Monitoring Connectivity and Climate Change in the Gully Marine Protected Area

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MONITORING CONNECTIVITY AND CLIMATE CHANGE IN THE GULLY MARINE PROTECTED AREA

by

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The Gully Marine Protected Area (MPA) is a large, offshore submarine canyon that hosts diverse communities of corals, sponges, fishes, and cetaceans, including a resident population of endangered Northern Bottlenose Whales (*Hyperoodon ampullatus*). The Department of Fisheries and Oceans Canada (DFO) is leading the development of a network of Marine Protected Areas to meet its international commitments for biodiversity conservation. The Canadian Conservation network is composed of bioregional subnetworks with the overarching goal to provide long-term protection of marine biodiversity, ecosystem function, and special natural features in Canada's oceans. Achieving this goal requires the application of core design features, including the incorporation of ecologically and biologically significant areas, ecological representation, replication, and connectivity. When applied with consideration for how climate change will influence the spatial-temporal aspects of conserved areas, these design principals will help to position the Canadian networks to achieve conservation objectives now and into the future. In 2010, a monitoring framework for the Gully was published, suggesting 47 indicators to effectively monitor the ecosystem over time. At that time however, the Gully existed in isolation of a broader regional Scotian Shelf – Bay of Fundy Conservation network, and this report was undertaken to investigate attributes of connectivity that are relevant to the Gully's conservation focus, and how to monitor connectivity over time. Similarly, climate change is an ever-growing threat to the global ocean, and we make suggestions on how to monitor the impacts of increasing temperatures, ocean acidification, and deoxygenation on the Gully ecosystem over time. Our key recommendations include using genomics, telemetry, and modeling to quantify and monitor connectivity among the Gully and other network sites, as well as recommendations to monitor biological indicators in concert with oceanographic indicators, and the effects of climate change.

RÉSUMÉ

Jeffery, N.W., Stanley, R.R.E., and Heaslip, S.G. 2021. Monitoring Connectivity and Climate Change in the Gully Marine Protected Area. Can. Tech. Rep. Fish. Aquat. Sci. 3453 : vii + 52 p.

La zone de protection marine (ZPM) du Gully est un vaste canyon sous-marin extracôtier qui abrite diverses communautés de coraux, d'éponges, de poissons et de cétacés, dont une population résidente de baleine à bec commune (*Hyperoodon ampullatus*), une espèce en voie de disparition. Pêches et Océans Canada (MPO) dirige l'élaboration d'un réseau d'aires marines protégées afin de respecter ses engagements internationaux à l'égard de la conservation de la biodiversité. Le réseau canadien de conservation est composé de sous-réseaux biorégionaux et vise principalement à assurer la protection à long terme de la biodiversité marine, de la fonction écosystémique et des caractéristiques naturelles particulières dans les océans du Canada. L'atteinte de ces objectifs nécessite l'application de caractéristiques de conception fondamentales, dont l'incorporation de zones d'importance écologique et biologique, la représentation écologique, la répétition, et la connectivité. S'ils sont appliqués en tenant compte de la façon dont les changements climatiques influeront sur les aspects sociotemporels des zones de conservation, ces principes de conception permettront aux réseaux canadiens et infrarégionaux d'aider à atteindre les objectifs de conservation maintenant et dans l'avenir. En 2010, un cadre de surveillance a été publié pour le Gully. On y suggérait 47 indicateurs pour surveiller l'écosystème de façon efficace au fil du temps. Toutefois, à cette époque, le Gully ne faisait pas partie du réseau de conservation plus large du plateau néo-écossais–baie de Fundy, et ce rapport visait à étudier les paramètres de connectivité pertinents pour les objectifs de conservation du Gully, et les moyens de surveiller la connectivité au fil du temps. De même, les changements climatiques sont une menace croissante pour les océans du monde, et nous formulons des suggestions sur la façon de surveiller les répercussions de l'augmentation des températures, de l'acidification des océans et de la désoxygénation sur l'écosystème du Gully avec le temps. Nos principales recommandations sont notamment d'avoir recours à la génomique, à la télémétrie et à la modélisation pour quantifier et surveiller la connectivité dans le Gully et les autres sites du réseau, et de surveiller les indicateurs biologiques de pair avec les indicateurs océanographiques, de même que les effets des changements climatiques.

INTRODUCTION

The Gully Marine Protected Area (MPA) was established in 2004 under the federal *Oceans Act* to protect the unique canyon ecosystem from anthropogenic impacts, such as commercial fishing and oil and gas exploitation (DFO 2008). The Gully formed as a shelf edge canyon between 150K-450K years ago as a result of fluvial, glacial, and erosive processes. At 40 km in length, 16 km wide, and with depths exceeding 3000 m as it approaches the abyssal plain, the Gully is the largest submarine canyon in the Northwest Atlantic (Figure 1). The Gully is rich in marine biodiversity, with numerous species of benthic and demersal fishes, a diversity of benthic habitats including its steep canyon walls, abundance and diversity of deep sea corals (Breeze et al. 1997, Cogswell et al. 2009, Kenchington et al. 2010), and high concentrations of cetaceans, including the endangered Northern Bottlenose Whale, *Hyperoodon ampullatus* (Moors-Murphy 2014).

The Gully area was originally designated a Whale Sanctuary in 1994. In 1997, the Department of Fisheries and Oceans Canada (DFO) was asked to lead a scientific review of the available information on the Gully ecosystem. This review team included 32 government, academic, and other (World Wildlife Fund, Nova Scotia Museum, Ecology Action Centre) researchers that summarized the current state of knowledge of the Gully, including its geology, hydrography, oceanography, fisheries, marine birds, and marine mammals; and identified information gaps (Harrison and Fenton 1998). In 1999, DFO funded a two-year research program to help fill some of these information gaps with projects investigating seasonal and tidal circulation, internal waves, nutrients, primary production, zooplankton, and benthic habitat and communities conducted by DFO and Natural Resources Canada. In 2001, a Gully Science Review meeting was held to present and review available results from these projects with a summary of proceedings reported in Gordon and Fenton (2002). Scientific research during this time involved collecting information on bathymetry using multibeam, benthic assemblages and habitat classifications, physical and chemical oceanography, and plankton production and distribution in the Gully (Gordon and Fenton 2002).

In May 2004, the Gully was designated as an MPA under the *Oceans Act* and published in the *Canada Gazette*, which established the MPA boundary and zoning. The first Gully MPA Management Plan published in 2008 (DFO 2008), outlined the steps leading to the establishment of the Gully as an MPA, and an overview of the conservation objectives. In 2017, the second edition of the *Gully Marine Protected Area Management Plan* (DFO 2017) was published, which updated the first Management Plan using new and revised knowledge on the Gully environment, advice received between 2008 and 2017, and experience on managing the Gully MPA.

The *Gully Marine Protected Area Management Plan* (DFO 2017) states a vision for the Gully MPA, provides guiding principles, and describes four conservation objectives as a focus for monitoring. The guiding principles for the Gully include:

- An ecosystem approach to management;
- Collaboration and stewardship with other organizations and stakeholders;
- The precautionary approach to evaluate proposed activities;
- Integrated management of human activities;
- Knowledge-based decision-making based on scientific information and traditional ecological knowledge;
- Adaptive planning and management as the ecosystem changes over time.

The conservation objectives were developed to address specific conservation-based priorities for the MPA, and were identified through scientific peer-review and discussions with stakeholders. These conservation objectives include:

- Minimize harmful impacts from human activities on cetacean populations and their habitats;
- Minimize the disturbance of seafloor habitat and associated benthic communities caused by human activity;
- Maintain and monitor the quality of water and sediments of the Gully; and
- Manage human activities to minimize impacts on other commercial and non-commercial living resources.

Kenchington (2010) provided an indicator framework for monitoring the Gully MPA to be undertaken by the Department of Fisheries and Oceans Canada and its partners. In total, 47 monitoring indicators (variables that can be monitored and provide information on the status of the MPA ecosystem) were recommended for 18 component programs. Kenchington (2010) emphasized that in addition to environmental monitoring of the biological and physical aspects of the Gully, monitoring of the socio-economic effects of the MPA on human interests and governance monitoring is necessary. Generally, a baseline needs to be established for each indicator to monitor temporal changes and effectiveness of the MPA and its management. Such baselines may include an estimation of population size for focal species (with associated variability), distributions of species of conservation interest, including benthic organisms (i.e., corals and sponges), evaluation of biological diversity associated with the Gully, and the overall physical state/attributes of the canyon itself.

Monitoring of an MPA is a long-term endeavour as some indicators may change rapidly over a seasonal or annual basis (e.g., plankton distributions, cetacean population sizes), whereas others fluctuate on a decadal or longer cycle (e.g., coral growth, physical condition of the canyon). Thus far, monitoring of the Gully MPA has been achieved through both long-term monitoring of some conservation priorities (Northern Bottlenose Whales) by DFO and Dalhousie University, and other information gained through short-term or opportunistic studies of the MPA. Monitoring of biological and oceanographic features of the Gully is primarily achieved by the Atlantic Zone Monitoring Program (AZMP), passive acoustic monitoring for cetaceans by the DFO cetaceans research team, surveys by the Whitehead Lab at Dalhousie University, periodic video and photo surveys for cold-water corals, sponges, and benthos, survey data including the summer ecosystem trawl survey, the DFO-Industry Halibut Longline Survey, the Snow Crab Survey, and fisheries-dependent data for large pelagic species including Swordfish and tunas. AZMP has four stations within the MPA that are regularly sampled for water chemistry characteristics, temperature, and zoo-/phytoplankton and provide a time series of baseline data for these characteristics. The Canadian Wildlife Service, a branch Environment and Climate Change Canada, opportunistically collects marine bird sightings data, usually in conjunction with a research cruise whose primary objective is oceanographic and marine biology focused research.

Data collection and analyses of these indicators is conducted by specific agencies within the Government of Canada and by academic researchers (e.g., the DFO cetaceans group and the Whitehead Lab of Dalhousie University are tasked with collecting acoustic and visual data on cetaceans of the Gully), none of which currently focus on evaluating the Gully's connectivity to surrounding ecosystems nor the impacts of climate change on the Gully ecosystem. Monitoring programs and proposed frameworks have considered the Gully MPA primarily in isolation and thus do not provide inference for how the Gully ecosystem is connected to, and potentially dependant on, the surrounding seascape.

In the years since establishment, planning for a regional conservation network has progressed (DFO 2018a) and the Gully is now considered one of a collection of sites and hierarchy of spatial conservation targets and objectives, despite it being first conceived and designed in absence of a network context. How the Gully MPA fits within this regional conservation network, in terms of representativity of network conservation targets and connectivity to existing or proposed sites, has not yet been evaluated. Although areal coverage and representativity have been advocated as of primary importance for conservation network design and monitoring (Costello and Connor 2019), studies have shown that enhanced persistence of biodiversity is dependant on conservation design that is both representative and well connected (Magris et al. 2018, Manel et al. 2019b). Further, it is necessary to explore the potential for shifts in the geographic distribution of representative communities, biodiversity hotspots, and patterns of connectivity due to climate change. Both the impacts of climate change and connectivity should be considered and incorporated into the design of a conservation network, as well-connected MPA networks can increase the resilience of ecosystems to the impacts of climate change (Balbar et al. 2020). However, connectivity and climate change impacts have rarely been considered in monitoring of individual MPAs or MPA networks (Balbar and Metaxas 2019), and even more rarely integrated together into the design phase (Magris et al. 2018, Magris et al. 2016). MPAs as fixed sites may offer little protection from the broad-scale influences of climate change on marine ecosystems; however, an effective network of MPAs should confer resilience through appropriate sizing and spacing of MPAs and the maintenance of diversity and ecosystem function via connectivity among MPAs (McLeod et al. 2009).

The monitoring framework proposed by Kenchington (2010) provides a comprehensive overview of the Gully ecosystem and the indicators that can be used to effectively monitor the Gully and its conservation objectives, and also identifies climate change as one the primary threats the MPA is facing. Climate change will inevitably impact the Gully's oceanography and ecology; therefore monitoring of biological indicators should be conducted simultaneously with physical and chemical oceanography indicators.

Climate change can directly impact connectivity of populations and communities through habitat fragmentation, and changes in larval survival or dispersal potential. Though these impacts largely cannot be mitigated by individual MPAs, networks of well-connected MPAs that are developed with consideration for how climate change will influence the system could provide some resilience to the anticipated change through recruitment to protected areas and providing refugia as habitat preferences shift (Munday et al. 2009, Nuñez et al. 2013). Currently monitoring frameworks and existing monitoring programs for the Gully MPA do not address either topic explicitly. In this working paper, we evaluate key attribute of connectivity that are relevant for the status of conservation priorities of the MPA. We further build on this by considering how climate change may influence conservation priorities of the MPA and how climate change may itself influence connectivity. Throughout this report we provide pragmatic approaches to measure and monitor connectivity and climate change within the MPA helping to better articulate performance in fulfilment of site and regional conservation network level objectives.

CONNECTIVITY AMONG NETWORK SITES

Connectivity refers to the movement of organisms, genes, energy, chemicals, or materials among habitats, populations, communities, and/or ecosystems. Numerous types of connectivity exist, including landscape, genetic, demographic, functional, and ecosystem connectivity, each with their own definitions (Carr et al. 2017). Connectivity can simply refer to the dispersal of larval or adult organisms from one location to another, or can be used to represent collective movement, survival, and successful reproduction of individuals across temporal and spatial scales (Carr et al. 2017). Connectivity is often regarded is a key feature for MPA network design and marine spatial planning, and is ecologically important as connected populations are essential for survival, dispersal, recovery from damage and perturbations, and adaptation (Gary et al. 2020). In a critical review of existing Canadian MPAs and other effective area-based conservation measures (OECMs), Lemieux and Gray (2020) state that effective protection of marine biodiversity can only be achieved in the Canadian networks with effective minimum standards, adequate representativity, resilience, and connectivity. The establishment of connectivity via dispersal corridors of suitable habitat (particularly those backed by legislation) is key to ensuring that a network of MPAs is greater than the sum of its parts (Balbar et al. 2020, Lemieux and Gray 2020).

