From local to regional seabed maps: Developing the methods and data products needed for marine conservation planning in Newfoundland and Labrador

A Thesis submitted to the
School of Graduate Studies
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
Department of Geography
Memorial University of Newfoundland

May 2025
St. John's
Newfoundland and Labrador

Abstract

Maps are essential tools for understanding the environment around us. This is especially true for the global ocean: the majority seafloor habitats are out of sight and beyond the reach of conventional survey methods. In this thesis, I use two case studies to demonstrate the utility of multibeam echo-sounding and biological sampling to map marine habitats in support of conservation planning. Habitat protection is a key pillar in the conservation strategy outlined by Canada's Species At Risk Act, yet information on critical habitat is not available for most marine species at risk. In Chapter 2, I use high-resolution multibeam, physical samples, and video surveys to identify biologically distinct habitats and delineate potential spawning and nursery areas for Atlantic wolffish. In addition to characterizing and mapping seafloor habitats, this work highlights potential vulnerability of nearshore wolffish spawning habitats to warming coastal waters. Habitat mapping is also important to Marine Protected Area (MPA) design and monitoring. In Chapter 3, I define and map the seafloor habitats of Newfoundland and Labrador's Eastport MPA to assess MPA design against stated management goals. Despite aiming to protect endangered wolffish, this small MPA does not include suitable wolffish habitats and, unfortunately, contributes little to regional biodiversity. This work highlights the importance of science-driven management and the challenges faced when single-species fisheries closures are redefined as broader conservation measures without adaptive management to support the expanded objectives.

These case studies add to mounting evidence that further investment in and effective use of marine habitat maps is key to effective conservation and sustainable management of our oceans. However, multibeam surveys are expensive and time-consuming. In Chapter 4, I outline a method for using low-cost crowd-sourced data to improve seafloor maps at a regional scale and higher spatial resolution than previously possible. I use this method to produce novel data products for over 670,000 square kilometres of the Newfoundland and Labrador shelf, including identification of almost 2000 km^2 of previously unmapped tributary submarine canyons. This research advances our understanding of Newfoundland and Labrador waters and presents tools that can be applied to science-based marine conservation planning regionally and globally.

Co-Authorship Statement

This dissertation is written in manuscript style; Chapters two, three, and four are published in scientific journals. I, Emilie Novaczek, am the primary researcher behind the work performed in each of the chapters, including developing the ideas, reviewing the literature, collecting and analyzing data, interpreting the results, and preparing the manuscripts.

Chapter 2, “High resolution habitat mapping to describe coastal denning habitat of a Canadian species at risk, Atlantic wolffish (*Anarhichas lupus*)” was published in 2017 in the Canadian Journal of Fisheries and Aquatic Sciences (vol. 74, p. 2073-2084). This manuscript was written with co-supervisors Dr. Rodolphe Devillers and Dr. Evan Edinger (Department of Geography, Memorial University), and with the help of committee member Dr. Luiz Mello (Fisheries and Oceans Canada). Co-authors contributed to research design, interpretation of results, and manuscript revision.

Chapter 3, “Limited contribution of small Marine Protected Areas to regional biodiversity: The example of a small Canadian no-take MPA”, was published in 2017 as part of the 4th International Marine Conservation Congress special issue of Frontiers in Marine Science (vol. 4, article 174). This manuscript was written with several co-authors. Dr. Rodolphe Devillers and Dr. Evan Edinger contributed to research design, interpretation of results, and manuscript revision. Fellow students Victoria Howse (Centre for Fisheries and Ecosystem Research, Marine Institute of Memorial University) and Christina Pretty (Department of Geography, Memorial University) contributed to data processing/analysis and manuscript revision. Former lab member Alison Copeland (Department of Environment and Natural Resources, Government of Bermuda) collected the regional biodiversity data used to compare the MPA to the surrounding area and also contributed to manuscript revisions.

Chapter four, “Generating higher resolution regional seafloor maps from crowd-sourced bathymetry” was published in 2019 in PloS one (vol. 14, issue 6, article e021679200). This manuscript was written with co-supervisors Dr. Rodolphe Devillers and Dr. Evan Edinger, who contributed to development of the manuscript concept, selection of data sources and methods, interpretation of results, and manuscript revision.

Through the thesis review process, the text of each chapter has been modified slightly from the published version. There is no change to the results or conclusions of these papers. The relevant references are listed below:

Novaczek, E., Howse, V., Pretty, C., Devillers, R., Edinger, E., Copeland, A. 2017. Limited contribution of small Marine Protected Areas to regional biodiversity: The example of a small Canadian no-take MPA. Frontiers in Marine Science, 4(174), 1-17. DOI: 10.3389/fmars.2017.00174

Novaczek, E., Devillers, R., Edinger, E., Mello, L. 2017. High resolution habitat mapping to describe coastal denning habitat of a Canadian species at risk, Atlantic wolffish (*Anarhichas lupus*). Canadian Journal of Fisheries and Aquatic Sciences, 74, 2073-2084. DOI: 10.1139/cjfas-2016-0414

Novaczek, E., Devillers, R., Edinger, E. 2019. Generating higher resolution regional seafloor maps from crowd-sourced bathymetry. PloS One, 14(6), e0216792. DOI: 10.1371/journal.pone.0216792

Acknowledgements

Thank you to my incredible team of supervisors: Dr. Rodolphe Devillers, for the high standards you cultivated in the Marine Geomatics Research Lab and for your trust in my ideas; Dr. Evan Edinger for your creativity and kindness; and Dr. Carissa Brown for your compassion, support, and patience. I was also lucky to work with so many talented students, including Dr. Ben Misiuk, Katy Macpherson, Dr. Vince Lecours, Dimitri Tzatzikis, Lara Miles, Victoria Howse, and Christina Pretty. Thank you all so much – I can't imagine this thesis without the many hours we spent together in the lab and on the water. I would also like to thank my committee members and colleagues from Fisheries and Oceans Canada (DFO), Dr. Luiz Mello and Dr. Dave Coté, for your guidance throughout this process. Thank you to Dr. Daniel Ierodiaconou and Dr. Mary Young for your mentorship; I am so grateful I was able to study with you and the Deakin University Marine Mapping Group. To the Memorial University Geography Department staff – Pamela Murphy, Valerie James, and Glenn Crewe—thank you for all your help over the years that made this work possible. Of course, thank you to the funders who supported me: the Natural Sciences and Engineering Council of Canada and P.E.O. International.

The research presented in Chapter 2 on Atlantic wolffish habitat was supported by the DFO Academic Research Contribution Program (ARCP) (project No. 3342008). I thank Mark Simpson who provided insight and expertise for the conception of this work and provided data on wolffish telemetry. Thanks also to Wayne Ledwell, Trevor Madigan, and Chris Holloway for assistance with field surveys and to the Thornbacks Dive Club members who submitted information on Atlantic wolffish denning sites. The study of the Eastport Marine Protected Area (MPA) described in Chapter 3 was also funded by the DFO ARCP (project 3342008). Thank you to specifically to Laura Park, who generously included me and my work in the annual

stakeholders meeting of the Eastport MPA and to the Eastport community members for your time and valuable insights. I thank the Canadian fishers who collected the bathymetric data that made the research of Chapter 4 possible, and Olex AS/Mackay Marine for making these data available. In particular, we thank Ole B. Hestvik for his time and insight regarding Olex data collection and processing methods. Thanks also to Elaine Hynick, for providing access to the DFO-NL Roxann data. This manuscript also benefitted from comments by Dr. Jean-François Bourillet and Dr. Dawn Wright.

I also want to thank my mother Irené, the first Dr. Novaczek and my first reviewer when I started applying for the programs, grants, and scholarships that brought me here. I hesitate to thank my father Ernest. I am sure he would prefer not to be mentioned but, alas, he has been an unfailing source of support. To my partner Phil, thank you for everything.

Finally, this research is dedicated to the memory of Callum Mireault, a young man who loved the ocean, mapping, and marine technology.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction and overview

1.1 Context

Managing human use of the environment is a profoundly complicated task. To make informed decisions we seek to understand infinitely complex ecosystems and this challenge is amplified when we consider vast and inaccessible marine ecosystems. Over >90% of the earth's biosphere is found in the ocean (Snelgrove, 2010), almost half of global primary production and atmospheric oxygen are generated by marine phytoplankton (Naselli-Flores & Padisak, 2022), and marine fisheries are crucial to global food security (FAO, 2020). Despite our reliance on healthy marine ecosystems, human impacts on marine biodiversity continue to accelerate and conservation efforts lag (O'Hara, et al., 2021). A recent review found that overexploitation and habitat loss are the leading anthropogenic threats for Canada's at-risk species, including marine fish (Woo-Durand, et al., 2020). Commercially harvested marine fish are similarly vulnerable (Kritzer, et al., 2016; Yan, et al., 2021). These threats are often cumulative for marine species and their supporting habitats. For example, mobile fishing gears like trawls and dredges capture both target and non-target species (Auster, et al., 1996), while also contributing to habitat homogenization or destruction (Gray, et al., 2006), and disrupting ecosystem function (Olsgard, et al., 2008). These impacts are not limited to the flattening of structurally complex habitats like coral and sponge fields (DFO, 2010); trawls and dredges also lead to homogenization of the soft sediment habitats (Gray, et al., 2006).

In addition to the direct impacts of human activity, anthropogenically induced climate change also threatens marine ecosystems (Poloczanska, et al., 2016). A global study of climate change driven marine species distribution shifts by Chen et al. (2011) found that changes in species distribution did not keep pace with thermal shifts, listing unidentified dispersal barriers, poor sampling resolution, or dominance of unmeasured drivers as the possible confounding variables. Furthermore, climate change is driving changes in habitat quality, not just distribution. Atlantic cod (*Gadus morhua*), for example, maintain their historic geographic range despite warming waters, at a metabolic and developmental cost (Neat & Righton, 2007). Factors such as local climate variability, reorganization of ecosystems, and the (un)availability of structural habitat features may severely limit marine species distributions as their existing habitats decline in extent or quality. Modeling of temperature range and habitat for fish species in the Mediterranean indicated that distribution was consistently overestimated when models did not incorporate physical habitat characteristics like seafloor slope and substrate type (Hattab, et al., 2014). Modeling the responses of 125 species to climate driven changes, McHenry et al. (2019) also found that relying on temperature yielded over estimates of species distribution and recommend multifactor habitat suitability models including seafloor characteristics like bathymetry and rugosity. As climate change alters benthic habitats, making them inaccessible or physiologically costly, future distributions of cold-water marine species may be more restricted that our projections indicate, due to a lack of consideration for structural habitat variables. Conservation and fisheries management efforts based on present-day distributions will be inadequate under changing conditions, and a better understanding of the distribution and vulnerabilities of benthic habitat (i.e., habitats of the seafloor) is urgently needed.

Mitigation of human impact on benthic ecosystems requires a robust understanding of seafloor habitats, their distribution, and their potential vulnerabilities. Practitioners have applied seafloor habitat mapping to fisheries management (Buhl-Mortensen, et al., 2015), seafloor use conflict resolution (Harris & Baker, 2012), offshore development impact mitigation (Pickrill & Todd, 2003) and conservation planning (Rowden, et al., 2017). However, seafloor habitat distribution and suitability at local and regional scales remains difficult to resolve and lack of spatial habitat information for commercial species presents a major barrier to fully integrated ecosystem based management (Moore, et al., 2016). The advancement and implementation of marine spatial planning is one of five policy challenges identified in a 2020 review on the progress and remaining challenges for the protection of Canadian marine biodiversity (Hutchings, et al., 2020). However, only a small fraction of the global seafloor has been mapped at the high resolution required to identify and monitor marine habitats (Mayer, et al., 2018).

1.2 Research problem

The ability to identify, characterize, and monitor changes in marine habitats is necessary to assess potential vulnerabilities, to review effectiveness of existing conservation initiatives, and to design and maintain successful protected areas. Through satellite altimetry and interpolation of existing depth records, GEBCO (the General Bathymetric Chart of the Oceans) maintains a bathymetric grid for the global ocean (Mayer, et al., 2018). However, the resolution of these data rarely captures the ecological relationships that define habitat (Rengstorf, et al., 2012). Ongoing national and global programs to increase coverage of high resolution seafloor mapping; however, significant data gaps remain. For areas like the Newfoundland and Labrador Shelves, high resolution seafloor mapping is limited to small, disconnected study areas. Although these local-scale studies provide value through characterization of habitat and potential threats to Species at Risk (e.g., Chapter 2) or assessment of MPA success (e.g., Chapter 3), managers still lack seafloor habitat data of sufficiently high resolution to capture ecological processes and with sufficiently broad extent to support regional decision making. This thesis aims to improve both the extent and resolution of seafloor maps for Newfoundland and Labrador, and contribute to our understanding of seafloor habitat in the region. Specifically, each chapter addresses a component of local or regional seafloor mapping that can inform study of seafloor habitats and support marine conservation planning for Newfoundland and Labrador. The study areas of each chapter are shown in Figure 1.1.

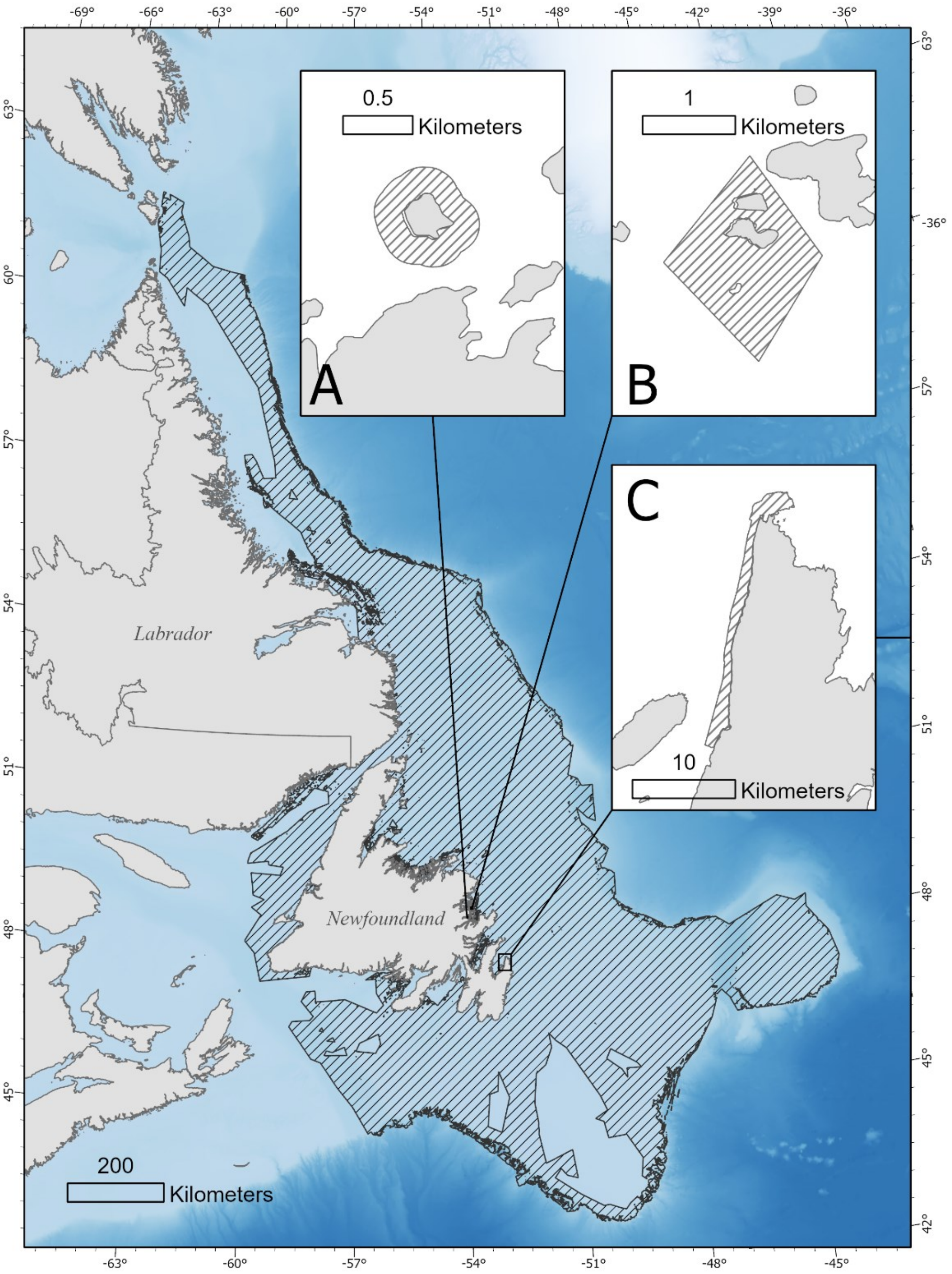


Figure 1.1 Study areas explored in this thesis (hatched areas), including the Eastport MPA Round Island (A) and Duck Island (B) closures, Atlantic wolffish habitat within Conception Bay, Newfoundland (C), and the Newfoundland and Labrador Shelves mapped by crowd-sourced bathymetry (main panel).

1.3 Research questions and manuscript objectives

1.3.1 Chapter 2: "High resolution habitat mapping to describe coastal denning habitat of a Canadian species at risk, Atlantic wolffish (*Anarhichas lupus*)"

The identification and protection of habitat is an essential component of conservation, particularly in the context of anthropogenic climate change (Government of Canada, 2002; Woo-Durand, et al., 2020). In support of species-at-risk management, we characterize and map the nearshore habitat of Atlantic wolffish. The research questions addressed in this chapter are:

- What are the characteristics of nearshore denning habitat of Atlantic wolffish?
- What are the habitat-related vulnerabilities for Atlantic wolffish?

As a demersal species, the relationship between Atlantic wolffish and seafloor habitat is measurable and can be used in predictive mapping of species distribution. This study of coastal habitats of Conception Bay, NL considers the denning habitat of Atlantic wolffish, which are characterized and mapped through multi-variate analysis and supervised classification of high-resolution multibeam bathymetry and backscatter, seafloor video, and sediment samples. Use of acoustic telemetry and water temperature data demonstrates seasonal movement of tagged wolffish, and identifies potential vulnerability of this habitat type in a changing climate. This chapter uses habitat mapping techniques to address management plan requirements and provides information on the emerging threat posed by warming inshore waters.

1.3.2 Chapter 3: "Limited contribution of small Marine Protected Areas to regional biodiversity: The example of a small Canadian no-take MPA"

This paper presents a case study on the use of marine habitat maps to assess the ability of a Marine Protected Area (MPA) to meet its stated conservation objectives. Specifically, I ask:

- Do the Eastport MPA closures protect threatened or endangered species?

- Do the Eastport MPA closures protect unique habitats or areas of high biodiversity?

The Eastport MPA was originally designed to protect a single-species fishery resource (American lobster), however, the management plan also lists conservation and protection of threatened or endangered species as an MPA objective (DFO, 2013). Protection of unique habitats and areas of high biodiversity are also objectives for MPAs designated under the Oceans Act (GoC, 1996). Success on these three objectives was assessed by mapping and characterizing the habitats of the MPA and the surrounding area. This study demonstrates the important role of seafloor habitat mapping in the planning and subsequent assessment of MPAs, to assess the success of the Eastport MPA specifically, and to inform more successful MPA planning going forward.

1.3.3 Chapter 4: "Generating higher resolution regional seafloor maps from crowd-sourced bathymetry"

Survey effort is one of the biggest impediments to extensive coverage of high resolution seafloor maps. Mayer et al. (2018) estimated that it would take over 900 years of continuous operation to fill the gaps in the in GECO2014 bathymetric grid. Crowd-sourced data offer one alternative to costly and time-consuming seafloor mapping exercises. Here, I ask:

- How can crowd-sourced data be leveraged to support improvement of regional seafloor maps?

This chapter presents a framework for the use of advanced interpolation (Empirical Bayesian Kriging) to leverage a large crowd-sourced dataset for low-cost, high-resolution mapping at the regional scale. This study aims to provide a reproducible method for development of low-cost regional bathymetric maps, and to develop new data products that will support regional habitat mapping for the Newfoundland and Labrador Shelves.

1.4 Approach

The vast majority of the seafloor lies beyond the reach of both light and now-ubiquitous global position system (GPS) signal, presenting an immense challenge for ocean cartographers. Many technologies have been developed to address the unique complications of mapping the seafloor, ranging from the early leadlines to satellite borne sensors capable of measuring gravity anomalies of the sea surface to reveal the features far below (i.e. satellite altimetry). This thesis focuses on echo-sounding from surface platforms, a mapping method that measures the returning echoes of high-frequency pulses of sound directed at the seafloor.

In the field of seafloor habitat mapping, multibeam echo-sounding is often the first method of choice. Multibeam data is collected in a large swath of continuous, high resolution digital bathymetric model of the mapped area (Smith & Sandwell, 2004). In addition to water depth (calculated based on the time of echo return), multibeam echo-sounding also provides information on composition of seafloor sediments, based on backscatter strength (Lucieer, et al., 2018). Chapters 2 and 3 make use of high-resolution multibeam data to develop seafloor habitat maps. However, collection of these data is both expensive and time-consuming, and global coverage remains extremely limited (Mayer, et al., 2018). In the absence of sufficient multibeam data coverage on the Newfoundland and Labrador Shelves to support regional habitat mapping, Chapter 4 explores the use of crowd-sourced single beam echosounder data as an alternative.. Single beam echosounders provide an accessible and affordable way for fishing, shipping, and recreational vessels to monitor water depth while at sea. While one individual single beam echosounder is less efficient and less informative for scientific mapping than multibeam, thousands of vessels simultaneously collecting single beam data can map extensive areas of the seafloor in a fraction of the time and cost. This study uses crowd-sourced single beam data and an advanced interpolation technique (Empirical Bayesian Kriging) to generate seafloor maps at a higher resolution and larger extent than previously possible.

Benthic habitats are defined as spatially recognizable areas where physical, chemical, and biological characteristics vary consistently from surrounding environments (Kostylev, et al., 2001). The challenging nature of biological sampling in the marine environment requires that the study of benthic habitats to rely heavily on surrogate variables; i.e. the easily measured characteristics that describe habitat and/or species assemblage (Harris & Baker, 2012). The selection of surrogate variables and scale of analysis are common sources of error, noise, and confusion in predictive mapping (Austin & Van Neil, 2010). The sheer volume of data required to produce a robust habitat map often means that a researcher is relying on several datasets that may have been collected for other purposes. Model inputs are often chosen based on available data and/or previous use, resulting in a near certainty that some predictors will be missed (Barry & Elith, 2006). Variables should be chosen under careful consideration using ecological theory or empirical evidence to explain which factors are most likely (or previously proven) to influence the target species and why (Austin & Van Neil, 2010). The field of seafloor habitat mapping is generally divided into two broadly defined approaches: supervised and unsupervised classification methods (Calvert, et al., 2015). The first two chapters of this thesis use unsupervised classifications of acoustic data (bathymetry, backscatter, and geomorphometry) to map benthic habitat boundaries. Seafloor images, video, and sediment samples were then used to assign habitat types based on the spatial overlap of classified map pixels and ground-truth data. Chapter 4 uses a supervised classification approach to identify common landforms and previously unmapped canyon features. A review of benthic marine habitat mapping literature by Harris and Baker (2012) identified depth, geomorphometry (i.e. seafloor shape), and sediment composition variables as the most frequently used predictors of benthic habitat and species distribution. Following that review, Lecours et al. (2017) demonstrated that six specific terrain attributes capture the majority of seafloor topographic structure: relative position, local standard deviation, slope orientation, local bathymetric mean, and slope. My thesis is heavily informed by the work of Harris and Baker (2012) and Lecours et al. (2017) for the selection of environmental variables for habitat mapping (see Chapters 2-3) and applies their guidelines to the development of fit-for-purpose, multi-scale data products (i.e. continuous bathymetry, geomorphometry, and landforms) that support regional benthic habitat mapping (see Chapter 4).

1.5 Significance

In this thesis I aimed to address current data gaps for marine conservation planning in Newfoundland and Labrador. Along with my co-authors, I used local case studies to demonstrate applications of benthic habitat mapping to management questions and expanded that work to generate novel methods and data products for the Newfoundland and Labrador Shelves in support of regional habitat mapping and decision making.

Chapter 2 provides high resolution mapping of coastal denning habitat for a species at risk (Atlantic wolffish). Characterizing and mapping habitat is an important part of species at risk conservation, and the Species at Risk Act (SARA) require mapping of critical habitat for Threatened and Endangered species. High resolution multibeam bathymetry, seafloor video, and substrate samples were used to describe and classify benthic habitats, with the objectives of identifying, characterizing and mapping coastal Atlantic wolffish habitat. Analysis of telemetry data and seasonal water temperature in the study area were also used to identify potential vulnerability of this habitat to seasonal maximum temperatures that exceed the thresholds identified for healthy development of eggs and larval fish. Our findings drove the development of the subsequent research chapter. If, as Chapter 2 suggests, Atlantic wolffish nearshore denning habitat is becoming physiologically costly for adult fish and/or damaging for egg and larval development during breeding periods, then continued conservation of this species will rely on the identification and protection of denning habitat beyond shallow, coastal waters that are exposed to increasing seasonal temperatures. At present, there are insufficient data to identify wolffish habitat in the offshore, due to incomplete coverage of high-resolution data and insufficient resolution of the broadly available data.

Chapter 3 demonstrates the importance of habitat mapping to inform the design and assessment of Marine Protected Areas (MPAs). This paper describes a benthic habitat survey in the small no-take MPA of Eastport, Newfoundland, and compares the protected habitats and species to the surrounding area and to the stated objectives of the MPA. Mapping benthic habitats in both established and prospective MPAs provides essential information on what is protected, what is left to protect, and which design strategies have been successful. We use the Eastport MPA as an example of a conservation effort that was socially successful, but ecologically insufficient due to the focus on a single, commercial species and limited size of the no-take area. The insights provided by detailed study and assessment of marine conservation progress to date will help inform MPA network planning and contribute to successful conservation efforts going forward. However, the bathymetry and habitat data currently available to support regional MPA network design are generally too coarse to capture biological and ecological processes.

Chapter 4 provides a framework for developing and/or improving regional seafloor maps through the use of crowd-sourced bathymetry. Here, I also produce a suite of important data products: 75 m grid bathymetry, terrain attributes, and landform classification that covers

672 900 km^2 of Newfoundland and Labrador Shelves, the highest resolution data available for the majority of this area. Finally, I demonstrate one of many applications of crowd-sourced bathymetric data: I present a novel semi-automated method for identification of submarine canyons is presented and used it to identify over 1800 km^2 of highly dendritic shelf-edge canyons that were previously unmapped.

Chapter 2. High resolution habitat mapping to describe coastal denning habitat of a Canadian species at risk, Atlantic wolffish (*Anarhichas lupus*)

2.1 Abstract

The Atlantic wolffish (*Anarhichas lupus*) is listed by Canada's Species at Risk Act as a species of special concern. Effective conservation strategies rely on accurate knowledge of habitat requirements, distribution, and vulnerabilities; however, current management plans cite lack of wolffish habitat data as a key limitation. For this study, coastal Atlantic wolffish denning habitat was characterized and mapped with high-resolution multibeam data and seafloor video in Conception Bay, Newfoundland. Four Atlantic wolffish dens, used for feeding, spawning, and egg-guarding, were surveyed and mapped. On the basis of the geomorphology and substrate of these dens, a supervised classification was applied to the multibeam bathymetry and backscatter data to identify other potential denning areas. Predicted denning habitat, limited by the occurrence of suitable rocky substrate, is most prevalent in shallow waters (<22 m) distributed over 1.6 km^2 (5.9%) of the study area. Shallow denning habitat is exposed to seasonal maximum temperatures that exceed the threshold for normal Atlantic wolffish egg development, a potential vulnerability for nearshore wolffish. As management efforts progress, this information will guide research and prioritization of conservation areas.

2.2 Introduction

The Atlantic wolffish is a large, slow-growing, demersal fish found throughout the North Atlantic Ocean (McCusker & Bentzen, 2010). In Canadian waters, the range of Atlantic wolffish extends from the Bay of Fundy to the Davis Strait (DFO, 2015). Wolffish are not commercially harvested in North America but are vulnerable to bycatch in 20 directed fisheries of Newfoundland and Labrador (DFO, 2008). Following an estimated loss of 60% of the mature population within two generations (Simpson, et al., 2013), the Atlantic wolffish was listed as a species of Special Concern under the Canadian Species at Risk Act (SARA) in 2003. Two other species of wolffish, the spotted wolffish (*Anarhichas minor*) and northern wolffish (*Anarhichas denticulatus),* are also listed under SARA as Threatened. Management of the species and habitat is a requirement for all species of Special Concern, and the identification of areas that are important to population recovery (i.e., nurseries, spawning areas, and feeding grounds) is a key information gap for all three wolffish species in Canadian waters (DFO, 2008). This paper presents recent efforts to characterize, predict, and delineate Atlantic wolffish habitat in a coastal area known to be occupied year-round.

Trawl-based surveys in the waters of Newfoundland and Labrador frequently record Atlantic wolffish at depths of 100–300 m (Albikovskaya, 1982), although they are known to occupy a much wider depth range. Atlantic wolffish have been documented in trawls up to 918 m depth (DFO, 2008), and they are also often observed by SCUBA divers nearshore, as shallow as 5 m (Pavlov & Novikov, 1993; Simpson et al. 2015). In coastal areas, Atlantic wolffish are associated with high-slope and high-rugosity boulder and bedrock habitats that form crevices and caves (Pavlov and Novikov 1993; Larocque, et al., 2008). Kulka et al. (2004) suggested that reproduction of inshore resident wolffish depends on the presence of appropriate rocky substrate for denning. On the Labrador Shelf and Grand Banks of Newfoundland, Atlantic wolffish occupy a variety of substrates, including coarse sand, gravelly sand, and boulder and rocks (Kulka, et al., 2004). Catch rates are highest on rock and sand with shell hash (Kulka, et al., 2004). Efforts to map broad-scale habitats species in the Gulf of St. Lawrence found Atlantic wolffish most commonly occupy coarse sandy substrates and rocky outcrops (Dutil, et al., 2014). It should be noted, however, that the spatial uncertainty related to trawl data may not facilitate accurate assessments of occupied substrates. Also, abundance may be underestimated on preferred habitats owing to the challenge of conducting trawl surveys over rocky, uneven seafloor (Thorson, et al., 2013; Fairchild, et al., 2015).

Several authors have reported seasonal movements of Atlantic wolffish and have explained this migration as the separation of habitats for spawning (Jonsson, 1982; Keats, et al., 1985; Nelson & Ross, 1992) and foraging (Fairchild, et al., 2015). However, the timing, scale, and prevalence of a seasonal migration are not clear and may vary geographically. Tagging and telemetry studies of Atlantic wolffish off Newfoundland suggest limited movement. In a mark–recapture study, most tagged wolffish were recaptured within 8 km of the release site after 5–7 years (Templeman, 1984). Nearshore tagging and continuous detection with acoustic receivers found that most individuals remained within or returned to a 4–8 km home range over a 2-year study period; however, detection rates varied seasonally (Simpson, et al., 2015). Traits such as long-term site fidelity, demersal life history, and substrate-dependent denning behaviour of Atlantic wolffish support habitat characterization efforts based on seafloor bottom-type and geomorphology. Similar approaches have been used successfully to predict habitat suitability and distribution of demersal rockfish with similar life history characteristics (e.g., *Sebastes flavidus, Sebastes rosaceus*) (Monk, et al., 2010; Young, et al., 2010).

Even if the substrate component of habitat remains relatively constant, Atlantic wolffish distribution responds to shifts in oceanographic conditions (Bianucci, et al., 2016). Due to the narrow preferred temperature range and reduced population size, the Committee on the Status of Endangered Wildlife in Canada recognizes Atlantic wolffish as a species that is potentially vulnerable to the impacts of climate change (COSEWIC, 2012). The expansion of oxygen-poor water masses in recent decades is a significant driver in the contraction of suitable wolffish habitat on the Scotian Shelf (Bianucci, et al., 2016). Hypoxia becomes lethal for juvenile wolffish at about 20% saturation (Le Francois, et al., 2001), and at <65%, habitat is considered suboptimal for Atlantic wolffish, below which heart rate is reduced (Bianucci, et al., 2016). Growth, fecundity, and recruitment will likely suffer among Atlantic wolffish limited to hypoxic habitat (Simpson, et al., 2013). Analysis of Atlantic wolffish area of occupancy confirms the avoidance of severely hypoxic areas. Only 1% of high-density Atlantic wolffish trawl sets were caught in areas with dissolved oxygen below 35% saturation; the majority (69%) of high-density catches were retrieved in areas of oxygen saturation over 55% (Simpson, et al., 2013).

