immig.	18	15	16	27	5	15
		Emig.	13	16	13	18	7	5
Point Michaud and Basque Islands	TBD	Same	60	58	58	55	72	64
		Immig.	17	15	16	21	2	12
		Emig.	10	12	12	15	5	9
Port Joli and Surrounding Areas	TBD	Same	76	71	76	72	88	83
		Immig.	16	16	15	21	3	10
		Emig.	17	22	17	21	4	4
Roseway Bank	TBD	Same	78	75	79	74	92	84
		Immig.	15	15	18	21	5	11
		Emig.	20	23	19	24	1	6
Sable Island Bank	TBD	Same	66	64	68	65	79	75
		Immig.	14	15	15	21	4	11
		Emig.	16	18	14	17	1	4
Sambro Ledges - Prospect	TBD	Same	63	61	66	59	73	68
		Immig.	16	13	14	24	7	15
		Emig.	14	16	11	18	6	6
Scotian Gulf	TBD	Same	83	78	81	75	83	80
		Immig.	6	7	7	13	5	8
		Emig.	16	21	18	24	6	5
South Grand Manan	TBD	Same	71	71	74	69	84	76
		Immig.	14	12	14	20	4	13
		Emig.	21	21	18	23	1	7
Southern Bight	TBD	Same	69	67	70	63	77	69
		Immig.	10	10	19	22	12	16
		Emig.	9	11	8	15	2	8

Site	Type	Func. Change	Present – Mid-century		Present – End-century		Mid-century - End-century	
			SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5
Western Jordan Basin	TBD	Same	63	59	65	55	81	69
		Immig.	19	21	18	25	2	11
		Emig.	20	24	18	28	1	11

Table B5: Ecological Disruption Index (EDI) for the proposed protected seascape features in the Fisheries and Oceans Canada Maritime Region. Sites are ordered alphabetically.

Site	**Type**	**Present – Mid-century**		**Present – End-century**		**Mid-century - End-century**	
		SSP1-2.6	**SSP1-8.5**	**SSP1-2.6**	**SSP1-8.5**	**SSP1-2.6**	**SSP1-8.5**
Big Glace Bay	TBD	0.18	0.16	0.17	0.26	0.01	0.14
Bird Islands	TBD	0.12	0.14	0.11	0.28	0.03	0.18
Bon Portage Island	TBD	0.23	0.23	0.23	0.32	0.01	0.14
Bras d’Or Lakes EBSA	TBD	0.18	0.14	0.17	0.24	0.02	0.15
Brier Island	TBD	0.21	0.21	0.20	0.25	0.01	0.14
Canso Ledges - Sugar Harbour Islands	TBD	0.17	0.17	0.17	0.24	0.03	0.13
Central Scotian Slope, Rise and Abyss	TBD	0.14	0.15	0.13	0.17	0.04	0.09
Chebogue	TBD	0.23	0.24	0.22	0.30	0.04	0.12
Chignecto Bay	TBD	0.11	0.16	0.14	0.24	0.05	0.16
Cold Seeps	TBD	0.30	0.34	0.30	0.33	0.10	0.10
Eastern Shoal	TBD	0.14	0.13	0.16	0.21	0.05	0.09
Eastern Shore Islands	AOI	0.16	0.14	0.13	0.23	0.05	0.12
Fundian Channel-Browns Bank	AOI	0.13	0.14	0.11	0.19	0.05	0.09
Georges Bank	TBD	0.17	0.19	0.16	0.24	0.05	0.09

Site	Type	Present – Mid-century		Present – End-century		Mid-century - End-century	
		SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5
Head Harbour, West Isles and The Passages	TBD	0.16	0.18	0.19	0.27	0.09	0.18
Horse Mussel Reefs	TBD	0.14	0.18	0.18	0.30	0.07	0.21
LaHave Basin	TBD	0.20	0.22	0.19	0.26	0.09	0.09
LaHave Islands	TBD	0.18	0.18	0.18	0.26	0.07	0.14
Long Eddy	TBD	0.16	0.18	0.20	0.27	0.10	0.16
Middle Bank-Canso Bank	TBD	0.18	0.21	0.17	0.25	0.03	0.10
Misaine Bank and Laurentian Channel	TBD	0.11	0.13	0.14	0.17	0.05	0.09
North of Emerald Basin Sea Pen Field	TBD	0.15	0.14	0.15	0.23	0.04	0.12
Northern Gulf of Maine	TBD	0.22	0.25	0.21	0.27	0.03	0.12
Pearl Island	TBD	0.19	0.19	0.18	0.27	0.07	0.12
Point Michaud and Basque Islands	TBD	0.18	0.19	0.19	0.25	0.05	0.14
Port Joli and Surrounding Areas	TBD	0.18	0.21	0.17	0.23	0.04	0.08