Connectivity is an important ecological process and design feature to consider when designing an MPA network; however, connectivity has only been partially considered or considered *post hoc* in the five priority bioregions for network design in Canada. To design a well-connected network of conserved areas, managers must first consider how conservation priorities are distributed and connected spatially and, in particular, identify spatial connections that influence the persistence and status of the conservation priority within a protected area or network of protected areas (Balbar et al. 2020, Balbar and Metaxas 2019, Smith and Metaxas 2018). For example, the spatial and temporal scales and direction (e.g., source-sink dynamics; Mouquet et al. 2006, Stortini et al. 2020) of linkages between network sites, connecting populations or life stages of conservation priority species whose persistence may depend on spatial linkages among network sites (e.g., recruitment from spawning or nursery grounds or other source populations) should be prioritized in overall network design (see example decision tree in Smith and Metaxas (2018)). Though the application of connectivity in MPA Network design is well supported conceptually, information on connectivity is lacking for many marine species, which makes the assessment of connectivity during the design process difficult. In particular, long-distance dispersal/connectivity (100s-1000s km), especially for deep-sea organisms, is not well understood (Manel et al. 2019b). However, evidence suggests that the interplay of pelagic larval duration and oceanographic current direction and velocity (i.e., physical connectivity) with species-specific environmental preferences (i.e., environmental filtering) contribute to strong geographic clines in community structure on the continental shelf (Cadotte and Tucker 2017, Moritz et al. 2013, Stanley et al. 2018, Stortini et al. 2020). On the Scotian Shelf, the Nova Scotia Current plays a significant role in water circulation with a predominant Northeast-to-Southwest flow. The directionality of this current in combination with the strong climatic differences between NE and SW halves of the shelf has been attributed to patterns of population structure (Stanley et al. 2018) and species turnover (Stortini et al. 2020).The influence of the Nova Scotia Current is likely most pronounced in the shallower portions of the Gully MPA, while less is known about the connectivity of slope habitats.

Existing MPAs within the Scotian Shelf-Bay of Fundy Bioregion include the Gully, St. Anns Bank, and the Musquash Estuary, and two “Areas of Interest” (AOIs) under consideration to become marine protected areas under the *Oceans Act* include: the Eastern Shore Islands AOI and the Fundian Channel-Browns Bank AOI. Though the Gully is the only *Oceans Act* MPA that is designed associated with a submarine canyon, there are several other conservation areas within the regional network that protect similar ecosystems/species that the Gully could be connected to via dispersal. To the southwest lies the Corsair and Georges Canyons Marine Refuge, covering an area of approximately 9100 km^2, established in 2016 to protect high densities of gorgonian corals and a diversity of other corals. Bottom contact fishing is restricted in the closure, with the exception of two “limited fishing” zones which allow fishing for Red Crab (*Chaceon quinquedens*). Near Corsair and Georges canyons also lies the Northeast Channel Coral Conservation Area (NECCCA), a relatively small (424 km^2) fisheries closure designed to protect high densities of corals. The NECCCA is overlapped by the Fundian Channel-Browns Bank AOI (7,184 km^2), an AOI in the Scotian Shelf-Bay of Fundy Bioregional Conservation Network (DFO 2020b). East of the Gully lies the 15 km^2 Lophelia Coral Conservation Area, the only known location of living reef-building coral *Lophelia pertusa* in Atlantic Canada. Finally, in 2018, Shortland and Haldeman Canyons, collectively known as the Eastern Canyons, were announced as a potential deep-water Marine Refuge under the *Fisheries Act*. The study area for this deep-water closure overlaps with the Gully MPA, and the *Lophelia* Coral Conservation Area, encompassing an area of approximately 64,000 km^2 (Lacharité and Stanley 2019). Protection potentially associated with this site would be similar to that of the Gully and Corsair and Georges Canyons, targeted towards to the sensitive benthic habitats in Haldimand and Shortland canyons east of the Gully (Lacharité and Stanley 2019).

CONNECTIVITY THROUGH MIGRATION AND OCEANOGRAPHY

Through biophysical transport, many of these MPAs, AOIs, and coral conservation areas may be connected (Lacharité and Stanley 2019), though connectivity was not considered *a priori* in the design of the currently existing Conservation network in the Scotian Shelf-Bay of Fundy Bioregion. A southwestward flow originating from the Labrador Current (the Shelf-Edge Current; Brickman and Drozdowski 2012, Loder et al. 1998, Wu et al. 2012, Xue et al. 2000), is prevalent in the shallow waters (200–3000 m) of the Eastern Canyons and the Gully. In contrast, a northeastward flow of “Warm Slope Water” (Kenchington et al. 2014, Themelis 1996), influenced by the Gulf Stream (Brickman and Drozdowski 2012), dominates the deeper waters (>3000 m). Evidence suggests that the flow rate in the Gully and nearby canyons decreases with depth (Etter and Bower 2015) as the direction of flow shifts from SW to NE. Further, upwelling and strong mixing via internal waves and tidal currents connect the deeper waters of the Gully (and other canyons) to the waters of the continental shelf (Baines 1982, 1983, Bell 1975, Gordon and Marshall 1976).

In summary, cold Labrador Current water, and waters from the Gulf of St. Lawrence, flow southward into the Gully via the upper continental slope, while warm water incursions from the northeastern flowing Gulf Stream and warm slope water carry organisms into the Gully, including krill, copepods, and subtropical or tropical fishes from southern and offshore waters via the deeper portions of continental slope (Rutherford and Breeze 2002). At least five water types, characterized by different temperature and salinity profiles, have been identified in the Gully: 1) surface outflows from the Gulf of St. Lawrence, 2) surface water from the Shelf-Edge Current, 3) subsurface water from the Cabot Strait, 4) slope water of intermediate depths, and 5) deeper slope waters influenced by the Gulf Stream (Strain and Yeats 2005). The substantial up-canyon flow (upwelling previously mentioned) through the Gully approximates 35,500 m^3s^{-1}

(0.02 ms^{-1}), taking approximately one month to transport water from the mouth of the canyon to its head (Greenan et al. 2014). The characteristics of these water masses and their flow regimes requires consideration when estimating connectivity (e.g., of nutrients, energy, and larvae) within the MPA network.

In most benthic and demersal species of macrophytes, invertebrates, and fishes, connectivity is achieved during the planktonic gamete or larval phase. Larval dispersal is both a passive and an active process, influenced by complex oceanographic processes (currents, upwelling and downwelling, eddies) and biological traits (e.g., swimming, vertical migrations, and pelagic larval duration) (Metaxas and Saunders 2009). Because information on these traits are most often lacking or difficult to quantify, many biophysical models of larval dispersal rely on the pelagic larval duration (PLD), or the developmental period of a species in the water column, to predict possible dispersal pathways for pelagic larvae (Hilário et al. 2015). However, empirically derived estimates of PLD (e.g., temperature-dependant durations), exist for fewer than 100 species that live deeper than 200 m (~78% of the Gully by area is deeper than 200 m), and more than 80% of these species are echinoderms (Gary et al. 2020). The lack of information on the pelagic larval duration of many species limits the quantification of connectivity for resident populations of other invertebrates and fish within the Gully. Post-settlement processes (e.g., adult movement, survival and successful reproduction) are not reflected in biophysical simulations of dispersal and thus on to themselves, these estimates only relate part a portion of the connectivity process. Because few measures will reflect all aspects of species movement throughout their life history, it is important that an ensemble of measures/simulations, including population genetics, natural (e.g., otoliths, stable isotopes) and artificial tagging (e.g., radio and satellite tags), biophysical modeling (e.g., considering oceanographic currents and PLD), and/or habitat suitability modelling (reviewed in Balbar et al. 2020), be applied with assessing connectivity.

Populations in the deep sea are often spatially isolated and fragmented, therefore understanding connectivity of these populations is necessary for their long-term management and evaluation of the Gully's performance as an MPA. Estimating connectivity in deep-sea habitats is hindered by a lack of knowledge on the interplay of deep- and mid-water currents and, as previously mentioned, on larval behaviours/durations of species found in the deep-sea. Biophysical simulations have demonstrated that vertical swimming behaviour of larvae from the deep-sea can influence spatial dispersal patterns more strongly than horizontal currents (Gary et al. 2020). However, this information is lacking for many sessile and meroplanktonic species, particularly those from the deep ocean (Kenchington et al. 2019). Of 15 sponge, sea pen, and Gorgonian coral species examined by Kenchington et al. (2019), the approximate spawning season is known for 10 species, while the PLD is only known for one sponge species (<2 weeks) and two coral species (measured in minutes). In lieu of detailed behavioural data, Hilário et al. (2015) propose that PLD can be used to estimate the minimum dispersal distance to design new MPAs, an approach commonly adopted when setting design-spacing guidelines for MPAs and MPA networks (e.g., Burt et al. 2014, Martone et al. 2021). In a review of eurybathic and deep-sea species, Hilário et al. (2015) estimate that PLDs of 35 and 69 days would ensure a minimal dispersal distance estimates for 50 and 75%, respectively.

Since the Gully includes a wide depth gradient and a number of different habitat types (e.g., shallow shelf waters, continental slope, canyon walls, and deep water fan; Mortensen and Buhl-Mortensen 2005), dispersal and connectivity of fauna that inhabit these habitats will likely be correspondingly variable. For example, juvenile and adult groundfish may disperse across the Scotian Shelf whereas cetaceans and Leatherback Sea Turtles (*Dermochelys coriacea*) generally travel along the continental slope or shelf during seasonal migrations. In contrast, deep-water invertebrates and fishes in the Gully may have relatively low dispersal rates and may only exhibit connectivity with/to areas with similar deep-water habitat (e.g., the Fundian Channel-Browns Bank AOI, Georges and Corsair Canyons Conservation Area) via larval dispersal.

Contributing further variability in connectivity among habitats, some species exhibit a wide range of habitat preferences across their life stages, and a well-connected MPA network will ensure protection of these various preferred habitats (White 2015). Many fish species undergo ontogenetic migrations, moving from juvenile nursery habitats to adult feeding or overwintering grounds. For example, some groundfish species such as Cusk (*Brosme brosme*), White Hake (*Urophycis tenuis*), Atlantic Cod (*Gadus morhua*), Haddock (*Melanogrammus aeglefinus*), and Pollock (*Pollachius virens*) are commonly caught as bycatch in fisheries in the Gully MPA and surrounding areas (Allard et al. 2015), and these species can also be found inshore as either adults on a seasonal basis, or as juveniles in nursery grounds (Clay et al. 1989, Hurlbut and Clay 1998, Laurel et al. 2003, Lilley and Unsworth 2014). The Eastern Shore Islands AOI is a coastal area with extensive Eelgrass, Rockweed, and kelp beds, salt marshes, estuaries, and rocky subtidal substrates that provide habitat for juvenile fishes (Jeffery et al. 2020). While no studies have been conducted specifically on connectivity between the Eastern Shore Islands (and coastal NS) and the Gully, it is possible that juveniles that inhabit the Eastern Shore

Islands, and adjacent coastal areas, may become Gully inhabitants in later life stages through ontogenetic migration.

Finally, larger, more mobile fauna including tunas, Swordfish, cetaceans, sea turtles, and marine birds seasonally visit the Gully ecosystem and travel thousands of kilometers from warmer water mating, calving, and breeding grounds (e.g., Kowarski et al. 2018). The Gully ecosystem and continental slope in general represent highly productive seasonal feeding grounds due to upwelling of nutrients, high concentrations of phytoplankton, and concomitant high levels of seasonal zooplankton and forage species (Gordon and Fenton 2002). As such, the Gully is part of a seasonal feeding ground for migratory species that regularly travel up the continental slope in the spring and summer.

In the sections that follow, we provide more detailed information that detail potential connectivity for various species groups within the Gully MPA. We focus this review primarily on the regional conservation network, detailing potentially connectivity among conserved areas, including MPAs, AOIs, and Marine Refuges.

COLD-WATER CORALS

Cold-water corals are typically observed at depths between 200 and 1000 m (but can be abundant at greater depths), and, along the Atlantic Continental Margin, are associated with slopes of 0 to 10, bottom temperatures ranging from 0.0 to 11 °C, and current velocities ranging from 0 to 207 cm s^{-1} (Bryan and Metaxas 2006). These corals provide important habitat as nurseries or foraging grounds for other invertebrates and fishes. There are numerous protected areas for cold-water corals (also known as deep-water corals) on the Scotian Shelf, including the *Lophelia* Coral Conservation Area, the Jordan Basin Conservation Area, Northeast Channel Coral Conservation Area, the Corsair and Georges Canyons Conservation Area, St. Anns Bank MPA, and the Gully MPA. There is a high diversity of corals within the Gully MPA owing to the high diversity of habitats within, and unique oceanographic properties of, submarine canyons (Mortensen and Buhl-Mortensen 2005). However, little is known about cold-water coral spawning and recruitment patterns, and hydrodynamics at the depths cold-water coral larvae are transported, and thus connectivity of corals across the Scotian Shelf has not been assessed. Because cold-water corals are sessile organisms that generally exhibit low recruitment rates and slow growth rates, and are susceptible to physical damage from fishing, connectivity is particularly important to assess to understand population persistence, range expansion, and potential for recovery from any physical damage.