Temperature is also a significant driver of Atlantic wolffish distribution, and as a result, the species has been called a “temperature seeker” (Simpson, et al., 2012) or “temperature keeper” (Kulka et al. 2007). In Newfoundland waters, Atlantic wolffish are found between –1 and 10°C, and offshore trawl catch biomass peaks within the narrow 1–4°C range (Kulka, et al., 2004). Dive surveys in the St. Lawrence estuary found that resident wolffish were vertically limited by the thermocline associated with the Gaspé current (Larocque, et al., 2008), and research in the North Sea links distribution of wolffish to temperature (Liao & Lucas, 2000). Temperature is particularly important to early life stages. Overall, Atlantic wolffish hatch success was reduced at temperatures above 7°C (Pavlov & Moksness, 1994) and normal fin ray development did not occur in incubations of 9°C or warmer (Pavlov & Moksness, 1995). Once hatched, however, larvae and fry may seek slightly warmer waters. Atlantic wolffish larvae raised under controlled conditions by McCarthy et al. (1998) demonstrated highest specific growth rates at temperatures of 11–14°C; however, survival was highest among fish raised at 8°C. Similar results were found for juvenile Atlantic wolffish between 9 and 12 months of age, with optimum temperatures for growth rate and efficiency between 9 and 11°C, but slightly higher survival at 8°C (McCarthy, et al., 1998). For both juvenile and mature wolffish, extreme warm temperatures result in reduced aerobic performance, impacting muscular activity, growth, and reproduction. Among mature Atlantic wolffish in culture, conditions between 7 and 9°C produced optimal growth rate, and growth rate declined during seasonal warm periods (Moksness, 1994). In Newfoundland nearshore waters, Atlantic wolffish pair and spawn between August and October, the warmest months of the year (Keats, et al., 1985), and newly hatched Atlantic wolffish remain close to the hatching location during the larval phase (Templeman, 1985). As ocean conditions change, optimal habitat will continue to shift and may deteriorate or disappear completely in some areas. It is important to understand the vulnerability of both occupied and potential habitats to anthropogenic impacts, including fishing effort, coastal and offshore development, and climate change.

Current knowledge of wolffish distribution is limited by relatively sparse records of the species and poor understanding of their habitat (Dutil, et al., 2014). In Conception Bay, dive surveys have recorded denning, pairing, feeding, and egg-guarding behaviours among Atlantic wolffish at four den sites (Simpson, et al., 2015); this area provides a valuable study site as a feeding ground, spawning area, and nursery. A better understanding of Atlantic wolffish denning habitat may also support management of Spotted wolffish (*Anarhichas minor*). Spotted wolffish, recognized as a Threatened species under SARA, kept in laboratories have been shown to use shelters similar to that of Atlantic wolffish (Lachance, et al., 2010). This study examines the geomorphology, temperature profile, and surrounding biological community associated with nearshore Atlantic wolffish denning habitat for the first time in Newfoundland waters. The main objectives are to characterize, delineate, and predict Atlantic wolffish denning habitat in a coastal area known to be occupied year-round.

2.3 Methods

The study area includes the nearshore waters (<200 m depth) of the northeastern coast of Conception Bay, Newfoundland and Labrador, eastern Canada (Figure 2.1). Of particular interest is a small area near the community of Bauline, where Atlantic wolffish dens have been identified and monitored by SCUBA surveys and tagged wolffish movements have been tracked by an array of moored acoustic receivers (Simpson, et al., 2015).

2.3.1 Bathymetry and backscattter

The 27 km^2 study area was surveyed by the Canadian Hydrographic Service 22–29 July 2013 (Figure 2.1). Seafloor acoustic data, including bathymetry and backscatter, were collected using a Kongsberg EM710 multibeam echo sounder. Bathymetric and backscatter data were processed by the Canadian Hydrographic Service using the software CARIS HIPS-SIPS. Additional processing of the backscatter data was conducted by the Marine Geomatics Research Lab of Memorial University, using Fledermaus software to remove acquisition artefacts. All multibeam data were gridded into 1m^2 pixels and imported into ArcGIS 10.1 for analysis and mapping.

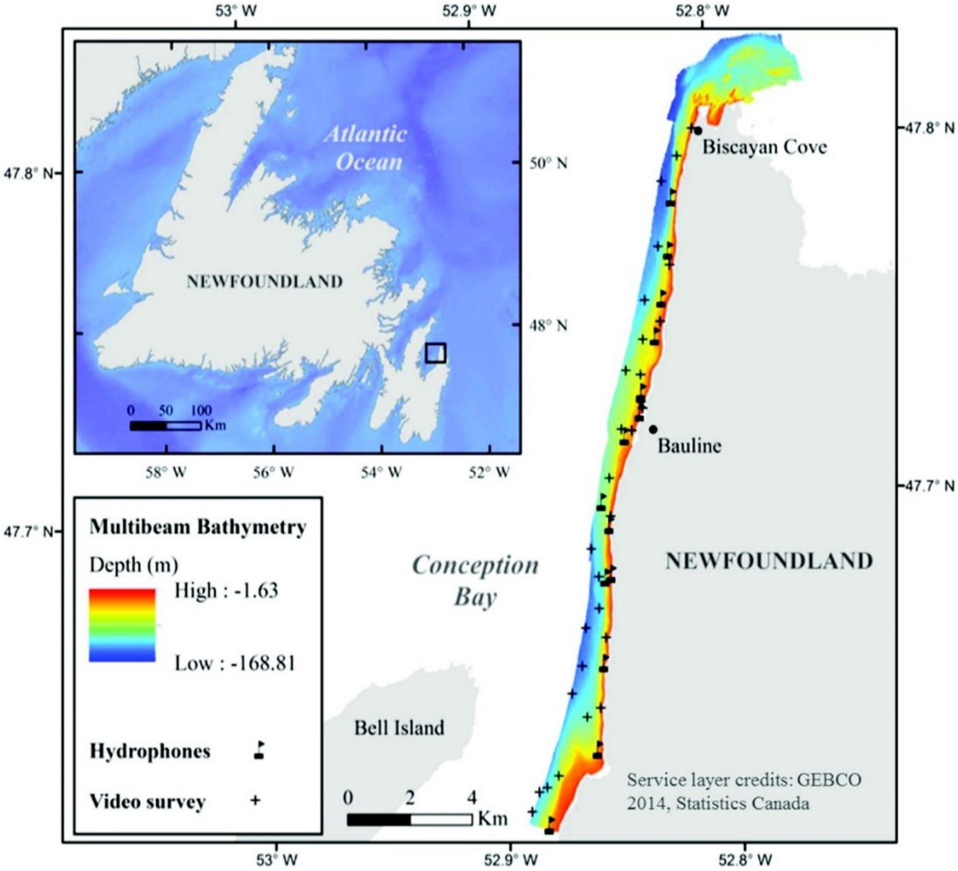


Figure 2.1 Study area in Conception Bay, Newfoundland, eastern Canada, including Canadian Hydrographic Service multi-beam bathymetry, DFO-NL acoustic receivers, and distribution of benthic video transect sites.

2.3.2 Seafloor video

Ground-truthing of the study area was conducted in the summer and early fall of 2014 (June–October) with a ship-based Deep Blue Pro drop video camera with video-embedded GPS overlay. Video surveys were conducted from two vessels throughout the study season: a 6.7 m Boston whaler (the DFO Newfoundland Seaskiff) and an 5.5 m rigid hull inflatable boat provided by Tangly Whales Inc. Continuous position of the survey vessel during transects was recorded by a wide area augmentation system enabled Garmin eTrex-10 hand-held GPS with an estimated horizontal accuracy of <3 m. This method avoids the use of high-cost underwater positioning equipment (e.g. Ultra-Short Baseline systems); however, it assumes the camera system remains directly below the vessel, and therefore, data collection is limited to very calm weather conditions, relatively shallow waters, and small survey platforms. Forty-five depth-stratified, randomly distributed sample stations were identified and 30 were successfully sampled (Figure 2.1). High sea states prohibited survey efforts beyond Biscayan Cove in the northern portion of the study area. Timed video transects (4 minutes, approximately 100 m length) were recorded, beginning at each randomly generated sample point and travelling in the direction of the dominant current for the duration of the video. All visible organisms in the videos were identified to the lowest taxonomic level possible and counted for each site from continuous video. Substrate was recorded as percent cover for five prevalent bottom types (mud, gravel, and mixed substrate; boulder–bedrock, coralline algae, and macroalgae-covered rock) in still frames extracted at 20 s intervals. Still-frame extraction was automated through the VideoLAN Client media player. A Michaelis–Menten (MM) species accumulation curve was plotted to test for adequate sampling of biota. MM computes the mean accumulation curve by averaging over all accumulation curves derived from the selected runs. This estimate of species richness and species accumulation was found to be very accurate at low and intermediate sampling effort of hard bottom marine habitats and overall was more precise than other methods across sampling level and habitat type (Canning-Clode, et al., 2008).

2.3.3 Substrate and community classification

An unsupervised classification of multibeam backscatter, bathymetry, slope, and curvature was carried out using the ArcGIS 10.1 iterative self-organizing (ISO) classification algorithm. This method provides a reproducible quantitative clustering of the multibeam data, without the influence of prior assumptions. Backscatter provides a proxy measure of sediment hardness, based on the strength (decibels) of the returning echo. Bathymetry, which co-varies with light, pressure, and temperature, exerts a first-order effect on species distribution. Geomorphometric variables (slope and curvature) were derived from bathymetry in ArcGIS 10.1 with the Benthic Terrain Modeler extension (Rinehart, et al., 2004). Slope and curvature were selected for inclusion in the classification routine to capture biologically relevant terrain attributes without internal correlation (Lecours, et al., 2017).

Biological communities were identified using PRIMER-E version 6 statistical software. Species counts were standardized for transect length and fourth-root transformed to prevent one or two very abundant species from dominating analysis of species composition similarity between sites. A Bray–Curtis similarity matrix was generated for the transformed data. Samples were grouped by underlying substrate type and tested for significant differences in species composition through nonmetric multidimensional scaling and analysis of similarity (ANOSIM). Biologically similar substrates were merged to represent community-level habitats. Accuracy of the resulting map was calculated through an error matrix comparing predicted habitat (based on unsupervised classification of multibeam substrate) and biological community (based observed species composition and abundance in the video data). Through this method, the full ground-truthing survey was available as an independent data set for accuracy assessment of the multibeam-based habitat map. A similarity percentages (SIMPER) analysis was also conducted to identify the characteristic taxa of each habitat.

2.3.4 Atlantic wolffish habitat

Atlantic wolffish were captured as bycatch in the local lobster fishery or targeted directly with modified crab pots deployed by DFO-NL. Acoustic transmitters (VEMCO V13 and V16) were surgically implanted in the abdominal cavity, providing a continuous and unique ping frequency for each fish (Simpson, et al., 2015). Acoustic telemetry data were recorded by 16 moored acoustic receivers in the study area between July 2011 and September 2012 (Simpson, et al., 2015). Each receiver has an estimated detection diameter up to 3.7 km under good conditions (i.e. low environmental or anthropogenic noise), allowing broad-scale assessment of presence and movement behaviour. Unique ping records were used to plot the paths of individual fish and to identify trends in seasonal detection rates.

Targeted SCUBA surveys were conducted over 2 days (5–6 August 2014) to record 25 m video transects at each den, travelling parallel to shore. All visible species were identified from the videos to the lowest taxon possible. The geomorphology of the confirmed den sites informed a supervised classification of multibeam data for the whole study area. Classification rules were generated for depth, backscatter value, slope, and distance to high slope, to identify areas similar to the wolffish dens. Areas that conformed to the den classification rules were plotted to generate a map of potential Atlantic wolffish denning habitat within the study area. Temperature data from conductivity, temperature, and depth sensor casts and temperature loggers moored near the den sites throughout 2013 characterized oceanographic conditions (Simpson, et al., 2015).

Recreational divers and citizen scientists were also invited to report sightings of Atlantic wolffish through the Newfoundland Thornbacks Dive Club network. Reported wolffish sightings were mapped to demonstrate the prevalence of inshore wolffish habitat beyond the study area and to inform future survey efforts.

2.4 Results

2.4.1 Substrate classification

The unsupervised ISO classification identified six distinct substrate types based on differences in bathymetry, backscatter, slope, and curvature (Figure 2.2). Class 1 is characterized by shallow depths and high backscatter response, which indicates hard, rocky substrate. Class 2 is similarly shallow and high backscatter, but is differentiated by high slope, which corresponds to steep rocky bottoms. Classes 3 and 4 include mid-range depths and backscatter values, which indicate mixed substrates. Class 5 is defined by deep water, low slope and low backscatter values, which indicates soft sediment; and Class 6 corresponds to deep water and mid-range backscatter response.

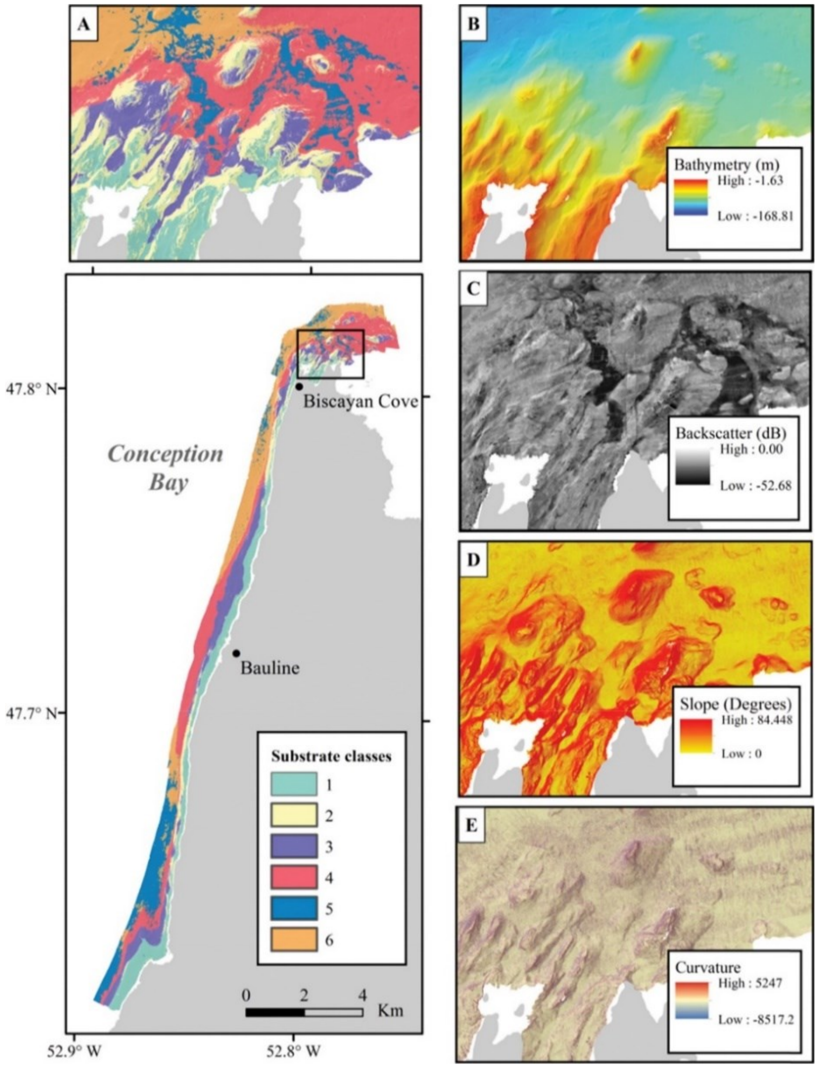


Figure 2.2 Unsupervised substrate classification. The inset (A) shows an area beyond Biscayan Cove with all six classes represented. These classes were identified on the basis of differences in (B) bathymetry, (C) backscatter, (D) slope, and (C) curvature.

2.4.2 Biological communities

The Michaelis–Menten species accumulation curve for the drop-video transects reached asymptote after about 12 sample stations, suggesting that sampling (N = 30) was sufficient to identify characteristic taxa of the survey area across all identified substrate types. A total of 33 animal taxa were identified from the video, including seven fish species: Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), winter flounder (*Pseudopleuronectes americanus*), rock gunnel (*Pholus gunnellus*), common cunner (*Tautogolabrus adspersus*), sculpin (*Myoxocephalus* spp.), and pout (*Zoarces* spp.). The vast majority of species identified were invertebrates, including toad crab (*Hyas araneus*), snow crab (*Chionoecetes opilio*), green urchin (*Strongylocentrotus droebachiensis*), Arctic cookie star (*Ceramaster arcticu*s), brittle star (*Ophiopholis aculeata*), basket star (*Gorgonocephalus arcticus*), frilled anemone (*Metridium senile*) Northern red anemone (*Urticina felina*), and strawberry soft corals (*Gersemia rubiformis*).

ANOSIM and SIMPER tests conducted on pairwise combinations of the substrate classes identified three statistically distinct biological assemblages across the six substrate classes: (i) urchin-dominated (substrate classes 1 and 2), (ii) brittle star-dominated (substrate classes 3, 4, and 6), and (iii) deep habitats characterized by the presence of snow crabs and Arctic cookie stars (substrate class 5). These three communities were visualized in a nonmetric multidimensional scaling plot (Figure 2.3). Full results of the ANOSIM and SIMPER analyses are included as supplementary materials (Table S2.1).

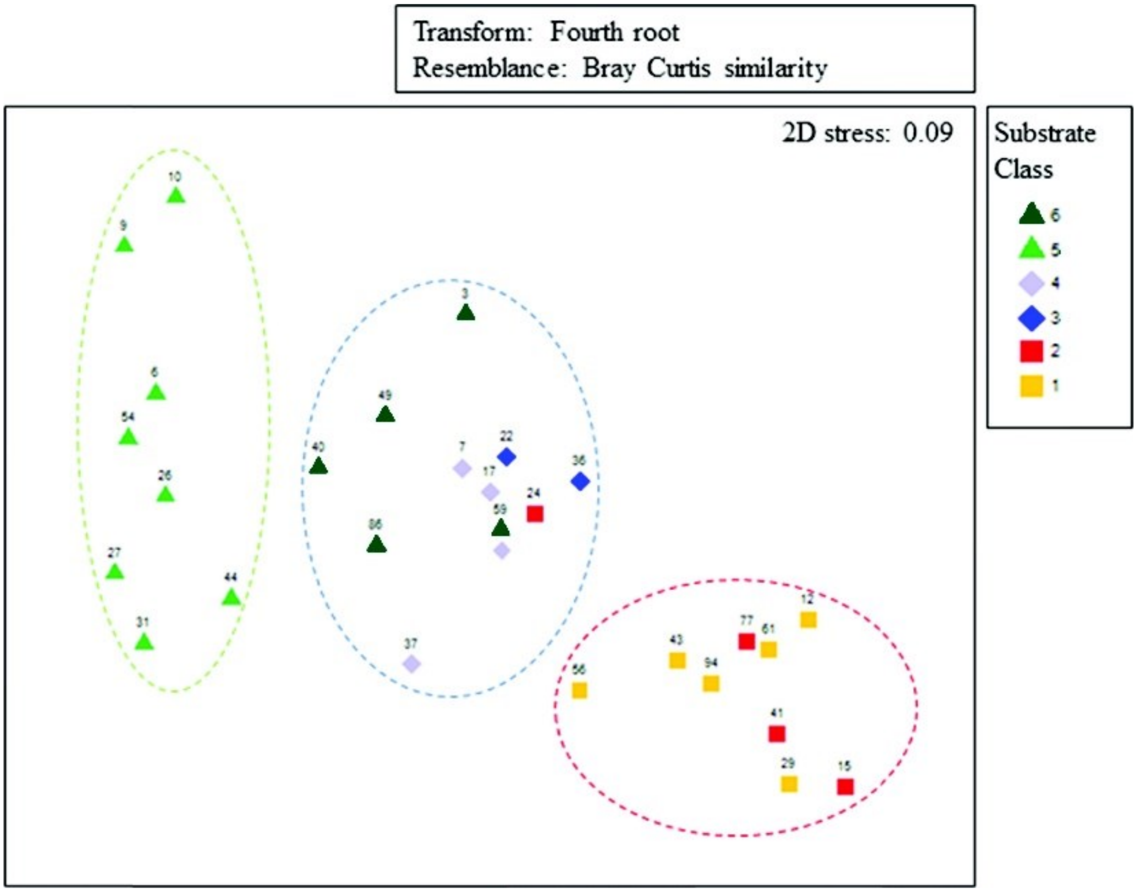


Figure 2.3 Nonmetric multidimensional scaling plot of species abundance and composition similarity within video transects conducted on six acoustically derived substrate classes

2.4.3 Characterization of benthic habitats

The three distinct biological communities and their corresponding substrate types are mapped in Figure 2.4. Substrate classes 1 and 2 were combined into a single habitat class, representing shallow boulder and bedrock habitats, including occasional patches of cobble, gravel, coarse sand, and mussel hash between boulders. These communities are characterized by a high density of green urchins and blue mussels (*Mytilus* spp.). Encrusting coralline algae (*Lithothamnion arcticus* and other *Melobesioideae* sp.) cover most rocky substrate in this habitat, with some patches of macroalgae, including sea colander (*Agarum* sp.) and Northern sea fern (*Ptilota serrata*). Substrate classes 3, 4, and 6 were combined, representing muddy cobble and muddy gravel habitats. These communities are characterized by the presence of brittle stars (*Ophiopholis aculeata*) and anemones (*Urticina* sp. and *Stomphia* sp.). Substrate 5 represents muddy habitat occupied by snow crab and Arctic cookie stars, with pelagic arrow worms (*Sagittidae* sp.) frequently observed above bottom.

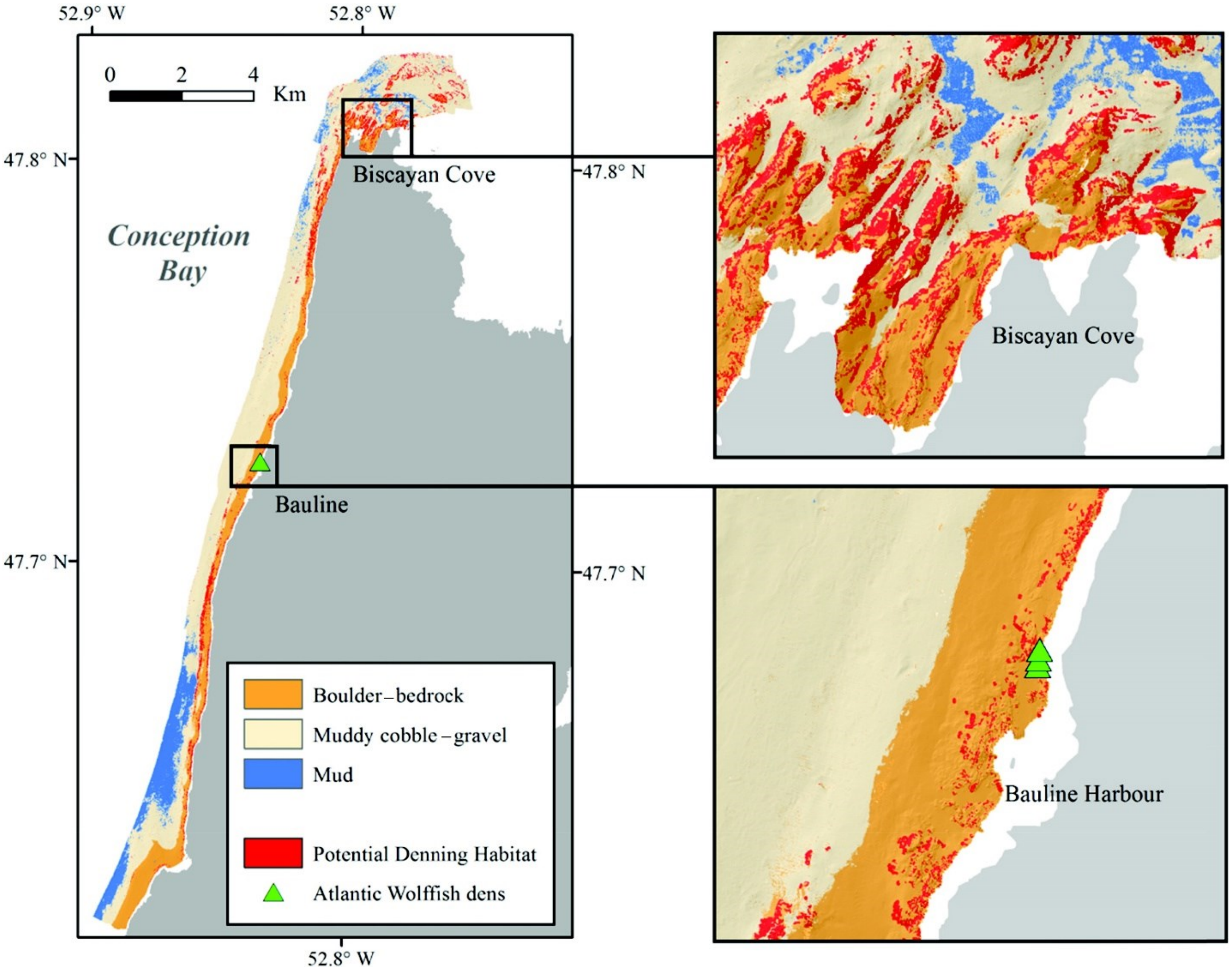


Figure 2.4 Benthic habitat types, Atlantic wolffish dens, and supervised classification of potential denning habitat in Conception Bay, Newfoundland and Labrador

The areas identified as “boulder–bedrock” habitat (6.99 km^2) were restricted to shallow depths, where coastal bedrock does not gather silt and where coralline algae receives sufficient sunlight (depth <50m). The “muddy gravel–cobble” habitat was found to be the most prevalent habitat in the study area (16.34 km^2) across the greatest depth range (50–150m). The "mud" habitat (3.74 km^2) was found in deep (>125m), low slope areas, though small patches of this habitat were predicted to occur in depressions sheltered by high slope bedrock and boulder features in the northern extent of the study area.

Table 2.1 presents the error matrix generated to evaluate the accuracy of the habitat map. Producer's accuracy refers to the likelihood that a pixel in habitat X is correctly classified as Class X. User accuracy refers to the likelihood that a pixel in classified as X truly represents habitat X. For example, a producer's accuracy of 100% indicates that all sites ground-truthed as boulder–bedrock were correctly identified in the classification routine. However, user's accuracy for this substrate (classes 1 and 2) is 81.8%, because two sites that were classified as boulder–bedrock were ground-truthed as muddy gravel–cobble. Mud and boulder–bedrock habitats were correctly identified by the unsupervised classification in all cases. The mixed muddy gravel–cobble habitats were misclassified in 15%; the ISO unsupervised classification procedure incorrectly boulder–bedrock to two muddy gravel-cobble sites. The accuracy across all habitat types was 93.3% (28 of 30 stations correctly classified).

Table 2.1 Error matrix for unsupervised substrate classification predictions of observed biological communities

	Unsupervised substrate class				
Groundtruthed habitats	**1, 2**	**3, 4, 6**	**5**	**Total number of sites**	**Producer's accuracy (%)**
Boulder-bedrock	9	0	0	9	100
Muddy gravel-cobble	2	11	0	13	84.6
Mud-silt	0	0	8	8	100
Total	11	11	8	30	
User's accuracy (%)	81.8	100	100	**Overall accuracy**	**93.3**

2.4.4 Atlantic wolffish habitat

Four Atlantic wolffish dens located in 15–17 m depth were documented and monitored annually by Simpson et al. (2015) near Bauline in the Conception Bay study area. No wolffish were observed during drop-video transects or SCUBA surveys in 2014. The wolffish dens are located in areas where boulder or bedrock features form crevices or caves with a high slope angle at their entrance (Figure 2.5). Multibeam data near the dens show high slope as well as a high backscatter response (>15dB). The slope at the recorded location of each den fell between 30° and 60°.

Supervised classification of the multibeam data, based on the slope and backscatter of the four surveyed wolffish dens of Bauline, identified 1.6 km^2 of potential denning habitat for Atlantic wolffish, distributed unevenly along the coast, covering 5.9% of the study area (Figure 2.4). Surveyed dens, and the majority of predicted denning habitat, occur within the boulder–bedrock habitat, which provides hard substrate, high slope features, and complex seafloor geomorphology. The area of Bauline, where the DFO-surveyed dens are found, represents a small portion of the predicted denning habitat. The northern extent of the study area, beyond Biscayan Cove, was predicted to have the greatest area and most continuous patches of denning habitat (Figure 2.4).

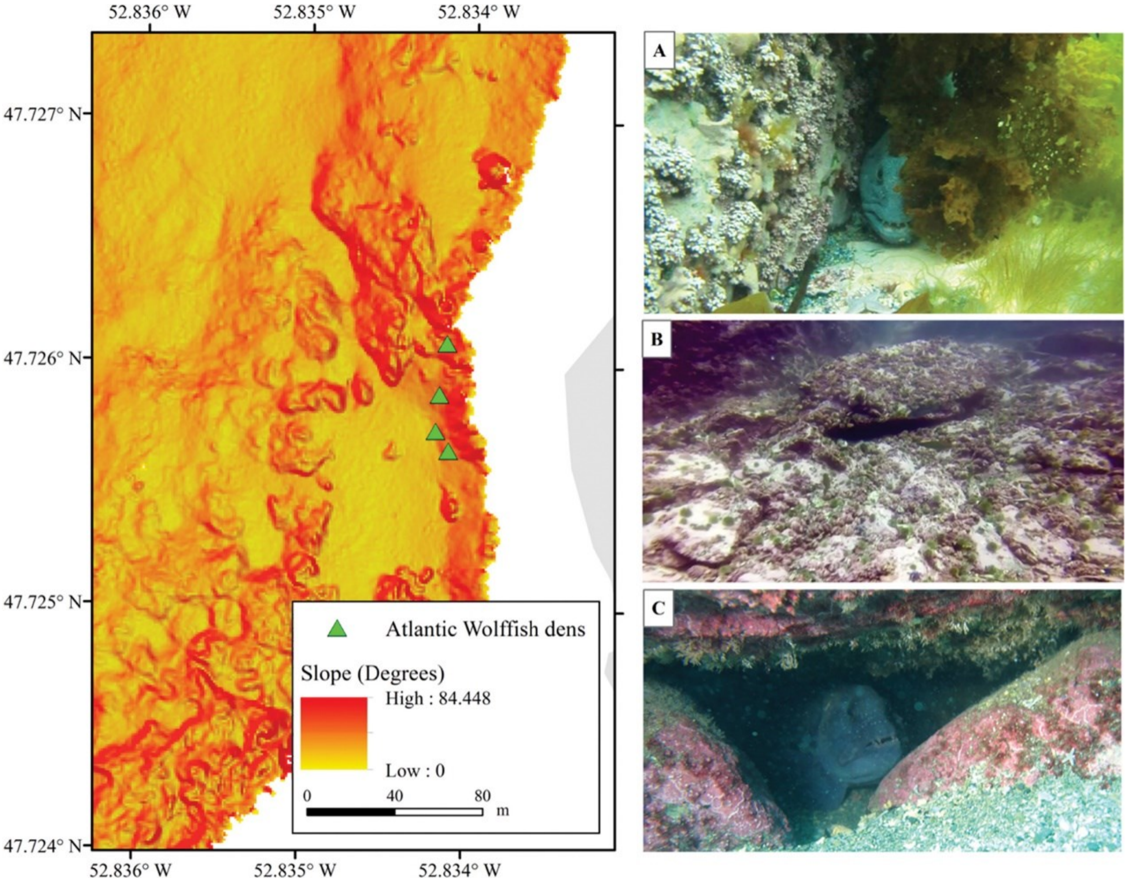


Figure 2.5 Atlantic wolffish and multi-beam derived slope (displayed with hillshade effect). Photos of Atlantic wolffish dens contributes by (A) Samantha Trueman, (B) Trevor Maddigan, and (C) Neil Burgess; published with their permission.

All four known dens occur below the summer thermocline, which was recorded at 10 m depth in July 2014, and where they are exposed to relatively cold temperatures (0–8°C) for most of the year. However, the recorded thermocline moved past the den depth to approximately 35 m depth by October 2014, exposing the dens to surface temperatures. Continuous thermographs moored at 20 m depth near the surveyed dens showed variable temperatures occasionally reaching highs of 12–15°C in the later summer and early fall of 2013. In addition to the surveyed dens, approximately 30% of all potential denning habitat is found above the fall thermocline (Figure 2.6).