Site	Type	Present – Mid-century		Present – End-century		Mid-century - End-century	
		SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5	SSP1-2.6	SSP1-8.5
Roseway Bank	TBD	0.18	0.20	0.19	0.23	0.03	0.09
Sable Island Bank	TBD	0.19	0.20	0.18	0.23	0.03	0.09
Sambro Ledges - Prospect	TBD	0.19	0.19	0.16	0.26	0.08	0.13
Scotian Gulf	TBD	0.12	0.15	0.13	0.20	0.06	0.08
South Grand Manan	TBD	0.20	0.19	0.18	0.24	0.03	0.12
Southern Bight	TBD	0.12	0.14	0.16	0.23	0.08	0.15
Western Jordan Basin	TBD	0.24	0.28	0.22	0.33	0.02	0.14

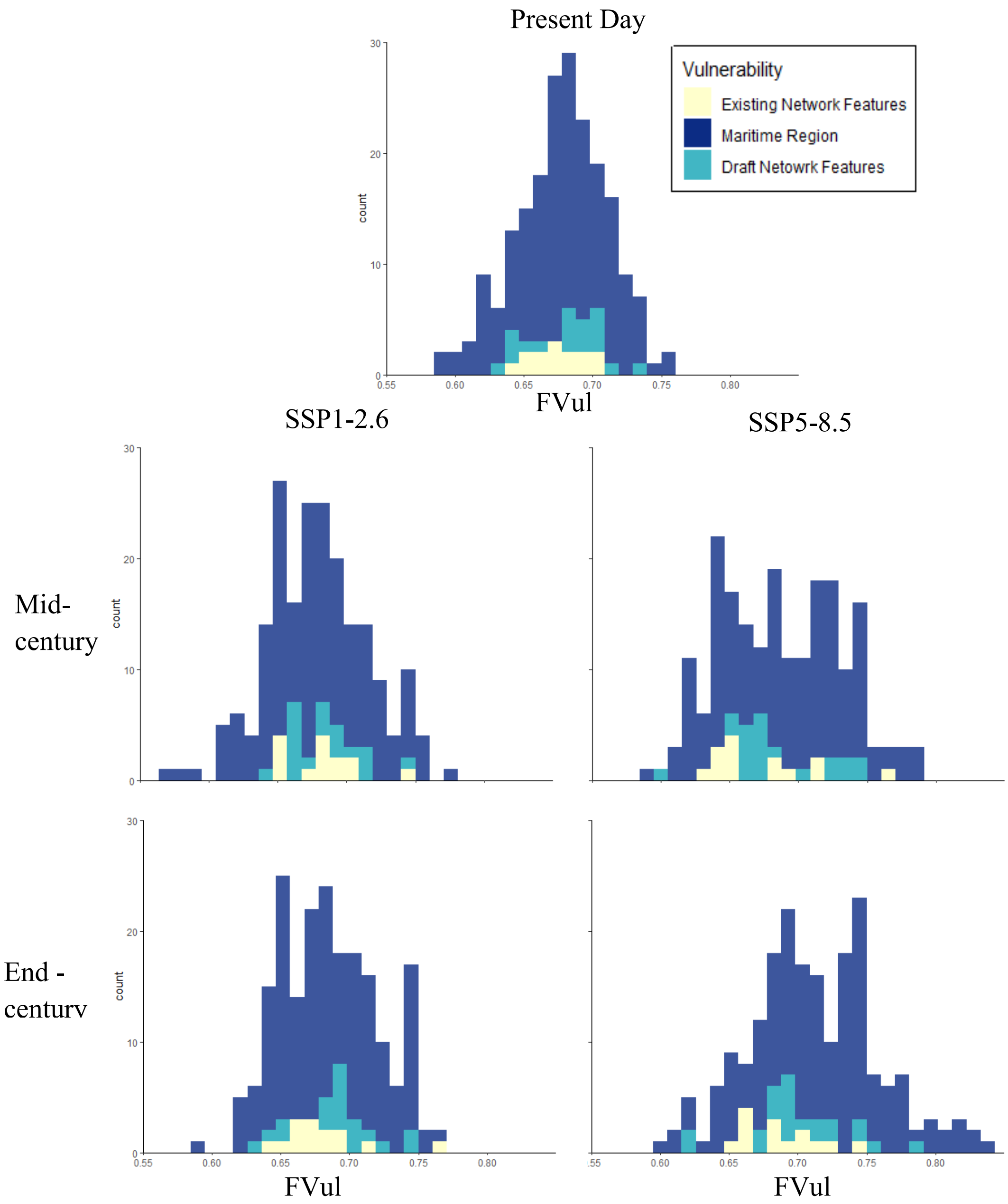

Figure B1. The distribution of functional vulnerability (FVul) as was calculated for each of the 201 grid cells across the Fisheries and Oceans Canada Scotian Shelf-Bay of Fundy Bioregion relative to all existing sites in the Maritime Conservation Network (Marine Protected Areas: 7 and Other Effective area-based Conservation Measures: 7,) and proposed network sites (areas of interest: 2, proposed: 31). The first row is present day, the second row is the mid-century, and the third row end-of-century. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