While studies of connectivity of coral populations among canyons have been rare, there have been direct studies of the connectivity of canyons with the coastal zone and the deep ocean beyond the continental slope (Metaxas et al. 2019). Two species of cold-water alcyonacean corals *Primnoa resedaeformis* and *Paragorgia arborea* have been the focus of conservation in Atlantic Canada, with both species occurring primarily along the continental shelf break but also in deep channels, basins, and canyons (Metaxas et al. 2019). Larvae typically remain in the water column for up to 30 days, and significant concentrations of larvae are found along the shelf edge (Smith and Metaxas 2018). In the NECCCA, recruitment rates of these corals in the denser coral thickets are approximately 300 colonies m^{-2} y^{-1}. In Corsair Canyon, both species are most abundant at depths between 484 and 856 m, usually attached perpendicular to hard rock faces and facing into the current. Using the Finite-Volume Community Ocean Model (FVCOM University of Massachusetts Dartmouth), Metaxas et al. (2019) found that hydrodynamic connectivity originates from canyons to the southwest of Corsair Canyon, while complex patterns of connectivity with the NECCCA only occurs in the winter and spring. Potential connectivity as far east as the Gully was not investigated, though the scale at which corals disperse in the western Scotian Shelf coupled with a short PLD suggests dispersal range is low (10s-100s km). Given this relatively small scale of dispersal, it is likely that connectivity between the Gully and the NECCCA (Fundian Channel-Browns Bank AOI) would take the form of sequential dispersal and recruitment events (e.g., stepping-stone connectivity; Kimura and Weiss 1964) facilitated by intermediate colonies present within canyons incising the shelf break between the Fundian Channel and the Gully MPA (e.g., Miller and Gunasekera 2017). The spawning season of these coral species still remains unknown, thus complicating the development of a hydrodynamic model that incorporates seasonal changes in water flows (Metaxas et al. 2019). Overall, it seems that self-recruitment of corals within canyons is high relative to recruitment from other populations due to the retentive nature of hydrodynamics within these ecosystems, and thus connectivity with other coral conservation areas is likely to be low (Smith and Metaxas 2018). Based on geographic proximity, the most significant connection to cold-water corals aggregations outside of the Gully would be with the adjacent Eastern Canyons sites (Haldimand and Shortland canyons).

To improve our understanding of connectivity among canyons, hydrodynamic models that resolve the complex boundary conditions associated the Canyon relief must be developed (e.g., FVCOM models used by Metaxas et al. (2019) and combined with high-resolution bathymetric datasets developed across a large spatial scale (e.g., Multibeam hydrographic survey), if available. Estimating larval dispersal of deep-sea species, including corals and sponges, using high-resolution hydrodynamic models, also requires a great deal more information on the basic biology of these species, including their spawning seasons and larval behaviours, such as vertical migrations (Metaxas et al. 2019).

Additional research should focus on evaluating larval dispersal traits of cold-water coral and sponge species (i.e., vertical position of larvae within the water column, timing of vertical migrations) or reviewing information collected from closely related species to serve as archetypes. Obtaining accurate and fine-scale substrate and bathymetric data for large spatial scales between conservation areas can also help refine both species distribution and oceanographic models to more accurately quantify connectivity in a network setting.

DEMERSAL AND BENTHIC FISHES

Atlantic Halibut

Atlantic Halibut represent an invaluable fishery to Atlantic Canada. This fishery has exhibited cyclical decades of decline and growth, and is concentrated off southwest Nova Scotia, along the continental shelf of southern Newfoundland, and in the Gulf of St. Lawrence. Despite intense fishing pressures and large declines throughout the 1990s, the Halibut fishery is currently flourishing and experiencing a period of high growth, recruitment, and concomitant landings (DFO 2020c). This contrasts with the Halibut fishery in the United States, which has been under a moratorium since 1999 (Shackell et al. 2016); Halibut is listed as a Species of Concern under the USA *Endangered Species Act.*

Halibut are managed as two stocks in Atlantic Canada: the Scotian Shelf and southern Grand Banks management unit, and the smaller Gulf of St. Lawrence stock. These management units were originally based on tagging data that showed migration among Newfoundland and Scotian Shelf Halibut and little to no intermixing with the Gulf of St. Lawrence resident population. Recent genomic evidence also supports these two stocks as genetically distinct, with little population structure across the large Scotian Shelf and southern Grand Banks unit (Kess et al. 2021). However, there is evidence, based on historical tagging data, that individual groups within management units may exist, despite observable levels of gene-flow among stocks.

Two areas of persistently high abundance of for juvenile Atlantic Halibut have been identified on the Scotian Shelf, with one hotspot located in close proximity to the shallow northwestern extent of the Gully MPA (Boudreau et al. 2017). The other persistent hotspot for juvenile halibut abundance is located southwest of the Gully within the Fundian Channel-Browns Bank AOI, where it has been recommended as a potential conservation priority for the site (Jeffery et al. in press). Boudreau et al. (2017) suggest that the Gully MPA and the groundfish closure on Browns Bank may support the persistence of these two areas as hotspots. Though over 20% of the Scotian Shelf is considered suitable habitat for juvenile Halibut, with the highest proportions in NAFO Divisions 4X and 4W, evidence of dispersal and connectivity across this range is limited (French et al. 2018).

Tagging studies conducted over the past few decades have revealed diverse behaviours in the migration patterns of this species. Atlantic Halibut tend to undergo seasonal migrations to deep, offshore waters in the winter, and shallower waters in the summer (Le Bris et al. 2018). However, some Halibut tagging studies suggest many individuals are resident, with some moving only a few kilometres to a few hundred kilometres over a period of years (Kersula and Seitz 2019, Le Bris et al. 2018). Tagged Halibut in the Gulf of Maine have primarily been recaptured close to their release point (median of 38 km distance traveled); however, some individuals traveled greater than 1500 km (mean 219 km) (Kersula and Seitz 2019). These relatively low dispersal rates could suggest the potential for fine-scale population structure driven by isolation by distance, or potentially local adaptation; however, firm evidence has yet to be obtained. A re-examination of tagged Halibut in NAFO areas 3 and 4 in the 1950s through the 1970s revealed that individuals released on the Scotian Shelf tended to move to the northeast (Stobo et al. 1988). Additionally, small fish (<75 cm in length) move further (>200 km) than large fish (>75 cm in length), which were typically recaptured within 200 km of their release site. Kohler (1964) revealed that in one year of tagging Halibut in the Gully, most fish were recaptured from the area of tagging or to the west of the Gully. However, in 1963 most tagged Halibut were recovered to the east of the Gully on the Grand Banks, having crossed the Laurentian Channel (Kohler 1964), suggesting the Laurentian Channel is not a barrier to dispersal (Stobo et al. 1988). Clearly a diversity of dispersal strategies exist among and even within presumed populations of Atlantic Halibut from the Gulf of Maine to Newfoundland. Based on tagging information, it seems likely that Halibut in the area of the Gully may exhibit connectivity with the Newfoundland Grand Bank. Boudreau et al. (2017) estimated connectivity of Halibut on the Scotian Shelf at approximately 250 km, an order of magnitude less than the size of the management unit (approximately 2000 km). This suggests that the persistent juvenile Halibut hotspots in the Gully MPA and on Browns Bank are not connected through migration. However, these results are contradicted by recent whole genome data for Halibut, which do not offer any evidence of strong population structure across the Scotian Shelf (Kess et al. 2021). This lack of genetic structure suggests extensive gene flow is occurring on the Scotian Shelf and even to the Newfoundland Shelf.

Conflicting information between genomic and tagging data exemplifies the difficulty at measuring/estimating connectivity *in situ* among sites in a network of MPAs. Tagging and tracking of marine fauna is a direct method of observing dispersal and migration, but is limited in scope in terms of the number of individuals that are tagged, and the short time scale (i.e., days to years) over which these studies are generally conducted. Genetic data provides estimates of gene flow, but typically over a greater temporal period (i.e., generations) compared to animal tracking studies. For Halibut, this disconnect might also reflect the biphasic life history of the species, where pelagic eggs and larvae disperse at a larger spatial scale than that expected of benthic life phase, which are the target for tagging studies. Manel et al. (2019a) suggest that genetic data provide more realistic estimates of overall dispersal potential relative to tagging data and that estimates of dispersal from genetic data are usually larger compared to other direct methods like tagging. In general, if the juvenile Atlantic Halibut hotspots are protected by the Gully MPA and a potential future Fundian Channel-Browns Bank MPA, Scotian Shelf Halibut should be well-represented for conservation. However, the lack of genetic population structure (and high connectivity) highlights that for some species, an MPA network may be well-connected, but may not be for others that are highly structured.

Atlantic Cod

Atlantic Cod are a demersal fish that are widespread across the Scotian Shelf, yet have declined precipitously over the past several decades due to historic overfishing. Cod are typically found in the highest abundance on offshore banks, the Bay of Fundy, and deeper geomorphic features including the Fundian Channel and the Gully (Ricard and Shackell 2013). Cod are broadcast spawners whose eggs and larvae drift passively for an average of 90 days, however, the PLD for this species can vary among populations and spawning seasons (Stanley et al. 2013). Spawning typically occurs on offshore banks, such as Browns Bank and Banquereau Bank, and is inferred from persistent concentrations of eggs and larvae found in the gyres that typically occur over these banks. Juvenile nursery areas include both inshore and offshore nurseries that contain complex habitat structure, including Eelgrass beds, boulder and cobble fields (Cote et al. 1998, Laurel et al. 2003, Lilley and Unsworth 2014), and cold-water corals (COSEWIC 2010a). Genetic studies have revealed evidence of complex Atlantic Cod population structure across its Canadian range, with a latitudinal-based genetic cline in the offshore punctuated by a break on the mid-Scotian shelf (separating the eastern and western Scotian Shelf; Bradbury et al. 2011, Stanley et al. 2018), in addition to distinct populations across the cline that typically correspond with spawning areas (Ruzzante et al. 1996). Differentiation between inshore and offshore stocks has also been identified across the species' Canadian range (Ruzzante et al. 1997), with recent observations noting different phenotypes of Atlantic Cod (coastal non-migratory and offshore migratory individuals) linked to chromosomal rearrangements (Kess et al. 2019).

Smith and Metaxas (2018) used Atlantic Cod as a case study to examine potential connections between regions and populations across the Scotian Shelf, Bay of Fundy, and into the Laurentian Channel. Using a combination of confirmed adult Cod movement based on the tagging literature, confirmed observations of larval dispersal, and presumed dispersal patterns based on particle tracking, Smith and Metaxas (2018) highlighted potential connectivity of all populations in the Scotian Shelf-Bay of Fundy bioregion via stepping-stones and combined adult and larval dispersal. Based on proximity, cod in the Gully MPA are most likely linked the Emerald-Western-Sable Island Bank complex. However, through oceanographic linkages and migratory potential to this mid-shelf complex, Atlantic Cod in the Gully could be connected through adult or larval dispersal to the St. Anns Bank MPA to the east and potentially as far as the Fundian Channel-Browns Bank AOI to the west, and the Eastern Shore Islands AOI as an inshore nursery area (Figure 4). Based on an analysis of genetic structure for multiple species and correlations with thermal gradients across the study area, Stanley et al. (2018) suggested a break occurring on the mid-Scotian shelf. Data for Atlantic Cod used in this study are limited near this presumptive break (samples taken near St. Ann's Bank and off southwest Nova Scotia and no samples from the Gully MPA); however based on the steep environmental gradient that correlated with the observed cline, it is likely that Cod from the Gully are more closely linked to those populations east of Emerald-Western-Sable Island Bank. Though these presumptions of connectivity are rooted in some genetic data, additional direct evidence of connectivity using observational or additional genetic data (particularly collected within and adjacent to the MPA) is required to confirm them.

Redfish

Two species of redfish commonly co-occur in Atlantic Canada: Deep-sea redfish (*Sebastes mentella*) and Acadian redfish (*S. fasciatus*). *S. mentella* typically occur further north than *S. fasciatus*, though both species can be found in and around the latitude of the Gulf of St. Lawrence (Cadigan and Campana 2017). Both species occur in cold waters along the continental slope and in deep channels to depths of up to 700 m. *S. fasciatus* generally occurs at shallower depths (150–300 m), while *S. mentella* occurs at depths of 300–500 m from the Gulf of St. Lawrence northward (Valentin et al. 2014). These two species are difficult to distinguish based on morphology, which is further complicated by the ability of these species to hybridize (Valentin et al. 2014). As such, these two species are managed as a single fishery in Atlantic Canada. Both species often occur near the bottom of the ocean, commonly associated with corals and sponges, though they also can form semi-pelagic schools (Cadigan and Campana 2017). Redfish (*Sebastes* spp.) are among the most frequently observed demersal fish observed in the Gully, occurring on 68% of video transects reported by (Mortensen and Buhl-Mortensen 2005).

A highly species-rich genus with a worldwide distribution, *Sebastes* redfish are long-living (up to 75 years), late-maturing, ovoviviparous fishes that have lecithotrophic larvae, which survive on their egg yolk. The primary dispersal phase for redfish occurs in the larval phase, although the benthic lecithotrophic nature of these larvae limit their travel distance. At the adult stage individuals are presumed to move very little (COSEWIC 2010b). Some seasonal, generally small-scale (10s -100s km), migrations have been noted with redfish in the Gulf of St. Lawrence known to move to the Laurentian Channel in the winter (Campana et al. 2007). Based on genetic data it appears that both larval dispersal and adult movements occur at relatively small scales (Benestan et al. 2021). Due to their long lifespan, it is possible that adults could make long-distance migrations, but evidence in support of this possibility has yet to be presented.

Microsatellites have revealed relatively weak population structure for both species in Atlantic Canada, with the exception of some isolated populations: 1) the Bonne Bay Fjord population is highly differentiated and exhibits low connectivity with other populations of *S. fasciatus* (Valentin et al. 2014), 2) the Gulf of St. Lawrence and Laurentian Channel (GSL-LCH) forms one genetically distinct population of *S. mentella*, which exhibits some hybridization with *S. fasciatus*, and 3) the Saguenay Fjord population of *S. mentella*, which represents a sink from the GSL-LCH (Valentin et al. 2014).

Recently, Benestan et al. (2021) used more than 24,000 single nucleotide polymorphisms (SNPs) to investigate redfish population structure at a finer scale. This work revealed that only two SNPs are needed to differentiate *S. mentella* and *S. fasciatus*, and identified three ‘ecotypes’ of *S. mentella*, as well as five populations of *S. fasciatus* in the Northwest Atlantic. These ecotypes of *S. mentella* correspond to the Gulf of St. Lawrence population, as well as distinct ‘shallow’ (300–500 m) and ‘deep’ (>500 m) populations (Benestan et al. 2021).

Demographic modeling shows low rates of migration and genetic exchange between species overall, as well as between shallow and deep ecotypes of *S. mentella*. The five *S. fasciatus* populations defined by these SNP data are primarily defined by geographic areas ranging from the Gulf of Maine to Labrador, but with overlap among populations. Based on this study, which did not sample within the Gully MPA, potential connectivity for *S. fasciatus* based on sampling locations nearest the Gully in Benestan et al. (2021) includes the Gulf of Maine, the Laurentian Channel, and Grand Banks of Newfoundland. *S. mentella* from the Gully may show connectivity with the GSL-LCH population, or potentially deep or shallow ecotype populations to the north of Newfoundland. However, genetic sampling from a variety of depths within the Gully MPA will be required to evaluate any fine-scale, within-MPA, genetic structure and to examine gene flow to and from other regions.