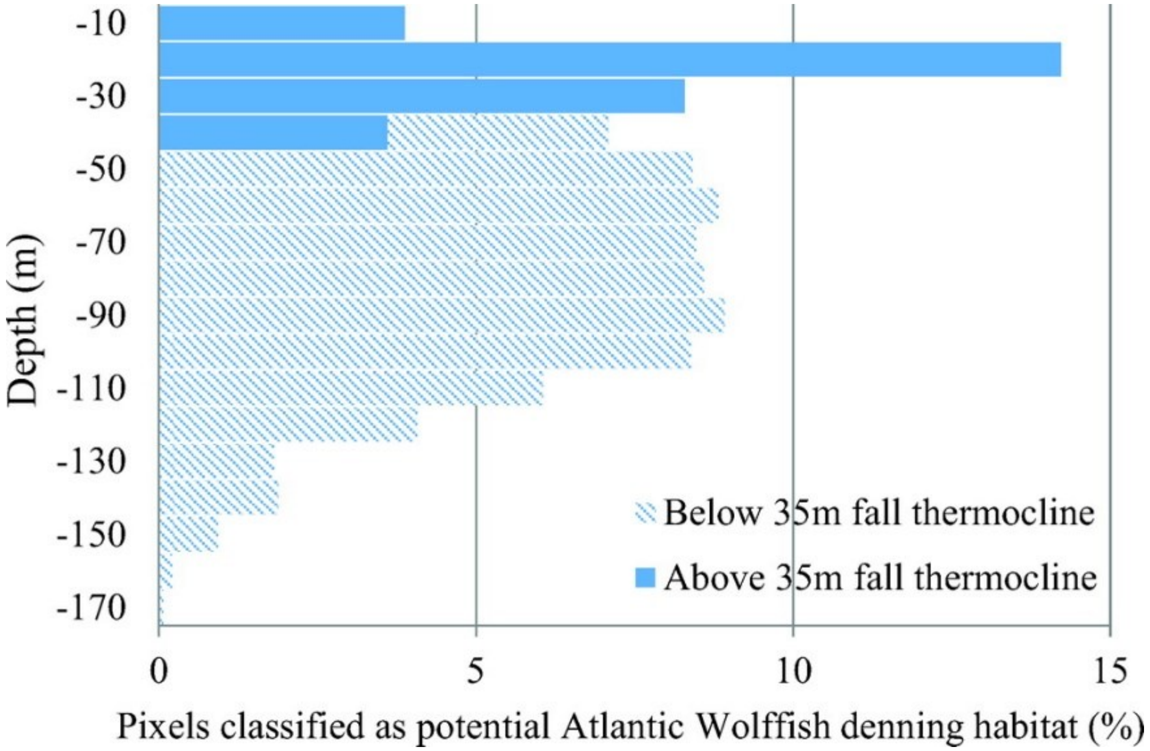
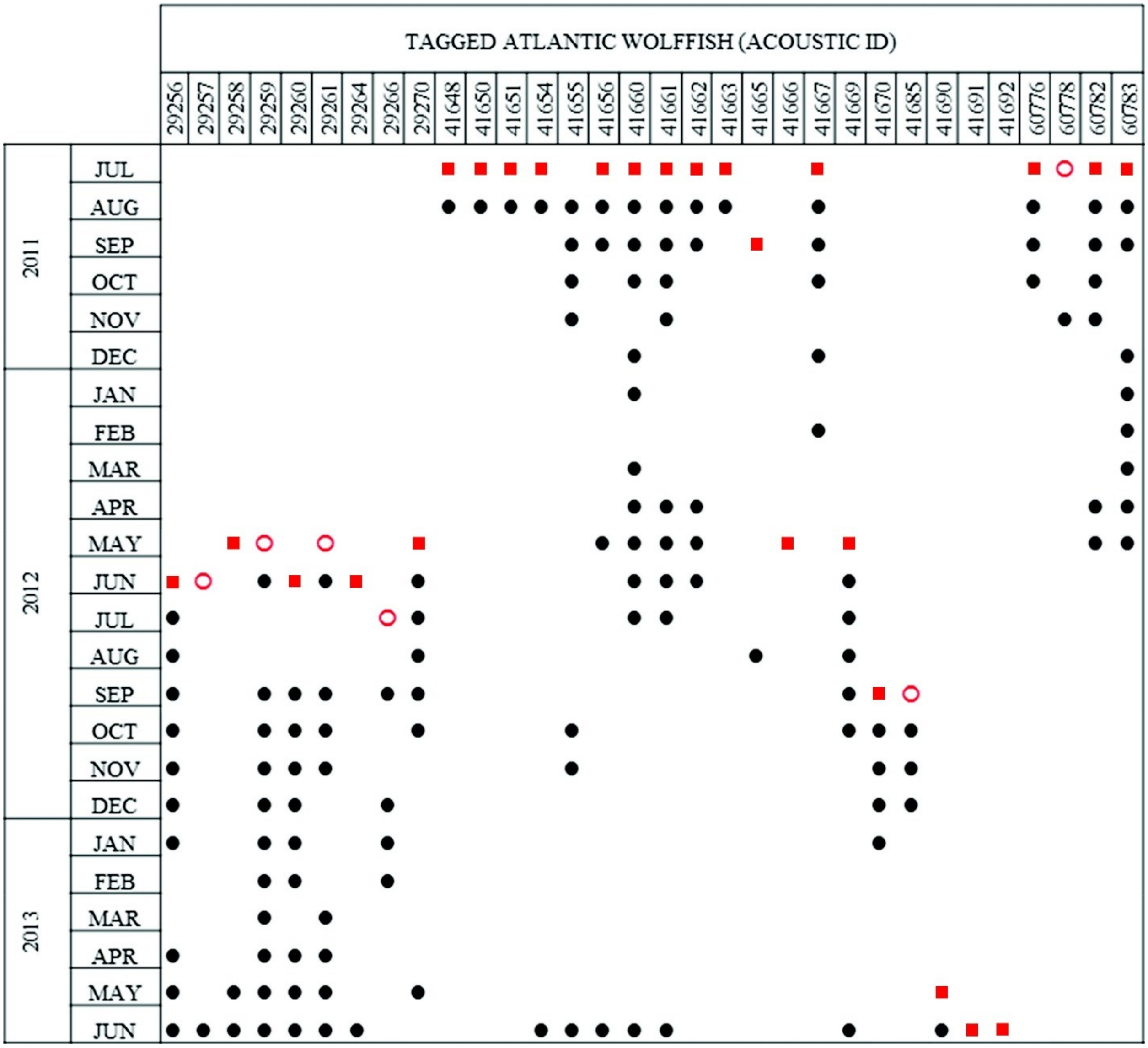


Figure 2.6 Depth distribution of pixels classified as potential denning habitat (percentage of total predicted area).

The 44 Atlantic wolffish tagged by DFO-NL between 2010 and 2013 ranged from 55 to 90 cm (mean length = 70.7 cm). Thirty-nine of the tagged Atlantic wolffish were recorded by moored receivers, and of these, 32 were recorded in more than one detection event during the July 2011 – June 2012 recording period (Figure 2.7). Most Atlantic wolffish (71%) remained within the range of one receiver (approximately 3.7 km) for months at a time and only 5% carried out long-distance movements beyond the study area (Simpson, et al., 2015).



		TAGGED ATLANTIC WOLFFISH (ACOUSTIC ID)																															
		29256	29257	29258	29259	29260	29261	29264	29266	29270	41648	41650	41651	41654	41655	41656	41660	41661	41662	41663	41665	41666	41667	41669	41670	41685	41690	41691	41692	60776	60778	60782	60783
2011	JUL										■	■	■	■		■	■	■	■	■			■							■	○	■	■
	AUG										●	●	●	●	●	●	●	●	●	●			●							●		●	●
	SEP														●	●	●	●	●		■		●							●		●	●
	OCT														●		●	●					●							●		●	
	NOV														●			●													●	●	
	DEC																●						●										●
2012	JAN																●																●
	FEB																						●										●
	MAR																●																●
	APR																●	●	●													●	●
	MAY			■	○		○			■						●	●	●	●			■		■								●	●
	JUN	■	○		●	■	●	■		●							●	●	●					●									
	JUL	●							○	●							●	●						●									
	AUG	●								●											●			●									
	SEP	●			●	●	●		●	●														●	■	○							
	OCT	●			●	●	●			●					●									●	●	●							
	NOV	●			●	●	●								●										●	●							
	DEC	●			●	●			●																●	●							
2013	JAN	●			●	●			●																●								
	FEB				●	●			●																								
	MAR				●		●																										
	APR	●			●	●	●																										
	MAY	●		●	●	●	●			●																	■						
	JUN	●	●	●	●	●	●	●						●	●	●	●	●						●			●	■	■				

Figure 2.7 Presence of tagged Atlantic wolffish within the Conception Bay study area, as recorded by moored receivers. Solid squares indicate new tagging events and detection within the same month; open circles indicate a tagging event without a detection record in the same month; solid circles show subsequent detection events.

The spatial resolution of this data provided useful information on the presence and movement of Atlantic wolffish throughout the year; however, it could not be applied to fine-scale occupation of substrate or habitat types. Presence was relatively consistent in the study area, and behaviour of most wolffish was sedentary. However, detection rate (% of released tags that were detected, calculate monthly) varied over time (Figure 2.8). In general, more of the tagged Atlantic wolffish were present in the summer and early fall, between June and October, when pairing and spawning is expected to occur (Kulka, et al., 2004). In the summer of 2012, however, fewer tagged fish were recorded in July, August, and September, at a time when mean monthly sea surface temperatures exceeded 15°C, well above the reported optimal thermal range of adult wolffish in the field (1–4°C; Kulka et al., 2004) and the laboratory (7–9°C; Moksness, 1994).

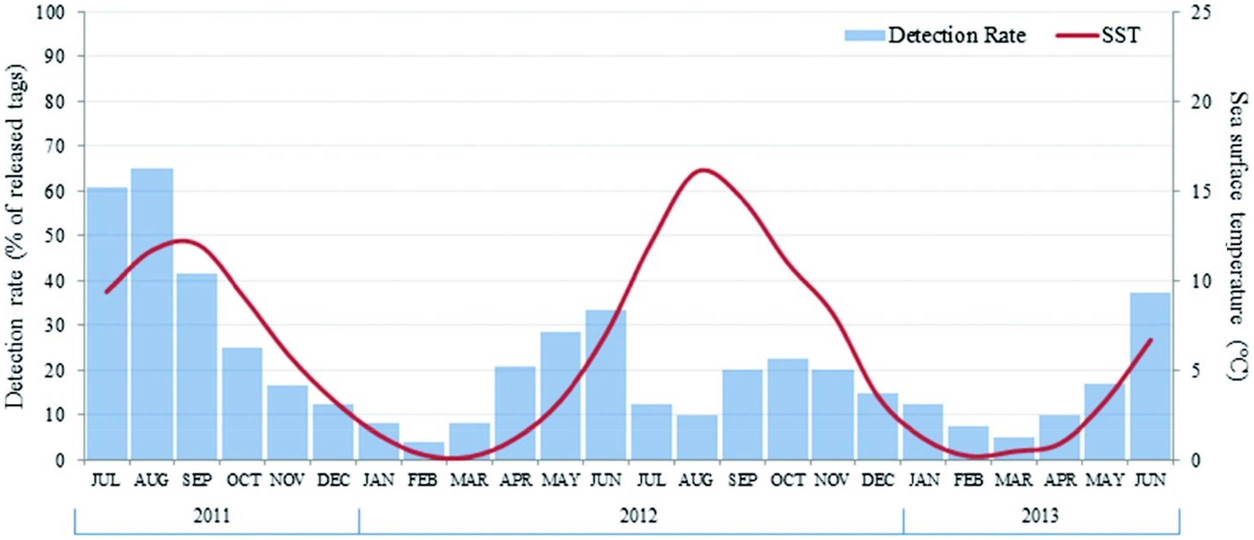


Figure 2.8 The number of Atlantic wolffish detected monthly by acoustic receivers within the Conception Bay study area July 2011 – June 2013. DFO-NL tagging events are displayed as bars and monthly mean sea surface temperature (SST) is displayed as a solid line (NOAA 2016).

2.4.5 Prevalence of inshore Atlantic wolffish habitat in Newfoundland

Recreational divers of the Newfoundland Thornbacks Dive Club reported wolffish dens at 13 locations, including Newfoundland west and south coasts and the Avalon Peninsula. Figure 2.9 shows the reported locations in addition to those previously reported by Kulka et al. (2004).

Seven of these sites represent areas where Atlantic wolffish have been consistently found by different divers over the course of 3 or more years, as far back as the 1970s in the case of Gadd's Point, Bonne Bay.

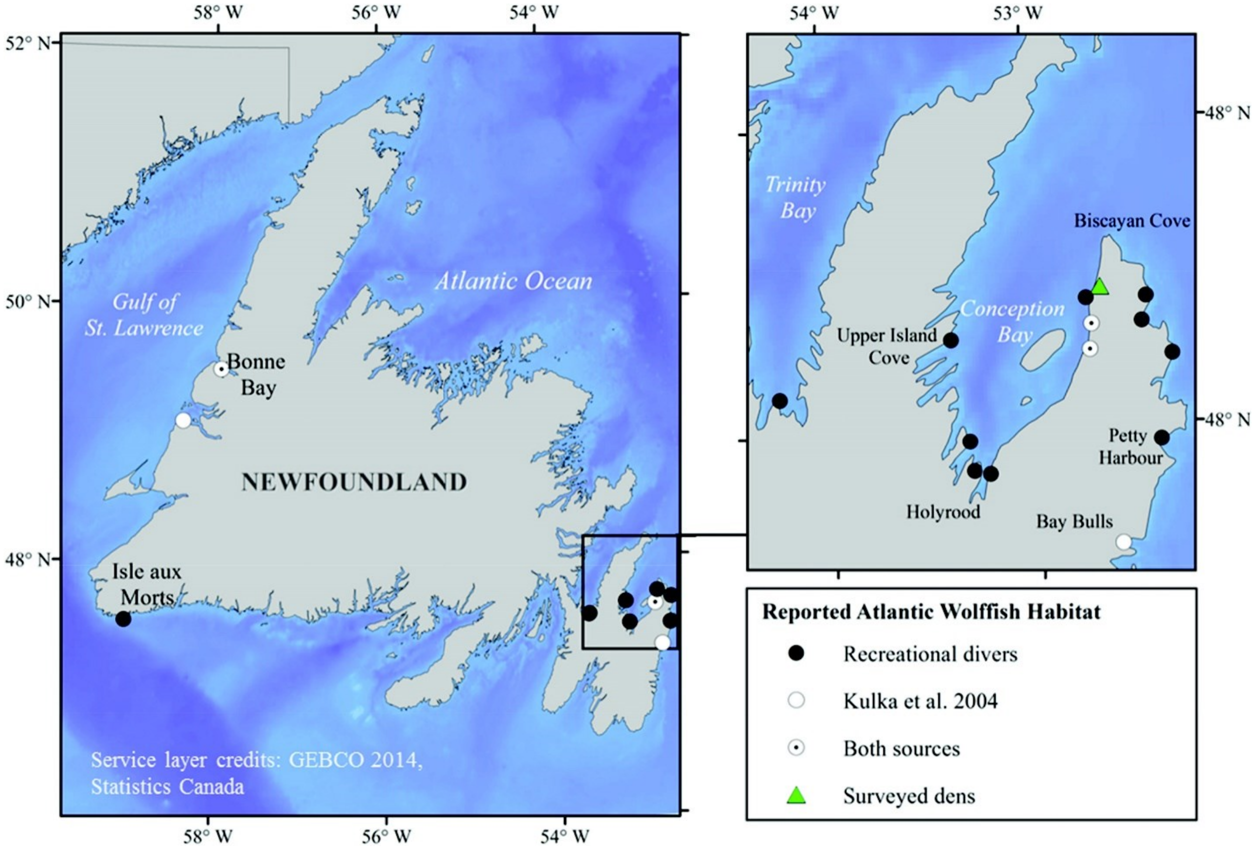


Figure 2.9 Atlantic wolffish den sites reported by members of the Thornbacks Dive Club or listed by previous Atlantic wolffish dive surveys (Kulka et al. 2004).

2.5 Discussion

Nearshore habitats (boulder–bedrock, muddy gravel–cobble, and mud) in Conception Bay were mapped with high overall accuracy (93%) on the basis of unsupervised classification of high-resolution multibeam data. Misclassification occurred only between the boulder–bedrock habitat and the muddy gravel–cobble habitat; these classification errors appear to be related to the fuzzy boundary between similar habitats, not due to spatial inaccuracy. The results of this study indicate that distribution of denning habitat for Atlantic wolffish is substrate dependent and that potential denning habitat is unevenly distributed throughout the study area. The muddy habitats do not provide features for dens and support very low prey density. According to multibeam analysis, some areas of the muddy gravel–cobble provide high seafloor complexity and may provide denning habitat. The vast majority of potential denning habitats, and the four confirmed dens analyzed for this paper, are found within the shallow boulder–bedrock habitat. No wolffish were observed during drop-video transects or SCUBA surveys in 2014 in Conception Bay; however, this may be due to the timing of the survey or limitations of wolffish detection, as fish may be concealed deep within dens and (or) avoiding contact with divers. Two of the four dens, however, were found to be occupied by pout (*Zoarces* sp.), a potential wolffish competitor. The characterization and prediction of denning habitat distribution for this study is limited by the small sample size of confirmed dens (N = 4); however, the findings presented here are generally consistent with, and add new high-resolution data to, previous research on denning habitat of Atlantic wolffish (Pavlov & Novikov, 1993; Kulka et al., 2004; Larocque et al., 2008). The Atlantic wolffish denning habitat surveyed for this study provides high densities of prey species, including green urchin, blue mussel, and rock crab. In coastal areas, green urchin appears to be the most important prey item, up to 75% of overall diet by weight (Keats, et al., 1986). Previous SCUBA surveys in this area have recorded evidence of feeding debris at den openings, confirming that the inshore habitat is used for foraging in addition to providing important habitat for reproduction and early life stages (Simpson, et al., 2015). It should be noted that dens are not the only habitat used by Atlantic wolffish; for example, seasonal foraging aggregations have been documented in areas unsuitable for denning (Fairchild, et al., 2015).

Hagen and Mann (1992) hypothesize that “undisturbed” populations of Atlantic wolffish and American lobster (*Homarus americanus*) may have helped control sea urchin population booms and supported development of complex macroalgal habitats, which serve as nursery areas for many fish species. The disappearance of highly productive kelp beds due to urchin herbivory in Nova Scotia waters in the 1970s has been linked to the reduction of sea urchin predators including Atlantic wolffish (Keats, et al., 1986; Steneck, et al., 2004). At sufficient abundance, Atlantic wolffish and similar predators may deliver conservation benefits through the increased biomass and diversity associated with complex macroalgal habitats in place of urchin barrens (Keats, et al., 1987; Scheibling, 1996; Hereu, et al., 2005).

Atlantic wolffish rely on extended parental care (Keats, et al., 1985), large egg size (6mm), and internal fertilization (Johannessen, et al., 1993) to increase reproductive success (DFO, 2008). In Eastern Newfoundland, Atlantic wolffish move into coastal habitats in the spring, establish mating pairs in the summer and spawn in rocky dens in the fall (Keats, et al., 1985). Post-hatch larvae remain near the den, which serves as an early nursery (Templeman, 1985). The conditions in Conception Bay may already place Atlantic wolffish at the upper limit of their thermal tolerance, particularly in the late summer and early fall (August–October) when temperatures are the highest and the fish are expected to be spawning (Keats, et al., 1985). The warm temperature extremes recorded in September and October (>12°C) exceed the healthy development threshold for Atlantic wolffish eggs and may reduce aerobic performance in adults (Moksness, 1994; Pörtner & Knust, 2007). At the shallow depths where dens are identified in Conception Bay (<20 m), temperature is highly variable. As atmospheric and ocean temperatures continue to increase, a temporal mismatch between habitat suitability and Atlantic wolffish reproduction may arise. Acoustic telemetry data confirmed wolffish presence in the area throughout the year, with highest presence and most activity in the summer and fall (Simpson, et al., 2015), aligning with recreational diver reports that wolffish are found in the summer and fall. However, in 2012, when mean monthly sea surface temperatures peaked in late summer, presence of tagged wolffish in the area declined, which may indicate a behavioural response to the warm temperatures (Figure 2.8).

Previous Atlantic wolffish monitoring efforts conducted by DFO-NL focused on the Bauline dens. Our study has shown that Bauline represents a small fraction of potential denning habitat in the study area (Figure 2.4), and throughout Newfoundland (Figure 2.9). Reports from recreational divers, in particular, indicate greater prevalence of inshore Atlantic wolffish denning habitat than previous records suggested. Dive surveys reported by Kulka et al. (2004) list Atlantic wolffish den sites in three areas: Bonne Bay, Portugal Cove, and Bay Bulls. Reports provided by members of a local dive club added 12 additional wolffish den sites to this list, including new areas in Conception Bay, Trinity Bay, and the south and east coasts of Newfoundland. The distribution of these reports is limited to areas where road and wharf access allow diving. It is likely that much more of the Newfoundland coast is used by denning and spawning Atlantic wolffish. Although this study focuses on inshore habitats, wolffish denning habitat may not be limited to shallow coastal areas. Characterization of Atlantic wolffish habitat offshore, such as in the Gulf of St. Lawrence, were associated with coarse sediments and high relief rocky outcrops (Dutil, et al., 2014), which is consistent with the surveyed and predicted denning habitat in this study. The resolution of bathymetric data in most offshore areas (e.g., 100 km^2 grid applied by Dutil et al. 2014), however, does not allow the identification of fine-scale denning structures as shown in this study. Limited evidence indicates that spawning may also occur offshore; Atlantic wolffish eggs have been recorded in trawl sets at 130 m on LaHave

Bank, Nova Scotia (Powles 1967). Two Atlantic wolffish adults, a clutch of eggs, and newly hatched larvae were also retrieved from Green Bank, Newfoundland, at 158 m in April 2014 (Centre for Fisheries Ecosystems Research, unpublished data).

The decrease in fishing effort in Newfoundland waters since the early 1990s, and live-release of most wolffish that are inadvertently caught by commercial fisheries have reduced fishing mortality for wolffish in recent years (Simpson, et al., 2013; Grant & Hiscock, 2013). However, the species remains at very low levels compared with pre-collapse abundance (DFO, 2015), and the impact of bycatch pressure on reproductive success remains a concern (Grant & Hiscock, 2013). Availability of suitable denning habitat is crucial to the recovery of Atlantic wolffish populations. Denning habitat, as characterized by this study, is defined by the occurrence of discontinuous rocky features, and cannot be identified by depth range and oceanographic variables alone. Mapping of potential denning habitat based on substrate types indicates that only 1.6 km^2 (5.9%) of the 27 km^2 surveyed in this study provides suitable denning habitat for Atlantic wolffish. Potential denning habitat identified by this study extends as deep as 165m, with a mean depth of 60m. Still, the den-forming bedrock and boulder features are most prevalent and most continuous between 7 and 40m, within the range influenced by highly variable and warming surface temperatures. For the Atlantic wolffish, which exhibit a low-fecundity – slow-growth life history and low abundance (DFO, 2008), the additional physiological cost of occupying a warming habitat may reduce the effect of conservation measures such as bycatch reduction and ultimately slow or halt population recovery (Pörtner & Knust, 2007; Rutterford, et al., 2015).

2.6 Conclusions

Nearshore habitats mapped in this study include very important potential denning areas for Atlantic wolffish, providing foraging, spawning, and nursery areas for early life stages. Substrate-dependent dens appear to be required for nearshore reproduction of Atlantic wolffish, underscoring the need for a better understanding of the distribution and vulnerabilities of this habitat. The research presented here has shown that high-resolution multibeam data provide a powerful surrogate for characterizing nearshore habitats with high accuracy, and these data can be applied as a useful tool for the identification of potential Atlantic wolffish denning habitat. Potential denning habitat mapped by this study was distributed unevenly and made up less than 6% of the study area.

Although the decline of Atlantic wolffish abundance in Canadian waters has slowed, and perhaps stopped (DFO, 2015), bycatch and habitat degradation remain important considerations as managers plan for population recovery. The impacts of warming waters and other threats, such as expanding hypoxic areas and habitat disruption by fishing gear, present significant challenges, and assessment of distribution-wide habitat vulnerabilities are often limited by lack of sufficient data. Continued efforts to identify and to better understand habitats of threatened or depleted fish species such as Atlantic wolffish, particularly the distribution of denning, spawning, and other critical habitats, are crucial to successful management and conservation.

Chapter 3. Limited Contribution of small Marine Protected Areas to regional biodiversity: The example of a small Canadian no-take MPA

3.1 Abstract

Over 5,000 marine protected areas (MPAs) exist around the world. Most are small (median size of ~2 km^2) and designed primarily for the conservation of a single flagship species. Internationally, there is an increasing focus on ecologically representative conservation; however the contribution of these small MPAs to the protection of regional biodiversity is often unknown. This paper presents a benthic habitat mapping exercise and reports on measures of biodiversity in the Eastport MPA and the nearby area of Newman Sound in Eastern Canada. The Eastport MPA is a 2.1 km^2 no-take reserve designated in 2005, based on a voluntary fishery closure implemented by the local community in 1997. The primary goal of the Eastport MPA is to protect and sustain American lobster (*Homarus americanus*) and thereby support the local commercial fishery. Benthic habitats were characterized and mapped using multibeam echosounder data and seafloor videos. Three statistically distinct benthic habitats were identified within the boundaries of the MPA: “shallow rocky,” “sand and cobble,” and “sand.” The distribution of species is primarily driven by depth and substrate type. The shallow rocky habitat (48% of the study area) contains complex bedrock and boulder features with high macroalgal cover. These characteristics are associated with juvenile and adult American lobster habitat. However, comparison of the MPA habitats to the surrounding Newman Sound area indicate that this small MPA contributes little to the conservation of the regional marine biodiversity. We recommend that adaptive management mechanisms be used to review such MPAs and expand them to better protect ecosystems representative of their regions.

3.2 Introduction

Marine protected areas (MPAs) are spatial management tools that can help sustain or increase marine biodiversity, species abundance and biomass, promote regrowth of marine vegetation, and conserve the integrity of sensitive habitats (Lester, et al., 2009; Green, et al., 2014; McLaren, et al., 2015). Not all MPAs are effective at meeting their goals and meaningful measurement of what constitutes adequate conservation of a species, habitat, or ecosystem remains a challenge. While there is no universal formula for ensuring MPA success (Moussaoui & Auger, 2015), size of the protected area is an important factor (Claudet, et al., 2010; Edgar, et al., 2014). In a global study of 87 MPAs, Edgar et al. (2014) identified five characteristics, called "NEOLI," that are shared by successful MPAs: No take, well Enforced, Old (>10 years), Large (>100 km^2), and Isolated. While large and isolated MPAs are increasing in popularity (Leenhardt, et al., 2013), most of the world's 5,000+ MPAs are small, with a median size around 2 km^2 (UNEP-WCMC, 2016). In some contexts, small MPAs provide significant increases in species biomass and abundance, depending on the species they protect and the nature of the relevant threats (Hamilton, et al., 2011; Batista, et al., 2015; McLaren, et al., 2015). Size recommendations made throughout the MPA literature are summarized by Calvert, et al. (2015): for MPAs designed to conserve biodiversity and support climate change resilience, moderate to large sizes (4–20 km across) are thought to be most effective. However, if the goal of the MPA is primarily to support fisheries, small reserves (0.5–1 km across) may be sufficient (Green, et al., 2014). Identifying the optimal size of an MPA can complex because it depends on many factors: management goals, species distribution and life traits, and threat type, among others. To explore the contribution of a small MPA to regional biodiversity, this study examines the Canadian

Eastport MPA, which possesses three of the five NOELI characteristics (i.e., no take, well-enforced, old) and is representative of the global median MPA size.

The Eastport MPA is one of the two existing Canadian federal MPAs in the Canadian province of Newfoundland and Labrador. Covering a total of 2.1 km^2, the two protected areas (Duck Island and Round Island) were first proposed as no-fishing zones in 1997 by the local fishing community before becoming an MPA under Canada's Oceans Act in 2005. Like many early Canadian protected areas (Roff & Evans, 2002), the Eastport MPA was designed with a focal species in mind; in this case, American lobster. In 2014, Fisheries and Oceans Canada (DFO) valued the Atlantic Canadian lobster fishery at $942 million Canadian, making it the most valuable fishery in Canada that year (DFO, 2016). Although the Newfoundland lobster fishery is not as profitable as the other Atlantic provinces, it has been a consistent fishery in terms of both value and weight of landings for the last 20 years (DFO, 2016). At the time of their creation, the Eastport fishery closures aimed to ensure a sustainable American lobster fishery in the region after the cod collapse shook the economy of Newfoundland (FRCC, 1995).

Although Eastport is now an MPA, it could have arguably reached similar objectives if it remained a fisheries closure focused on sustaining the commercially American lobster. The Canadian Fisheries Act defines a fisheries closure as a provision to regulate human fishing of commercial species (Jamieson & Lessard, 2001). Marine Protected Areas have a different, broader set of goals. The Canadian Oceans Act defines MPAs as areas designated for the conservation of commercial and non-commercial fishery resources and their habitats; threatened and endangered species and their habitats; unique habitats; areas of high biodiversity or biological productivity; and/or any other marine resources or habitat at the discretion of the minister (Government of Canada, 1996). Delineation of the Eastport MPA was originally informed by reports of high lobster catches, but no detailed habitat mapping or assessment of biodiversity was incorporated into the original implementation of the closures. The difference in management goals for fisheries closures and MPAs manifests in different priorities and decisions regarding the size of the protected area (as discussed above), as well as placement, enforcement and how success is defined for the MPA. When the Eastport closures were legally established as an MPA in 2005, DFO incorporated conservation of threatened wolffish (*Anarhichas denticulatus* and *A. minor*) in the new management plan. No alterations were made to the MPA boundaries at that time and no evidence existed that this area was of importance for those species prior to their inclusion in the management plan (DFO, 2013). As Roff and Evans (2002) note, a conservation strategy developed for a flagship or focal species may have advantages, including facilitation of public outreach and easily measurable management goals, however it is important that managers examine the relationship between the focal species and conservation of representative habitats and biodiversity.

As a signatory to the Convention on Biological Diversity, Canada has committed to protect at least 10% of coastal and marine waters by 2020 through ecologically representative and well-connected area-based conservation measures under Aichi Target 11 (CBD, 2010). To meet this commitment, the Canadian Government is currently working to implement an MPA Network, paired with the assessment of other area-based management measures to determine how existing efforts, such as fisheries closures, contribute to biodiversity conservation (DFO, 2011; DFO, 2016). As more nations move toward the implementation of marine conservation networks, understanding the contribution of existing small MPAs and fishery closures to broader conservation goals could help better integrate those areas into resilient MPA networks.

MPAs, like other spatial management tools, require knowledge of the biotic and abiotic environments under pressure from human activities. Seafloor maps can provide valuable data to quantify and monitor ecological changes and offer baseline data for MPA development and monitoring (Young & Carr, 2015). In addition to water depth, bathymetric maps can provide high resolution estimates of seabed rugosity, slope, curvature, and other bathymetric derivatives that are often crucial when describing or modeling species distributions (Kaplan, et al., 2010). Protection of diverse habitats, in turn, protects greater biodiversity, and provides benefits to surrounding fisheries (Gaines, et al., 2010). This paper reports on a benthic habitat mapping exercise in the small no-take MPA of Eastport, Newfoundland, combined with a comparison of species and habitat diversities between the MPA and its region. Mapping benthic habitats to better understand what is protected, what is left to protect, and which strategies have been successful in the past will help inform the MPA network planning process and contribute to the other goals and objectives highlighted by the Convention on Biological Diversity.

3.3 Methods

The study area includes the Eastport MPA and surrounding marine habitats located in the Newman Sound region of Bonavista Bay, on the northeast coast of the island of Newfoundland in Eastern Canada (Figure 3.1). Bonavista Bay is an area of diverse geomorphology, with extensive narrow sounds, sheltered fjords, shallow sills, low relief bays, and islands (Cumming, et al., 1992; Anderson, et al., 2002). The nearby Terra Nova National Park (400 km^2) and Terra Nova Migratory Bird Sanctuary were created to protect the coastline and adjacent terrestrial environments (Charest, et al., 2000; ECCC, 2016). Newman Sound has been intensively studied, primarily for its eelgrass (*Zostera marina*) beds (with patches up to 80m^2) that provide refuge and nursery grounds for several fish species, specifically juvenile Atlantic cod, *Gadus morhua* (Cote, et al., 2004; Gorman, et al., 2009; Rao, et al., 2014).