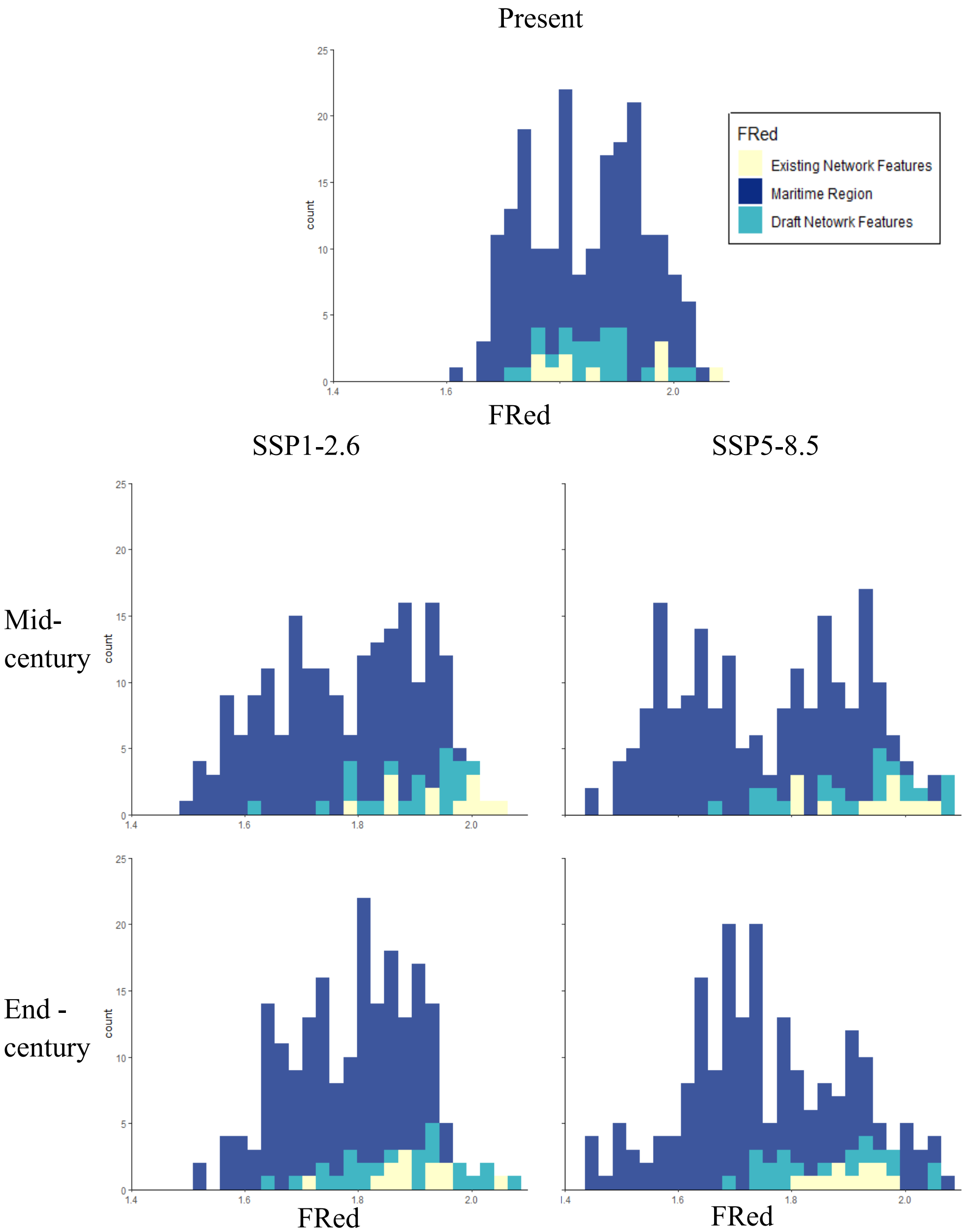

Figure B2. The distribution of functional redundancy (FRed) as was calculated for each of the 201 grid cells across the Fisheries and Oceans Canada Scotian Shelf-Bay of Fundy Bioregion relative to all existing sites in the Maritime Conservation Network (Marine Protected Areas: 7 and Other Effective area-based Conservation Measures: 7,)) and proposed network sites (areas of interest: 2, proposed: 31). The first row is present day, the second row is the mid-century, and the third row end-of-century. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

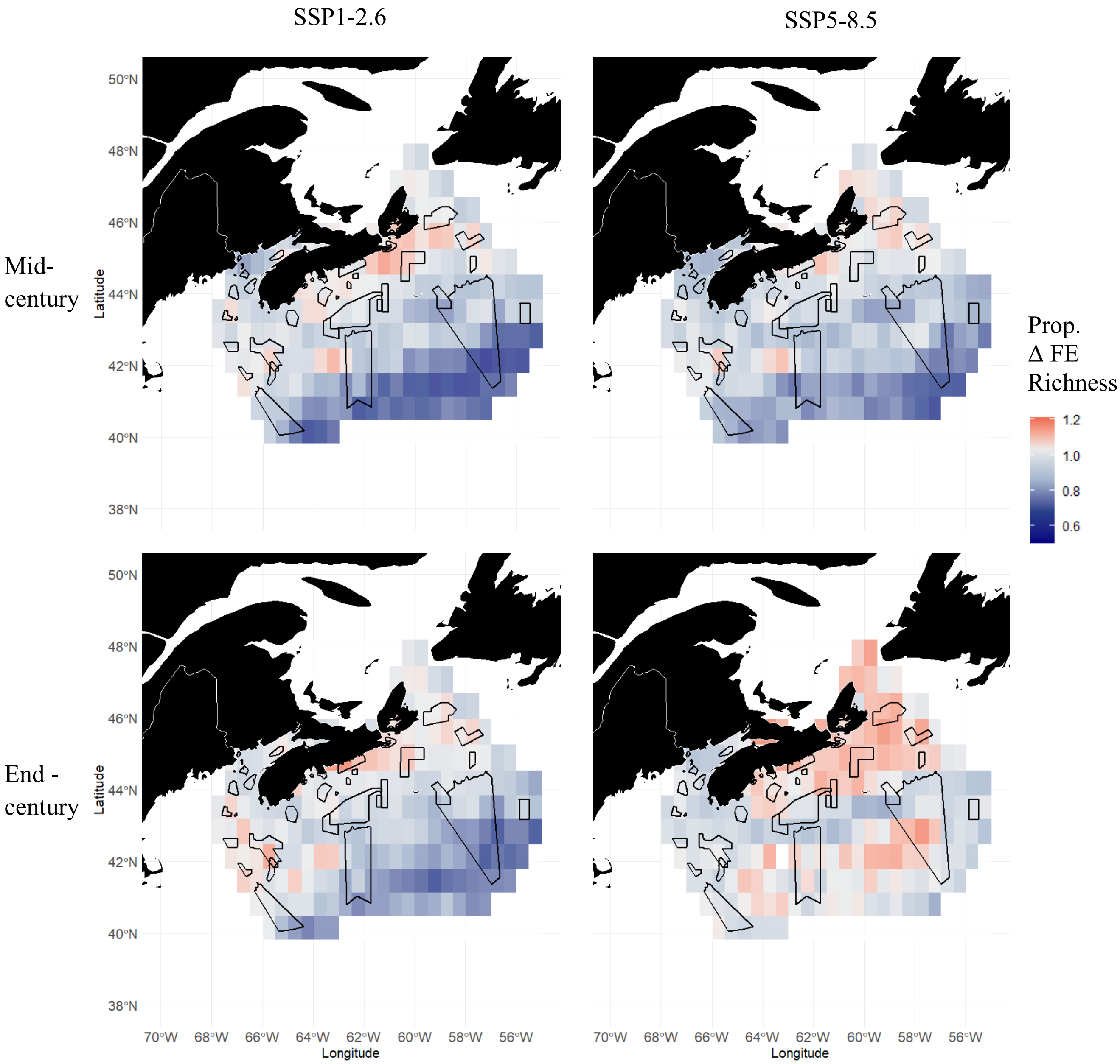

Figure B3. Proportional change in functional entity (FE) richness relative to present day for the Fisheries and Oceans Canada Maritimes Region. The first row is the proportional change in FE richness from present day to mid-century and the second row is the proportional change in FE richness from present day to end-of-century. The columns indicate SSP1-2.6 and SSP5-8.5 respectively.