CETACEANS

Northern Bottlenose Whales

A resident population of Northern Bottlenose Whales is a key ecological feature of the Gully ecosystem and a primary reason the Gully was designated an MPA. These whales feed at mesopelagic depths within the Gully canyon, especially on *Gonatus* squid and mesopelagic fishes. Bottlenose Whales are divided into two designatable units in Atlantic Canada: the endangered Scotian Shelf population and the northern Baffin Bay-Davis Strait-Labrador Sea population. The Scotian Shelf population was designated Endangered under the *Species at Risk Act* in 2006, and its Endangered status was reassessed and confirmed in 2011, while the Baffin Bay-Davis Strait-Labrador Sea population was assessed as Special Concern (COSEWIC 2011). There are approximately 140 individuals remaining in the Scotian Shelf population, though it appears to be stable (O'Brien and Whitehead 2013). Northern Bottlenose Whales are susceptible to a variety of threats, including entanglements in fishing gear, ship strikes, and noise produced by vessels and oil and gas seismic surveys (COSEWIC 2011).

Species distribution models for Northern Bottlenose Whales in the Northwest Atlantic have been used to identify potentially suitable habitat and priority monitoring areas off eastern Canada, including shelf breaks of the eastern Scotian Shelf, and the Newfoundland and Labrador shelves. Potential habitats in these areas include submarine canyons (Gomez et al. 2017). Haldimand and Shortland canyons, near the Gully MPA are also designated critical habitat for NBW, and the areas in between these three canyons have been identified as important foraging and migratory areas (DFO 2020a). Sightings and acoustic detections of Northern Bottlenose

Whales indicate that they also occur along the continental slope on the Western Scotian Shelf, at the mouth of the Fundian Channel, and beyond the mouth of the Laurentian Channel (DFO 2020a).

Northern Bottlenose Whales are typically residents of deep water areas and submarine canyons, and little is known about potential movements among suitable habitats. While individual whales move between the three large canyons of the eastern Scotian Shelf (the Gully, Shortland, and Haldimand canyons) and use the inter-canyon areas for foraging (DFO 2020a), seasonal migrations on a large scale are not made (COSEWIC 2011). Passive acoustic monitoring indicates that Northern Bottlenose Whales are present within the Gully and inter-canyon areas throughout the year. Photographic evidence also confirms that some individuals have been observed in the Gully, Shortland Canyon, and Haldimand Canyon, with regular movement among these three canyons (DFO 2020a). There is consistent movement in and out of the Gully, at approximately one individual per day; this combination of acoustic and photographic evidence supports a high degree of connectivity among the three canyons (DFO 2020a). This work highlights not only the importance of the canyon ecosystems for Northern Bottlenose Whales, but also the inter-canyon habitats that must allow for adequate space for unobstructed movement of individuals (DFO 2020a).

Genetic evidence (full mitogenomes and 37 microsatellites) differentiates the Scotian Shelf and Baffin Bay-Davis Strait-Labrador Sea populations (Feyrer et al. 2019). Demographic inference using these mitogenomes suggests that after the last glacial maximum the Scotian Shelf population began to decline, with a sharp drop in effective population size over the past 200 years, coinciding with increases in human activity (Feyrer et al. 2019). Both populations show low overall genetic diversity, and connectivity among the Scotian Shelf and northern region populations is estimated to be low (

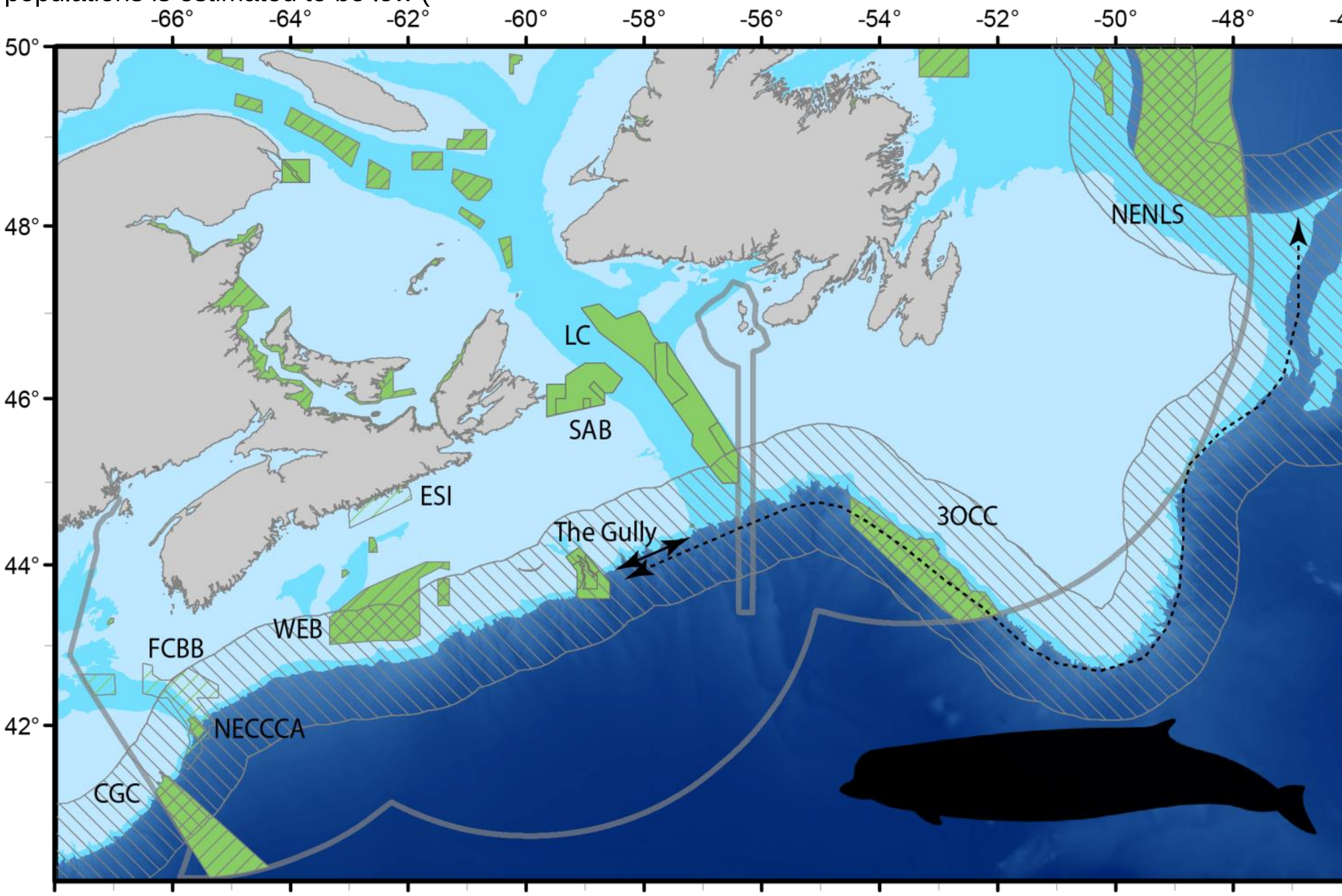

Figure 5). However, individuals sampled off Newfoundland could not be assigned to either the Scotian Shelf or northern population definitively, suggesting there may be some mixing between the two designatable units on the Newfoundland shelf (Feyrer et al. 2019). Barriers to connectivity for this species include areas of unsuitable habitat (i.e., shallow shelf areas, lack of deep-sea canyon habitat) or offshore anthropogenic activities.

Large Toothed Whales

Other large toothed whales that have been observed in the Northwest Atlantic include Sperm Whales (*Physeter macrocephalus*) and other beaked whales, including Sowerby’s Beaked Whale (*M. bidens*), Cuvier’s Beaked Whale (*Ziphius cavirostris*), Blainville’s Beaked Whale (*Mesoplodon densirostris*), True’s Beaked Whale (*M. mirus*), and Gervais’ Beaked Whale (*M. europaeus*). Of the beaked whales, Sowerby’s Beaked Whale (Special Concern – COSEWIC and SARA) has perhaps the best described distribution, being endemic to the North Atlantic, with numerous records off North America and Europe (MacLeod et al. 2005).

Sowerby's Beaked Whales were rarely observed in the Gully in the 1990s (Hooker and Baird 1999) but are now considered a "staple" of the Gully biota as a result of a 21% per year increase between 1988 and 2011, possibly as a result of reduced anthropogenic noise and other disturbance (Whitehead 2013). Sowerby's Beaked Whales are also present in the adjacent waters including Shortland and Haldimand canyons, and have been observed or detected further south in the Fundian Channel and canyons off the United States (Hooker and Baird 1999). Observations and predicted suitable habitat for Sowerby's Whales in the Scotian Shelf Bioregion occur primarily along the continental slope and in deep, submarine canyons, including the Gully, Shortland, and Haldimand canyons (Gomez-Salazar and Moors-Murphy 2014). Based on the presumed distribution of suitable habitat suggests, it is likely that corridors for connectivity operate along the continental shelf between areas to the north and south of the Gully MPA, though it remains unclear whether distinct populations of Sowerby's Whale exist throughout Atlantic Canada, and connectivity among potential populations has not been investigated. More basic research, including dispersal patterns and population genetics (*sensu* genetic studies on Northern Bottlenose Whales) would be invaluable to better understand movement patterns, habitat connectivity, and gene flow for odontocete whales.

Baleen Whales

Baleen whales are generally seasonally present in Atlantic Canadian waters (typically spring through fall, though at least some individuals of the various baleen whale species occur in eastern Canadian waters throughout the year) and exhibit migratory connectivity. Migratory connectivity can be defined as the links between breeding and nonbreeding areas, such as seasonal movements between breeding grounds and foraging areas (Webster et al. 2002). Migratory connectivity has important implications in the evolution, ecology, and conservation of migratory animals, and seeks to determine whether individuals from single or multiple breeding grounds travel to the same foraging or overwintering areas, or vice versa (Webster et al. 2002). Since highly migratory animals will be exposed to a variety of stressors across the wide geographic range they travel, the importance of migratory connectivity has become increasingly acknowledged in terms of marine policy and conservation (Dunn et al. 2019).

Baleen whales travel north from southern calving and mating grounds along the continental shelf and slope in the spring and summer months to feed on rich plankton blooms and forage fishes in Atlantic Canadian waters. In the Gully MPA, a number of baleen whales have been observed or acoustically detected, including Humpback (*Megaptera novaeangliae*), Fin

(*Balaenoptera physalus*), Blue (*Balaenoptera musculus*), Sei (*Balaenoptera borealis*), Minke (*Balaenoptera acutorostrata*), and North Atlantic Right (*Eubalaena glacialis*) whales (Davis et al. 2017). Gomez et al. (2020) used cetacean sightings data and environmental variables to develop species distribution models (SDMs) and predict potentially suitable habitats for a number of toothed and baleen whales throughout waters off Nova Scotia, Newfoundland, and Labrador as part of a recommendation for the use of SDMs for spatial planning. Priority areas for monitoring these cetaceans, defined as the areas of predicted suitable habitat, are summarized in Gomez et al. (2020), but in general, suitable habitat for most baleen whales was predicted to occur across the Scotian Shelf, suggesting all network sites could confer protection and connectivity for cetaceans in Atlantic Canada. Predicted suitable habitat for both Fin and Minke whales occurred across most of Atlantic Canadian waters, though deeper waters were not predicted to be as suitable. Priority areas for Blue Whales are described in Gomez et al. (2017) and Moors-Murphy et al. (2019), and include the Scotian Shelf, continental slope, and the south shelf break off Newfoundland, including the Laurentian Channel (DFO 2018b). Humpback Whales are predicted to occur on the Scotian Shelf, Newfoundland Shelf, and part of the Labrador Shelf, and Sei Whales priority monitoring areas include the Scotian Shelf, Bay of Fundy, Newfoundland Shelf, and part of the Labrador Shelf. Acoustic data suggests the Gully MPA may be a migratory corridor for Humpback Whales, which have also been detected within and outside the MPA in the winter months, possibly to mate (Kowarski et al. 2015).

Like most seasonally-occurring, highly mobile marine animals, baleen whales may visit any number of offshore or inshore marine conservation areas within Atlantic Canada, including the Gully MPA. However, it is important to note that though conservation initiatives at the regional and national level can provide protection for these transient species, their time in Canadian waters primarily represents seasonal foraging behaviours and thus does not cover all life history stages that ultimately underpin connectivity among other areas important for baleen whales, such as breeding and calving that typically occurs in tropical and subtropical regions. Continued monitoring of highly migratory species such as baleen whales should consider that conservation outcomes (e.g., evaluated efficacy of a protected area) will be strongly dependent on outcomes beyond Canadian jurisdiction.

LEATHERBACK TURTLES

Some Leatherback Turtles from the Northwest subpopulation undertake annual migrations from their southern breeding grounds to temperate waters off eastern Canada to feed on seasonally abundant scyphozoan jellyfish and other gelatinous invertebrates (James et al. 2005). Analyses of satellite telemetry data from tagged individuals have previously identified three areas of important habitat for Leatherback Turtles, including waters east and southeast of Georges Bank and off the Northeast (Fundian) Channel; the southern Gulf of St. Lawrence and waters off Cape Breton Island, including portions of the Laurentian Channel (another MPA); and waters south and east of the Burin Peninsula, Newfoundland, including part of Placentia Bay (DFO 2020d). The waters off Georges Bank and the Northeast Channel may be areas of relatively higher-use early in the foraging season, with many turtles proceeding onto the Scotian Shelf as waters warm and moving into Sydney Bight, the Gulf of St. Lawrence, and south coast of Newfoundland later in the foraging season (DFO 2020d). Satellite tracking data suggests that relatively few Leatherbacks make use of the waters around the Gully MPA for prolonged periods, but areas used near the Gully may be more important in early fall (September and October) (DFO 2020d).