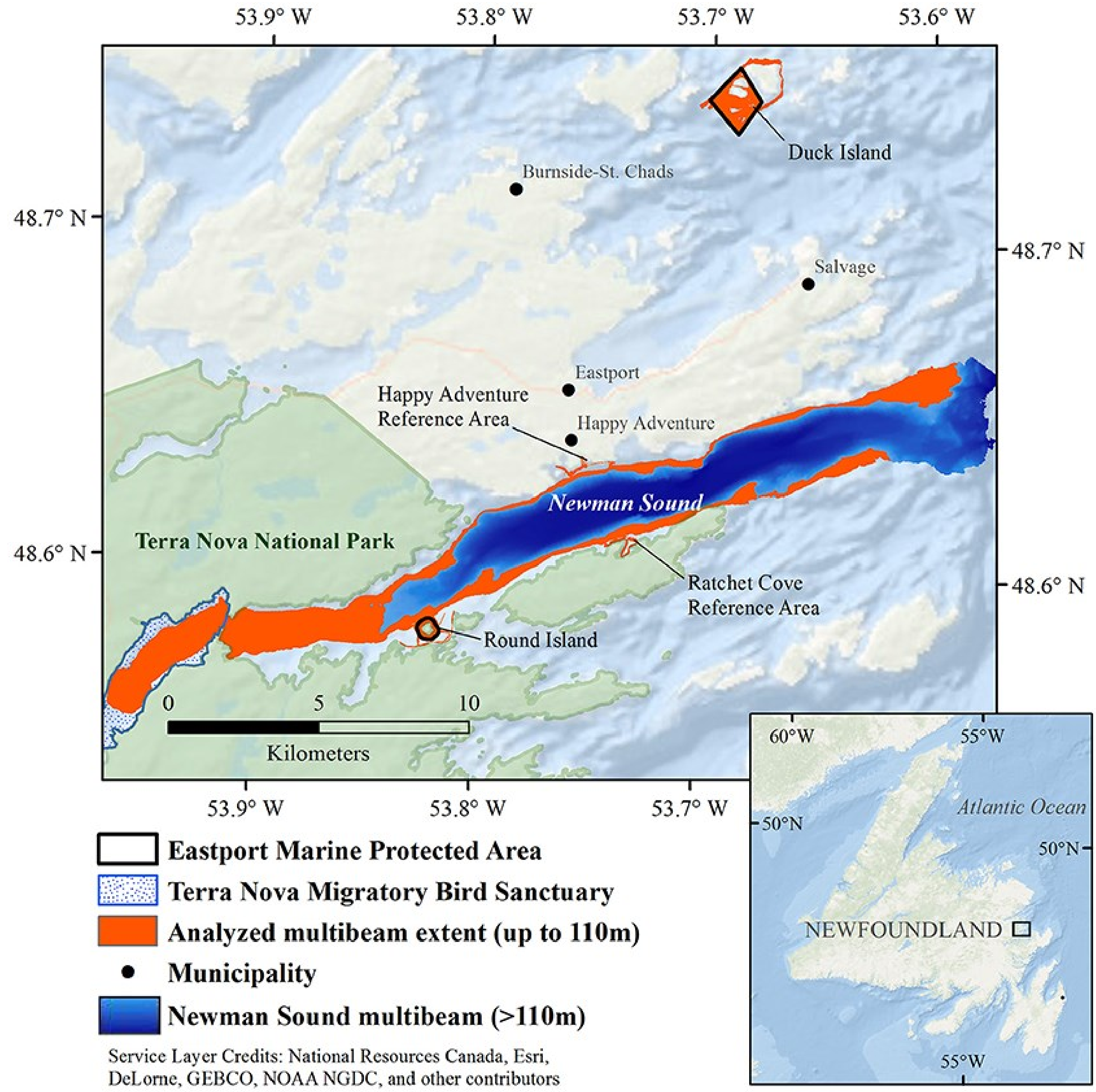


Figure 3.1 Newman Sound and the Eastport Marine Protected Area closures, Bonavista Bay, Newfoundland.

3.3.1 Bathymetry

High resolution bathymetric data were collected in the two Eastport MPA closures and DFO reference areas (Figure 3.1) between April 26–May 11, 2015, using an R2Sonic 2024 multibeam echosounder (200–400 kHz) installed on an International Submarine Engineering (ISE) Explorer Autonomous Underwater Vehicle (AUV). AUV position was recorded by a Sound Ocean Systems Inc. GPSR-X015G Differential Global Positioning System fed into an iXBlue PHINS fiber optic gyroscope inertial navigation system. Sound velocity profiles (SVP) were collected using a SonTek Castaway CTD (connectivity, temperature, and depth sensor) for the Round Island closure and a Seabird Electronics (SBE) 19+ CTD for the Duck Island closure. Tidal data, obtained from the Canadian Hydrographic Service, were used along with the SVP for post-processing the multibeam data in the CARIS HIPS & SIPS v9.0 hydrographic data processing software, in order to generate 2 m resolution bathymetric surfaces for the two MPA closures and reference areas.

The Eastport multibeam data, and subsequent substrate and habitat classifications, were also compared to the best available habitat data for the surrounding area. Multibeam data were collected in Newman Sound (see Figure 3.1) by the Canadian Hydrographic Service in 2002. Data were collected using a vessel-mounted Simrad EM 3000 multibeam echosounder. Multibeam bathymetric and backscatter data from this survey were processed by the Geological Survey of Canada. Raw bathymetric data were manually cleaned using CARIS HIPS & SIPS and were gridded at a resolution of 10 m using Geographic Resources Analysis Support System (GRASS). Newman Sound multibeam data collected within the depth range of the Eastport MPA closures (<110m) were extracted from this dataset using ArcGIS 10.2.

3.3.2 Seafloor video

A depth-stratified, randomly distributed seafloor video survey was conducted from June 21 to 27, 2015, within the boundaries of the Eastport MPA and reference areas (N = 87). Benthic video transects were recorded on a custom drop camera system, with a pair of mounted LED lights and red scaling lasers (5 cm apart), from a 40 ft inshore fishing vessel chartered from a local fisher. Seafloor video was recorded with continuous WAAS global positioning system (GPS) overlay of vessel position using a standard definition 250 m tethered Deep Blue Pro camera. Simultaneous high-definition video was recorded with a mounted GoPro Hero 3 Black Edition at all sites <70m. Video recording was monitored on board via live feed to maintain a distance of ~1 m between the camera and the seafloor. Each transect recorded 4 minutes of bottom time while the vessel drifted slowly. Still images from the video were scaled and measured for frame area using ImageJ software. Location, UTC (coordinated universal time), elapsed video time and video area were recorded from the tethered Deep Blue Pro camera footage. For sample stations <70 m, substrate type and coverage, flora/fauna identification, and abundance were determined from GoPro camera footage. For deeper sample stations, all the analyses were based on the Deep Blue Pro footage. Substrate and macroalgae presence were recorded every 10s or more frequently if abrupt changes in the dominant substrate were observed. To record benthic fauna, every visible individual was identified and counted for the entire bottom time for each transect. Individual organisms were identified to the lowest possible taxonomic level. All abundance data were standardized by length (m) of the video survey transects.

An archival seafloor video dataset, collected by Copeland (2006) to ground-truth the Newman Sound multibeam data, was also employed for comparison of the MPA with its surrounding area. This dataset consists of species presence/absence recorded along video transects stratified by acoustic backscatter value, collected via SCUBA video transects, drop video and Remotely Operated Vehicle (ROV) transects. Fifty-meters long SCUBA video transects were recorded via Sony digital video camera in an Amphibico housing by divers at depths <20 m in July of 2004. Unmanned video transects were recorded using a SeaView BW-150 drop camera deployed from a vessel in November 2004 and a Videoray Pro ROV video operated by DFO from the Canadian coastguard ship Shamook in December 2004, extending the survey range to 80 m water depth.

3.3.3 Substrate classification

Geomorphometric characteristics were derived from the Eastport multibeam bathymetry data using ArcGIS 10.2, NOAA's Benthic Terrain Modeler (BTM) extension, and the Terrain Attribute Selection for Spatial Ecology (TASSE) ArcGIS toolbox (Lecours, 2015; Lecours, et al., 2017). Slope (3x3 cell analysis window), Benthic Position Index (BPI; inner radius of 3 cells, outer radius of 25 cells), curvature (3x3 window), and standard deviation (3x3 window) were calculated for all study areas. BPI refers to relative elevation, identifying crests and depressions; in terrestrial studies, this is called Topographic Position Index (Verfaillie, et al., 2007). These variables capture the majority of variation in the seafloor (Lecours, et al., 2017). The terrain attributes were applied in two substrate classification routines to separate correlated variables; both were tested for agreement with patterns of biodiversity through non-metric Multidimensional Scaling (nMDS) and analysis of similarity (ANOSIM) tests. The classification with best fit (i.e., lowest dimensional stress and significant separation of species groups by substrate class) was carried forward for further analysis. Substrate classifications were generated using the ArcGIS 10.2 ISO unsupervised classification tool. This tool combines a maximum likelihood clustering with an iterative self-organizing (ISO) algorithm. Unsupervised classifications are easily reproducible, do not require a priori assumptions about ecological relationships, and have been shown to produce results equal to or better than supervised classification methods when used to map biotic assemblages (Eastwood, et al., 2006). In areas of hard substrate and high geomorphological complexity, as found in the Eastport MPA study area, unsupervised classification of bathymetry and bathymetric derivatives match performance of acoustic backscatter in segmenting seafloor substrate types (Calvert, et al., 2015).

For comparison to the Newman Sound data, the Eastport multibeam data were resampled at a 10 m resolution using ArcGIS 10.2 and both datasets were combined in a single mosaic. Geomorphometric variables were generated again at 10 m resolution following the methods listed above, and an unsupervised substrate classification was generated for the entire area.

3.3.4 Biological communities

All statistical analyses of the video data were completed in PRIMER (Plymouth Routines in Multivariate Ecological Research) v7. Biological datasets were first processed with the PRIMER Dispersion Weighting protocol to balance contribution from highly variable species counts based on a Poisson model of cluster centers (Clarke & Warwick, 2001). This approach normalized the influence of highly abundant, highly clustered species on similarity matrices. The dataset was then square root transformed to balance the contribution of high-abundance species with consistent, but low-abundance species to the measure of between-site variance. A Bray-Curtis similarity matrix was generated on the transformed dataset, and nMDS, Analysis of Similarity (ANOSIM) and Similarity Percentages (SIMPER) procedures were carried out on the similarity matrix. These analyses were conducted to test the efficacy of the unsupervised substrate classes as predictors of the distribution of taxonomic composition and, where applicable, to merge substrate classes occupied by statistically indistinguishable biological communities into continuous habitats. Species-area curves were generated to assess sampling completeness by habitat. These plots show the cumulative number of unique species identified as the total area of analyzed seafloor images increased. Area was calculated using ImageJ software to measure the total area in view for the analyzed images, scaled by the camera-mounted lasers in each frame.

The accuracy of the resulting habitat map was calculated using an error matrix, which compares the predicted habitat type (according to unsupervised multibeam classification) to the observed habitat type in the video survey. Two standard types of accuracy were measured: the user accuracy, indicating how likely a user is to find a particular habitat where predicted, and the producer accuracy, indicating how likely it is that each observed habitat was correctly classified.

Habitats were also explored through an analysis of the combined Newman Sound and Eastport MPA datasets. For this analysis, all biological abundance data were transformed into presence/absence to match previously collected Newman Sound video data. Some taxonomic resolution was also sacrificed to make this comparison, because some taxa identified to species level in the Eastport MPA dataset were comparable only to taxa identified to the genus or family level in the archival Newman Sound data. Otherwise, the same methods were applied as described above.

3.4 Results

3.4.1 Bathymetry and geomorphology

The multibeam survey of the Eastport MPA and reference areas covered a total area of 3.4 km^2. Bathymetric data were processed and analyzed at a 2 m resolution grid, with depths recorded by the survey ranging from <1 m to a maximum depth of 108 m (Figure 3.2). Depths within the Duck Island closure reach 101 m in the southern part, although about 64% of the protected area around Duck Island falls within the 0–50 m range. Benthic Position Index (BPI) values indicate high topographic variation, with many ridges, crests, and depressions surrounding the island. Slopes around these features reach highs of 65°. The majority of the Round Island closure is shallower than 20m, gradually deepening to a maximum of 50 m toward the center of Newman Sound. The highest slopes are found on the northern side of Round Island, reaching a maximum of 48° along the sides of a depression about 70 m from the coast. Generally, there is very little topographic variation within the Round Island closure. The reference areas share the shallow depth range (0–50m) and low topographic variation of the Round Island closure.

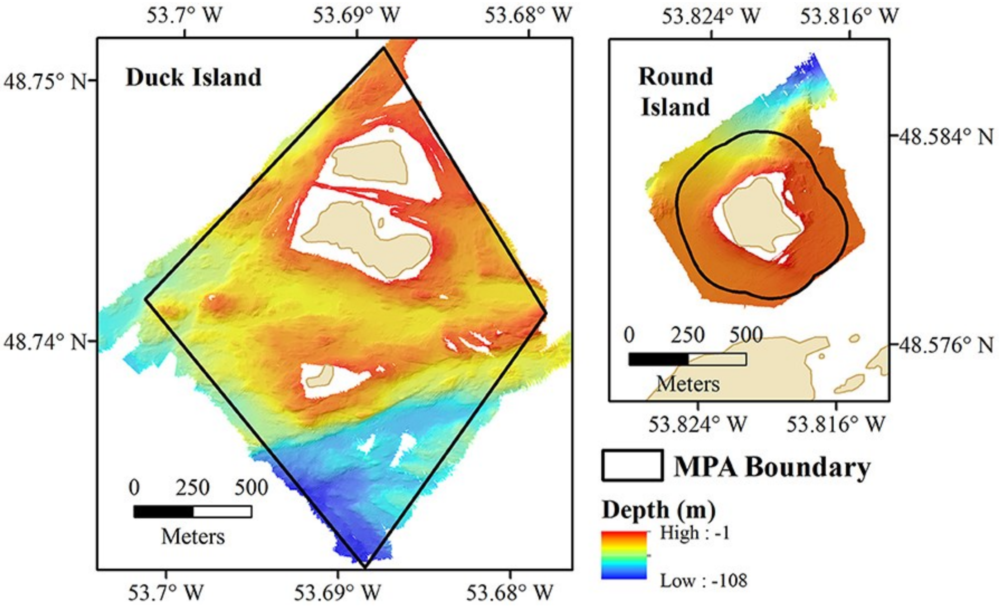


Figure 3.2 Bathymetry within the Eastport MPA, visualized with hillshade effect.

3.4.2 Substrate classification

Unsupervised classifications were tested with two combinations of input variables (bathymetry, slope, and BPI; bathymetry, bathymetric standard deviation and BPI), chosen to reflect variations in the seafloor without internal correlation. The unsupervised classification using bathymetry, slope, and BPI provided the best fit with the biological data. Five substrate classes were identified, characterized by distinct seabed morphologies (Figure 3.3).

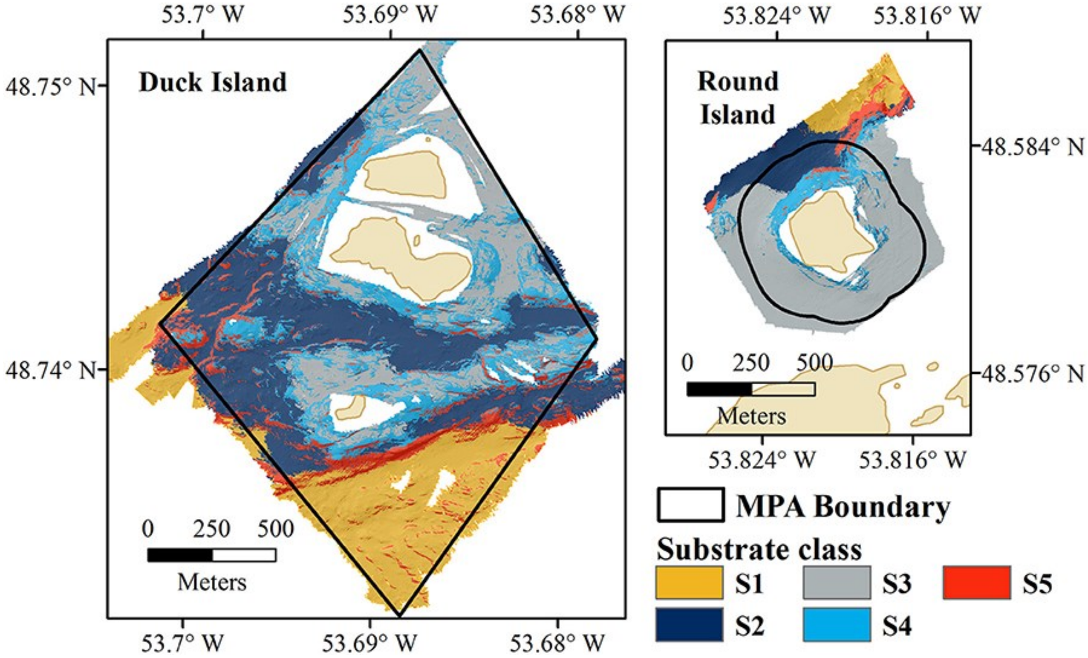


Figure 3.3 Eastport MPA substrate classification results for Duck Island and Round Island.

Substrate class S1 is found in the deepest portions of the study area, characterized by moderate slopes (Figure 3.4). Substrate classes S2 and S3 dominate the study area; S2 is found in moderate depths and slopes and S3 is found in shallow depths and low slopes. Substrate class S4 shares the shallow depth range of S3, and includes moderate slopes and slightly more variation in BPI. Substrate class S5, found across the entire depth range of the Eastport MPA, is characterized by the steepest slopes within the survey area and large variations in BPI, indicating the presence of ridge and trench features.

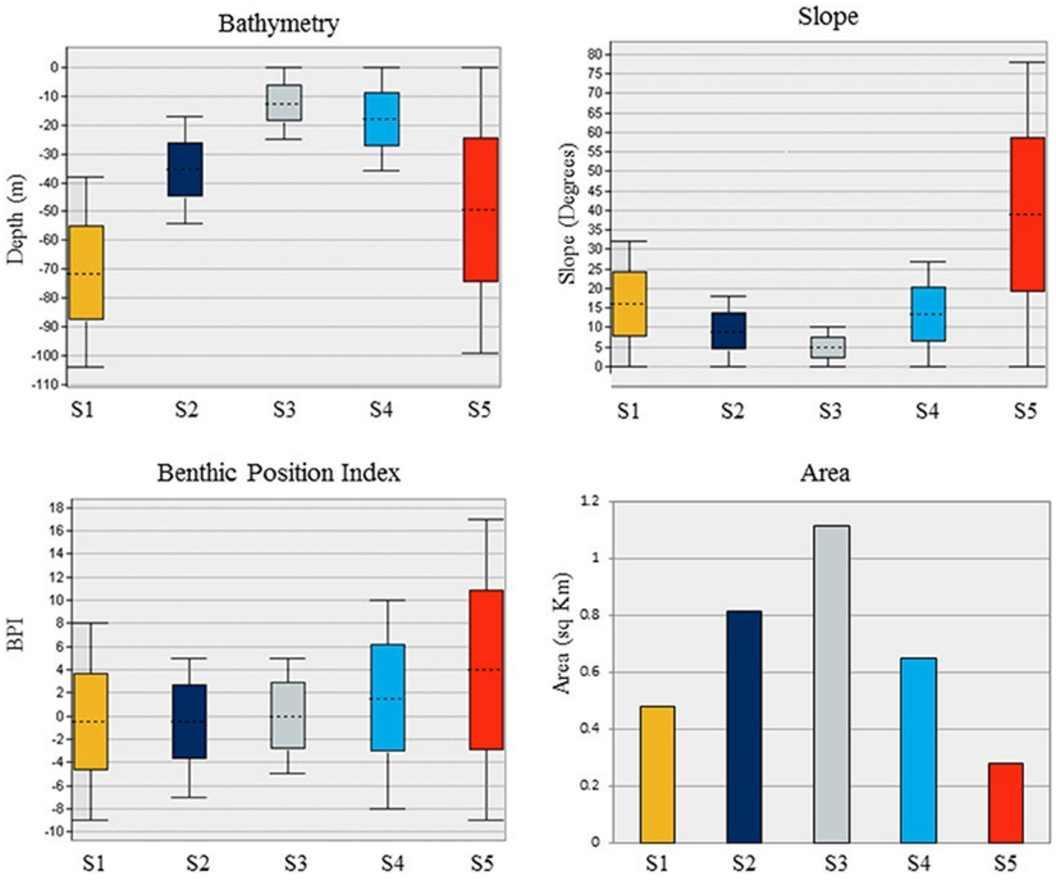


Figure 3.4 Characteristics of the five substrates identified in the Eastport Marine Protected Area based on depth, slope, BPI, and total area.

3.4.3 Biological communities

A total of 87 video transects were recorded in 2015 and analyzed throughout the Eastport MPA and reference areas. Video transects covered a total linear distance of 2179 m and a total area of ~903 m^2 ranging from 8 to 96 m depth. Visual analysis of the videos identified 39 different species, including 34 within MPA boundaries (29 species identified within the Duck Island MPA closure and 32 species identified within the Round Island MPA closure). Observed species include 5 fishes, 20 invertebrates and 14 species of algae (Supplementary materials Table S3.1). Of 8,392 individual organisms identified in the videos, only 47 individuals (0.56%) could not be confidently identified and were excluded from further analysis: 27 unknown anemones, 12 unknown sea stars, 4 unknown fish, and 4 unknown crustaceans. Capelin (*Mallotus villosus*) were occasionally observed during camera descent but, as a primarily pelagic species, were not included in the benthic habitat map.

Species-area accumulation curves (Species observed, Jacknife 1, Jacknife 2, and Michaelis-Menten; Figure 3.5) reached asymptote early in the survey, indicating that the overall area was sufficiently sampled (N = 87, ~903m^2). The 2D nMDS plot indicated very little separation of taxonomic composition recorded across all of the video transects sampled within the Eastport MPA (Figure 3.6; 2D stress = 0.21). It should be noted, that while a 2D nMDS with a stress value >0.2 provides a useful visualization of the data, other methods (ex. ANOSIM) should supplement the identification of cluster groups (Clarke & Warwick, 2001). Groups of co-occurring species found to be statistically distinct from other groups, based on the pairwise ANOSIM tests on abundance and composition of species (i.e., between different substratum categories), were considered to be distinct biological communities associated with the different substratum categories. Species composition in the reference areas were not found to be significantly different from the videos collected within the MPA closure.

Pairwise ANOSIM tests show significantly different species composition between S1 and S2, S3, and S4. Similarly, S2 was biologically distinct from S1, S3, and S4 ($p < 0.05$; Supplementary Materials Table S3.2). Of the pairwise combinations, S3 and S4 were not significantly different ($p > 0.05$). S5 was not significantly different from S1, S2, and S4, although those three substrates appear to differ biologically in each of their respective pairwise tests. However, S5 is not very prevalent, and was surveyed by few video transects (N = 6).

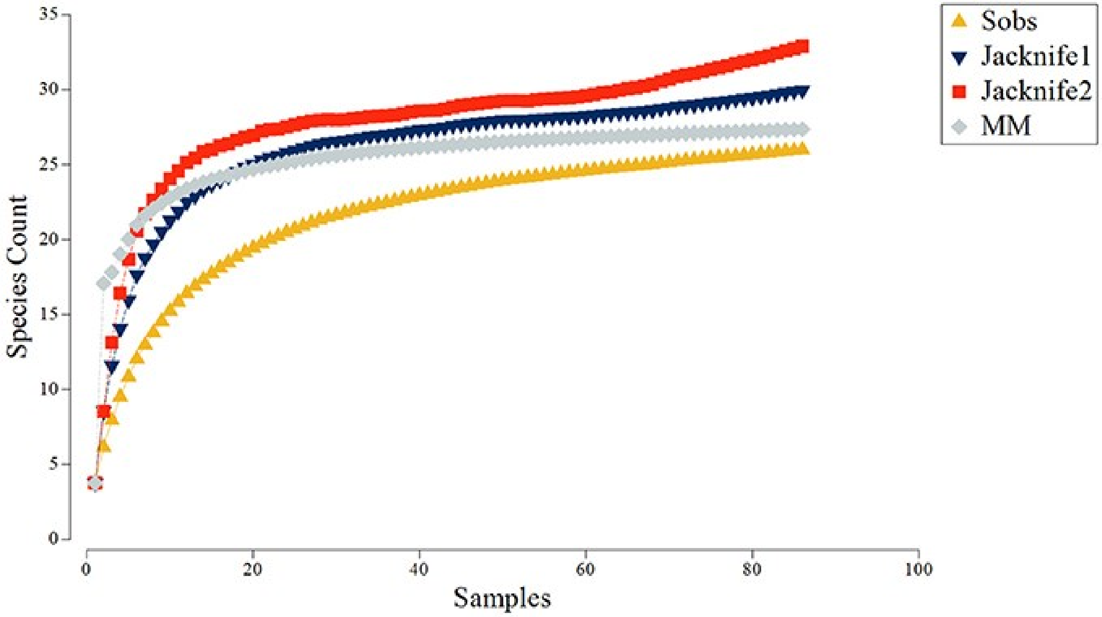


Figure 3.5 Species accumulation curves derived from video samples collected in the Eastport MPA in 2015: Species observed (Sobs), Jacknife1, Jacknife2, and Michaelis-Menten (MM).

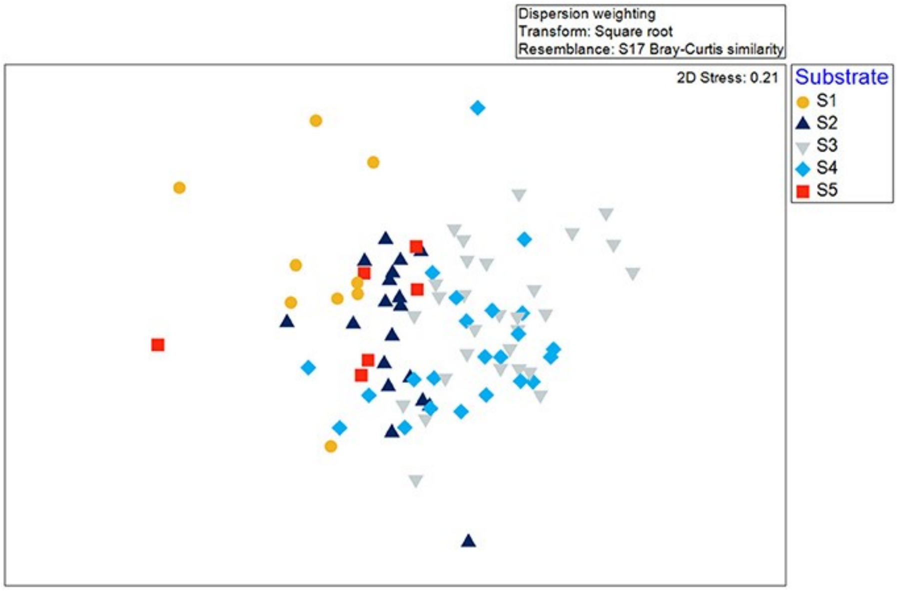


Figure 3.6 Non-metric multidimensional scaling (nMDS) of video transect data collected in the Eastport MPA in 2015. Symbol shape and color indicate the unsupervised substrate classification.

3.4.4 Characterization of benthic habitats

Three distinct benthic habitats were identified within the Eastport MPA based on similarities in species composition between substrate classes (Figure 3.7). Habitat 1 (H1—shallow rocky habitat) includes S3 and S4, Habitat 2 (H2—sand and cobble) occurs on S2, and Habitat 3 (H3—sand) on S1. S5 was not identified as a unique habitat because it was not found to be significantly biologically different from S1, S2 and S4, but could not be confidently grouped with any identified habitat.

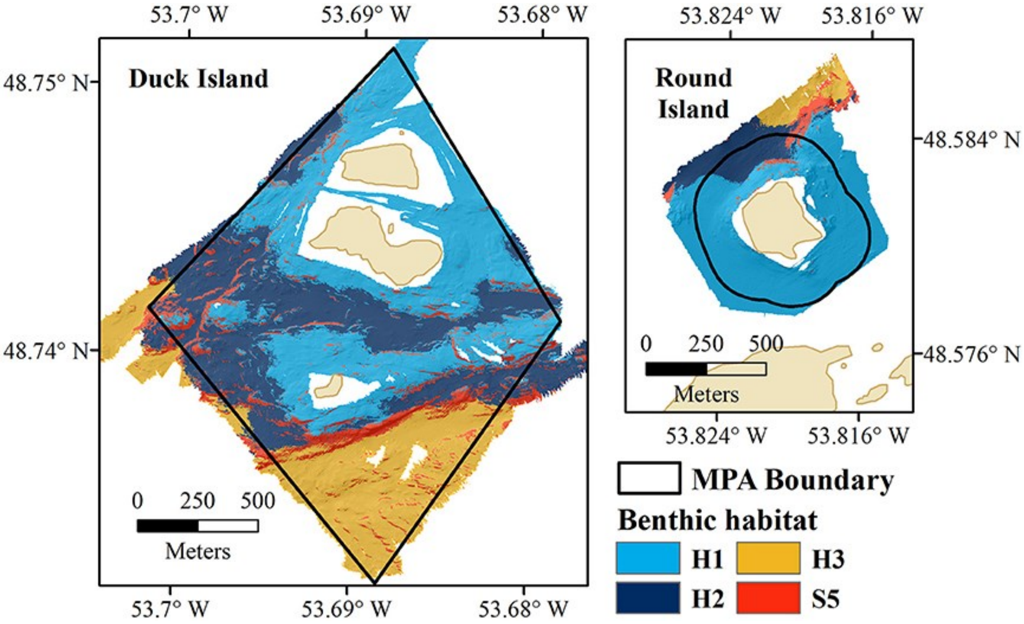


Figure 3.7 Benthic habitats of the Eastport MPA (Duck Island and Round Island); H1, shallow, rocky habitat; H2, sand and cobble; H3, sand; and S5, high profile bedrock features.

Species-area curves (Figure 3.8) generated for the fauna identified within each habitat type of the Eastport MPA indicate that the shallow rocky habitat (H1) was very well-sampled. The majority of species observed in this habitat were recorded within the first 200m^2 of seafloor video. The sand and cobble habitat (H2) follows a roughly similar curve, and appears to be adequately sampled after 200m^2 of seafloor video. Sandy habitat (H3) was not adequately sampled by this survey largely due to the low prevalence of this habitat type within the MPA (0.28 km^2, 15% of MPA area). Similarly, the high profile bedrock and boulder features (S5), which made up a very small fraction of the MPA (0.149 km^2, 8% of MPA area), were insufficiently sampled for species composition.

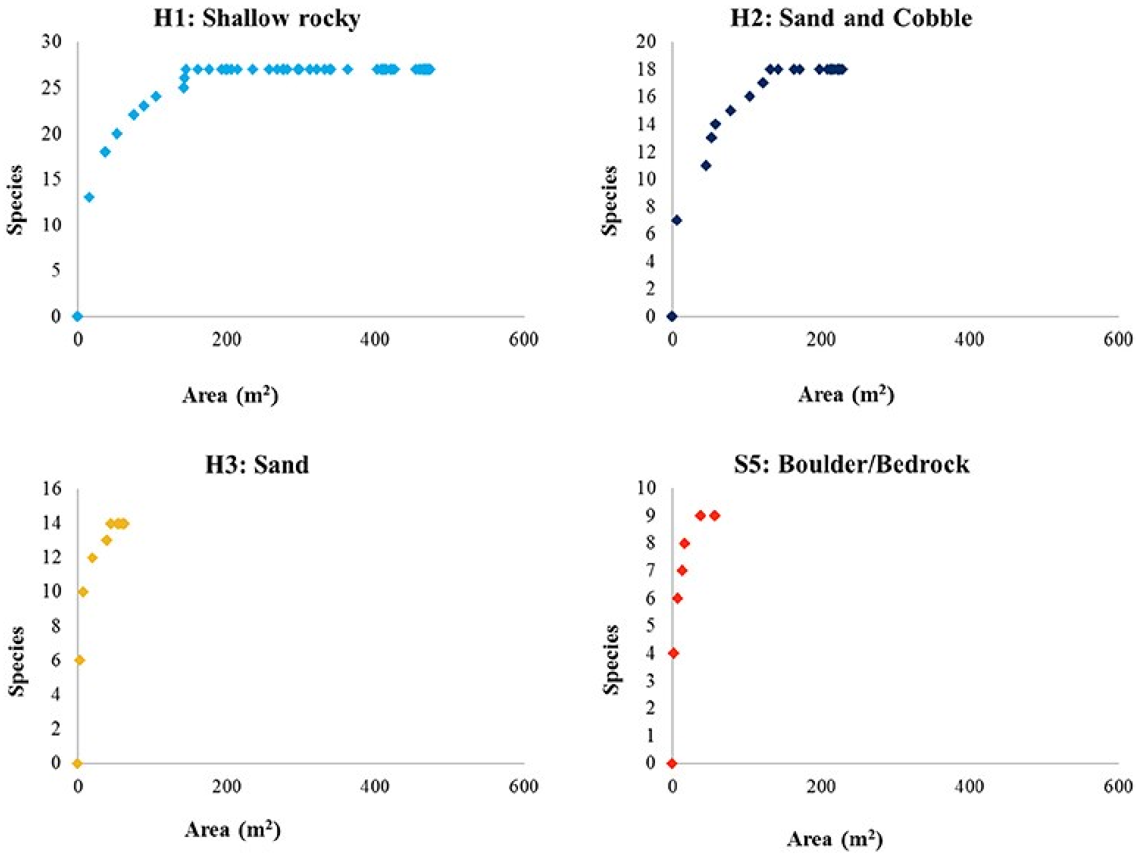


Figure 3.8 Species-area curves of fauna identified from seafloor video within the mapped habitats of the Eastport MPA.