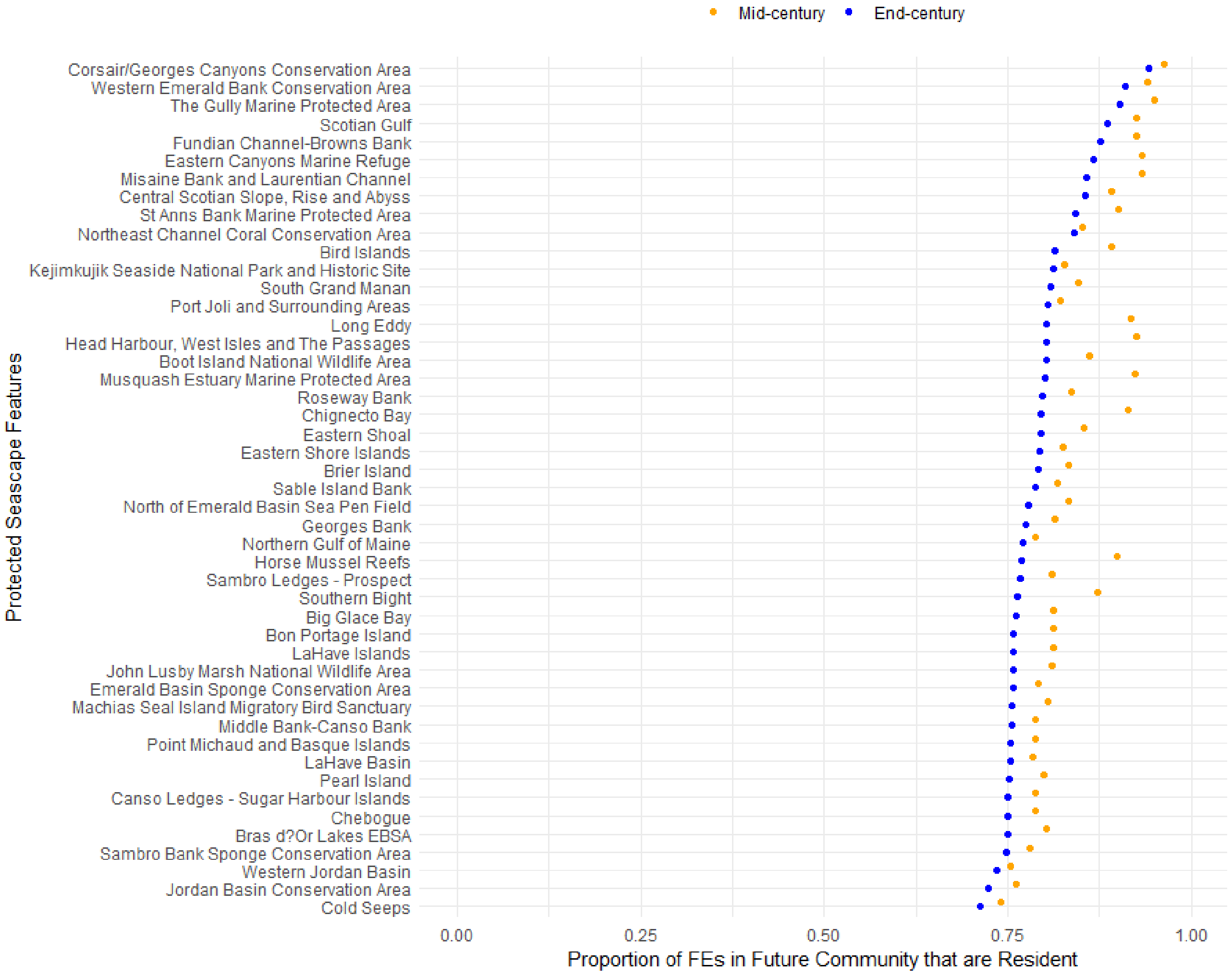

Figure B4. The average proportion of functional entities (FEs) that were the same as present day for each protected seascape site (existing and proposed) in the Fisheries and Oceans Canada Maritime Conservation Network. Protected seascape sites are ranked from highest to lowest proportions of remaining residents in the end-century. Mid- and end-century (averaged across high and low emissions scenarios) are indicated by orange and blue dots, respectively.