Important habitat for Leatherback Turtles was identified as a conservation priority for St. Anns Bank MPA (Ford and Serdynska 2013) and some leatherbacks pass through the Fundian Channel-Browns Bank AOI, Gully MPA, St. Anns Bank MPA, and the Laurentian Channel MPA during inshore and offshore foraging movements on their way to the Gulf of St. Lawrence or south coast of Newfoundland, or when returning south to their breeding and wintering grounds. Most of Atlantic Canada shelf and slope waters seem to be suitable migration corridors for leatherbacks though in the summer months satellite tracking data suggests leatherback density may be higher in inshore areas (DFO 2020d). While leatherbacks do not breed in Canadian waters, migrating turtles may pass through a number of marine conservation areas in Atlantic Canada. Although Leatherback Turtles may forage within the Gully, this and other protected areas of Atlantic Canadian shelf waters represents only a small portion of the habitat range of this species and thus conservation outcomes (e.g., species recovery/increased abundance) are also dependant on management activities conducted in areas beyond Canadian jurisdiction (e.g., southern nesting beaches and wintering grounds).

POTENTIAL IMPACTS OF CLIMATE CHANGE

GENERAL IMPACTS OF CLIMATE CHANGE

Climate change driven by anthropogenic carbon emissions is leading to changes, and in many cases declines, in ocean health and productivity through warming, acidification, deoxygenation, sea-level rise, more frequent storm events, and altered hydrodynamics (Levin and Le Bris 2015). The interactions of these stressors in shallow and deep-sea ecosystems are complex, leading to reductions in available habitat for marine flora and fauna, physiological stress, and mortality (Table 1). Warming of only 1°C can lead to physiological stress and shifts in depth and latitudinal habitat distributions in the deep sea. Warming ocean temperatures can also impact species that undergo long-distance migrations and that experience a wide range of environments during their lives; this can trigger behavioural responses and shifts in their distribution over time (Almpanidou et al. 2019). Furthermore, a warmer ocean contains less oxygen, and increased stratification in a warming ocean can lead to extensive reductions in oxygen, particularly at depths of 200 to 700 m (Levin and Le Bris 2015). Deoxygenation can lead to reduced available habitats for pelagic, mesopelagic, and demersal fishes that are hypoxia intolerant, while potentially expanding habitat for hypoxia-tolerant species (Gilly et al. 2013). Increases in hypoxic and anoxic environments in the ocean can also lead to changes in food web dynamics and mass mortality events (Roberts et al. 2017).

Ocean acidification is caused by absorption of atmospheric CO_2 in the water column, and acidic surface and mid-level waters can subduct into the deep sea via thermohaline circulation (Gehlen et al. 2014). Ocean acidification is particularly relevant for calcifying species, such as corals, where elevated CO_2 levels will lead to under-saturation of aragonite and other forms of calcium carbonate in the water column (Hofmann et al. 2010). Corrosive ocean waters will increase the energetic cost for corals and other invertebrates to build their skeletons that provide biogenic habitat for numerous other organisms (Yesson et al. 2012). For example, the reef-forming coral *Lophelia pertusa*, found in the Gulf of Mexico and North Atlantic Ocean, shows a decline in calcification rates as pH decreases, and increases in mortality rate with warmer temperatures (particularly >14°C) and lower oxygen levels (Lunden et al. 2014). However, increased partial pressures of CO_2 and low pH can also have direct physiological consequences for other marine organisms aside from those with calcifying skeletons (Hofmann et al. 2010). Acute changes in ocean conditions may thus lead to widespread mortality or habitat reductions for cold-water corals, though long-term studies on acclimation or adaptation to climate change should be conducted. Reduced pH and increased dissolved CO_2 can have negative impacts on zooplankton survival as well, thus disrupting the marine food web. Marine copepods such as *Calanus* spp., which undergo vertical migrations and cross a range of CO_2 partial pressures on a daily basis show reduced susceptibility to high CO_2 in a controlled setting, while species such as *Oithona similis*, which do not undergo vertical migrations, show reduced survival when exposed to high CO_2 (Lewis et al. 2013). Ocean acidification, through global climate change, will thus impact marine organisms at numerous trophic levels, posing a significant threat on a large geographic scale.

CLIMATE CHANGE IN MARINE PROTECTED AREAS AND NETWORKS

MPAs may help preserve marine biodiversity under climate change due to the removal or reduction of other stressors that can have a cumulative effect on marine life (e.g., fishing, anthropogenic noise, underwater mining) and through adequate connectivity among network sites (McLeod et al. 2009); however, climate change is often not considered when designing or managing an MPA or MPA network. Like connectivity, there is a strong theoretical and empirical basis that emphasizes the need to actively integrate climate change into MPA planning and management (e.g., Brock et al. 2012), and several frameworks for how to operationalize climate change strategies and integrate dynamic responses to climate change over time are available (e.g., Tittensor et al. 2019). In an MPA network, individual marine reserves and protected areas can provide genetic or demographic rescue (Xuereb et al. 2019), stepping-stones for dispersal, and-or possible refugia under climate change (Roberts et al. 2017). The efficacy of MPAs, either considered individually or as a part of network, will be principally challenged by the contrast of their primarily static nature (all MPAs and OECMs counting towards Canada’s Conservation Targets are static by design - DFO 2016) and the dynamic elements introduced by climate change. Static MPAs that may currently protect conservation priorities may no longer provide adequate protection under a rapidly changing climate over the years and decades. Consequently, interest in dynamic area-based management is growing (e.g., D'Aloia et al. 2019). While there are a variety of tools and approaches available to estimate how species or populations may respond to climate change (see growing body of literature using habitat modelling and climate projections to forecast biological responses, i.e., Species Distribution Models (SDMs)), targeted monitoring in MPAs will provide information on how environmental changes are influencing biological conservation priorities and thus provide the basis on which to re-examine conservation priorities and MPA/MPA network designs over time.

Aside from impacting the physical ocean, individual species’ physiologies, and community dynamics, climate change will also affect how an MPA relates to its surrounding areas by altering the environment through which dispersal and connectivity occur. Larval transport and survival may be reduced, patterns of gene flow will be altered, suitable habitat may be gained or lost, and phenology may change (i.e., mismatches between primary production and larval release) (Munday et al. 2009). For example, in the Mediterranean Sea Protected Area network, modeling has revealed that by 2099, climate change impacts will decrease larval dispersal distance by 10%, the shelf area seeded by larvae will decrease by 3%, and larval retention on the shelf will increase by 5% based on general hydrodynamic modeling and biological parameters based on Dusky Grouper (*Epinephelus marginatus*) (Andrello et al. 2015). However, connectivity among network sites is also predicted to increase due to increases in suitable habitat among MPAs (Andrello et al. 2015). This research exemplifies how climate change can impact all aspects of connectivity, either positively or negatively, which will require investigation on a regional basis.

CLIMATE CHANGE IN THE DEEP SEA AND THE GULLY MPA

Kenchington (2010) identified ocean acidification associated with climate change to be the primary threat to corals in the Gully MPA. The environmental stability of the deep ocean coupled with the longevity of fishes (years to decades) and corals (hundreds to thousands of years) may reduce the capacity to tolerate or adapt to climate change, relative to shallower water systems (Smith et al. 2008). Under the Representative Concentration Pathway (RCP) Scenario 8.5, benthic ocean biomass is projected to decrease by 5.2% by 2091-2100, and declines in the size of infaunal biota are also predicted (Jones et al. 2014). In fact, among the habitats investigated by Jones et al. (2014), cold-water corals are predicted to suffer the greatest declines with more than 93% of areas with the reef-forming coral *L. pertusa* expected to exhibit declining total benthic biomass. Out of more than 8,600 canyons identified in the global ocean, 85% are predicted to suffer from declines in benthic biomass over the next century, including canyon systems in the North Atlantic. While canyon ecosystems at large are expected to be somewhat more buffered to change compared to shelf and other deep-sea habitats, they are still expected to experience declining biomass up to 5% (Jones et al. 2014).

Submarine canyons are large geomorphic features along the continental shelves of the global ocean that are characterized by steep and complex topography (Fernandez-Arcaya et al. 2017). Canyon features provide heterogeneous habitats to various fishes and invertebrates, and influence currents flowing through and over them. Canyon habitats have been found to sequester carbon, provide nursery habitats, and are typically characterized by vulnerable biogenic habitats such as corals and sponges. As the climate changes and the ocean warms, increased ocean temperatures and altered oceanographic patterns are predicted to have myriad direct effects on species living across various latitudes (Table 1). These impacts are not only associated with biological responses (e.g., shifting distributions and community composition) but also the physiographic properties of submarine canyons, including altered flows of nutrients and water masses among the coastal zone, continental shelf, and deep sea, and altered carbon storage (Fernandez-Arcaya et al. 2017).

The Gully MPA encompasses communities unique to the eastern Scotian Shelf, the continental slope, and deep water and abyssal regions. O'Brien et al. (in press) modeled demersal fish and benthic invertebrate assemblages in the DFO Maritimes, Gulf, and Newfoundland and Labrador regions, and developed a list of indicator species for each unique assemblage within these regions. The eastern Scotian Shelf cluster, which encompasses the shallower reaches of the Gully MPA, is known to differ considerably from the western Scotian Shelf in terms of community composition, with the western Scotian Shelf assemblages including a higher prevalence of various groundfish including hake, Pollock (*Pollachius virens*), and skates, in contrast to the eastern Scotian Shelf species assemblages that tended to include more invertebrates such as decapods and echinoderms, and some fish species including American Plaice (*Hippoglossoides platessoides*) and Eelpout (*Lycodes vahlii*) (O'Brien et al. in press). In general, under mild to severe climate change scenarios, species assemblages near the Gully are expected to change to exhibit a composition more similar to what we currently observe on the western Scotian Shelf, and the Scotian Shelf, in general, will become more homogenous with species that can tolerate or prefer warmer surface and bottom temperatures. Species such as Snow Crab, sandlance (*Ammodytes americanus* and *Ammodytes dubius*), Moustache Sculpin (*Triglops murrayi*), Capelin (*Mallotus villosus*), and some species of skates are vulnerable to severe (+3°C) climate warming, while moustache sculpin are particularly vulnerable to both mild (+0.7°C) and severe climate change (Stortini et al. 2015).

Genomic evidence has revealed clines in population structure associated with climate in the Northwest Atlantic, with a genetic break in warm and cold-water adapted “ecotypes” of Atlantic Cod, American Lobster (*Homarus americanus*), Sea Scallop (*Placopecten magellanicus*), Northern Shrimp (*Pandalus borealis*), and European Green Crab (*Carcinus maneas*) (Stanley et al. 2018). Using climate projections (RCP 8.5) and species distribution models that are refined using this genomic data, Stanley et al. (2018) predict a northward shift in the distributions (centre of mass) of these populations species by more than 200 km by the year 2075. Aside from Green Crab, these species can be found in the shallow portions of the Gully MPA. Should ocean warming continue on its current trajectory, the warm-water adapted ecotypes of these species will likely move into the eastern Scotian Shelf and Gully MPA following the expansion of warm-water habitat (Stanley et al. 2018). While these species are not explicitly listed as conservation priorities for the Gully, they represent a diversity of life histories and dispersal phenotypes and thus may serve as a signal that other warm-water species are moving into the area. Moreover, the multi-species genetic structure observed notes a pervasive biogeographic break following a steep thermal gradient on the mid-Scotian shelf, southwest of the Gully MPA. This suggests that changes associated with climate change are more complex than overall species ranges shifts (incursions of warm water species) and may also include changes in genetic spatial structure and correspondingly connectivity as adapted ecotypes respond to changes in available habitat.

Climate change may limit growth of Atlantic Halibut on the Scotian Shelf and in the Gully as well (Table 1). Experimental studies show that aerobic scope (the difference between normal and maximum metabolic rates) and cardiac performance of Atlantic Halibut increase after 14-16 weeks of exposure to seawater with elevated temperature (18°C) and reduced pH (pH 7.8 relative to 8.2) (Gräns et al. 2014). While metabolism and cardiac performance is not compromised under conditions of higher temperatures and increased acidity, a decrease in pH at ambient ocean temperatures was associated with a decline in growth rates (Gräns et al. 2014). This suggests that Atlantic Halibut may experience reduced growth rates under climate change, with negative implications for fish populations in the North Atlantic. However, a recent study by Czich (2020) found that the abundance of juvenile Halibut has increased with increasing ocean temperatures since 2001, based on RV survey catch data in Atlantic Canada. While juvenile Halibut were not present at temperatures less than 3°C, there was no upper thermal limit yet identified for juvenile Halibut (Czich 2020). Further, the amount of suitable habitat for juvenile Halibut increased at a rate of nearly 0.2% $year^{-1}$ among all sampled regions, corresponding with an increase in temperature since 2001. This research suggests that climate change may have some (at least temporarily) positive influences (stable or increased biomass) on some species native to Atlantic Canada, though the longer-term impacts of increasingly warming ocean temperatures require further study.

The impacts of climate change on Northern Bottlenose Whales in the Gully are uncertain, but given the relative small population size associated with the Gully, it is likely climate change could have a pronounced effect on the overall health of this population (O'Brien and Whitehead 2013). Like many marine species, the ranges of Northern Bottlenose Whales and other beaked whale species, including Sowerby’s Beaked Whale and the warmer water Cuvier’s Beaked Whale, are expected to shift northwards as ocean temperatures warm (MacLeod 2009). In addition to a range shift, cool water beaked whales like the Northern Bottlenose Whale may also experience a range contraction due to their preference for offshore canyons. This northward movement is predicted to be 'unfavourable' to the conservation of both Northern Bottlenose and Sowerby's beaked whales; however, climate change may be 'favourable' to warm water beaked whales, such as Cuvier's Beaked Whale (MacLeod 2009). Overall little is known about how meso-pelagic ecosystems will be influenced by climate change, further complicating any prediction of how these whale species may respond to indirect changes in the canyon ecosystem (i.e., changes to the distribution and abundance of their primary prey source). The direct physiological and energetic impacts of climate change on beaked whales in general also remains unknown, and requires further investigation (Hooker et al. 2019).