Shallow Rocky Habitat

Rocky habitat (H1) was found in shallow waters (<36 m), in areas of relatively low slope, and low to moderate BPI values. SIMPER analysis indicates that internal similarity is mainly driven by the high abundance of green sea urchin (*Strongylocentrotus droebachiensis*) and northern seastar (*Asterias vulgaris*). The shallow rocky habitat covers approximately half of the MPA (48.9%), including most of the Round Island closure (86.3%). The mixed cobble, boulder, and bedrock substrate provides a surface for leafy and encrusting algae, and this habitat is characterized by both high algal cover and high algal richness. All 14 species of algae observed in the study area occur within the shallow rocky habitat. The most abundant invertebrate fauna include green urchin, northern seastar and frilled anemone (*Metridium senile*). Several invertebrate species were exclusive to this habitat, including smooth sunstar (*Solaster endeca*), northern seastar, sea cucumber, and finger sponge (*Haliclona oculata*). The vast majority of sessile species, including mussels (95% of all observations), all stalked jellyfish (*Lucernaria quadricornis*; 73.7%) and frilled anemones (79%), were recorded in the shallow rocky habitat, where hard surfaces for attachment are most prevalent. A total of five fish species were observed in the video survey, and all were present within the shallow rocky habitat. The most abundant fish species was the common cunner (*Tautogolabrus adspersus*), which was found exclusively within this habitat. Atlantic cod (*Gadus morhua*), generally of smaller size (~30–40 cm, estimated from video scaling lasers), were also exclusively recorded in shallow, rocky areas.

Sand and Cobble Habitat

The sand and cobble habitat (H2) occurs at intermediate water depths (16–54 m), with mixed cobble and sandy bottom substrates. In some areas this habitat overlaps in depth range with the shallow rocky habitat; however, the majority of this sand and cobble habitat was found beyond the macroalgae-dominated shallows. Approximately 28% of the protected areas are predicted to be sand and cobble habitat. Coralline encrusting algae (*Lithothamnion* sp.) was present in all of the sand and cobble habitat video transects. Sea colander (*Agarum* sp.) and northern sea fern (*Ptilota serrata*) were also very common in these areas, present in 84 and 68% of videos respectively. Overall, algal richness in the cobble and sand habitat was half that of the shallow rocky habitat (7 species total). Green urchin, brittle star (*Ophiopholis* sp.), stalked jellyfish, toad crab (*Hyas areneus*), and burrowing anemones (*Pachycerianthus borealis*) were common. Eelpout (*Zoarcidae*) and sculpin (*Myoxocephalus* sp.) were the only fish species recorded.

Sandy Habitat

The sandy habitat (H3) was found in deeper waters (40–108 m, mean depth 70 m), with substrates dominated by sand and finer sediments (>80% bottom coverage from video analysis). Only about 15% of the protected areas were classified as sandy habitat, and all protected sandy habitat was found within the Duck Island closure. Few algae species (5 of 14) were recorded in the sandy habitat, limited by light penetration. The deep sandy habitat was characterized by brittle star, burrowing anemone, and snow crab (*Chionoecetes opilio*). Snow crabs were rare in general (only three recorded in the entire survey) and only found on sandy habitat. Eelpout, sculpin, and flatfish were all recorded in the sandy habitat at greater abundance per meter than in the shallower habitats.

High Profile, High Slope Boulder, and Bedrock Features

Substrate 5 (S5) was classified as a distinct substrate from the three habitats but could not be classified as a unique habitat. ANOSIM analysis indicates that S5 does not differ biologically from any other substrate except S3, the shallowest and lowest slope substrate. S5 covers the smallest area (8%) of the MPA. Characterization of S5 is limited, with only few video transects in these areas (N = 6). It appears that S5 is populated by the most abundant species of the other habitats (e.g., green urchin, brittle star, frilled anemone, coralline algae). Kelp (*Laminaria* sp), sea colander, and northern sea fern were also present, though rare.

3.4.5 Habitat map accuracy

The overall accuracy of the habitat map was ~70% (Table 3.1). Shallow rocky habitat is predicted to include rocky mixed substrates (including cobbles, boulders, and bedrock), as well as macroalgae-dominated substrates. Sand and cobble habitat is predicted to include sand-dominated substrates with occasional cobbles, and sandy habitat includes the deepest areas, where sand is continuous (>80% cover). The shallow rocky habitat (H1; "mixed" and "macroalgae" in the videos) and the deepest sandy habitat (H3; sand) were accurately predicted (user's accuracy 82.4 and 88.9% respectively), while the sand and cobble habitat (H2) and high profile bedrock features (S5) had a lower accuracy (user's accuracy 36.8 and 50% respectively). Producer's accuracy was relatively high for all of the observed substrates except for bedrock.

Table 3.1 Eastport Marine Protected Area habitat map error matrix (N = 87).

	Habitat Class					
Observed Substrates	**H1** Shallow Rocky	**H2** Sand + cobble	**H3** Sand	**S5** Bedrock	**Total**	**Producer's accuracy**
Mixed	**28**	5	1	3	37	75.7%
Macroalgae	**14**	3	0	0	17	82.4%
Sand and cobble	4	**7**	0	0	11	63.6%
Sand	2	2	**8**	1	13	61.5%
Bedrock	3	2	0	**4**	9	44.4%
Total	51	19	9	8	87	
User's accuracy	82.4%	36.8%	88.9%	50.0%	**Overall accuracy**	**70.1%**

3.4.6 Diversity and species richness

The Duck Island closure showed greater benthic habitat and faunal diversities (H' = 1.33) than Round Island (H' = 1.09). The Round Island closure is dominated by shallow rocky habitat, and the diverse algal community found there resulted in greater benthic species richness. The sandy, and sand and cobble habitats showed much lower algal richness and low epifaunal diversity overall (Table 3.2).

Table 3.2 Species Richness and Diversity (Shannon's H and Simpson's Diversity Index calculated for fauna only).

	Round Island	**Duck Island**	**H1** Shallow Rocky	**H2** Sand + cobble	**H3** Sand	**Eastport MPA**	**Total Area**
Transects (N)	26	53	52	20	9	79	87
Species	32	29	37	22	16	39	40
Algal richness	13	7	14	7	5	14	14
Faunal richness	19	22	23	15	11	25	26
Shannon’s H	1.1	1.3	1.0	0.9	0.76	1.4	1.1
Simpsons DI	0.47	0.6	0.43	0.35	0.34	0.55	0.45

3.4.7 Comparison to Newman Sound

Unsupervised classification of the 10 m resolution multibeam data delivered five distinct substrate types throughout the Eastport and Newman Sound area within the <110 m depth range represented by the protected areas. Distribution of substrates is consistent with the classification carried out at 2 m resolution within the MPA boundaries (Table 3.3, Figure 3.9). All five Newman Sound substrate classes are represented within the MPA. Of the total area, 4.2 km^2 is made up of shallow, rocky substrates, ranging from continuous bedrock to mixed cobbles and boulders (NS5). This substrate type and the corresponding habitat(s) are well-protected; ~22% of the shallow rocky habitat in the surveyed area falls within the boundaries of the Eastport MPA. Fine substrate habitats (NS1 and NS2) receive much less protection, with only 0.31 km^2 represented within the MPA boundaries (4.4% of total surveyed fine substrates ≤110 m).

Table 3.3 Representation of Newman Sound (NS) unsupervised substrate classes within Eastport MPA boundaries.

Substrate description	**NS class (10 m grid) / Eastport class (2 m grid)**	**Total (km^2)**	**Protected (km^2)**
Sand/muddy sand (>80 m depth)	NS1 / S1	4.88	0.07 (1.48%)
Sand/muddy sand (<80 m depth)	NS2 / S1	6.25	0.24 (3.87%)
Pebble, cobbles, or boulders on sand	NS3 / S2	8.11	0.42 (5.18%)
High slope boulder and bedrock	NS4 / S5	3.46	0.22 (6.21%)
Shallow cobble, boulder, and bedrock	NS5 / S3 and S4	4.17	0.91 (21.83%)
	TOTAL	**26.87**	**1.86**

A total of 58 taxa were identified in the two benthic surveys (Newman Sound and the Eastport MPA). Of these, 22 were present in both the Eastport MPA and Newman Sound, 12 were only found within the MPA boundaries and 24 were only found outside of the MPA. At the species presence/absence level available in the Newman Sound archival data, habitats could not be distinguished biologically throughout the Eastport/Newman Sound areas using the methods described above. Species composition was found to be significantly different (ANOSIM, $p < 0.01$) between videos recorded within the Eastport MPA and videos recorded within the same depth range (<110m) in the broader Newman Sound area (Figure 3.10). This difference indicates that the habitats identified within the MPA may not be transferrable to the similar substrates of Newman Sound.

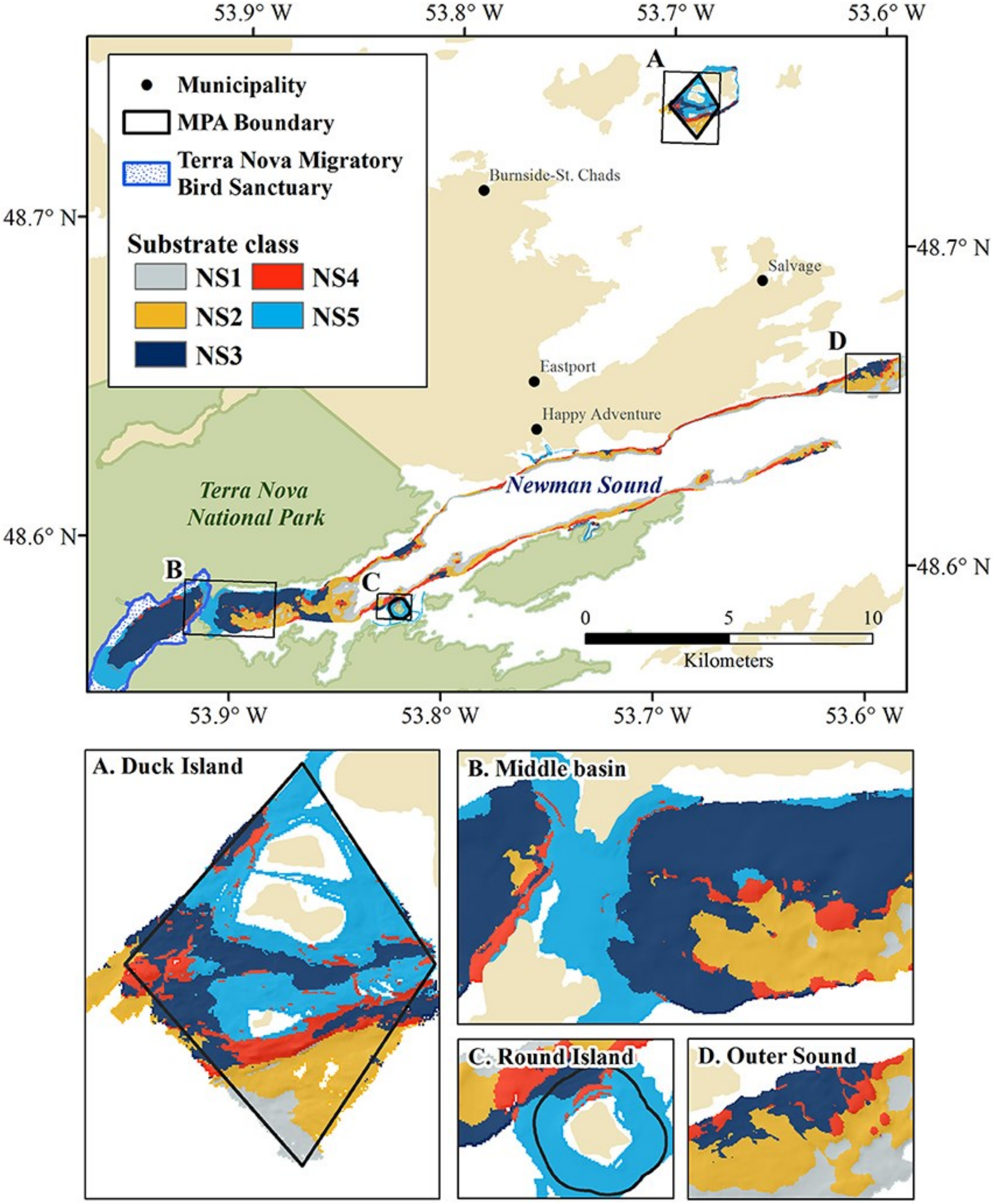


Figure 3.9 Unsupervised substrate classification of Newman Sound and the Eastport MPA at 10 m resolution. MPA closures and features of interest shown in insets: (A) Duck Island Closure, (B) Middle Basin narrows and shallow sill, (C) Round Island Closure, (D) Outer Sound fjord mouth.

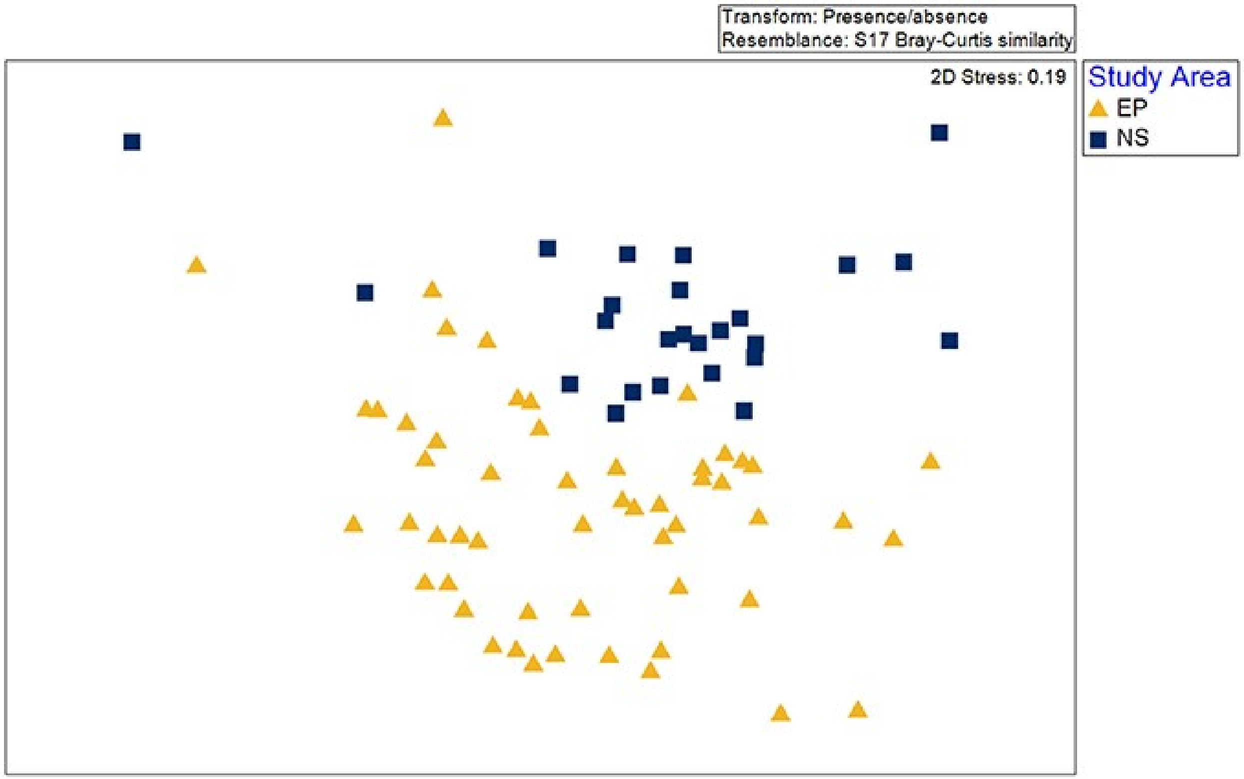


Figure 3.10 Non-metric multidimensional scaling (nMDS) of difference between species composition within video transects collected in the Eastport MPA (EP) and the surrounding Newman Sound (NS) area.

3.5 Discussion

3.5.1 Benthic habitats of the Eastport MPA

Species distribution within the Eastport MPA appears to be controlled mainly by depth and substrate type. The limited size (2.1 km^2) and depth range (0–110 m) of the Eastport Duck Island and Round Island MPA closures capture a limited portion of the regional biodiversity. The vast majority of the protected area (95.7%) is within the photic zone, at depths <80 m. Within the MPA, substrate ranges from algal dominated rocky shallows near the islands' coasts to cobble and sand habitats at the greatest depths. The most abundant species are relative generalists in shallow coastal areas, able to utilize a range of available habitats. Green urchins, for example, were recorded on every substrate and habitat type.

The algae-rich shallow rocky habitat that makes up the majority of the Eastport MPA may offer important predation cover for juvenile fishes and invertebrates. Juvenile Atlantic cod have been shown to prefer the complex habitat provided by shallow, seaweed-dominated habitats in Newfoundland waters. Urchin barrens, the result of grazing by large urchin populations, reduce habitat complexity. Field experiments conducted in Conception Bay, Newfoundland, demonstrated that removal of urchins from rocky barrens resulted in the colonization and growth of macroalgae species and a simultaneous increase in juvenile cod density (Keats, et al., 1987). The shallow rocky habitat was the most prevalent in the MPA, and was very well-sampled by this survey. The species-area curve (Figure 3.8) indicates that the protection of this habitat (0.911 km^2) is likely sufficient to protect at least 90% of associated species, a minimum area threshold identified by MPA network planners in California to ensure adequate habitat representation (Vasques, 2010). However, the small size of the MPA and the limited number of individuals protected may not be sufficient to ensure a viable population. Assessing the size of closure required to elicit population level effects would require further study on the population dynamics that go beyond our study. Species richness and faunal diversity (measured by Shannon's H and Simpson's Diversity Index) were higher in the shallow rocky habitat and lower in the deeper, sandy flats. Species diversity is often closely linked to habitat complexity in marine coastal environments (Kostylev, et al., 2005), a pattern that is reflected in the Eastport MPA. It should be noted that these analyses are based on vertical seafloor video conducted during the summer season; cryptic, mobile, or seasonal species are not represented by this survey and may alter the species-area curves and diversity metrics.

The cobble and sand habitat included species of both the shallow rocky and deep sand habitats, though in lower abundances. This species composition reflects the transitional nature of this habitat, as the coastal gradient shifts from rocky shallows to the sand-dominated depths. Generally, the sand and cobble habitat appears to be a suboptimal spillover habitat for most of the species represented in this survey. There are no species unique to this habitat and the vast majority of species are much more abundant in either the shallow rocky habitat or the deeper, sandy habitat. The bay scallop (*Argopecten irradians*) was the only species more common among the sand and cobble habitat, when compared to other habitat types. The sandy habitat appears to be well-sampled by this survey (Figure 3.8), and the MPA appears to protect 90% of the species found in this habitat (0.52 km^2 protected).

Snow crab, a locally harvested species, was recorded in the deep sandy habitat, although all appeared to be immature individuals. Despite low abundance in this survey, this pattern agrees with a previous study of snow crab habitat in Bonne Bay, Newfoundland, which indicates that immature snow crabs are most abundant between 50 and 100 m on fine substrates (Comeau, et al., 1989). In total, about 15% of the MPA (0.28 km^2) may protect suitable juvenile snow crab habitat. Eelpout, sculpin, and flatfish were also more prevalent per meter of video transect in the sandy habitat, though they likely move between habitats to feed. For example, a study of eelpout diet indicates that green urchins are a staple (62% of overall diet by weight; (Keats, et al., 1987) and this species likely uses the shallower, urchin-dense habitats to hunt. Brittle stars, the most abundant prey species available in sandy habitat, make up only 6% of eelpout diet in Newfoundland studies (Keats, et al., 1987). Deep sandy habitat is not prevalent in the MPA, and as a result, the species-area curve for this habitat type indicates that it was not well-sampled by this survey. It is not possible to conclude whether the area within the MPA boundary is sufficient to protect 90% of associated species without additional surveys.

Shallow rocky habitat was very accurately predicted (user's accuracy 82%). The deep sandy habitat was also very well-predicted by the unsupervised substrate classification (user's accuracy 88.89%). The mid-depth sand and cobble habitat, however, was not well-predicted, possibly due to its transitional nature. The sand and cobble classification misidentified transects from all substrate types. This may be due, in part, to the video classification procedure. The difference between the observed habitats was marginal at times; mixed cobble substrate with less than 60% sand cover observed in the video was recorded as mixed-rocky, while areas of 60–80% sand were listed as sand and cobble, and over 80% sand cover was simply listed as sand.

3.5.2 Management objectives of the Eastport MPA

American lobster

The primary conservation objective of the Eastport MPA is “to maintain a viable population of American lobster through the conservation, protection, and sustainable use of resources and habitats” (DFO, 2013). While no American lobsters were recorded within or surrounding the MPA boundaries during this survey, this species is cryptic and the sampling strategy used in this study was not designed to confirm lobster presence but to map benthic habitat more generally. Lobsters spend much of their time during the day in rocky shelters and are unlikely to be found by a bottom-facing camera (Ennis, 1984). American lobsters occupy a variety of habitats from sandy substrates to bedrock, but commonly utilize coarse rocky substrates with suitable crevices (Tanaka & Chen, 2015). Previous research and the active fishery in the area indicate that the species is present in the MPA in relatively high abundance (DFO, 2014). Baited lobster traps have been used to sample lobster in the MPA (Janes, 2013). A decade after the original fishery closures were created, Janes (2009) demonstrated several changes within the American lobster population, including higher abundance of large, ovigerous females and increases in mean size of both male and female lobsters. Small coastal MPAs (collectively protecting 2.2 km^2) on the Norwegian Skagerrak coast have shown similar increases in mean size and abundance of lobster within the closures (Moland, et al., 2013). These results demonstrate the potential of small coastal MPAs as an effective management tool for this species.

The shallow rocky habitat that dominates the Eastport MPA has several characteristics of optimal juvenile lobster habitat. The area provides complex rocky features with many crevices and a thick seaweed canopy that provides cover from predators. Experiments conducted by Johns and Mann (1987) suggest that settling juvenile lobsters (stage IV) have a strong preference for seaweed-covered rocky habitats over mud, pebbles, or sand. Both laboratory (Hovel & Wahle, 2010) and field experiments (Wahle & Steneck, 1992) have shown early stage lobsters are more likely to settle on cobble substrate and rocks colonized by macroalgae; they settle faster in these habitats and experience lower predation mortality. The shallow rocky habitat and bedrock features of S5 also provide the complex structure that adult lobsters use for shelter (Christian, 1995). Lobster grounds are defined by Hooper (1997) as mixed rocky substrate areas characterized by the presence of green urchin, mussels, brittle stars, toad crab, and rock crab—an accurate description of the shallow rocky habitat identified within the Eastport MPA. Results of this habitat mapping exercise also agree with local ecological knowledge: harvesters described the MPA location as suitable lobster habitat (Rowe & Feltham, 2000), known for the rocky bottoms with depths generally <25 m (Ennis, et al., 1989). Based on maps generated by Rowe and Feltham (2000), ~0.208 km^2 of lobster habitat is found within the Round Island closure and 0.114 km^2 within the Duck Island closure. The habitat maps presented in this report suggest that there is slightly more lobster habitat within MPA protection than previously expected: 0.254 km^2

of shallow rocky habitat was recorded in the Round Island closure and 0.659 km^2 in the Duck Island closure.

Wolffish

The secondary conservation objective of the Eastport MPA is "to ensure the conservation and protection of threatened or endangered species," specifically mentioning threatened wolffish (DFO, 2013). This target was included in management plans after 2005, when the fishery closure was gazetted as an MPA under the Canadian Oceans Act, and did not inform design or placement of the protected areas. This addition was likely an attempt to broaden the scope of the MPA beyond the protection of American lobster, which are common throughout Atlantic Canadian waters. Spotted wolffish (*Anarhichas minor*) and northern wolffish (*A. denticulatus*) are currently listed as Threatened Species under Canada's Species at Risk Act (SARA), though they are not listed to species level by the Eastport MPA Management Plan (DFO, 2013). It is highly unlikely that either spotted wolffish or northern wolffish are protected by the Eastport MPA; these species are typically found in Newfoundland waters between 200 and 1,000 m (DFO, 2008), well-beyond the depth range found within MPA boundaries. Atlantic wolffish (*Anarhichas lupus*) are the most likely wolffish species to be found in the Eastport MPA, due to their relatively shallow depth range (DFO, 2008). Atlantic wolffish are currently recognized as a species of Special Concern under SARA (DFO, 2008), but are not specified in the Eastport MPA management plan, which only refers to threatened and endangered species (DFO, 2013). Previous characterization of Atlantic wolffish habitat in Conception Bay identified denning habitat occurring in boulder and bedrock substrates of high slope (>30°) (Novaczek, et al., 2017). Approximately 6% (0.12 km^2) of the Eastport MPA provides adequate slope for potential wolffish denning habitat, and several prey species are present throughout the MPA (green urchin, blue mussel, and rock crab) (DFO, 2008).

While there is some potential habitat for Atlantic wolffish within the MPA, there is no evidence that this MPA is used by wolffish of any species. No wolffish, or any other species listed by Canada's Species at Risk Act (SARA), were recorded in this survey. Like the American lobster, Atlantic wolffish may not be easily detected in vertical video surveys because, in addition to being relatively rare, they spend much of their time in rocky dens (Larocque, et al., 2008). Since 2007, when DFO began an organized campaign among harvesters to recognize and report wolffish, there have been no reported sightings in or near the MPA (Janes, 2013). When the results of this study were presented to local stakeholders in 2016, fishers reported that they had not observed wolffish as bycatch in any fisheries near the MPA.

Additional Management Goals

The Eastport MPA management plan also aims to investigate possible economic benefits from the MPA as a result of resource conservation, research, and education initiatives. Two commercial species (Atlantic cod and snow crab) were found within the boundaries of the MPA, although not in high abundance. Mussels and scallops, which are harvested recreationally in Newman Sound, were also recorded within the MPA, indicating that the MPA protects at least a small portion of their habitat and may contribute to the sustainability of harvested populations outside the MPA.

Mapping of the Eastport MPA and Newman Sound indicates that all major substrate types are represented within the MPA boundaries. However, patch sizes are very small; NS1 and NS2, which correspond with sand and finer sediments, make up only 0.072 and 0.242 km^2 of the

MPA respectively. Further field surveys, including species abundance data, will be required to deliver a more complete estimate of habitat and biological community representation.

Previous habitat mapping efforts identified 10 distinct habitats throughout Newman Sound mainly based on depth and multibeam acoustic backscatter signature (Copeland, 2006):

- Bedrock with sponges with anemones and echinoderms;
- Laminaria covered seabed;
- Rhodolith beds;
- Boulder gravel with anemones and echinoderms;
- Pebble and cobble gravel with foraminifera, bryozoans, and grazing epifauna;
- Shallow sand with sand dollars and macroalgae;
- Deep sand;
- Gravelly sand with bivalves and echinoderms;
- Gravelly muddy sand with ophiuroids, infaunal bivalves, and polychaetes; and,
- Mud with polychaete worms and infaunal bivalves.

The shallow rocky habitat and bedrock features identified in the Eastport MPA are similar in substrate and species composition to Copeland's “Laminaria covered seabed,” “bedrock,” and “boulder gravel” habitats, including common species such as coralline algae, kelp, frilled anemone, and green urchin. However, several species of the bedrock and boulder habitats in Newman Sound were not observed within the Eastport MPA, including northern red anemone (*Telia felina),* purple sunstar (*S. endeca*), breadcrumb sponge (*Halichondria panacea*), sea peach (*Halocynthia pyriformis*), and hydroids (*Hydrozoan* sp.). It does not appear that sand or gravelly sand habitats identified by Copeland in Newman Sound support the same biotic communities as the sandy habitat protected by the Eastport MPA, despite similar substrate.

Species richness across all habitats surveyed by Copeland (2006) is much greater in Newman Sound (N = 96) than within the boundaries of the Eastport MPA (N = 34). Within the depth range represented by the Eastport MPA (<110 m), which was mapped and analyzed for this paper (28.73 km^2 total), the difference in species richness is less dramatic, however even when controlling for depth, fewer taxa were recorded within the MPA (N = 34) than outside (N = 44). Of the 58 taxa identified across the Eastport MPA and Newman Sound datasets, 22 were present in both the Eastport MPA and Newman Sound, 12 were only found within the MPA boundaries and 24 were only found outside of the MPA.

Anderson et al. (2002) produced single-beam acoustic seabed classifications within Bonavista Bay, roughly 100 km south of the Eastport MPA. They identified seven different acoustically distinct seabed types within the 24 km^2 study area: “high relief/cobble,” “sparse algae/cobble,” “true algae,” “rock,” “gravel,” “loose gravel,” and “mud.” Of these, the shallow “true algae,” “sparse algae/cobble,” and “high relief/cobble” appear to be represented within the Eastport MPA within the shallow rocky habitat, sand and cobble habitat, and the high profile rock features of S5. These are also the three habitat types that Anderson et al. suggest are important areas for Atlantic cod. In this survey, cod were only observed within the shallow rocky habitat, which, like Anderson's “true algae” habitat, is characterized by dense algal cover including kelp and Irish moss (*Chondrus crispus*) (Anderson, et al., 2002).

Of 13 coastal marine habitats identified by Hooper (1997) in Newfoundland waters, only a few appear to be represented within the Eastport MPA: “kelp beds,” “lobster grounds,” (shallow rocky habitat) and clam beds (sandy habitat). A Community-based Coastal Resource Inventory (CCRI) was commissioned to identify important species within the Eastport area (KEDC, 2001). Two of the three CCRI algae species are protected by the Eastport MPA:

Laminaria and Irish moss. Most invertebrates identified by the CCRI were observed within MPA boundaries; however, few of the fish species were recorded. Of 17 listed "key" fish species, only three were observed within the MPA: cod, flounder, and capelin. Several decades of study on eelgrass beds of Newman Sound have demonstrated that these habitats are both sensitive to human impact and ecologically important as fish nursery areas (Gorman, et al., 2009; Rao, et al., 2014). No eelgrass habitat is included within the boundaries of the Eastport MPA.

3.5.3 Conservation Contribution of the Eastport MPA

As a single-species management tool designed to support the American lobster fishery, the Eastport MPA closures are celebrated and respected by the local community. The most prevalent habitat of the MPA (shallow rocky) appears to be suitable for juvenile lobster settlement and survival. Monitoring of the Eastport MPA through mark recapture studies have demonstrated higher proportions of ovigerous females inside the MPA compared to the surrounding commercial area, indicating the MPA protects reproductively active adults (Janes, 2009). This contributes to the MPA's primary conservation goal: protecting the American lobster population and, by extension, the local fishery. Further study confirming larval dynamics, settlement and connectivity could help better define the effectiveness of this MPA for protection of lobster throughout life stages. However, our study suggests that this small MPA offers little additional benefit and plays a very limited role in protecting regional biodiversity. While the MPA appears to provide protection for species associated with shallow rocky habitats, it does not protect the deeper, fine sediment habitats as well. The small size of the closure also raises questions on the ability of the MPA to support healthy lobster populations in the region. Comparison to previous research in the Newman Sound area shows that species diversity and richness within the MPA is relatively low, as is the representation of most substrate types (1–5%

of mapped area; Table 3.3). Furthermore, this study focuses exclusively on representation of substrates and associated biodiversity within the 110 m depth range of the MPA boundaries. Deeper habitats and associated species receive no protection from the MPA.

The fishery enhancement goals of the Eastport MPA provide little “umbrella effect” for protecting representative benthic biodiversity, sensitive habitats, or species at risk. Eelgrass beds, demonstrated to be both sensitive to anthropogenic impacts and important habitat for juvenile fish in the Newman Sound/Eastport area, are not protected by the MPA despite their close proximity to the closures. No species at risk were recorded in the MPA, and the analysis of available habitat demonstrates that it is extremely unlikely that the area is used by the threatened species (northern or spotted wolffish) targeted by the Eastport MPA Management Plan. These findings are important as countries like Canada aim to meet the Aichi Biodiversity Target 11, which is explicit that protected areas included under the commitment should be ecologically representative (CBD, 2010). The Canadian Government intends to reach Target 11 through a combination of new protected areas and existing MPAs, National Marine Conservation Areas, National Wildlife Areas and “other effective area-based conservation measures,” including fisheries closures (DFO, 2016).

3.6 Conclusions

Assessing the effectiveness of spatial marine conservation efforts is an ongoing challenge in ocean and coastal management. The success of marine conservation efforts depends on careful consideration of the goals and design criteria early in the process, including spatial representation of target species' distribution (Klein, et al., 2015). The Eastport MPA was not designed to protect ecosystems representative of its region, species at risk, or habitats known to be unique and/or vulnerable to human impact. Instead, like many MPAs around the world, it resulted from the will of a community to sustain a local fishery. A clear limitation of the Eastport MPA is its size. While small MPAs can, in some contexts, provide conservation benefit (Moland, et al., 2013), the size of the MPA must be appropriate to its goals. Our study finds that the Eastport MPA, which has goals very similar to the ones of a fishery closure, has been expected to deliver conservation benefits (i.e., protection of threatened or endangered species) that do not match its size, boundaries, or other management efforts. Further research is ongoing to examine how the Eastport MPA could be redesigned to improve conservation of biodiversity and vulnerable habitats. Appropriate changes may include increased MPA size, change in MPA boundary to include more diverse habitat types, or an expanded network of additional small closures. A shift toward ecosystem-based management and the use of indicators such as species richness and distribution can aid in assessing the more general contribution of an MPA (Soykan & Lewison, 2015). The ability to revise MPA boundaries and regulations in light of their measured effectiveness (i.e., to conduct adaptive management) is a critical challenge for the next several decades. Habitat mapping provides the baseline knowledge important to the successful design and implementation of MPAs. If fisheries closures, or MPAs that share similar goals and design, are to be included within conservation commitments at any level (local, national, or international), it is crucial that managers proceed carefully and use the best available tools to establish that both existing and proposed protected areas have demonstrated the ability to meet management goals.