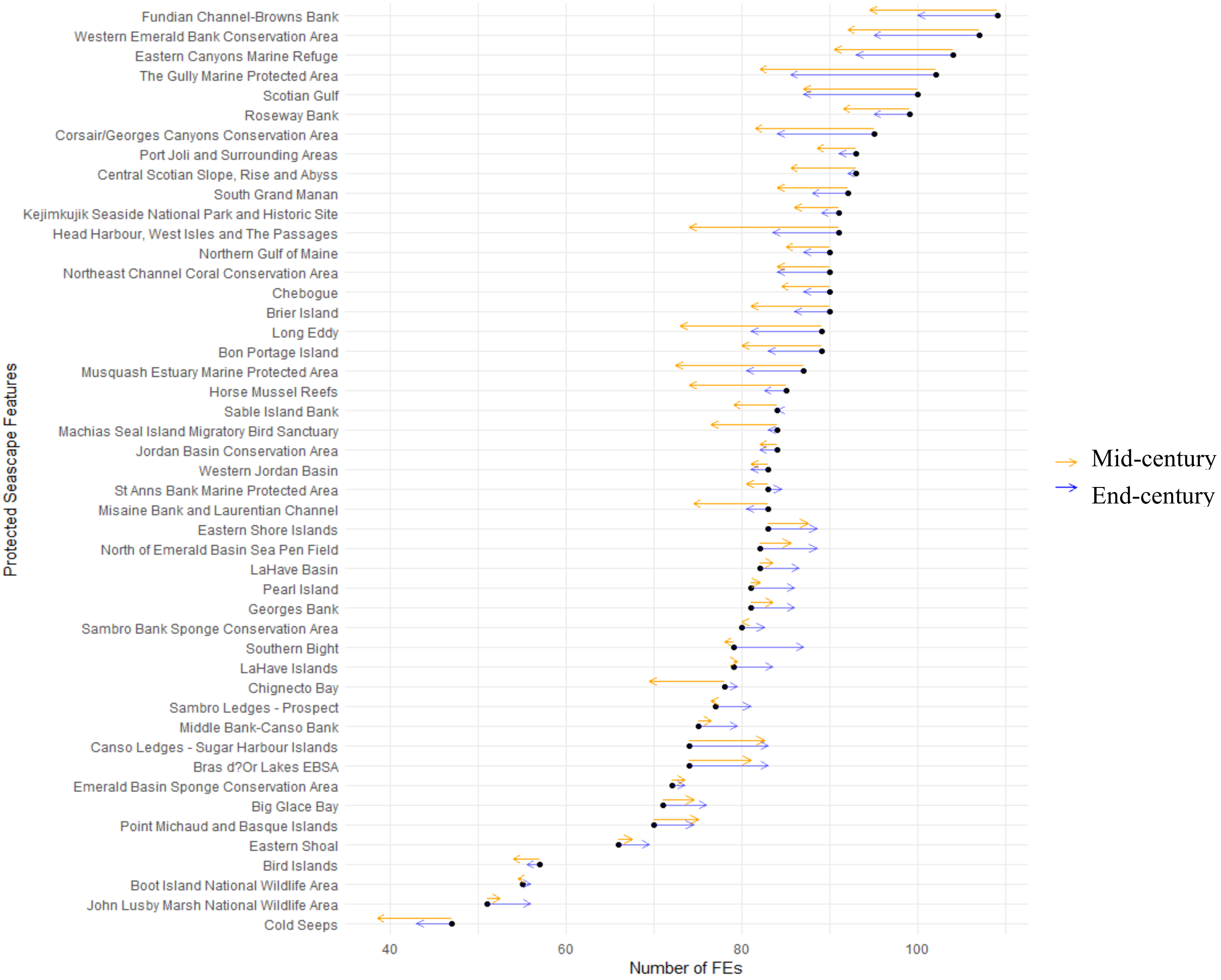

Figure B5. All proposed (33) and existing Marine Protected Areas (n = 7) and Other Effective area-based Conservation Measures (n = 7) within the Fisheries and Oceans Canada Maritime Conservation Network ranked by number of functional entities (FEs) protected overall. The change in the number of FEs protected by each protected seascape site into mid-century and end-of-century (averaged across both low-emissions and high-emissions scenarios) indicated by orange and blue arrows, respectively.