RECOMMENDATIONS FOR MONITORING CLIMATE CHANGE IN THE GULLY

To monitor the effects of climate change, adequate baseline data is required. This includes, but is not limited to: local physical and chemical oceanography, including temperature, pH, upwelling, surface, and bottom currents; seasonal magnitudes of phytoplankton and zooplankton blooms; distributions and growth rates of corals and sponges; abundances of forage species, such as lanternfish (myctophids) and squid; abundances, distributions, and growth rates of benthic fishes, including Atlantic Halibut; resident cetacean population body sizes and general health; and common species of marine birds that rely on the Gully's prey base for foraging. These data are necessary to evaluate the impact of warming water temperatures, ocean acidification, hypoxia, and altered oceanography over time on the Gully's conservation objectives. For example, episodic incursions of the warm gulf stream onto the Scotia Shelf have been shown to have been empirically shown to influence distribution of marine species (O'Brien et al. in press, Zisserson and Cook 2017). By characterizing the environmental niche of species within the Gully, climate-driven thresholds that are indicative of species response or of phase shifts could be used to provide early warning signs that trigger enhanced monitoring or management action (Wilson et al. 2020). Further, climate forecast models (e.g., Bedford Institute of Oceanography North Atlantic Model – BNAM; Brickman et al. 2016) could be combined with these assessments of environmental niche to project change that could guide spatial (e.g., stratified sampling based on forecasted change) and temporal (e.g., timelines for when environmental 'thresholds' can be expected) aspects of monitoring survey design. Continued collection of oceanographic data, including physical and chemical ocean properties, by continued support from programs such as the AZMP and research vessel surveys will be necessary to evaluate change within the Gully and the Northwest Atlantic at large. Ideally these physical data would be complemented by ongoing data collection on the biology and ecology of the Gully, including benthic ecosystem surveys, meso-pelagic fish surveys, marine mammal and bird observation programs, and opportunities to collect benthic imagery, deployment of acoustic instruments, and collaborations with industry for fisheries-dependent pelagic species, such as Swordfish and tuna. Continued collaboration and support from academic partners (e.g., the Whitehead Lab at Dalhousie University, who collect and analyze a regular time series of data in support of cetacean monitoring indicators), other government agencies (e.g., Environment and Climate Change Canada, responsible for maintaining data on marine bird sightings and behaviour), environmental non-governmental organizations, and stakeholders (e.g., fishers) will be necessary to adequately monitor change in the Gully over time.

Monitoring changes in connectivity over time as a result of climate change will also be necessary, especially if a fully developed network of MPAs in the Maritimes planning region or across Atlantic Canada comes to fruition. Where the impacts of climate change are distributed across a planning area, connectivity between sites can help mitigate the impacts of climate change and other stressors through demographic exchange and gene flow (i.e., exchange of genetic variants better adapted for novel environmental conditions) among individual MPAs (Carr et al. 2017, Xuereb et al. 2019). Climate change may, in the short-term, lead to faster growth rates and survival of larval marine animals, but in the long-term can lead to habitat fragmentation, reduced larval dispersal and survivorship rates, and changes in spawning time. Connectivity will be an essential element of MPA networks that can help mitigate some of the influences of climate change by ensuring that more impacted areas in the network can be supplemented (i.e., through enhanced larval production and connectivity from other less affected sites) (Munday et al. 2009). Though connectivity in MPA Networks for the most part remains a largely conceptual idea (see Balbar and Metaxas 2019), understanding how the persistence of species within the Gully ecosystem depend on outside areas, and how these connections might be changing with climate change, remains an essential element for evaluating the efficacy of the MPA. There are a variety of tools available to measure/model connectivity including, species distribution models that can be leveraged to predict habitat based on (near) future conditions using climate forecast projections under different scenarios (Brickman et al. 2016), which can in turn be used to inform various methods to monitor connectivity (reviewed in Balbar et al. 2020). A better understanding of the basic biology of many animal species living in the Gully, including their spawning season, pelagic larval duration, and migration patterns, and how these traits are vulnerable to climate change, will provide essential information required to fully comprehend how the Gully is connected to areas outside and within the existing conservation network in Atlantic Canada.

MPAs are generally designed to conserve marine biodiversity and protect against stressors; however, they cannot necessarily resist the direct effects of climate change (but see Roberts et al. 2017). As the climate changes the global ocean will be affected, though some areas will change more than others – those that remain more stable may act as climate ‘refugia’, where oceanographic or geomorphologic features can buffer against change (Tittensor et al. 2010). Climate refugia could be targeted for inclusion in regional MPA networks, though their identification in temperate systems is still rare (Ban et al. 2016). There is growing interest in the use of adaptive management and dynamic MPAs, rather than solely static MPAs, to respond to the threat of climate change (D'Aloia et al. 2019, Tittensor et al. 2019). Ongoing monitoring of both static and dynamic marine conservation areas will be needed to respond to the spatio-temporal impacts of climate change. Furthermore, some conservation priorities will be more vulnerable to climate change than others, and this information can help to develop new monitoring indicators to inform adaptive management for both individual MPAs and the MPA network (Whitney and Conger 2019). In the case of the Gully, an *Oceans Act* MPA, considerable consultation would be needed to adaptively change the boundaries or conservation priorities of this network site (or zonation there within). However, the physical construct (largest submarine canyon) of the Gully, which contributes to its many other characteristics warranting conservation (e.g., high biodiversity and unique communities), will not be altered by climate change and as such, the Gully as a static feature should serve as an anchor point around which the Scotian Shelf-Bay of Fundy Conservation Network should be built.

SUMMARY

The Gully MPA conservation objectives specifically make reference to protecting cetacean populations, particularly resident beaked whales for which the Gully canyon is critical habitat; the seafloor habitat and benthic ecosystem; and maintaining the water quality and canyon habitat within the MPA. The Gully is one of three currently existing MPAs in the Scotian Shelf-Bay of Fundy bioregion, and one of eight across Atlantic Canada. It is currently the third largest MPA under the *Oceans Act* in Atlantic Canada, and the only MPA that includes submarine canyon habitat. The Gully is one component of a growing conservation network in Atlantic

Canada, yet how this MPA fits into this network in terms of resilience, representativity, and connectivity with other network sites requires more information. Though the basis for how conservation priorities of the Gully may respond to climate change have been, for the most part, developed, there remains a need to adapt focus and current monitoring efforts to evaluate how the area will ultimately perform as a conservation tool, relative to its conservation priorities, in a changing marine environment.

Northern Bottlenose Whales in the Gully are resident and form a distinct genetic population compared to populations to the north, with a potential mixing zone of northern and southern populations off Newfoundland (Feyrer et al. 2019). This suggests that connectivity between the Scotian Shelf and northern populations is low. However, whether the Gully population is genetically distinct from individuals to the south (i.e., those that have been detected in the Fundian Channel) remains unknown; it is possible connectivity with the Fundian Channel-Browns Bank AOI exists based on suitable slope habitat connecting these areas along the slope and between intermediate canyons, but genetic data are needed to confirm this. Similarly, Atlantic Halibut may show connectivity between the Gully and Fundian Channel – Browns Bank AOI based on genetic data, though tagging and modeling data suggests connectivity is only realized at distances under 250 km (Boudreau et al. 2017). Other groundfish species, like redfish and Atlantic Cod, likely show connectivity among populations immediately to the west and east of the Gully due to relatively low dispersal rates, though there is no genetic data from individuals sampled from the Gully. The Gully lies on the edge of a known North Atlantic biogeographic break (Stanley et al. 2018), connectivity is expected to be higher among northeastern populations, but lower between populations existing in the western Scotian Shelf (west of Emerald Bank), but this may change as the region warms and southwestern species/populations track northeastward (e.g., O'Brien et al. in press).

Connectivity of benthic invertebrates with other network sites, including corals and sponges, remains largely unknown, and a combination of hydrodynamic modeling and genetic information could help identify connectivity among network sites. Experimental work that details dispersal phenotypes, in larval timing, duration and behaviour, of corals and sponges would provide essential information needed to develop biophysical models that could be used to provide a more accurate inference of dispersal patterns.

Migratory animals such as baleen whales and Leatherback Sea Turtles that migrate from southern breeding grounds to northern feeding grounds may pass through the Gully on their way north in the spring or south in the fall or winter, but these animals do not breed in Canadian waters and thus represent migratory connectivity. Migratory connectivity is receiving renewed attention in marine conservation planning and trans-boundary initiatives in marine spatial planning (Dunn et al. 2019, Webster et al. 2002). Monitoring of connectivity will require first an assessment of those conservation priorities that are likely to be connected to and influenced by areas (i.e., network sites) outside the Gully (e.g., Smith and Metaxas 2018). A preliminary assessment of connectivity for those conservation features whose status is influenced by connections to outside areas must then be conducted in order to track any status and change moving forward. Tools such as genomics (e.g., parentage analysis), otolith chemistry, directly tagging animals (e.g., acoustic tags, mark-recapture studies), or preferably, a combination of methods can all be applied to first develop a baseline and then monitor for changes (see Balbar et al. 2020 for a review of connectivity monitoring approaches).

Deep-sea habitats and submarine canyons, like the rest of the global ocean, will be impacted by climate change, including warming waters, an increase in acidity, deoxygenation, and potentially altered oceanographic currents. Each of these impacts will alter the Gully ecosystem over time. Under a warming ocean, resident beaked whales may be extirpated and forced to move to northern canyon ecosystems while warm-water species may move northward into the region (MacLeod 2009). Cold-water corals and other species that rely on calcium carbonate may show reduced growth rates and recruitment may be reduced due to ocean acidification. The impacts of climate changes on migratory species or benthic and demersal fishes in the Gully is largely unknown, though physiological and behavioural changes can be expected as a result of climate change impacts. To monitor the effects of climate change, we recommend regular monitoring of ocean chemistry (pH, dissolved oxygen, nutrient levels) and water temperatures through the Atlantic Zone Monitoring Program and other surveys, coupled with fish diversity, abundance, and size distribution data from the summer RV survey, snow crab survey, and Halibut survey. Regularly monitored stations for corals and sponges using video and photography can help couple changes in growth rates and reproduction with physical and chemical oceanographic changes. Regular acoustic and visual surveys for Northern Bottlenose Whales and other cetacean species of interest will be needed to monitor the population status under climate change as well. Information on connectivity collected as part of a longitudinal monitoring program can also highlight how climate change not only influences the ecosystem within the Gully but those surrounding and connected to it.

KEY CONCLUSIONS AND RECOMMENDATIONS

- The Gully is potentially connected to a variety of nearby canyons and conservation network sites through migration and gene flow, including St. Anns Bank and the Laurentian Channel MPAs, the Eastern Shore Islands and Fundian Channel – Browns Bank Areas of Interest, and fisheries closures including the Eastern Canyons and the Western Emerald Bank Closure.
- The collection of genetic data for groundfish and invertebrate species collected in the Gully, including corals, sponges, Atlantic Cod, and redfish, would help define population structure and potential source-sink dynamics in the northwest Atlantic. Other species that are considered conservation priorities for the Gully, including Atlantic Halibut and Northern Bottlenose Whales, have recent genetic data that has been useful in investigating connectivity among populations.
- Basic information critical for simulating dispersal from benthic conservation priority species (e.g., corals and sponges) is lacking. Additional work should focus on collecting information on the timing of spawning, larval behaviour and importantly expected larval duration, to aid in improving biophysical models that can help to elucidate important source-sink dynamics of the Gully ecosystem.
- Tagging, using acoustic or satellite tags, of migratory species such as baleen whales and sea turtles, as well as groundfish species such as Atlantic Cod, could help provide direct evidence for migratory connectivity among the Gully and other network sites.
- Hydrodynamic modeling of larval dispersal will help provide an understanding the recruitment potential and connectivity of coral and sponges with other deep-water populations. Experimental work in a laboratory setting can provide baseline biological information on larval traits to help inform modeling exercises, rearing of deep-water organisms remains challenging.
- The identification of climate tipping points or thermal thresholds for species of conservation interest could help structure programs monitoring how the Gully ecosystem is being influenced by climate change. For example, temperature thresholds linked to physiological inhibition or declining fitness could be used as benchmarks for designing monitoring programs (i.e., frequency of monitoring relative to projections) and to direct additional monitoring efforts (e.g., enhanced monitoring for conservation priorities after thresholds have been recorded). This information can also be used to predict future changes in distribution if direct monitoring is not possible or is infrequent.
- Monitoring of the physical and chemical oceanography of the Gully’s waters (i.e., temperature, pH, oxygen levels, and primary productivity) should be conducted concordantly with the biological indicators of conservation interest (cetaceans, benthic and demersal fishes, benthic invertebrates). Programs such as the Atlantic Zone Monitoring Program coupled with biodiversity surveys (e.g., trawl, longline, and video/photography surveys) will be required to help evaluate how climate change is influencing the Gully Ecosystem and thus help to inform adaptive management within the MPA.
- Monitoring shifts in cetacean distributions – including resident Northern Bottlenose Whales – due to climate change is recommended. Any changes in abundance will likely be noted through ongoing monitoring by DFO and Dalhousie University, though links to climate change will need to be made through monitoring of the physical ocean.

- The physical structure of the Gully MPA canyon is a hub for biodiversity and unique communities that inhabit the shallow reaches, the sub-marine canyon, and deep mesopelagic and benthic habitats the approach the abyssal plain below 3000 m. Notwithstanding the anticipated broad ecological changes associated with climate change on the Scotian Shelf, this unique submarine canyon will likely remain as an area of high diversity, despite potential shifts in the community composition as the ocean warms.
- Protecting connectivity among network sites, rather than just the individual MPAs and marine refuges themselves, will be vital to allow for populations to shift and persist under climate change. As populations of invertebrates, fishes, cetaceans, and other marine organisms move northward, protection from other stressors such as fishing and offshore development will be imperative to increasing their resilience in the face of climate change.