Chapter 4. Generating higher resolution regional seafloor maps from crowd-sourced bathymetry

4.1 Abstract

Seafloor mapping can offer important insights for marine management, spatial planning, and research in marine geology, ecology, and oceanography. Here, we present a method for generating regional bathymetry and geomorphometry maps from crowd-sourced depth soundings (Olex AS) for a small fraction of the cost of multibeam data collection over the same area. Empirical Bayesian Kriging was used to generate a continuous bathymetric surface from incomplete and, in some areas, sparse Olex coverage on the Newfoundland and Labrador shelves of eastern Canada. The result is a 75 m bathymetric grid that provides over 100x finer spatial resolution than previously available for the majority of the 672,900 km^2 study area. The interpolated bathymetry was tested for accuracy against independent depth data provided by DFO (Spearman correlation = 0.99, $p<0.001$). Quantitative terrain attributes were generated to better understand seascape characteristics at multiple spatial scales, including slope, rugosity, aspect, and bathymetric position index. Landform classification was carried out using the geomorphons algorithm and a novel method for the identification of previously unmapped tributary canyons at the continental shelf edge are also presented to illustrate some of many potential benefits of crowd-sourced regional seafloor mapping.

4.2 Introduction

Marie Tharp and Dr. Bruce Heezen used early single-beam echosounders to produce the first continuous, three dimensional visualization of the North Atlantic seafloor in 1957 (Makowski & Finkl, 2016). Twenty year later, their World Ocean Floor map provided compelling evidence for the then radical theory of continental drift and remains a landmark in the field, highlighting the important role of seafloor mapping in the study of natural processes (Heezen & Tharp, 1977; Barton, 2022). In the decades that followed, single-beam echo sounding and many other technologies, including side-scan sonar, multibeam echo-sounding, Light Detection and Ranging (LiDAR), and satellite imagery have expanded our capacity to study, map, and understand seafloor environments (Mayer, 2006). Simultaneously, increased human reliance on ocean resources and a growing commitment to ecosystem-based management have created a need for better seafloor maps, including the spatial distribution of marine substrates, geomorphic features, and benthic biodiversity (Cogan, et al., 2009). Study of the benthic environment often involves study of the patterns and processes that shape the seabed itself (i.e. geomorphology). The relationship between a species or a community and their environment is fundamental to the concept of habitat (Odum & Kroodsma, 1976). For many marine species, depth, substrate type, and seafloor shape are very important factors in that relationship (Harris & Baker, 2012). Seafloor mapping is also an important part of marine geo-hazard assessment (Hough, et al., 2011). Submarine landslides can trigger tsunamis and flood events, resulting in considerable infrastructure damage and loss of life (Liverman, et al., 2000). Digital terrain models (DTMs) are commonly used to identify geomorphic features through manual expert interpretation, or the application of automated or semi-automated classification tools. Geomorphometry, the quantitative study of terrain, can be separated into two classes: general and specific. General geomorphometry refers to continuous terrain attributes that can be calculated and queried to characterize an area (Lecours, et al., 2016). Specific geomorphometry refers to the study and classification of discrete landforms through analysis of topographic or bathymetric structure (Evans, et al., 2015). Analyses of seafloor geomorphology and geomorphometry have been used to identify tsunamigenic landslides (Casalbore, et al., 2011), to study mass transport complexes (Rovere, et al., 2014), and to identify the triggers and frequency of submarine slope failures (Deering, et al., 2018). As a result, bathymetric maps and their derivatives have become key sources of information used to inform various ocean management decisions.

The most widely used seafloor dataset is the General Bathymetric Chart of the Oceans (GEBCO, 2018). GEBCO bathymetry is an international compilation of satellite altimetry and, where available, single or multibeam echo sounding data (Weatherall, et al., 2015), made available for free as a 30-arc second world grid (approximately 925 m resolution at the equator). GEBCO provides an excellent resource for mapping large seafloor features (ex. continental shelves, large deep sea trenches, seamounts) and tectonic processes (ex. seafloor spreading zones). However, due to the relatively low spatial resolution associated with satellite altimetry (Mayer, et al., 2018), these data are too coarse to answer many research questions. For example, Ross et al. (2015) compared a 200 m bathymetric grid against GEBCO bathymetry for development of deep-sea habitat maps and found that the higher resolution models outperformed GEBCO-based models (Mayer, et al., 2018). Similarly, Rengstorf et al. (2012) tested species distribution models for the cold-water coral *Lophelia pertusa* using 50, 100, 250, 500, and 1000 m bathymetric grids and associated terrain attributes, and found that accurate predictions of this habitat type required bathymetric data finer than a 250 m grid. Development of 100 m grid regional bathymetry for the Terre Ade´lie and George V continental margin in Antarctica has also shown to greatly improve geomorphological interpretation over existing bathymetric datasets (GEBCO and ETOPO1), including new information on the extent and complexity of inner-shelf valleys (Beaman, et al., 2011). Many other research questions in resource management (Pickrill & Todd, 2003), oceanography (Stow, et al., 2009), geohazards (Chiocci, et al., 2011), and marine geomorphology and geology (Misiuk, et al., 2018) have been answered using higher resolution bathymetry than is available through satellite altimetry.

Multibeam echo-sounding tends to be the method of choice when collecting high resolution bathymetric data. Di Stefano and Mayer (2018) commented that multibeam has become “one of the most valuable tools to study seafloor habitat”. However, collection of multibeam data is expensive and time-consuming. While many countries are working to increase bathymetric surveys, as of 2018, continuous high-resolution multibeam coverage is currently only available for approximately 9% of the seafloor (Mayer, et al., 2018). It is estimated that, with current technology, it would take over 900 ship years to achieve full MBES coverage of the global oceans (Weatherall, et al., 2015). Alternative approaches to bathymetric data collection can help meet current information needs. Our study focuses on the potential benefits of crowd-sourced seafloor mapping, a relatively recent field of study with the capacity to provide large amounts of data at minimal cost (Montella, et al., 2017). The International Hydrographic Organization (IHO) has promoted crowd-sourced bathymetry projects as a low-cost approach to expand and improve current seafloor maps since 2014 (Rosenberg, et al., 2017), and interest in these platforms is growing (Sedaghat, et al., 2013). Globally, the IHO Data Centre for Digital Bathymetry is collecting crowd-sourced bathymetry and developing a system that will allow the public to upload and download depth data directly (Russel & Wright, 2017). These data, along with other forms of bathymetry, will also be used by Seabed 2030, an international collaboration that aims to increase resolution of seafloor maps over the next decade (Mayer, et al., 2018). With a sufficiently large participating community, crowd-sourcing is a very efficient way to collect large amounts of data (Raymond, 1999). Furthermore, repeated sampling by different actors helps reduce overall error rate and size (Heipke, 2010). At sea, large numbers of fishing vessels routinely collect depth soundings for navigation and selection of fishing grounds, providing an opportunity to crowd-source bathymetry in many regions (e.g. continental shelves where fishing activity is prevalent). Since 1997, Olex AS has commercialized a charting system that allows fishing vessels to record and share bathymetry with other participating vessels. In many areas, these shared soundings provide higher resolution bathymetry than existing navigational charts or regional datasets. Elvenes et al. (2013) demonstrated the utility of Olex bathymetry for sediment and biotope mapping through the extensive Norwegian MAREANO research program. In Newfoundland and Labrador, Canada, crowd-sourced bathymetric data have previously been applied to the study of glaciotectonism in the Notre Dame Trough (Shaw, et al., 2011). Through the work of many researchers, Olex data have helped to advance knowledge of seabed features, however these studies have generally relied on visual geomorphological interpretation of the Olex grid (Graham, et al., 2008; Spagnolo & Clark, 2009; Stewart, 2017), which limits the potential applications of the data. This paper reports on the first study that has, to our knowledge, accessed Olex point data and used them outside the proprietary system. Here, we leverage crowd-sourced depth soundings to map bathymetry and terrain attributes of the Newfoundland and Labrador shelves, Eastern Canada, with the goal of supporting future ecological research and marine spatial planning.

Our study area is part of a passive continental margin (Harris, et al., 2014) and is broadly characterized as a post-glacial landscape, subsequently reworked by wave action and iceberg scour (Shaw, et al., 2014). This area is divided into three sub-regions by Shaw et al. (2014): the Grand Banks of Newfoundland (made up of a series of banks separated by shelf crossing troughs), the Northeast Newfoundland Shelf (relatively deep banks and troughs characterized by coarse glaciogenic sediments), and the Labrador Shelf (made up of complex coastal fjords and, towards the shelf edge, shallow banks separated by deep saddles). Submarine canyons are common at the shelf edge throughout the region (Harris, et al., 2014), and these features are of particular interest to marine biologists and conservation planners (Fernandez-Acaya, et al., 2017). Research from around the world shows that canyons provide important habitat for many species, including feeding areas for cetaceans (Rennie, et al., 2009), nursery habitat for demersal fish (Fernandez-Arcaya, et al., 2013), and refugia for vulnerable cold-water corals (Davies, et al., 2014). ROV surveys conducted on three canyons at the Newfoundland shelf-edge recorded 28 cold-water corals, showing that these features provide habitat for most of the coral species that have been identified throughout all Newfoundland and Labrador waters (Baker, et al., 2012). We interpolated Olex data over an area of approximately 673,000 km^2 and tested the accuracy of the resulting bathymetry against independent depth collected in the annual DFO Science multi-species survey. The interpolated bathymetry we have produced is a 75 m grid; over 100 times finer than existing GEBCO data which is the best bathymetry for most of this region. In this paper, we describe the geostatistical methods used to generate continuous bathymetry. We also provide a few examples of how crowd-sourced bathymetry can contribute to an improved understanding of the region through the quantification of terrain attributes, classification of bedforms, and identification of previously unmapped tributary canyons. This work opens the door to various applications in marine ecology, conservation, resource management, marine geology, and oceanography.

4.3 Methods

4.3.1 Bathymetry

Olex AS provides a commercial charting system that allows fishing vessels to collect and share bathymetric data (OceanDTM, 2014). The equipment used by participating vessels ranges from survey-grade multibeam to single-beam fish-finders and all soundings are georeferenced by global positioning systems (GPS). Each vessel has the option of sharing their depth soundings with Olex AS, and in return they gain access to the rest of the crowd-sourced database. To date, Olex has compiled over 8.6 billion depth measurements from approximately 10 000 vessels globally, making it the largest existing crowd-sourcing initiative for bathymetric data.

Once collected and provided to Olex AS, bathymetric data are corrected based on predicted tides and local chart datum reference levels. Variables like sound velocity, echosounder installation depth, and vessel heave/pitch/roll are rarely associated with the provided depth soundings. Instead, transducer depth correction and a sound velocity coefficient are calculated based on comparison to the rest of the crowd-sourced dataset. If new data contributions provide soundings within a 5.6 m cell that is already populated, the shallowest depth value is retained.

A simple linear interpolation is also applied to the Olex data to produce the 45 m grid used in this study, however each cell contains at least one real sounding from the underlying 5.6m grid. Olex reports vertical accuracy of approximately 0.3 m, based on comparisons of their processed data to independent bathymetry. For this study, processed Olex bathymetry data for the Newfoundland and Labrador waters of Canada’s east coast were made available as XYZ points.

The study area, defined by the spatial coverage of the provided Olex data, includes the continental shelf and some shelf edge throughout North Atlantic Fisheries Organization (NAFO) Sub-divisions 0B, 2GHJ, 3KLMNOPs, and 4RS, including the Flemish Cap, and a portion of the Laurentian Channel (Figure 4.1). Olex data available for the Newfoundland and Labrador region extends from 60°Wto 43.36°W and from 42.73°N to 65°N. Olex sounding density is a function of the distribution of fishing vessels, and is extremely variable throughout the region.

Olex point density per 10 km^2 in the study area was calculated using the Point Density tool in ArcGIS Pro 2.0. Areas with fewer than 100 data points per 10 km^2 were excluded from further processing as this level of sampling was insufficient to inform the interpolation. This exclusion resulted in some gaps in the final bathymetric coverage.

Interpolation of the Olex data was carried out using Empirical Bayesian Kriging (EBK), a geostatistical interpolation technique that estimates the spatial relationship of the input data (defined by a semi-variogram) through many iterative models that are weighted and combined using Bayes Theorem (Krivorouchko, 2012). This method was tested using ArcGIS Pro 2.0 to produce a spatially continuous 75 m bathymetric grid. The grid resolution was selected based on multiple interpolation tests made in sample areas characterized by variable data density, using a range of spatial resolutions. A grid resolution of 75 m offered the best compromise between a high spatial resolution and a reduction of interpolation artefacts in areas of low data density. Because Olex data points were dense along fishing vessel trajectories but absent elsewhere, the interpolation method provided a robust method for filling most of the gaps that have not be sampled by vessels. Unlike many other interpolation algorithms, EBK can handle moderate non-stationarity in the data, and the use of iterative semi-variograms (100 per local model for this study) allows for more accurate estimation of standard error and produces high accuracy bathymetric interpolation (Danielson, et al., 2016). For stationary data, the mean and the semi-variogram are constant throughout the data extent, however the assumption of stationarity is rarely proven for real-world data (Danielson, et al., 2016).

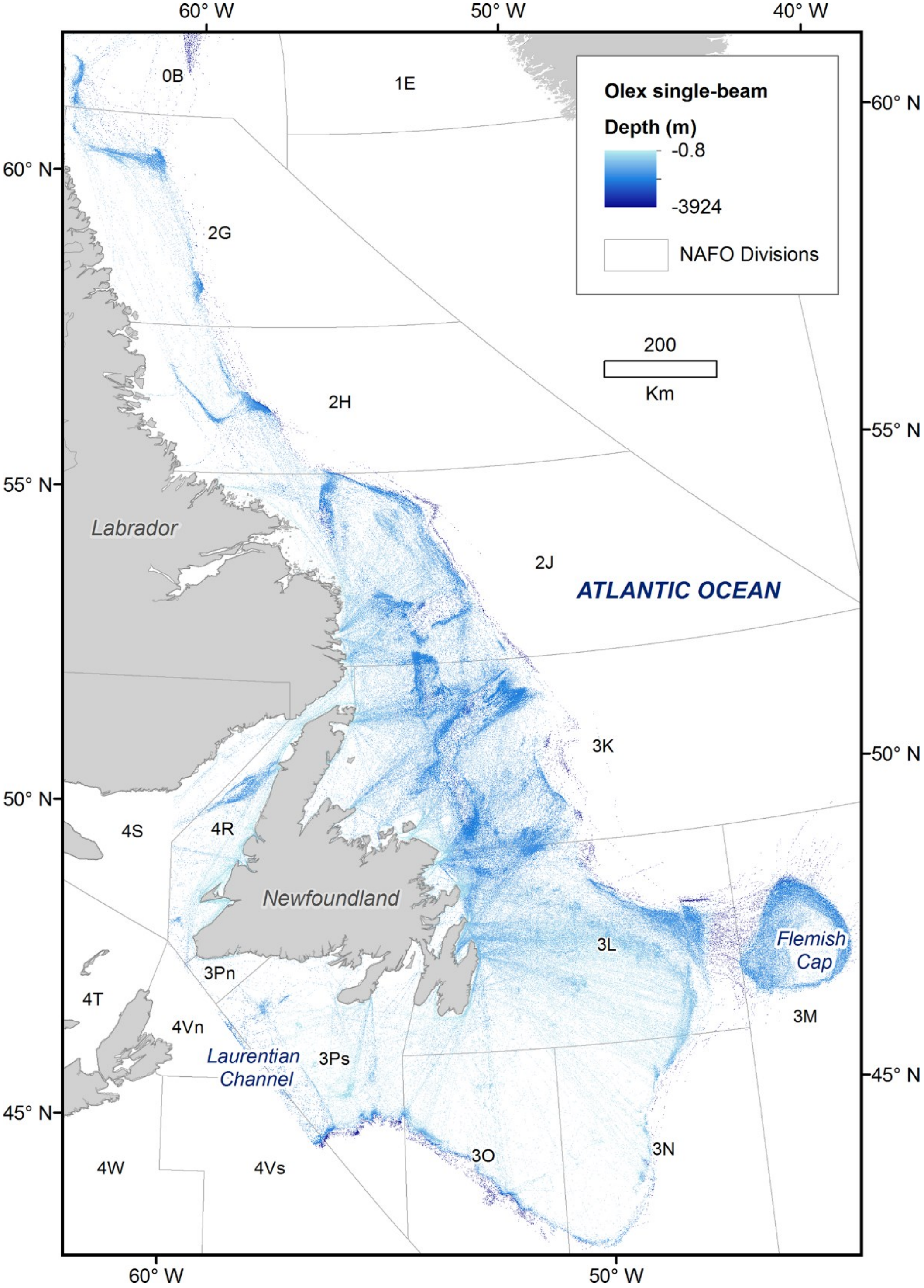


Figure 4.1 Olex data coverage for the Newfoundland and Labrador region.

The input Olex data were first divided into 129 spatial subsets of 100x100 km with 2.5%

overlap to reduce processing time and non-stationarity within each subset. Each 100x100 km subset was run through the EBK protocol independently (Figure 4.2). All input data were transformed (log-empirical) to prevent positive interpolated values (i.e. values above the water surface). The input data were divided into local model subsets of 500 data points and a semi-variogram was derived for each of them. A K-Bessel semi-variogram was selected based on best fit to the dataset calculated in the ArcGIS Pro 2.0 Geostatistical Wizard. Each derived semi-variogram model was used to simulate new data for each known depth value. This iterative semi-variogram simulation process was repeated 100 times for each local model and Bayes' rule was applied to assign a weight to each semi-variogram, based on how well the observed value was estimated from that semi-variogram. This protocol produced a weighted distribution of 100 semi-variograms which was used to interpolate unknown depth values within the neighbourhood of each local model (Krivorouchko, 2012). Neighbouring models were assigned high overlap (overlap factor = 5). A single data point may be included in several local models, and the overlap factor determines the degree of overlap between neighboring models. A higher overlap factor delivers a smoother output surface, but requires more processing time.

The output for each kriging window was cropped by 2.5% to remove depth estimates influenced by edge effect and to remove overlaps between analysis windows. Standard error of the interpolated values was also calculated, and all pixels with a standard error >10 m were excluded from further processing as a quality control measure. Cropped kriging windows were assembled in a mosaic with blended seam lines in ArcGIS Pro 2.0. Validation of the resulting bathymetric surface was achieved through a comparison of interpolated depth values to the GEBCO_2014 Grid, version 20150318 (OceanDTM, 2014) and analysis of correlation between the interpolated bathymetry and independent depth data. Single-beam depth soundings

(Schlaginweit, 1993) provided by DFO were used for this validation because they represent an independent source of bathymetry collected at a resolution comparable to Olex over a large portion of the study area but along different vessels trajectories (Fig 4.3).

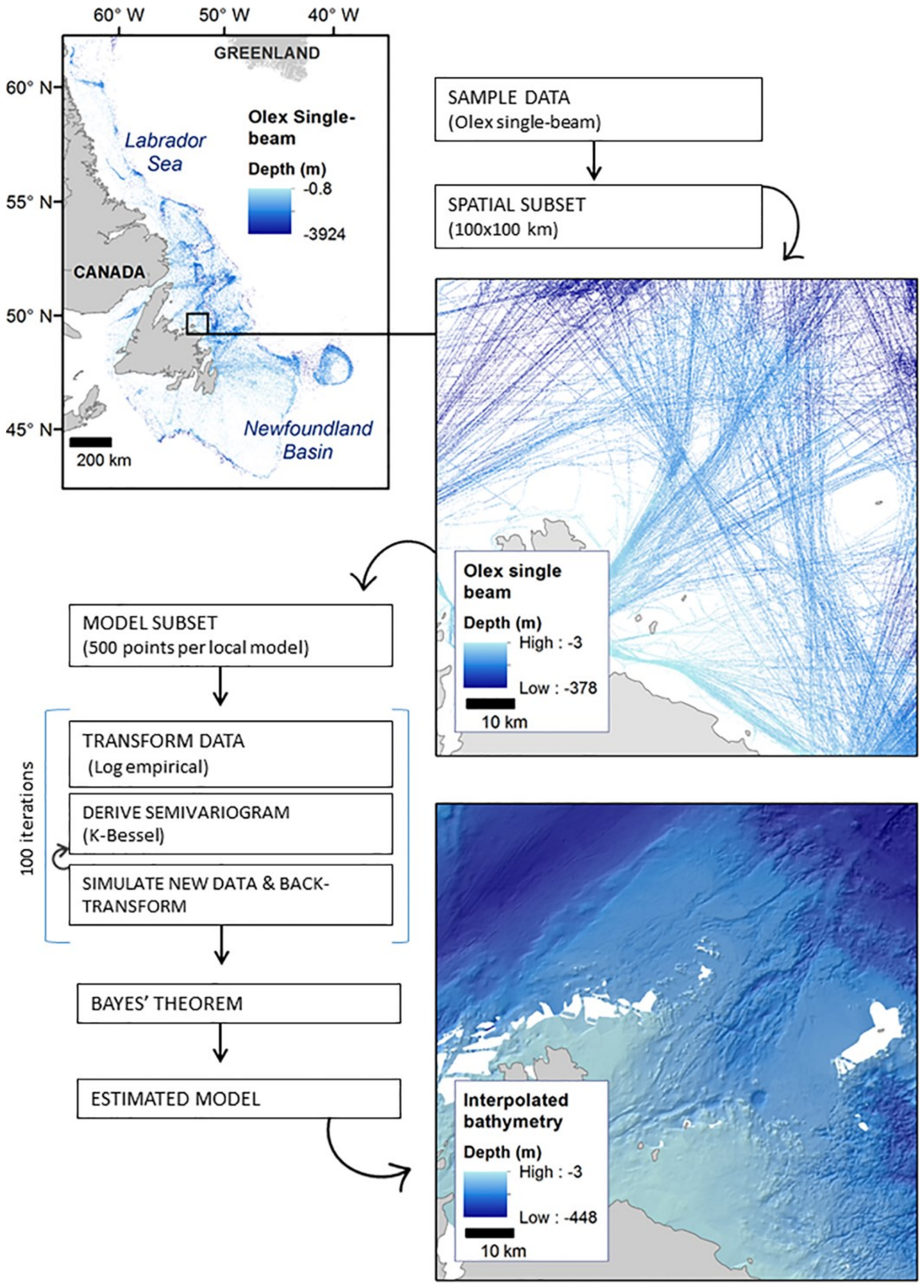


Figure 4.2 Conceptual diagram of the Empirical Bayesian Kriging process as employed in ArcGIS Pro 2.0.

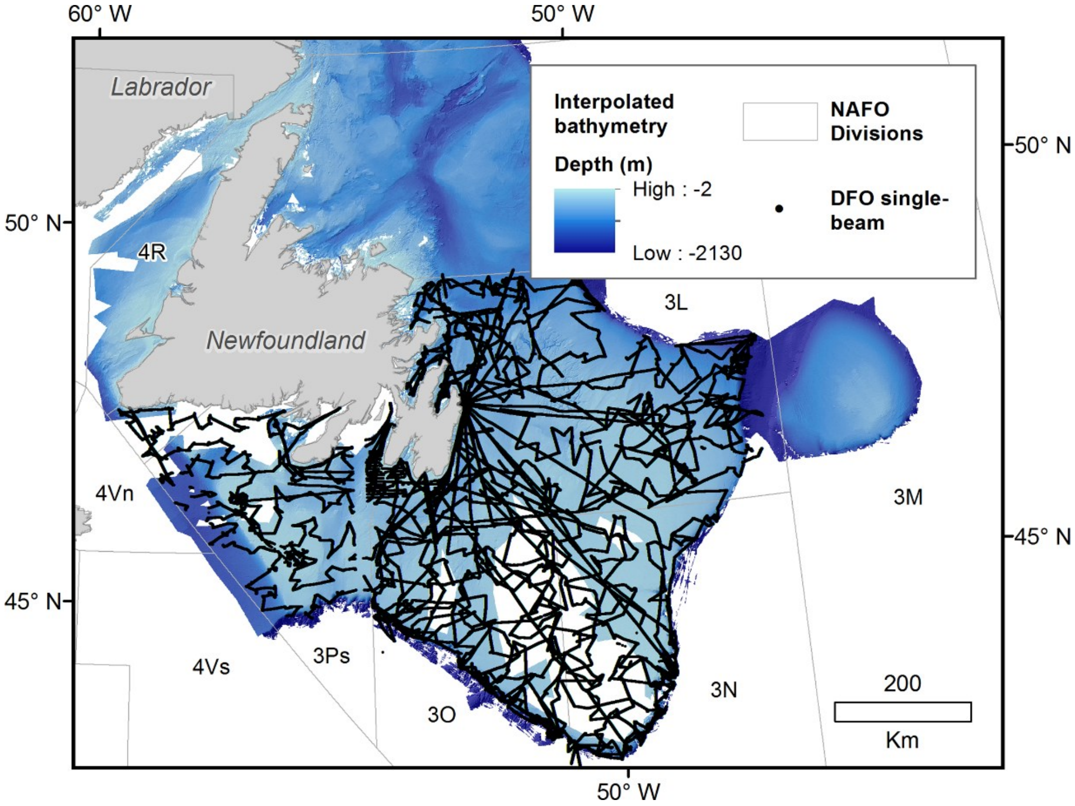


Figure 4.3 Distribution of single-beam depth soundings collected by Fisheries and Oceans Canada (NAFO Subdivision 3LNOPs) used to validate interpolated bathymetry.

4.3.2 Geomorphometry

Lecours et al. (2017) demonstrated that six terrain attributes capture the majority of seafloor topographic structure: relative position, local standard deviation (as a measure of rugosity), slope orientation (easterness and northerness), local bathymetric mean, and slope. This combination of terrain attributes outperforms alternative combinations when used as abiotic surrogates for predictive marine habitat mapping (Lecours, et al., 2017). Based on these recommendations, the following five terrain attributes were derived from interpolated bathymetry for our study area: bathymetric position index (a measure of relative position), two measures of rugosity (standard deviation and vector ruggedness measure), slope orientation (easterness and northerness), local mean, and slope (Table 4.1). All bathymetric derivatives were calculated using ArcGIS Benthic Terrain Modeler toolbox (Walbridge, et al., 2018), executed in ArcGIS 10.5, with the exception of local bathymetric mean, which was calculated using the focal statistics tool in ArcGIS Pro 2.0. Areas of low, moderate, and high seafloor relief were mapped by classifying the multiscale bathymetric standard deviation layer based on Jenks Natural Breaks, an approach that was adapted from Harris et al. (2014). The r.geomorphons tool (Jasiewicz & Stepinski, 2013) was used in GRASS GIS 7.4 to classify specific geomophometry based on ten of the most frequent landforms (i.e., flats, slopes, shoulders, foot slopes, spurs, valleys, hollows, ridges, peaks and pits). This tool identifies landforms based on elevation differences between the central pixel of an analysis window and its surrounding pixels. In a recent comparison of automated seafloor classification methods, r.geomorphons was identified as a scale-flexible and robust method that is appropriate for identification of marine bedforms (Di Stefano & Mayer, 2018).

Table 4.1 Terrain attributes generated for this study based on recommendations made by Lecours et al. (2017), including tools and parameters.

Lecours et al. (2017)	**Generated for this study**	**Tool and parameters**
Relative position	Bathymetric Position Index (BPI) • Fine • Moderate • Broad	Benthic Terrain Modeler 3.0 • 8 cell inner/16 cell outer radius • 25 cell inner/50 cell outer radius • 100 cell inner/500 cell outer radius
Local standard deviation	Rugosity measures • Standard deviation • Vector ruggedness measure	Benthic Terrain Modeler 3.0 • 9 cell neighbourhood • 21 cell neighbourhood
Slope orientation	Statistical aspect • Easterness • Northerness	Benthic Terrain Modeler 3.0, 3x3 cell analysis window

Local mean	Bathymetric mean	ArcGIS Pro focal statistics tool; mean depth calculated over n^2 cells, where n=2, 4, 8, 16
Slope	Slope	Benthic Terrain Modeler, 3x3 cell analysis window

Scale dependence is a fundamental problem in spatial analysis (Lecours, et al., 2015). Substrate distribution modeling based on bathymetry and terrain attributes generated at multiple scales by Misiuk et al. (2018) has shown that the same variable calculated at different spatial scales can produce very different substrate response curves, highlighting the importance of multi-scale analysis in marine geomorphometry and seafloor mapping. In addition to the original interpolated resolution (75 m grid), the ArcGIS Pro 2.0 focal statistics tool was used to calculate mean depth over n^2 cells, where $n = 2, 4, 8$, and 16, producing bathymetric surfaces at lower spatial resolutions. All terrain attributes were calculated for the five bathymetric surfaces to capture topographic structure of the seafloor across multiple scales. Finally, the mean value was calculated across all scales of each terrain attribute to generate a single data layer representing multiscale geomorphic structure. This method for multi-scale analysis was previously described by Dolan (2012) and was chosen in this study to minimize bathymetric artefacts created by the original data and the interpolation method.

The r.geomorphons model was also applied at multiple scales through application of a variable analysis window (Table 4.2). The flatness distance parameter corresponds to the scale of features identified by the algorithm. This number must fall between the assigned inner and outer search radii and was set as double the inner search radius for the models presented here. The flatness threshold refers to the difference between the zenith and nadir line-of-sight. A higher flatness threshold will yield a map with more “flat” areas. As the scale of the input DTM increases, the flatness threshold should decrease. For example, a flatness threshold of 1 degree when applied to a 1 x 1 km DTM will correspond to several meters of vertical distance (Jasiewicz & Stepinski, 2016).

Table 4.2 Parameters used to generate r.geomorphons classifications at multiple spatial scales.

Layer name	Inner search radius (m)	Outer search radius (m)	Flatness threshold (˚)	Flatness distance (m)
Geomorphon_fine	0	225	1	0
Geomorphon_med	300	1200	0.5	600
Geomorphon_broad	900	3300	0.5	1800
Geomorphon_broad2	1875	7500	0.25	3750

4.3.3 Shelf-edge canyons

In addition to the terrain forms classified by r.geomorphons, a semi-automated approach was developed to identify shelf incising canyons in order to illustrate how the higher resolution bathymetry can be used to generate new information in the study region. This novel approach involves a two-step hierarchical bathymetric position index (BPI) classification. Areas identified as terrain lows through Broad scale BPI (Table 4.1) were manually filtered to isolate the shelf edge. This layer was used to spatially constrain a second, finer scale BPI classification with an inner search radius of 5 cells (375 m) and an outer search radius of analysis of 15 cells (1125 m). These parameters were informed by the measurement of 10 manually identified submarine canyons (see supplementary materials; Figure S4.7 and Table S4.1). Further filtering was required to exclude non-elongated features (i.e. non-linear and non-dendritic) and elongated features oriented parallel to the shelf edge.

4.4 Results

4.4.1 Bathymetry

A continuous bathymetric grid was generated for a total area of 672,900 km^2 (an increase of 532,563 km^2 over the original Olex coverage for the study area). The interpolated bathymetry reaches up to 64 km offshore, ranges from 1 to 2133 m depth and extends from 60.06˚W to 43.72˚W and from 42.74˚N to 61.95˚N (Figure 4.4). This area represents 56% of the total Atlantic Canadian continental shelf (GAC, 2013) and covers approximately 70% of the Newfoundland and Labrador Shelf Large Marine Ecosystem (Sherman & Hempel, 2008).

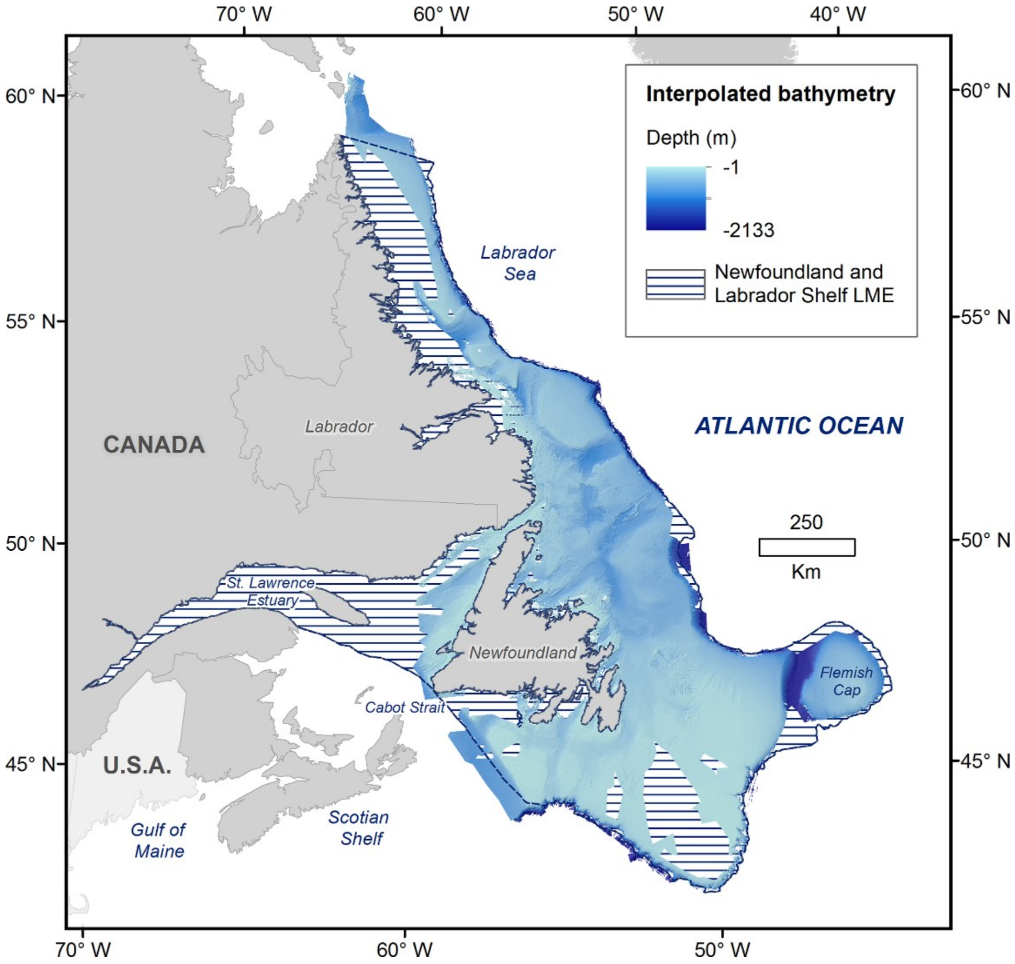


Figure 4.4 Interpolated bathymetry coverage of the Newfoundland and Labrador Large Marine Ecosystem (LME).

Spearman's correlation between the interpolated bathymetry and independent depth data (n = 1,796,313 test points) was both very high (0.99) and significant ($p<0.001$). This calculation was repeated specifically for areas where interpolated bathymetry was informed by low sounding density, because this is where bathymetric artefacts are expected to be most prevalent. Correlation was similarly high (0.95) and significant ($p<0.001$) when only validation data points over areas of low Olex sounding density were tested (n = 427,633 test points). Low sounding density is defined here by the lowest quartile (<22 soundings/ km^2). Bathymetric profiles of tunnel valleys on the Grand Bank were also used to compare the interpolated bathymetry to the previously available GEBCO grid (Figure 4.5). The two independent datasets show close agreement on the larger features, despite the difference in collection method and resolution (Figure 4.5, Profile 1). However, the interpolated bathymetry is able to capture the much finer seafloor features that are not visible in the GEBCO grid (Figure 4.5, Profile 2).

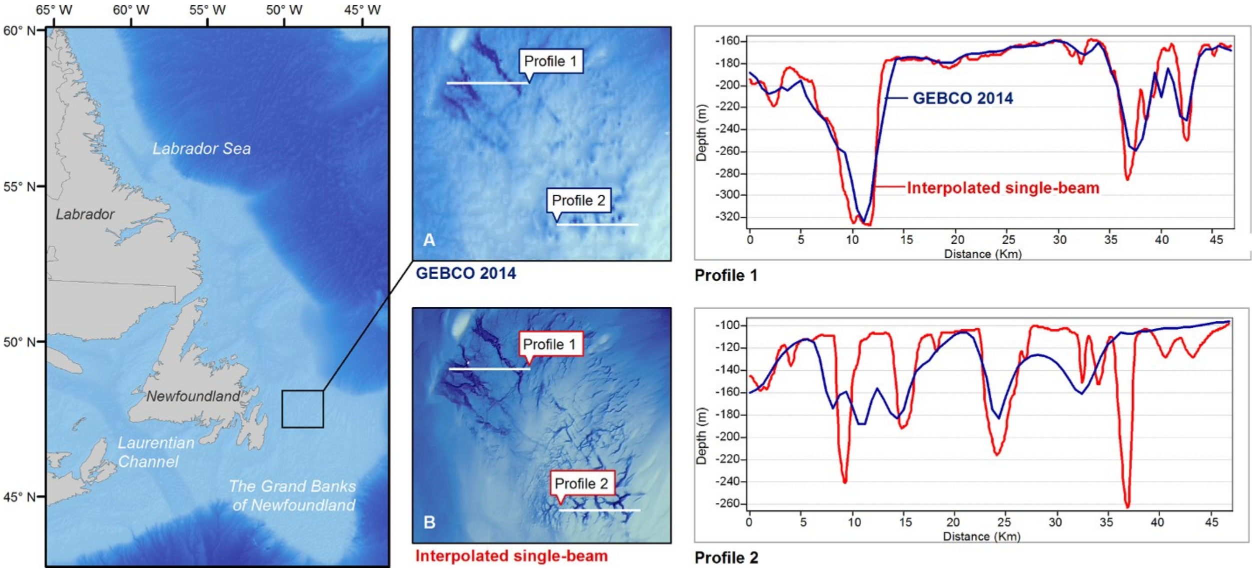


Figure 4.5 Bathymetric surfaces and horizontal depth profiles of tunnel valley systems on the Grand Banks of Newfoundland. (A) General Bathymetric Chart of the Oceans (approx. 930 x 630 m grid at this latitude) and (B) the interpolated bathymetry (75 x 75 m grid).

4.4.2 Geomorphometry

Terrain attributes—slope, BPI, standard deviation, rugosity, and aspect (i.e. easterness and northerness)—were generated at multiple spatial scales (examples shown in Figure 4.6; additional surfaces are included in supplementary materials Figures S4.1-4.6). The highest slopes and greatest terrain variation (bathymetric position index, bathymetric standard deviation and VRM) occur near the coast, on the shelf edge, and in on-shelf tunnel valleys. The majority of the Newfoundland shelf (84.5%) was classified as flat or low relief based on bathymetric standard deviation values of <3.7 m (Figure 4.7a). Areas of moderate (3.7–14.9 m) and high relief (>14.9 m) are relatively rare (11.7% and 2.0% of the study area respectively), and are concentrated near the coast, on the shelf edge, and around discrete on-shelf features, such as banks and glacial troughs.

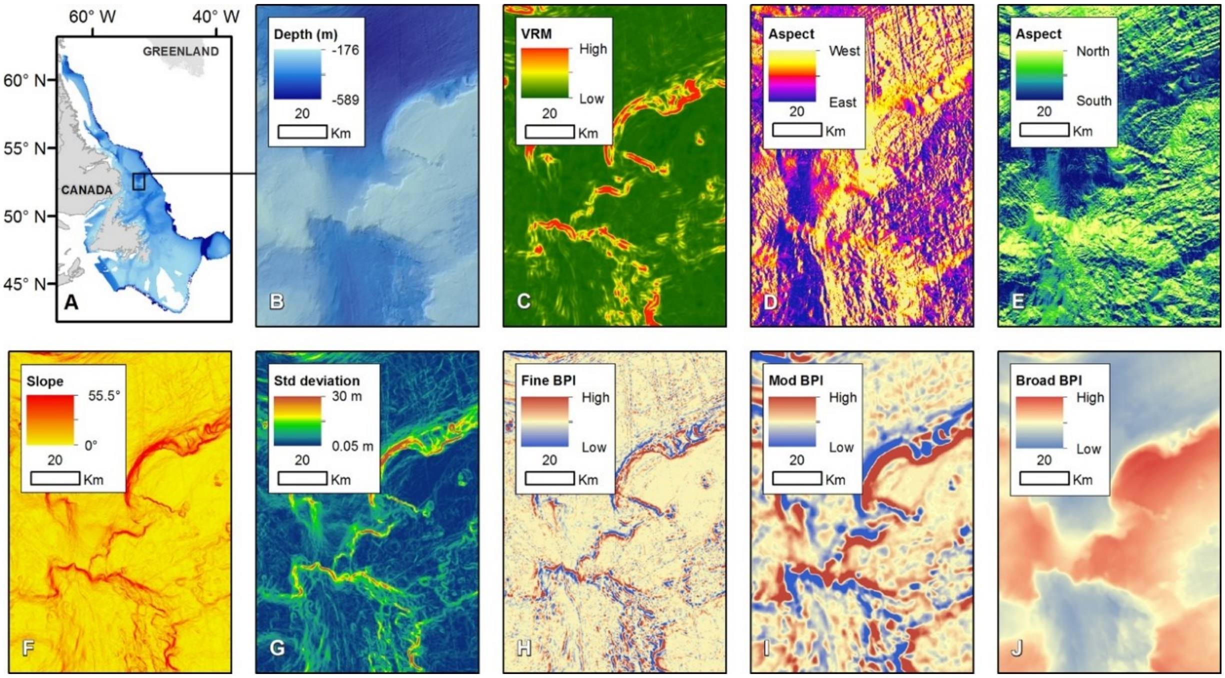


Figure 4.6 Study area and terrain attributes calculated with Benthic Terrain Modeler 3.0.(A) footprint of interpolated bathymetry, (B) interpolated bathymetry (75 m), C) Vector Ruggedness Measure (multiscale), D) Aspect quantified as easterness (multiscale), E) Aspect quantified as northerness (multiscale), F) Slope (multiscale), G) Rugosity, quantified as standard bathymetric deviation (multiscale), H) Fine BPI (75 m), I) Moderate BPI (multiscale), and J) Broad BPI (1200 m).

The r.geomorphons terrain classifications were generated at multiple spatial scales; the broadest scale (Table 4.2) is discussed here (Figure 4.7c), however all outputs are included as supplementary materials (Figure S4.8a-d). As indicated by the classification of seafloor relief, flat areas are the most prevalent geomorphologic phenotype, accounting for 43.5% of the study area (292,898 km^2). Slopes are the second most prevalent features, making up 24.3% of the study area (164,159 km^2), followed by shoulders (9.2%, 62,017 km^2), and foot slopes (6.9%, 6277 km^2). Spurs, valleys, hollows, and ridges are roughly equally prevalent in coverage (3.6-4.0%, 24,268–27,243 km^2). Peaks and pits are the rarest terrain types, covering 0.3% (2098 km^2) and 0.4% (3115 km^2) of the study area respectively.

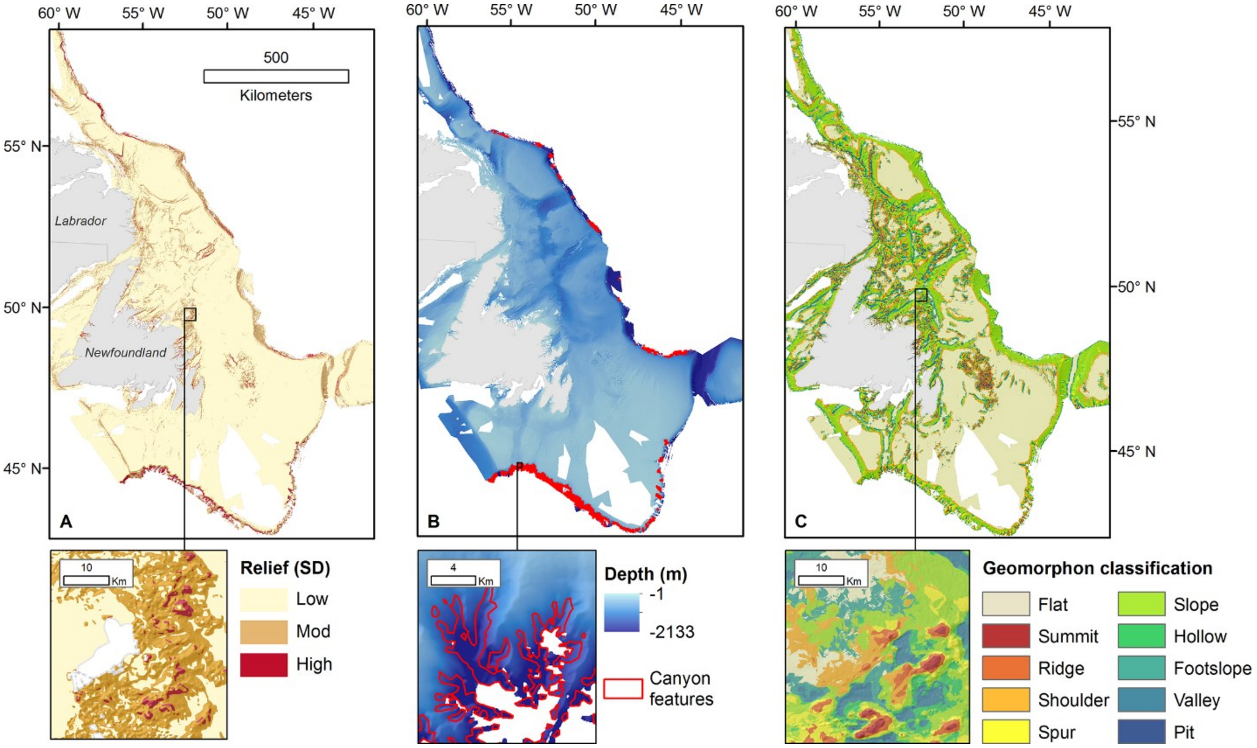


Figure 4.7 Geomorphometric classification of interpolated bathymetry for the Newfoundland and Labrador shelves: (A) Seafloor relief based on multiscale bathymetric standard deviation, (B) submarine canyons, and (C) geomorphologic phenotype.

4.4.3 Shelf-edge canyons

Submarine canyons are steep-sided, V-shaped valleys that cross the continental slope, with heads at or near the shelf edge (Amblas, et al., 2008). We identified canyons through a novel semi-automated, hierarchical classification of BPI that extracted narrow valleys perpendicular to the edge of the Newfoundland and Labrador shelves. Canyon features were mapped over 1852 km^2 of the study area, concentrated on the southern shelf break (Figure 4.7b). The features we identified are highly dendritic and several polygons may form tributaries that join and connect to a single, larger canyon. The mean water depth within mapped canyon features is 973m, and the deepest point of each feature ranges from 270 m to 1960 m. Canyon depth from flank to thalweg ranges from 5-1265 m; the mean canyon depth is 128m. Although slope was not explicitly included in our classification, the use of BPI to extract valleys implicitly requires relatively high slope around each feature. Average slope within the mapped canyon features (14˚) is much higher than mean slope for the rest of the study area (0.74˚) and canyon walls reach slopes of 50–65˚. Most of these canyon features are too small to be identified by GEBCO bathymetry (Figure 4.8) and many appear to be tributary canyons (Amblas, et al., 2008) which may alter the interpretation of features previously mapped at a coarser scale. (Figure 4.9).

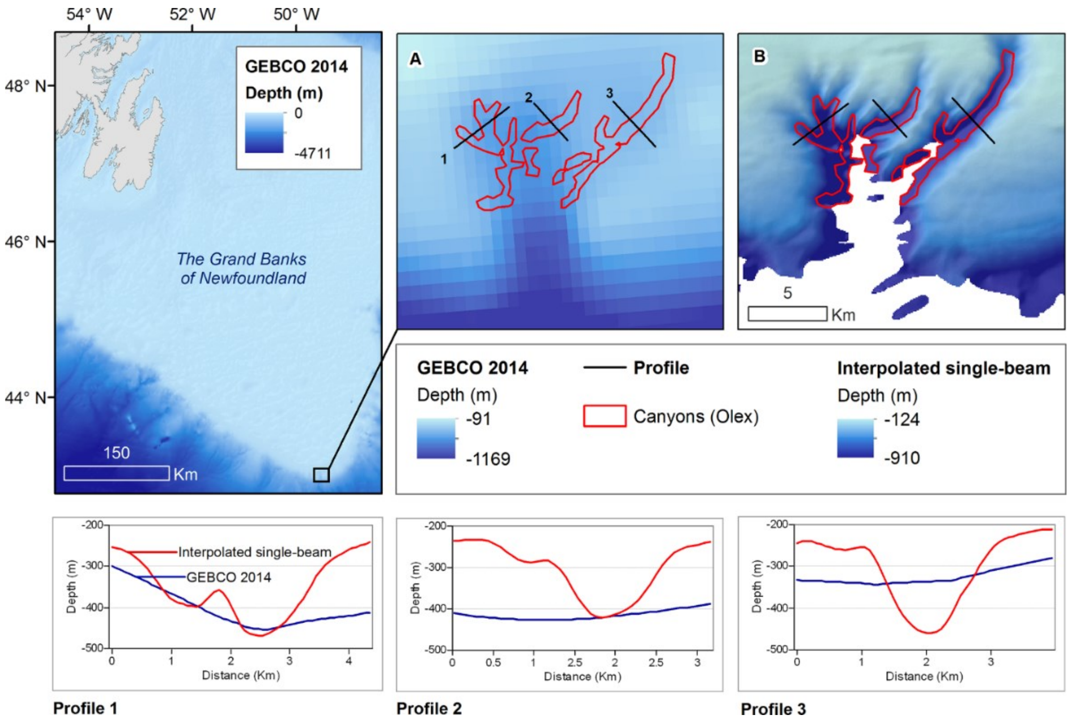


Figure 4.8 Features identified by hierarchical BPI classification of submarine canyons.

Comparison of the features mapped using interpolated bathymetry to canyons mapped by Harris et al. (2014) reveal that these features are much more complex than previously known even for well-studied canyons like the Halibut Channel (Fig 4.9a). This additional detail also suggests that some canyons that appeared to be blind based on GEBCO bathymetry, may in fact be shelf-incising canyons (Figure 4.9b). The potential to combine crowd-sourced detailed bathymetry of the upper reaches of these canyons with satellite derived bathymetry and, where available, MBES collected below the shelf break can expand our understanding of the morphological development of submarine canyons in this area.

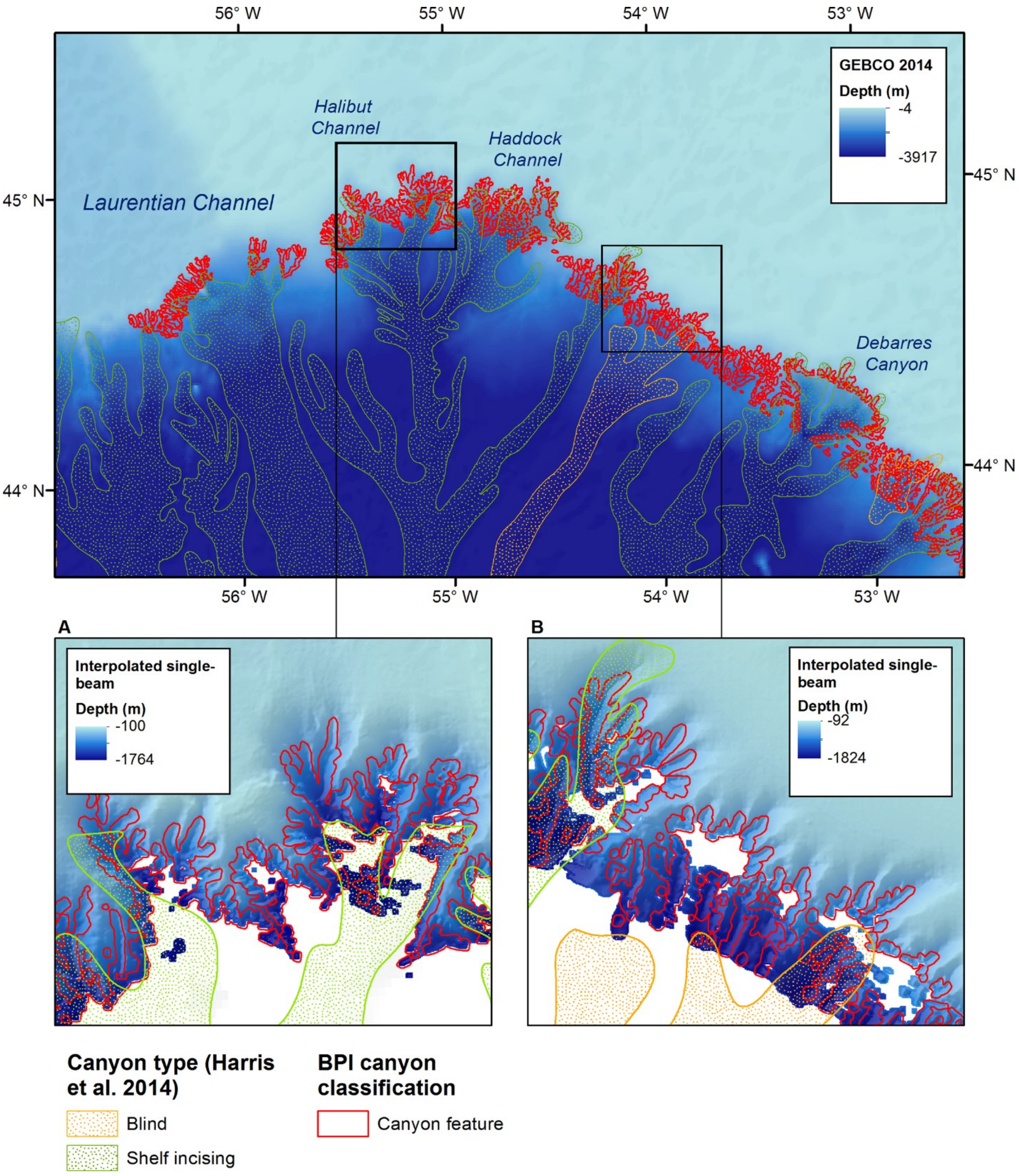


Figure 4.9 Comparison of newly mapped canyon features to canyons mapped and classified by Harris et al. (2014), including (A) Halibut Channel and (B) apparently blind canyon features West of Halibut Channel.

4.5 Discussion

4.5.1 Bathymetry

While the crowd-sourced bathymetry presented here cannot match high-resolution of hydrographic multibeam surveys, we have been able to generate a bathymetric grid with a hundred times finer resolution than GEBCO data for a fraction of the cost of a multibeam survey. Such data can be instrumental in supporting studies in oceanography (Stow, et al., 2009), marine geology (Misiuk, et al., 2018), geohazard assessment (Chiocci, et al., 2011), ecological research (Rengstorf, et al., 2012), marine conservation (Buhl-Mortensen, et al., 2015), and fisheries management (Marshak & Brown, 2017). Elvenes et al. (2013) report that although the high-resolution bathymetry and backscatter (a measure of seabed hardness and roughness) from MBES systems provide more complete information on seabed features, Olex data can provide sufficient information for sediment and biotope mapping at a regional scale. They concluded that the results of biotope mapping with MBES and interpolated Olex data were comparable for the purposes of regional management (Elveness, et al., 2013). Crowd-sourced bathymetry has been used previously to study seafloor features, most frequently through visual interpretation of bathymetry layers that have been prepared by Olex, without clearly described interpolation methods (Graham, et al., 2008; Spagnolo & Clark, 2009; Stewart, 2017). The work presented here represents an expansion in scope, to include specific and general geomorphometry, increased spatial coverage, and a significant increase in transparency of the applied interpolation method.

Regional biodiversity assessments and marine habitat mapping are fundamental to marine spatial planning (Foley, et al., 2010) and ecosystem-based management (Baker & Harris, 2020). In Canada, for example, a recent summary of opportunities and challenges in ecosystem-based management lists the identification of marine habitats of special importance and sensitivity as one of eight high priority research areas (DFO, 2007). The resolution of the bathymetric and geomorphometric data presented here fall well within the thresholds of ecological relevance identified by previous studies (Rengstorf, et al., 2012; Ross, et al., 2015). These data can help generate habitat maps to support management of Marine Protected Areas, parks, or reserves (Malcolm, et al., 2016), contribute to fisheries management (Marshak & Brown, 2017), and inform marine spatial planning across sectors including offshore energy, and seabed mining (DFO, 2007).

Although this study represents a >100-fold increase in bathymetric resolution for most of the study area and provides regional maps suitable for marine spatial management efforts, we do not consider seafloor mapping within this study area to be complete. Research on the impact of digital bathymetric model resolution on the prediction of marine substrates (Erikstad, et al., 2013) and the identification of biodiversity hotspots within submarine canyons (Robert, et al., 2014) indicate that continued development of finer bathymetric maps is still required to fully understand benthic ecosystems in the region. Coverage of the study region is also not complete; due to the irregular nature of fishing vessel trajectories, there are large gaps in our interpolated bathymetry on the Grand Banks of Newfoundland and coastal Labrador. These data gaps could be filled with bathymetry from surveys by the Canadian Hydrographic Service or DFO Canada.

For this study, only data for the Newfoundland and Labrador region were requested from Olex AS, however additional Olex data could be procured to extend this map across the Cabot Strait, into the St. Lawrence Estuary and southward onto the Scotian Shelf, providing a continuous seafloor map of the Canadian east coast. Crowd-sourced mapping efforts such as Olex represent an immense amount of seafloor data worldwide and the methods presented here could contribute to improved seabed maps for many continental shelf and upper continental slope regions throughout the world.

4.5.2 Geomorphology

Prevalent landforms and the processes that shape local geomorphology have been previously described for this region based on seabed imagery, sediment samples, and interpretation of side-scan sonar data (Amos & King, 1984). Greater extent and higher resolution bathymetry support further qualitative and quantitative interpretation of Newfoundland and Labrador marine geomorphology. For example, this work reveals on-shelf tunnel valleys with nearly orthogonal orientations at all scales that were not visible in the GEBCO data. Knowledge of the shape and structure of these features supports interpretation of their origins, which in this case could be related to preexisting faults (Sanderson & Jorgensen, 2017). Tunnel valleys may host distinct biological assemblages (Pearce, et al., 2012); distributional data could inform the planning of future surveys or contribute to on-going conservation efforts.

The terrain attributes presented here provide quantified characterization of many forms of general geomorphometry which are powerful surrogates for the distribution of substrate type, benthic biodiversity (Novaczek, et al., 2017) and identification of marine geohazards (Hough, et al., 2011). Classification of specific geomorphometry provides further information on the shape and structure of the seafloor through an automated process that is systematic, intuitive, and reproducible at multiple scales. These classified data layers provide valuable insight for the mapping and characterization of marine habitats (Althaus, et al., 2012).

4.5.3. Shelf-edge canyons

The method presented here for identification of submarine canyons is a very simple approach which classifies elongated features of low bathymetric position index that are roughly perpendicular to the shelf edge. This approach has several limitations; it relies on the quality of the training dataset, it is not fully automated, and it does not explicitly incorporate all characteristics of shelf-incising canyons, like steep walls or branching order (Amblas, et al., 2008). This classification may also be compromised by bathymetric artefacts, which are more prevalent at the edge of the dataset where fishing activities are less frequent, and therefore provide less input data for interpolation. Nonetheless, the ability to map the upper limits of submarine canyon features may greatly aid in understanding the morphology and evolution of submarine canyons, especially if combined with multibeam sonar or other high-resolution bathymetry in the deeper portions of canyons. High-resolution geomorphometry of the upper reaches of submarine canyons is particularly valuable in regions like Newfoundland and Labrador with a complex history of glacial and deglacial conditions, and sea level variation (Piper, et al., 2012)

4.6 Conclusions

In this paper we have described a novel method for generating continuous bathymetry from a large crowd-sourced echosounder data at a much higher spatial resolution than previously available via satellite altimetry and much larger spatial extent than available from existing MBES surveys. With very minimal thresholds applied for quality control, even areas of sparse coverage were successfully interpolated with high accuracy when tested against independent bathymetric data. The resulting interpolated bathymetry, which covers an area greater than half of the entire Atlantic Canadian shelf and provided a 480% increase in coverage when compared to the input sounding coverage for the study area, can help answer a number of scientific questions that were not possible using previously existing regional bathymetry datasets, despite the long history of bathymetric surveys in Canadian waters (Pickrill & Kostylev, 2007). The approach presented can be easily reproduced for other regions of the world where similar crowd-sourced data are available. Olex data, which is only one of several potential sources of crowd-sourced bathymetry, is collected globally, including European waters, along the US East Coast, and in the waters of Western Africa. In this paper we also provided some examples of novel information we can obtain from such data, including both general and specific geomorphometric properties of the seascape.

Particular attention was given in this paper to the mapping of submarine canyons. These features are complex systems associated with high rates of ocean mixing (Carter & Gregg, 2002), biological productivity (De Leo, et al., 2010), and carbon storage (Masson, et al., 2010). The BPI-based classification of canyon features presented here is limited by data availability at the shelf edge and is dependent on the scale of analysis. However, due to the ecological and geological significance of submarine canyons, this simple approach provides useful information to guide further surveys, to assess representation of canyons in conservation planning, and to characterize marine habitats at little cost and minimal processing effort. It is important to note that many of the submarine canyons identified by our methods are not resolved by GEBCO bathymetry. The presence of previously unmapped tributary canyons demonstrates that the shelf edge in this region is more complex than previously thought, and this information may contribute to a better understanding of canyon formation and maturity on the Newfoundland and Labrador shelves (Amblas, et al., 2008).

The crowd-sourced bathymetric data used in this paper are collected and compiled internationally wherever participating commercial vessels are active, however these data remain largely unused for the quantitative and systematic study of seafloor geomorphometry and benthic habitats. Our method offers a robust and reproducible method to make use of crowdsourced data for applications including, but not limited to, marine conservation, resource management, and marine geology. In much of the study area, this work represents the finest resolution bathymetry data currently available, and was produced at a fraction of the cost of conventional surveys.

Chapter 5. Synthesis and future directions

The importance of habitat is enshrined in the legislation that governs marine conservation and management of marine resources, including but not limited to the Fisheries Act (1985), the Oceans Act (1996), and the Species at Risk Act (2002). In order for these legal provisions to be effective, we need robust research on the biological components that define marine habitat, their spatial distribution, and potential threats. This need poses a significant challenge to both marine managers and scientists. When mapping terrestrial, ice, and even shallow water habitats, there are technological solutions for collection of precise spatial data for remote or challenging areas: for example, satellite imagery used to map seal and penguin habitats in the Antarctic (Larue, et al. 2022) or LiDAR used to map bat habitat in dense canopy forest (Rauchenstein, et al., 2022). The vast majority of the seafloor, however, remains inaccessible to conventional survey methods due to the combination of pressure, darkness, and physical limitations (Mayer, et al., 2018). The most complete ocean mapping includes depth measurements for an estimated 20.6% of the global seafloor and relies heavily on interpolation of sparse data (GEBCO, 2021). Furthermore, the resolution of these data (15 arc-second grid) are insufficient to capture many of the ecological relationships that define habitat (Rengstorf, et al., 2012). National and global programs have increased coverage of high resolution seafloor mapping over the past decade (e.g. Seabed 2030) but significant data gaps remain (Mayer, et al., 2018).

Currently, technical and financial constraints mean that high resolution seafloor mapping is limited to small, disconnected study areas on the NL Shelves. While these studies provide value through localized research on characterization of habitat and potential threats to Species at Risk (Chapter 2), or Marine Protected Area (MPA) effectiveness (Chapter 3), managers are still lacking seafloor habitat data at both the high resolution required to capture ecological processes and the broad extent required to inform regional decision making. The aim of Chapter 4 was to address this gap for Newfoundland and Labrador through the use of crowd-sourced depth sounding to generate high resolution maps of bathymetry, seafloor geomorphometry, and distribution of important features like submarine canyons.

5.1 Findings and contributions

5.1.1 Habitat mapping for Marine species at risk

Marine species are underrepresented by Canada's Species at Risk Act (SARA) due to both political and scientific challenges (McDevitt-Irwin, et al., 2015). When SARA came into force, Atlantic, Spotted and Northern Wolffish were listed through the adoption of COSEWIC recommendations. Between 2002 and 2016, COSEWIC recommended listing 25 other marine fish species as endangered or threatened; only two were accepted and listed under SARA. In contrast, COSEWIC listing advice over the same period was accepted for birds, reptiles, amphibians (Hutchings, et al., 2016). Analysis by Schultz et al. (2013) on the economic value of endangered species showed that even small anticipated costs to commercial fisheries resulted in denial of listing recommendations for marine fish. If these political barriers are overcome and the recommendation to list under SARA is accepted, the work to develop recovery strategies and actions plans begins. Habitat protection is an essential part of conservation planning for species at risk (Bird & Hodges, 2017), and that protection hinges on the classification and mapping of habitats. However, our understanding of marine habitats is limited by a fundamental barrier: the vast majority of the ocean remains unmapped (Mayer, et al., 2018).