TABLES AND FIGURES

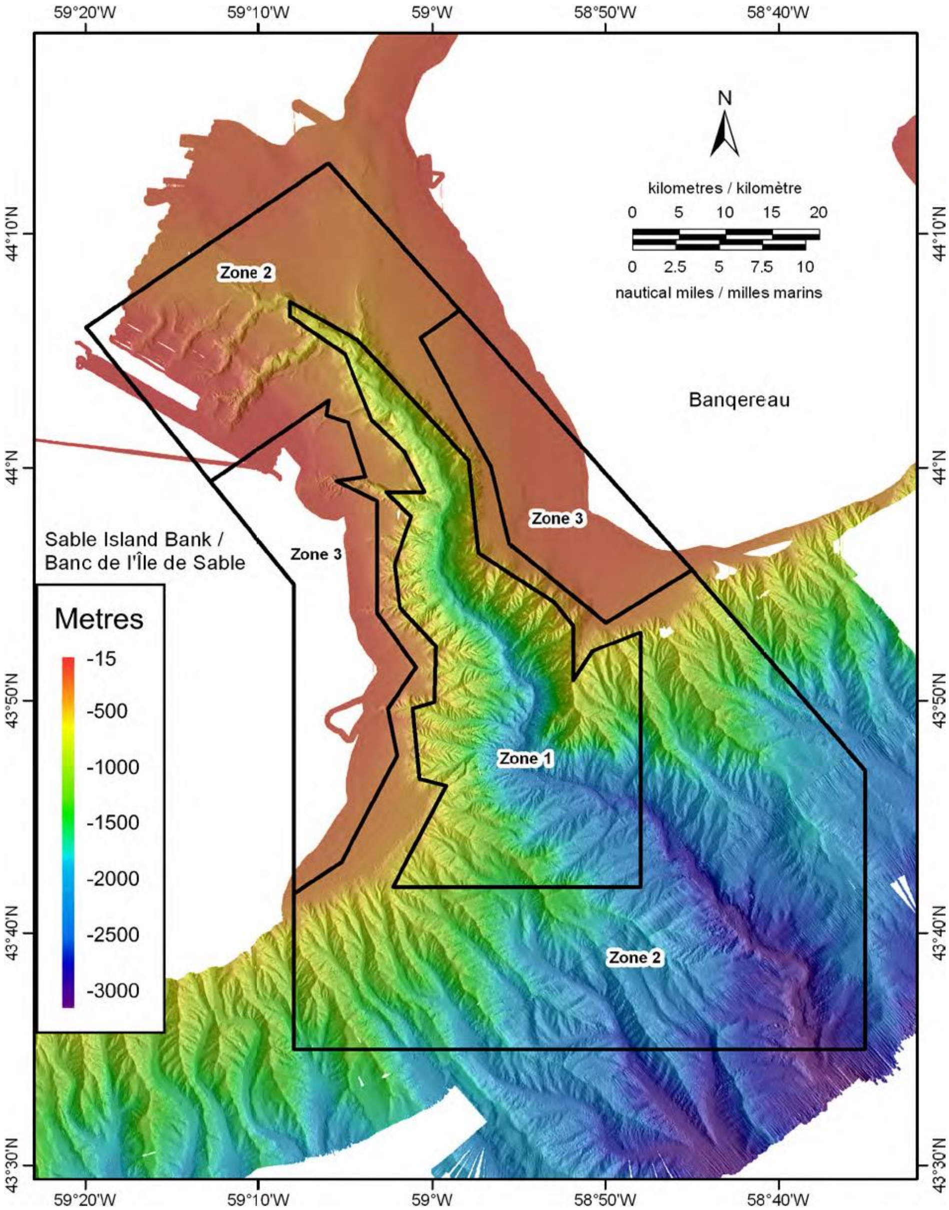

Figure 1. The Gully Marine Protected Area boundary and zones. The bathymetry of the area, based on multibeam data, is shown in colour.

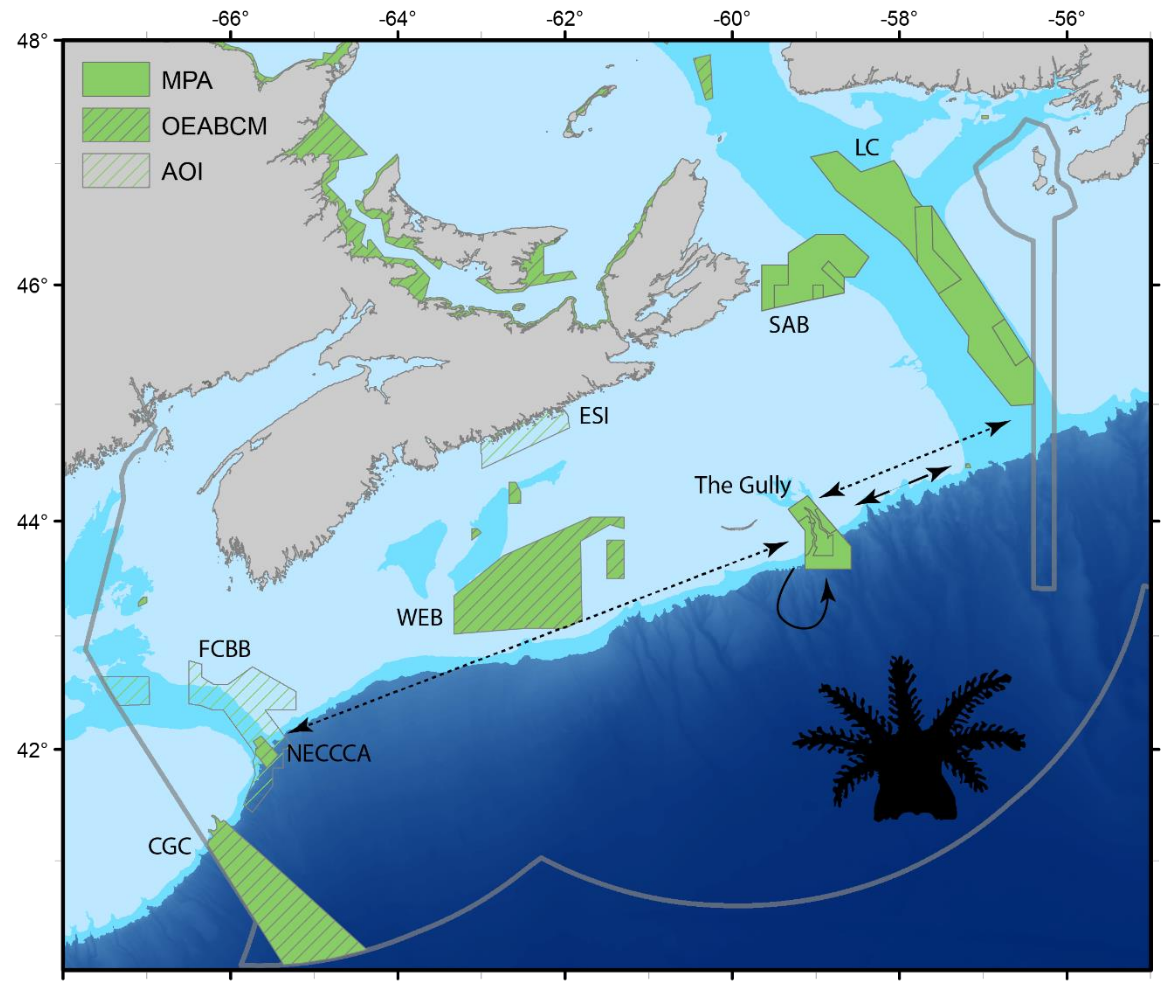

Figure 2. Map of current Conservation Areas including Marine Protected Areas, Other Effective Area-based Conservation Measures, and Areas of Interest for potential Marine Protected Areas across the Scotian Shelf, southern Gulf of St. Lawrence, and southern Newfoundland. Arrows show potential connectivity for gorgonian corals which typically self-recruit in canyon ecosystems, though larval dispersal via deep and mid-water currents is possible. Dotted lines indicate potential linkages based on suitable habitat or possible larval dispersal, dashed lines indicate potential linkages based on modeling, and solid lines indicate empirical linkages based on genetic or observational data.

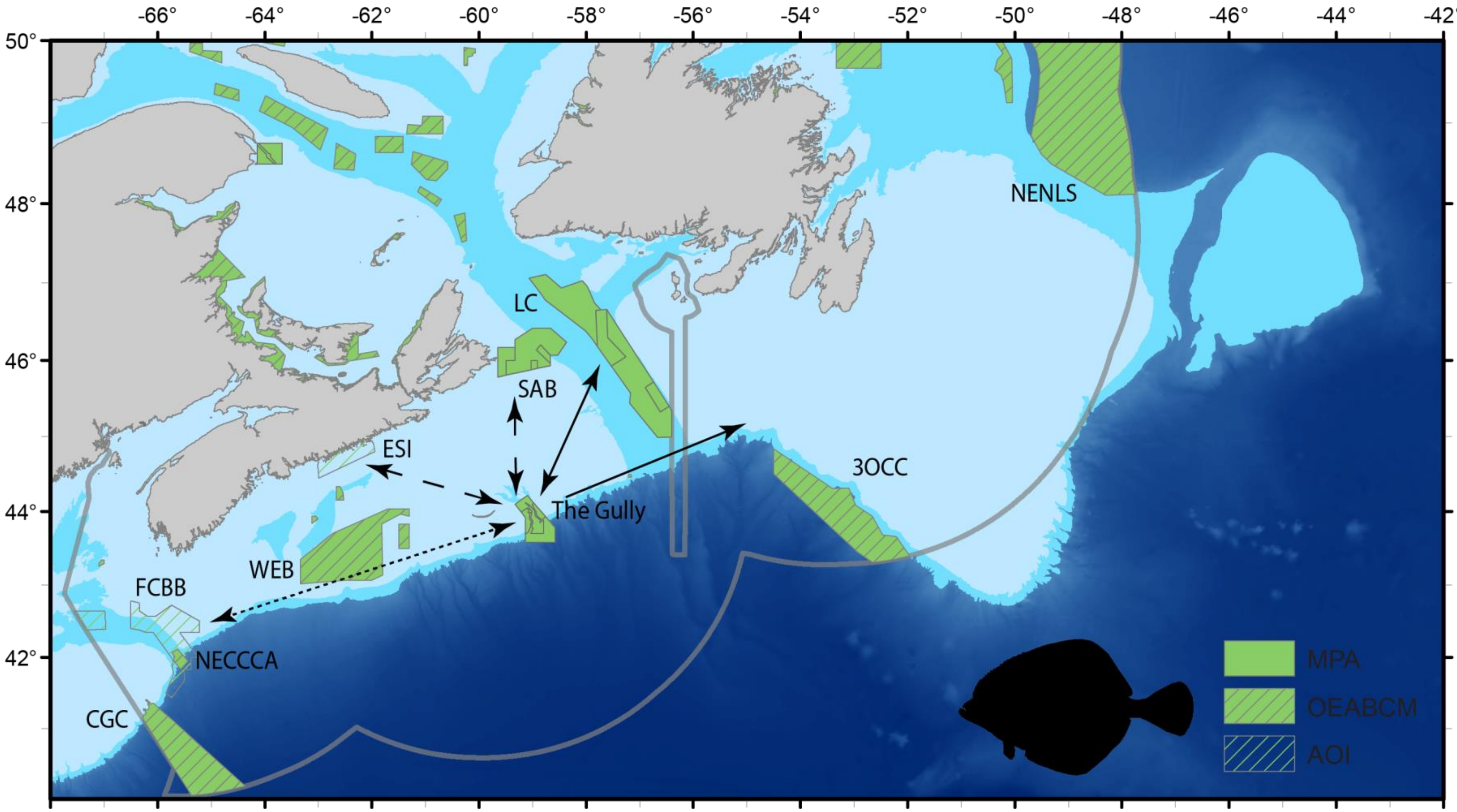

Figure 3. Map of current Conservation Areas including Marine Protected Areas, Fisheries Closures, Areas of Interest for potential Marine Protected Areas in the Maritimes Region, and arrows showing potential connectivity for Atlantic Halibut (Hippoglossus hippoglossus). Tagging studies have confirmed movements between the Gully and Laurentian Channel and genetic data suggests widespread gene flow across the Scotian Shelf and southern Newfoundland. Dotted lines indicate possible linkages based on suitable habitat or possible larval or adult dispersal, dashed lines indicate probable linkages based on modeling, and solid lines indicate definite linkages based on genetic, tagging, or observational data.

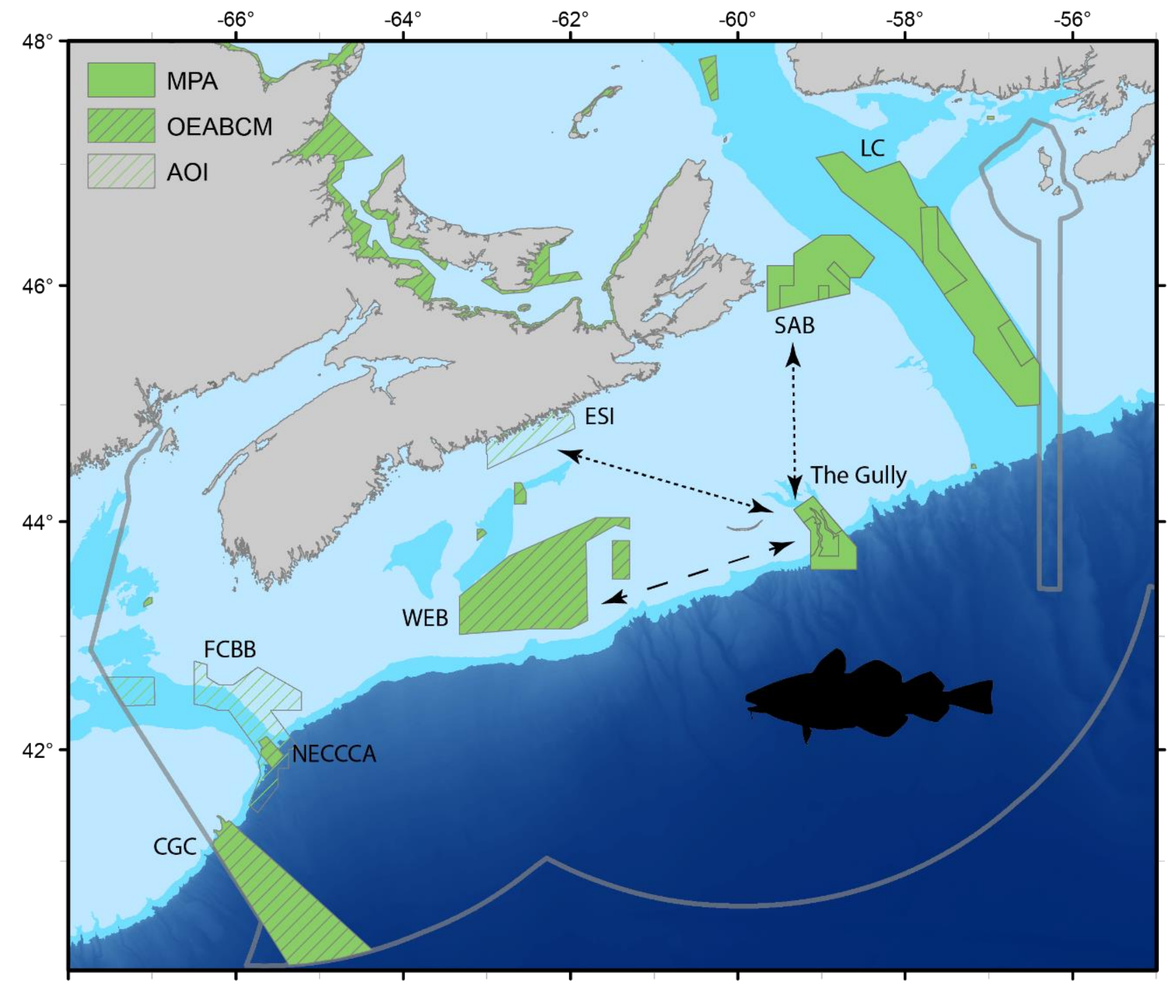

Figure 4. Map of current Conservation Areas including Marine Protected Areas, Fisheries Closures, Areas of Interest for potential Marine Protected Areas in the Maritimes Region, and arrows showing potential connectivity for Atlantic Cod (Gadus morhua) to and from the Gully MPA. A genetic divide at approximately 45° latitude separates northern and southern ecotypes of Atlantic Cod, with limited gene flow across this divide (Stanley et al. 2018). Cod in the Gully may be connected to Saint Anns Bank (SAB), the Eastern Shore Islands (AOI), and Western/Emerald Banks (WEB) through larval dispersal, and adult or ontogenetic migration. Migration among other cod populations, such as those in the Western Scotian Shelf and Bay of Fundy also occurs, but is not shown here. Dotted lines indicate possible linkages based on suitable habitat or possible larval or adult dispersal, and dashed lines indicate probable linkages based on modeling.

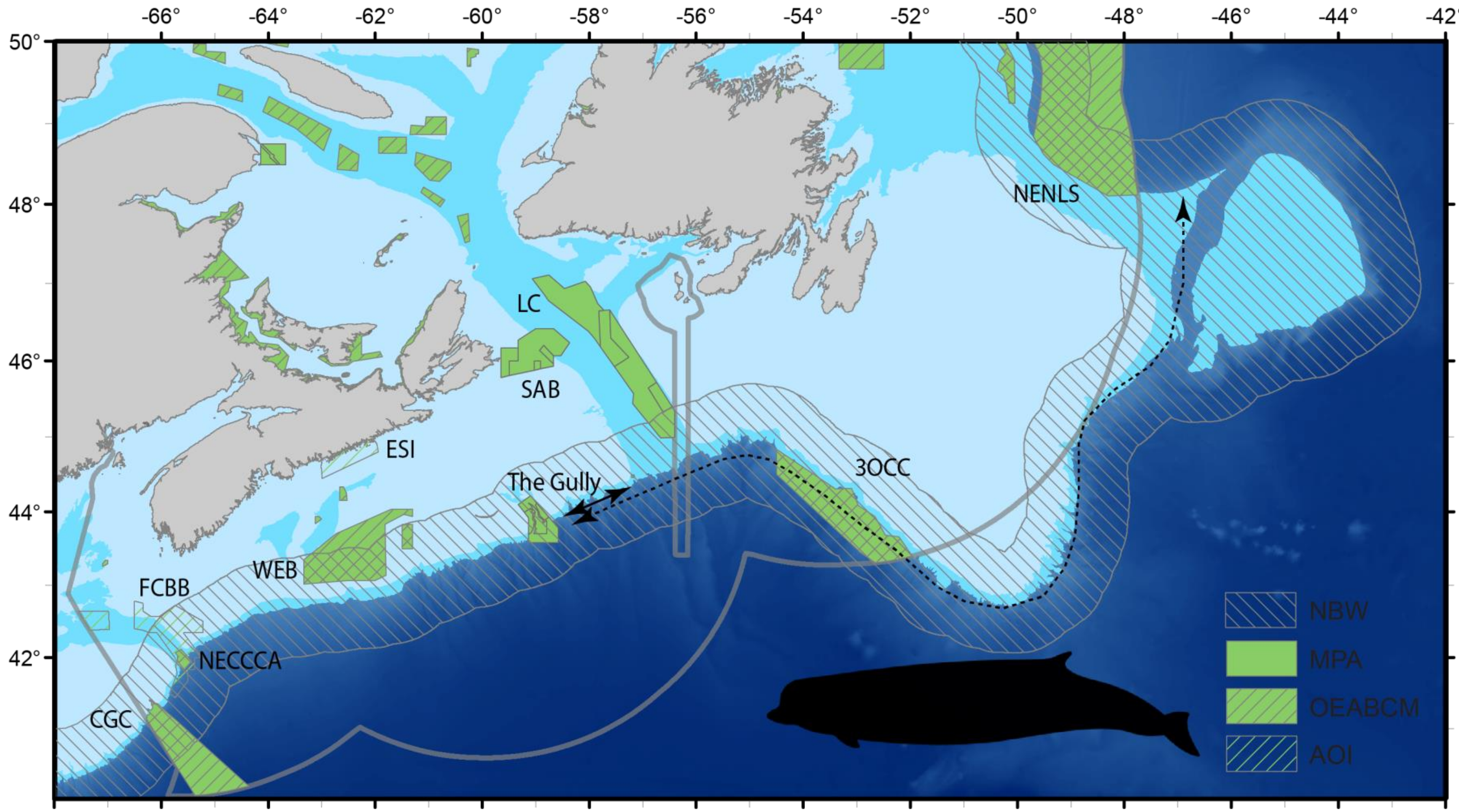

Figure 5. Map of current Conservation Areas including Marine Protected Areas, Fisheries Closures, Areas of Interest for potential Marine Protected Areas in Atlantic Canada, and arrows showing potential connectivity for Northern Bottlenose Whale (Hyperoodon ampullatus). The hashed area along the shelf break shows a 50 km buffer around the 1000 m isobaths, which indicates core NBW habitat (Feyrer 2021). Northern Bottlenose Whales regularly move between the Gully, Haldimand, and Shortland canyons (indicated by the solid arrow based on observational data), but migration is estimated to be low between northern and Scotian Shelf populations. Dotted lines indicate possible linkages based on suitable habitat and genetics indicating the uncertainty ancestry of individuals found in eastern Newfoundland, which may be an area of mixing between northern and Scotian Shelf populations (Feyrer et al. 2019).

Table 1. The potential impacts of climate change on some of the indicators developed for the Gully MPA by Kenchington (2010).

Indicators	**Ocean Warming**	**Lower pH**	**Deoxygenation**	**Current Data Source**	**Additional Data Sources Required**
1, 2, 3, 5 - Northern Bottlenose Whale indicators	Change in prey (squid and mesopelagic fishes) distribution; changes in suitable habitat; direct physiological/energetic effects	Change in prey (squid and mesopelagic fishes) distribution; changes in suitable habitat; potential direct physiological/energetic effects	Change in prey (squid and mesopelagic fishes) distribution; changes in suitable habitat; potential direct physiological/energetic effects	Whitehead Lab visual surveys (1988 onward) Acoustic hydrophone surveys (DFO Cetaceans Team) AMARS (fixed point acoustic recorders) Biopsy samples (1996-97, 2002-03) for genetic diversity	Mesopelagic trawl data for mesopelagic fishes and invertebrates; eDNA for presence/absence monitoring; hydroacoustic surveys
7, 8 - relative abundances and presence of other cetaceans in the MPA	Altered migration patterns, prey distributions, calving and mating ground shifts	Changes in prey distribution; Physiological/energetic stress; consequences largely unknown	Changes in prey distribution (positive or negative or neutral impact on abundance?); Physiological/energetic stress; consequences largely unknown	Whitehead Lab (1988 onward) Acoustic surveys and passive acoustic monitoring (DFO)	Commence monitoring of planktonic prey distributions and abundances; ongoing monitoring of cetacean abundance/presence in the Gully

9 - Number of reported strandings of Scotian Shelf bottlenose whales	Physiological/energetic stress due to warming waters	Physiological/energetic stress; consequences largely unknown	Physiological/energetic stress; consequences largely unknown	MARS database, DFO MAR Cetacean Sightings database, at-sea observer reports	Additional methods to increase data acquisition are needed, including greater observational effort
13–16 - corals and benthic habitats	Direct impacts on coral survival and reproductive success; declines in coral abundance and distribution predicted	Direct impacts on coral survival and reproductive success; declines in coral abundance and distribution predicted	Direct impacts on coral survival and reproductive success; declines in coral abundance and distribution predicted	CAMPOD, video/photographic data, ROPOS (DFO)	Regular and ongoing monitoring of select sites with corals present, as no repeat surveys have been conducted
17 - relative abundances, size distributions and diversity of selected groundfish and trawl-vulnerable invertebrates	Shift in community; reduced survival and reproductive capability; reduced growth rates and/or body size	Shift in community; reduced survival and reproductive capability; reduced growth rates and/or body size	Shift in community; reduced survival and reproductive capability; reduced growth rates and/or body size	DFO Summer RV Survey	Continued monitoring using trawl surveys at fixed stations rather than random strata; continue snow crab trawl survey to add data to the time series
18 - Relative abundances, size distributions and diversity of selected longline-vulnerable species	Shift in community; reduced survival and reproductive capability; reduced growth rates and/or body size	Shift in community; reduced survival and reproductive capability; reduced growth rates and/or body size	Shift in community; reduced survival and reproductive capability; reduced growth rates and/or body size	Industry/DFO longline halibut survey (1998 onward) fixed station	Continued monitoring using longline survey

20 - Relative abundances, size distributions and diversity of selected mesopelagic nektonic species	Shift in community, reduced survival and reproductive capability, increased interest in fishing mesopelagic fish as benthic and pelagic fish are depleted	Shift in community, reduced survival and reproductive capability, increased interest in fishing mesopelagic fish as benthic and pelagic fish are depleted	Shift in community, reduced survival and reproductive capability, increased interest in fishing mesopelagic fish as benthic and pelagic fish are depleted	Mesopelagic trawls conducted between 2007-10	Not actively monitored – if possible, additional mid-water trawls should be conducted; eDNA metabarcoding of water samples may be more efficient to survey mesopelagic fish and invertebrate diversity
21, 22, 23 - Physical and chemical environment	Ocean temperatures will increase as the global temperature increases	Ocean pH will decrease as carbon dioxide is sequestered by the global ocean	Dissolved oxygen will decrease as ocean temperatures warm	AZMP, AZOMP, Dedicated Gully study (2006-2007), SSIP (1978-1982)	Monitoring of key ocean temperature and chemistry parameters should continue during regular surveys
24 - weather conditions at Sable Island weather station (wind, air pressure, air temperature)	Increase in air temperature associated with increasing ocean temperature and general climate change	N/A	N/A	Environment and Climate Change Canada Sable Island weather station	Monitoring of weather conditions at Sable Island should continue
25 - three-dimensional distribution and	Shifts in magnitude and velocity of prevailing currents and	N/A	N/A	2006-2007 field program (moorings and CTD/ADCP casts)	Moored- and mobile ADCP data could be collected with regularity

movements of watermasses within and around the MPA	water mass movements as temperatures increase				to update models and monitor changes in water mass movements; however, monitoring watermass movement remains difficult and costly
26–27 - phyto- and zooplankton production/biomass and community composition, and biomass	Declines in abundance and diversity of cold-water adapted species, shifts in community composition as waters warm	Direct physiological consequences for plankton biomass and possible community composition shift to species able to tolerate reduced pH	Direct physiological consequences for plankton biomass and community composition	AZMP, BIONESS sampling system; flow cytometry of water samples for bacteria and phytoplankton, taxonomic identification of zooplankton	Continuous plankton recorder data, eDNA sampling for phyto- and zooplankton in associated with AZMP and RV survey cruises.
29 - distribution and abundance of seabird species within the MPA	Potential shifts in prey distribution (e.g. forage fish, zooplankton) and concomitant shift in seabird community	Potential shifts in prey distribution (e.g. forage fish, zooplankton) and concomitant shift in seabird community	Potential shifts in prey distribution (e.g. forage fish, zooplankton) and concomitant shift in seabird community	PIROP (1966-1992), ECSAS (2006-present; regular but opportunistic data collection)	Seabird diversity and abundance recorded opportunistically; seabird observers from the Canadian Wildlife Service take part in annual trawl surveys, and should continue

32, 33 - commercial fishing effort in or in close proximity to the MPA	Shifts in fishing effort can be expected as fish and invertebrate communities change under warmer temperatures; productivity expected to decline as species ranges shift	Shifts in fishing effort can be expected as fish and invertebrate communities change under changes in ocean pH, productivity expected to decline as species ranges shift	Shifts in fishing effort can be expected as fish and invertebrate communities change as ocean dissolved oxygen levels decline, productivity expected to decline as species ranges shift	Logbook data, MARFIS database	Partnerships with fishing industry, local ecological knowledge to inform changes in fish distributions, set monitoring stations in the Gully for fisheries-dependent and –independent surveys
46 - reports of known invasive species in the MPA	Increased occurrence of warm-water fish and/or invertebrate species in the Gully, possible competition with native species and extirpation	Possible introductions of pH- or dissolved CO_2-tolerant species	Unknown impacts	DFO AIS program, no regular reporting for AIS in the Gully	Targeted qPCR and metabarcoding of eDNA samples, collaboration with AIS researchers for video monitoring

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