In Chapter 2 (Novaczek, et al., 2017), the coastal habitats of Northeast Conception Bay, NL were characterized and mapped with a focus on the denning habitat of Atlantic wolffish, a species of Special Concern protected by Canada's Species at Risk Act. Timing of wolffish presence at (and movement away from) the denning sites were compared to water temperature, indicating that these shallow dens are vulnerable to rising ocean temperatures that make them inaccessible or unsuitable for wolffish denning and spawning. This paper was completed in collaboration with DFO-NL to support conservation planning for Atlantic wolffish. My work demonstrated the role of habitat mapping to better understand emerging threats for species at risk. Since publication, this study has been cited in subsequent literature on the methods and applications of high-resolution marine habitat mapping (Lee, et al., 2017; Kokinou, 2021; Nemani, et al., 2022; Proudfoot, et al., 2020), on the characterization of wolffish habitat (Lavin, et al., 2022), and on the vulnerability of wolffish to rising temperatures and the importance of protecting habitats essential to key life stages (Bluemel, et al., 2022). Bluemel et al. (2022) describe the status of Atlantic wolffish in the North Sea, based on commercial landings (bycatch) and scientific trawl survey data. Their results support the conclusion that Atlantic wolffish are a temperature-sensitive species with increased vulnerability to climate change and the authors' recommended management actions include protection of spawning and denning habitats.

As inshore waters continue to warm, it is crucial to expand our habitat mapping and conservation efforts to include potential areas of refuge for species like the Atlantic wolffish that are at risk of thermal exclusion from key habitats. In the Newfoundland and Labrador region, there is evidence of Atlantic wolffish spawning offshore (Powles, 1967), however broad-scale assessment of offshore benthic habitats is limited by the lack of high resolution bathymetry and substrate data.

5.1.3 Addressing data gaps for regional marine habitat mapping

Chapter 4 (Novaczek, et al., 2019) presented a framework for the use of advanced interpolation to leverage a large crowd-sourced dataset for low-cost, high resolution mapping at the regional scale. Empirical Bayesian Kriging was used to generate a continuous bathymetric surface from incomplete and, in some areas, sparse Olex coverage on the Newfoundland and Labrador shelves of eastern Canada. The result was a 75 m bathymetric grid covering the 672,900 km^2 study area. The interpolated bathymetry was tested for accuracy against independent depth data provided by DFO (Spearman correlation = 0.99, $p<0.001$). Quantitative terrain attributes were generated to better understand seascape characteristics at multiple spatial scales, including slope, rugosity, aspect, and bathymetric position index (BPI). Landform classification was also carried out using the geomorphons algorithm in GRASS GIS and a novel method for the identification of previously unmapped tributary canyons at the continental shelf edge was presented to illustrate some of many potential benefits of crowd-sourced regional seafloor mapping. This study aimed to address the data gaps highlighted by the previous chapters for the characterization and protection of benthic habitats through the development of new data products that will support regional habitat mapping for the Newfoundland and Labrador Shelves.

Since publication, this work has been cited in the literature on developments in the seafloor mapping field and best practices (Bosboom, 2019; Bosboom, et al., 2020; Buhl-Mortensen, et al., 2021; Mata, et al., 2021; Misiuk, et al., 2021; Rodriguez-Perez & Sanchez-Carnero, 2022; Xu & Dabiri, 2022) and in subsequent work on the application of geomorphometry analysis in the marine environment (Dolan & Bjarnadottir, 2022; Gawrysiak & Kociuba, 2020; Young, et al., 2022). This chapter has also been cited in the growing literature on the use of crowd-sourced data to support seafloor mapping and management of marine species (Cairns, et al., 2020; Cairns, 2022; Radic, et al., 2023).

5.2 Emerging research questions

Data gaps remain, both in the Newfoundland and Labrador study area and globally. Almost 80% of the global ocean remains to be mapped though direct measurement and data are completely absent for remote coastal zones and areas of the deep-sea that are beyond the reach of fisheries or shipping lanes (Wolfl, et al., 2019). Local, regional, and global efforts are underway to improve our understanding and our maps of the seafloor, and to make these data available to researchers. The Canadian Hydrographic Service first published an open access database of non-navigational bathymetry in 2018, which now includes 100 m and 10 m grids within Canadian territorial waters (CHS, 2018). The Global Multi-Resolution Topography Synthesis compiles and edits ship-based multi-beam to provide an open access digital elevation model that currently includes over 42 000 km^2 of high resolution bathymetry from 1,554 cruises (GMRT, 2025). The most ambitious of these efforts is the Seabed 2030 Project, which aims to compile a complete, high resolution map of the global seafloor by 2030 “which will empower the world to make informed policy decisions, use the ocean sustainbly, and undertake scientific research based on detailed bathymetric information” (Coley, 2022).

My thesis research contributes to the development and refinement of marine habitat mapping methods through application to real conservation challenges and provides essential data products to support future research on the benthic habitats of the Newfoundland and Labrador shelves. The high resolution bathymetry and geomorphometry data generated in Chapter 4 are now being used in ongoing work to generate and publish substrate distribution maps for the region. The availability of shelf-wide bathymetry, geomorphometry, and, in the future, substrate distribution will support several lines of research, including shelf-wide species distribution modeling and/or habitat mapping. Future research made possible by my thesis may include the assessment of representativity and/or effectiveness of MPA and Marine Refuge networks, similar to the work carried out for the Eastport MPA in Chapter 3 applied at a regional scale. These data may also support an extension of the existing habitat mapping for species at risk, including identification of wolffish habitat offshore in areas with a more stable temperature regime, and/or habitat-informed projections of climate driven range shifts for vulnerable species (ex. McHenry et al. 2019). Work is ongoing to apply the data products from Chapter 4 to the development of substrate distribution models for the Newfoundland and Labrador shelves. Knowledge of substrate combined with previous work on distribution of fishing effort (Koen-Alonso, et al., 2018) could also be used in the development of benthic disturbance models in support of fisheries management (e.g. Smeltz et al. 2019).

5.1.2 Habitat mapping for MPA design, monitoring, and adaptive management

Between 2015 and 2023, Canada increased the coverage of marine conservation areas from <1% to 14.66% of territorial waters, including Oceans Act MPAs, National Marine Conservation Areas, Marine Refuges, and other area-based conservation measures (OECMs) (DFO, 2023). This expansion in marine protection has not been without challenges. For example, between the identification of an ecologically and biologically significant area (EBSA) in the Laurentian Channel in 2007 and designation of the Laurentian Channel MPA in 2019, the boundaries of the area of interest were reduced by 33.4%. Analysis of the process revealed that these changes were not subject to scientific review and the results favoured resource extraction over environmental protection. The modified MPA boundaries resulted in a 65.5% reduction of the estimated of fisheries loss (calculated as foregone benefit due to fisheries exclusion) and a

43% reduction in the protection of target species.. Authors cautioned that MPA effectiveness is degraded when scientific advice is not observed throughout the conservation planning process (Muntoni, et al., 2019).

Chapter 3 (Novaczek, et al., 2017) describes habitat mapping carried out in the Eastport MPA. The Eastport MPA is a small protected area with two regulatory objectives: the maintenance of a viable population of American lobster, and the conservation of threatened or endangered species. The monitoring program is more specific, listing lobster and wolffish as the conservation targets (DFO, 2013). However, our habitat mapping of the MPA did not identify habitat for any of the three SARA listed species of wolffish within the MPA boundaries. Analysis by Lewis et al. (2017) concluded that the Eastport MPA had "little to no effect on the enhancement of the local [lobster] fishery," specifically citing the small size of the MPA as a limitation to potential success. These findings demonstrate the importance of science-driven MPA design to ensure that conservation efforts are sufficient to meet their objectives.

With 17 additional marine areas currently under consideration for protection, Canada is on track to meet commitments to protect 25% of territorial waters by 2025 and 30% by 2030 (DFO, 2023). The lessons learned through review of past MPA successes and failures are essential to ensuring that our continued efforts to protect ocean environments produce meaningful results rather than paper parks (Devillers, et al., 2014). The mismatch between conservation objectives and protected habitats in the Eastport MPA also highlights the importance of adaptive management. As new information is collected, as monitoring tools advance, and as ecosystems shift under anthropogenic climate change it is essential that our philosophy for protected areas reflect a commitment to meaningful conservation rather than simple numerical targets, static boundaries, or ease of management at the expense of marine species.

Since publication, this paper has been cited as part of the literature on the history, development, and outcomes of the Eastport MPA (e.g. see Charles et al. 2020; Stanley et al. 2018) and was included in a synthesis of how the Aichi Biodiversity Targets are considered in the research on Marine Protected Areas (Drejou et al. 2020). Proudfoot et al. (2020) applied similar habitat mapping methods to the habitats beyond the MPA boundaries and presented a method for the integration of landscape ecology metrics into the Marxan decision support tool for MPA design. This work has also provided a foundation for further research on the surrounding ecosystems of the Eastport MPA and Newman Sound (Proudfoot, et al., 2020b), as well as development of recommendations for adaptive management in the region (Stanley, et al., 2018).

5.3 Conclusions

The impacts of human activity on the ocean are diverse and cumulative. To mitigate environmental damage, we need robust and creative approaches to better understand complex and changing ocean ecosystems. Existing policies for marine resource management (ex. Fisheries Act, Species at Risk Act, Oceans Act) and rapidly developing fields of Marine Spatial Planning and ecosystem-based management require improved spatial data for the marine species and habitats that we seek to protect (Baker & Harris, 2020). As climate change alters ecosystems, these needs only become more urgent as species and fisheries shift, habitats degrade, and new vulnerabilities emerge. Through my thesis research, my aim was to improve seafloor maps for NL Shelves, contribute to our understanding of seafloor habitats in the region, and to demonstrate the uses of improved seafloor maps for achieving marine spatial planning goals.

Specifically, each chapter addresses a component of local or regional seafloor mapping with direct applications to conservation planning in the Newfoundland and Labrador region.

References

Albikovskaya, L., 1982. Distribution and abundance of Atlantic wolffish, Spotted wolffish, and Northern wolffish in the Newfoundland area. *NAFO Scientific Council Studies,* Volume 3, pp. 39-32.

Althaus, F. et al., 2012. Evaluating geomorphic features as surrogates for benthic biodiversity on Autralia's Western continental margin. In: P. Harris & E. Baker, eds. *Seafloor Geomorphology as Benthic Habitat.* London: Elsevier, pp. 665-679.

Amblas, D. et al., 2008. Submarine canyons and gullies. In: A. Micallef, S. Krastel & A. Savini, eds. *Submarine Geomorphology.* New York: Springer, pp. 251-272.

Amos, C. & King, E., 1984. Bedforms of the Canadian Eastern Seaboard: A comparison with global occurences. *Marine Geology,* Volume 57, pp. 167-208.

Anderson, J., Gregory, R. & Collins, W., 2002. Acoustic classification of marine habitats in coastal Newfoundland. *ICES Journal of Marine Science,* Volume 59, pp. 156-167.

Auster, P. et al., 1996. The impacts of mobile fishing gear on seafloor habitats in the gulf of Maine (Northwest Atlantic): Implications for conservation of fish populations. *Reviews in Fisheries Science,* 4(2), pp. 185-202.

Austin, M. & Van Neil, K., 2010. Improving species distribution models for climate change studies: variable selection and scale. *Journal of Biogeography,* 38(1), pp. 1-8.

Baker, E. & Harris, P. T., 2020. Habitat mapping and marine management. In: *Seafloor Geomorphology as Benthic Habitat (Second Edition).* s.l.:Elsevier, pp. 17-33.

Baker, K. et al., 2012. Distributional patterns of deep-sea coral assemblages in three submarine canyons off Newfoundland, Canada. *Marine Ecological Progress Series,* Volume 445, pp. 235-249.

Barry, S. & Elith, J., 2006. Error and uncertainty in habitat models. *Journal of Applied Ecology,* 43(3), pp. 413-423.

Barton, C., 2022. Marie Tharp, oceanographic cartographer, and her contributions to the revolution in the Earth. In: D. Oldroyd, ed. *The Earth Inside and Out: Some Major Contributions to Geology in the Twentieth Century.* London: Geological Society of London Special Publication 192, pp. 215-228.

Batista, M., Henriques, S., Pais, M. & Cabral, H., 2015. A framework for the assessment of MPA effectiveness based on life history of fishes. *Ocean and Coastal Management,* Volume 118, pp. 75-87.

Beaman, R., O'Brien, P., Post, A. & DeSantis, L., 2011. A new high-resolution bathymetry model for the Terre Adelie and George V continental margin, East Antarctica. *Antarctic Science,* 23(1), pp. 95-103.

Bianucci, L. et al., 2016. Ocean biogeochemical models as management tools: a case study for Atlantic wolffish and declining oxygen. *ICES Journal of Marine Science,* 73(2), pp. 263-274.

Bird, S. C. & Hodges, K. E., 2017. Critical habitat designation for Canadian listed species: Slow, biased, and incomplete. *Environmental Science & Policy,* pp. 71: 1-8.

Bluemel, J. et al., 2022. Decline in Atlantic wolffish Anarhichas lupus in the North Sea: Impacts of fishing pressure and climate change. *Journal of Fish Biology,* 100(1), pp. 253-267.

Bluemel, J. et al., 2022. Decline in Atlantic wolffish Anarhichas lupus in the North Sea: Impacts of fishing pressure and climate change. *Journal of Fish Biology,* 100(1), pp. 253-267.

Bosboom, J., 2020. *Quantifying the quality of coastal morphological predictions (Doctoral Dissertation),* Delft: Delft University of Technology.

Bosboom, J., Mol, M., Reniers, A. & Stive, M. d. V. C., 2020. Optimal sediment transport for morphodynamic model validation. *Coastal Engineering,* Volume 158, p. 103662.

Buhl-Mortensen, L., Buhl-Mortensen, P., Dolan, M. & Gonsalez-Mirelis, G., 2015. Habitat mapping as a tool for conservation and sustainable use of marine resources: Some perspectives from the MAREANO Programme, Norway.. *Journal of Sea Research,* Volume 100, pp. 46-61.

Buhl-Mortensen, P., Lecours, V. & Brown, C., 2021. Seafloor mapping of the Atlantic Ocean. *Frontiers in Marine Science,* Volume 8, p. 721602.

Cairns, D. et al., 2020. *Methods and data sources to support American eel population analysis,* St. John's: Canadian Science Advisory Secretariat Research Document 2020/031.

Cairns, D. et al., 2022. Thirteen novel ideas and underutilised resources to support progress towards a range-wide American eel stock assessment. *Fisheries Management and Ecology,* Volume 29, pp. 516-541.

Calvert, J. et al., 2015. An evaluation of supervised and unsupervised classification techniques for marine benthic habtiat mapping using multibeam echosounder data. *ICES Journal of Marine Science,* 72(5), pp. 1498-1513.

Carter, G. & Gregg, M., 2002. Intense, variable mixing near the head of Monterey Canyon. *Journal of Physical Oceanography,* Volume 32, pp. 3145-3165.

Casalbore, D., Romagnoli, C., Bosman, A. & Chiocci, F., 2011. Potential tsumanigenic landslides at Stomboli Volcano (Italy): Insights from marine DEM analysis. *Geomorpholofy,* Volume 126, pp. 42-50.

CBD, 2010. *Aichi Biodiversity Targets,* Montreal: Secretariat of the Convention on Biological Diversity (CBD).

Charest, R., Brouillet, L., Bouchard, A. & Hay, S., 2000. The vascular flora of Terra Nova National Park, Newfoundland, Canada: a biodiversity analysis from a biogeographical and life form perspective. *Canadian Journal of Botany,* Volume 78, pp. 629-645.

Chiocci, F., Cattaneo, A. & Urgeles, R., 2011. Seafloor mapping for geohazard assessment: state of the art. *Marine Geophysical Research,* Volume 32, pp. 1-11.

Christian, J., 1995. *Patterns of diel activity and movements of the American lobster Homarus americanus, as determined by ultrasonic telemetry (Masters Thesis),* St. John's: Memorial University Research Repository.

CHS, 2018. *Canadian Hydropgraphic Service non-navigational (NONNA) bethymetric data.* [Online]
Available at: https://open.canada.ca/data/en/dataset/d3881c4c-650d-4070-bf9b-1e00aabf0a1d

Clarke, K. & Warwick, R., 2001. *Change in marine communities: An approach to statistical analysis and interpretation.* Pymouth: PRIMER-E Ltd.

Claudet, J. et al., 2010. Marine reserves: fish life history and ecological traits matter. *Ecological Applications,* Volume 20, pp. 830-839.

Cogan, C., Todd, B., Lawton, P. & Noji, T., 2009. The role of marine habitat mapping in ecosystem based management. *ICES Journal of Marine Science,* 66(9), pp. 2033-2042.

Coley, K., 2022. A global ocean map is not an ambition, but a necessity to support the ocean decade. *Marine Technology Society,* Volume 3, pp. 9-12.

Comeau, M. et al., 1989. Growth, spatial distribution, and abundance of benthic stages of the snow crab (Chionoecetes opilio) in Bonne Bay, Newfoundland, Canada. *Canadian Journal of Fisheries and Aquatic Science,* Volume 55, pp. 262-279.

Copeland, A., 2006. *Benthic habitat mapping with multibeam sonar in Newman Sound, Terra Nova National Park, Newfoundland (PhD Thesis),* St. John's: Memorial University of Newfoundland Research Repository.

COSEWIC, 2012. *Assessment and status report on the Atlantic wolffishh Anarhichas lupus in Canada,* Ottawa: Committe on the Status of Endangered Wildlife in Canada.

Cote, D. et al., 2004. Habitat use and early winter movements by juvenile Atlantic cod in a coastal area of Newfoundland. *Journal of Fish Biology,* Volume 64, pp. 665-679.

Cumming, E., Aksu, A. & Mudie, P., 1992. Late quaternary glacial and sedimentary history of Bonavista Bay, northeast Newfoundland. *Canadian Journal of Earth Science,* Volume 29, pp. 222-235.

Danielson, J. et al., 2016. Topobathymetric elevation model development using a new methodology: Coastal National Elevation Database. *Journal of Coastal Research,* Volume 76, pp. 75-89.

Davies, J. et al., 2014. Defining biological assemblages (biotopes) of conservation interest in the submarine canyons of the South West Approaches (offshore United Kingdom) for use in marine habitat mapping. *Deep Sea Research,* Volume 104, pp. 208-229.

De Leo, G. et al., 2010. Submarine canyons: Hotpots of benthic biomass and productivity in the deep sea. *Proceedings of the Royal Society of London Biological Sciences,* Volume 277, pp. 2783-2792.

Deering, R., Bell, T., Forbes, D. & Campbell, C. E. E., 2018. Morphological characterization of submarine slope failures in a semi-enclosed fjord, Frobisher Bay, eastern Canadian Arctic. *Geological Society of London Special Publications,* Volume 477, pp. 367-376.

Devillers, R. et al., 2014. Reinventing residual reserves in the sea: are we favouring ease of establishment over need for protection?. *Aquatic Conservation,* 25(4), pp. 480-504.

DFO, 2007. *A new ecosystem science framework in support of integrated management,* Ottawa: Fisheries and Oceans Canada - Communications Branch.

DFO, 2008. *Recovery strategy for Northern Wolffish (Anarhichas denticulatus) and Spotted wolffish (Anarhichas minor), and management plan for Atlantic wolffish (Anarhichas lupus) in Canada,* Ottawa: Fisheries and Oceans Canada.

DFO, 2010. Occurrence, sensitivity to fishing, and ecological function of corals, sponges, and hydrothermal vents in Canadian waters. *Canadian Science Advisory Secretariat Science Advisory Report 2010/041,* pp. 1-54.

DFO, 2011. *National framework for Canada's network of Marien Protected Areas,* Ottawa: Fisheries and Oceans Canada.

DFO, 2013. *Eastport Marine Protected Area Management Plan.* [Online] Available at: https://waves-vagues.dfo-mpo.gc.ca/Library/40675294.pdf

DFO, 2014. *Review of the Eastport Marine Protected Area Monitoring Indicators, Protocols and Strategies,* St. John's: Canadian Science Advisory Secretariat Science Advisory Report 2014/14.

DFO, 2015. *Wolffish in the Atlantic and Arctic Regions,* St. John's: Canadian Science Advisory Secretariat Research Document 2014/022.

DFO, 2016. *Guidance on identifying "Other Effective Area-Based Conservation Measures" in Canadian coastal and marine waters,* St. John's: Canadian Science Advisory Secretariat Science Advisory Report 2016/002.

DFO, 2016. *Seafisheries Landings.* [Online] Available at: www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm [Accessed October 2016].

DFO, 2023. *Canada's marine protected and conserved areas.* [Online] Available at: https://www.dfo-mpo.gc.ca/oceans/conservation/areas-zones/index-eng.html

Di Stefano, M. & Mayer, L., 2018. An automatic procedure for the quantitative characterization of submarine bedforms. *Geosciences,* 8(1), p. 28.

Dolan, M., 2012. *Calculation of slope angle from bathymetry data using GIS - Effects of computation algorithm, data resolution, and analysis scale,* Oslo: MAREANO NGU Report 2012-041.

Dolan, M. & Bjarnadottir, L., 2022. Highlighting broad-scale morphometric diversity of the seabed using geomorphons. *GEUS Bulletin,* Volume 52.

Dutil, J. et al., 2014. Distribution and environmental relationships of three species of wolffish (Anarhichas spp) in the Gulf of St. Lawrence. *Aquatic Conservation: Marine and Freshwater Ecosystems Journal,* Volume 24, pp. 351-368.

Eastwood, P. et al., 2006. Mapping seabed assemblages using comparative top-down and bottom-up classification approaches. *Canadian Journal of Fisheries and Aquatic Sciences,* Volume 63, pp. 1536-1548.

ECCC, 2016. *Terra Nova migratory bird sanctuary,* St. John's: Environment and Climate Change Canada - Atlantic Region.

Edgar, G. et al., 2014. Global conservation outcomes depend on marine protected areas with five key features. *Nature,* Volume 506, pp. 216-220.

Elveness, S., Dolan, M., Buhl-Mortensen, P. & Bellec, V., 2013. An evaluation of compiled single-beam bathymetry data as a basis for regional sediment and biotope mapping. *ICES Journal of Marine Science,* 71(4), pp. 867-881.

Ennis, G., 1984. Territorial behaviour of the American lobster Homarus americanus. *Transropts of the American Fisheries Society,* Volume 113, pp. 330-335.

Ennis, G., Collins, P. & Dawe, G., 1989. *Fisheris and population biology of lobsters (Homarus americanus) at St. Chads--Burnside, Newfoundland,* St. John's: Canadian Technical Report of Fisheries and Aquatic Sciences No.1651.

Erikstad, L., Bakkestuen, V., Bekkby, T. & Halvorsen, R., 2013. Impact of scale and quality of digital terrain models on predictability of seabed terrain types. *Marine Geodesy,* Volume 36, pp. 2-21.

Evans, J., Peckett, F. & Howell, K., 2015. Combined application of biophysical habitat mapping and systematic conservation planning to assess efficiency and representativeness of the existing High Seas MPA network in the Northeast Atlantic. *ICES Journal of Marine Science,* 72(5), pp. 1483-1497.

Fairchild, E., Tallack, S., Elzey, S. & Armstrong, M., 2015. Spring feeding of Atlantic wolffish (Anarhichas lupu) on Stellwagen Bank, Massachusetts. *Fisheries Bulletin,* 113(2), pp. 191-200.

FAO, 2020. *The state of world fisheries and aquaculture 2020,* Rome: United Nations Food and Agriculture Organization.

Fernandez-Acaya, U. et al., 2017. Ecological role of submarine canyons and need for canyon conservation: A review. *Frontiers in Marine Science,* 4(5), pp. 1-16.

Fernandez-Arcaya, U. et al., 2013. Reproductive biology and recruitment of the deep-sea fish community from the NW Mediterranean continental margin. *Progress in Oceanography,* Volume 118, pp. 222-234.

Fisheries and Oceans Canada, 2013. *Eastport Marine Protected Areas Management Plan.* [Online]
Available at: www.icomnl.ca

Foley, M. et al., 2010. Guiding ecological principles for marine spatial planning. *Marine Policy,* 34(5), pp. 955-966.

FRCC, 1995. *A conservation framework for Atlantic Lobster: Report to the Minister of Fisheries and Oceans,* Ottawa: Fisheries Resource Conservation Council.

GAC, 2013. *Backgrounder - Canada's continental shelf submission,* Ottawa: Global Affairs Canada.

Gaines, S., White, C., Carr, M. & Palumbi, S., 2010. Designing marine reserve networks for both conservation and fisheries management. *Proceedings of the National Academy of Science,* Volume 107, pp. 18286-18293.

Gawrysiak, L. & Kociuba, W., 2020. Application of geomorphons for analysing changes in the morphology of a proglacial valley (case study: The Scott River, SW Svalbard). *Geomorphology,* 371(15), p. 107449.

GEBCO Compilation Group, 2021. *GEBCO 2021 Grid.* [Online]
Available at:
https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2021/

GEBCO, 2018. *General Bathymetic Chart of the Oceans,* Liverpool: British Oceanographic Data Centre.

GMRT, 2025. *Global Multi-Resolution Topography Data Syntehsis.* [Online] Available at: https://www.gmrt.org/

GoC, 1996. *Oceans Act, c.31. Section 35: Marine Protected Areas.* [Online] Available at: http://laws-lois.justice.gc.ca/

Gorman, A., Gregory, R. & Schneider, D., 2009. Eelgrass patch size and proximity to the patch edge affect predation risk of recenly settled age 0 cod. *Journal of Experimental Marine Biology and Ecology,* Volume 371, pp. 1-9.

Government of Canada, 1985. *Fisheries Act (R.S.C., 1985, c. F-14).* [Online] Available at: https://laws-lois.justice.gc.ca/eng/acts/f-14/FullText.html

Government of Canada, 1996. *Oceans Act (S.C. 1996, c. 31).* [Online] Available at: https://laws-lois.justice.gc.ca/eng/acts/o-2.4/FullText.html

Government of Canada, 2002. *Species at Risk Act (S.C. 2002, c. 29).* [Online] Available at: https://laws.justice.gc.ca/eng/acts/S-15.3/

Graham, A. et al., 2008. A new bathymetric compilation highlighting extensive paleo-ice sheet drainage on the continental shelf, South Georgia, sub-Antarctica. *Geochemistry, Geophysics, Geosystems,* Volume 9, p. Q07011.

Grant, S. & Hiscock, W., 2013. Post-capture survival of Atlantic wolffish (Anarhichas lupus) captured by bottom otter trawl: Can live release programs contribute to the recovery of species at risk. *Fisheries Research,* Volume 151, pp. 169-176.

Gray, S., Dayton, P., Thrush, S. & Kaiser, M., 2006. On effects of trawling, benthos and sampling design. *Marine Pollution Bulletin,* Volume 52, pp. 840-843.

Green, A. et al., 2014. Designing marine reserves for fisheries management, biodiversity conservation, and climate change adaptation. *Coastal Management,* Volume 42, pp. 143-159.

Hagen, N. & Mann, K., 1992. Functional response of the predators American lobster Homarus americanus (Milne-Edwards) and Atlantic wolffish Anarhichas lupus (L.) to increasing numbers of the green sea urchin Strongylocentrotus droebachiensis (Müller). *Journal of Experimental Biology and Ecology,* Volume 159, pp. 89-112.

Hamilton, R., Potuku, T. & Montembault, J., 2011. Community-based conservation results in the recovery of reef fish spawning aggregations in the Coral Triangle. *Biological Conservation,* Volume 144, pp. 1850-1858.

Harris, P. & Baker, E., 2012. Why map benthic habitats?. In: P. Harris & E. Baker, eds. *Seafloor geomorphology as benthic habitat.* London: Elsevier, pp. 3-22.

Harris, P., Macmillan-Lawler, M., Rupp, J. & Baker, E., 2014. Geomorphology of the oceans. *Marine Geology,* Volume 352, pp. 4-24.

Hattab, T. et al., 2014. Towards a better understanding of potential impacts of climate change on marine species distribution: A multiscale modelling approach. *Global Ecology and Biogeography,* 23(12), pp. 1417-1429.

Heezen, B. & Tharp, M., 1977. *World ocean floor.* [Online]
Available at: https://www.loc.gov/item/2010586277/

Heipke, C., 2010. Crowdsourcing geospatial data. *ISPRS Journal of Photogrammetry and Remote Sensing,* 65(6), pp. 550-557.

Hereu, B., Zabala, M., Linares, C. & Sala, E., 2005. The effects of predator abundance and habitat structural complexity on survival of juvenile sea urchins. *Marine Biology,* 146(2), pp. 292-299.

Hooper, R., 1997. *A general coastal marine classification system for Newfoundland,* St. John's: Report for Department of Fisheries and Oceans Newfoundland and Labrador, Habitat Management.

Hough, G. et al., 2011. A geomorphological mapping approach for the assessment of seabed geohazards and risk. *Marine Geophysical Research,* 32(1), pp. 151-162.

Hovel, K. & Wahle, R., 2010. Effects of habitat patchiness on American lobster movement across a gradient of predation risk and shelter competition. *Ecology,* Volume 91, pp. 1993-2002.

Hutchings, J. A. et al., 2020. Sustaining Canadian marine biodiversity: Policy and statutory progress. *FACETS,* 5(1), pp. 264-288.

Hutchings, J., Stephens, T. & VanderZwaag, D., 2016. Marine Species at Risk protection in Australia and Canada: Paper promises, paltry progressions. *Ocean Development & International Law,* Volume 47.

Jamieson, G. & Lessard, J., 2001. *Marine Protected Areas and Fishery Closures in British Columbia,* Nanaimo: Canadian Special Publication of Fisheries and Aquatic Sciences 131.

Janes, J., 2009. *Assessing Marine Protected Areas as a conservation tool: a decasde later, are we continuing to enhance lobster populations at Eastport, Newfoundland?,* St. John's: Canadian Technical Report of FIsheries and Aquatic Sciences 2832.

Janes, J., 2013. *Eastport Marine Protected Area Monitoring Report 2012,* St. John's: DFO-NL Ecosystems Management Publication Series.

Jasiewicz, J. & Stepinski, T., 2013. Geomorphons - A pattern recognition approach to clasification and mapping of landforms. *Geomorphology,* Volume 182, pp. 147-156.

Jasiewicz, J. & Stepinski, T., 2016. *R.geomorphon.* [Online]
Available at: grass.osgeo.org/grass74/manuals/addons/r.geomorphon.html
[Accessed 2018].

Johannessen, T., Gjøsaeter, J. & Moksness, E., 1993. Reproduction, spawning behavior and captive breeding of the common wolffish *Anarhichas lupus*. *Aquaculture,* Volume 115, pp. 41-51.

Johns, P. & Mann, K., 1987. An experimental investigation of juvenile lobster habitat preference and mortality among habitats of varying structural complexity. *Journal of Experimental Marine Biology and Ecology ,* Volume 109, pp. 275-285.

Jonsson, G., 1982. Contribution to the biology of catfish (*Anarhichas lupus*) at Iceland. *Rit Fiskideidar,* Volume 6, pp. 2-26.

Kaplan, D. et al., 2010. New tools for the spatial management of living marine resources. *Current Opinions in Environmental Sustainability,* Volume 2, pp. 88-93.

Keats, D., South, G. & Steele, D., 1985. Reproduction and egg guarding by Atlantic wolffish (*Anarchichas lupus: Anarhicidae*) and ocean pout (*Macrozoarces americanus: Zoarcidae*) in Newfoundland waters. *Canadian Journal of Zoology,* 63(11), pp. 2565-2568.

Keats, D., Steele, D. & South, G., 1986. Atlantic wolffish (*Anarhichas lupus L.*; Pisces Anarhichidae) predation on green sea urchins (S*trongylocentrotus droenbachiensis* O.F.

Mull.; Echinodermata: Echinoidea) in eastern Newfoundland. *Canadian Journal of Zoology,* 64(9), pp. 1920-1925.

Keats, D., Steele, D. & South, G., 1987. Eelpout (*Macrozoarces americanus*) predation on green sea urchins (*Stronglyocentrotus droebachiensis*) in eastern Newfoundland. *Canadian Journal of Zoology,* Volume 65, pp. 1515-1521.

Keats, D., Steele, D. & South, G., 1987. The role of fleshy macroalgae in the ecology of juvenile cod (*Gadus morhua*) in inshore waters off eastern Newfoundland. *Canadian Journal of Zoology,* Volume 65, pp. 1515-1521.

KEDC, 2001. *Community based coastal resource inventory (CCRI),* St. John's: Kittiwake Economic Development Corporation (prepared for the Department of Fisheries and Oceans).

Klein, C. et al., 2015. Shortfalls in the global protected area network at representing marine biodiversity. *Nature Scientific Reports,* Volume 5, p. 17539.

Koen-Alonso, M. et al., 2018. *Analysis of the overlap between fishing effort and Significant Benthic Areas in Canada's Atlantic and Eastern Arctic marine waters,* St. John's: Canadian Science Advisory Secretariat Research Document 2018/015 .

Kokinou, E., 2021. Automatic pattern recognition and GPS/GNSS technology in marine digital terrain model. GPS and GNSS. *Technology in Geosciences,* pp. 241-254.

Kostylev, V., Erlandsson, J., Ming, M. & Williams, G., 2005. The relative importance of habitat complexity and surface area in assessing biodiversity: fractal application on rocky shores. *Ecological Complexity,* Volume 2, pp. 272-286.

Kostylev, V., Todd, B. F. G., Courtney, R. C. G. & Pickrill, R., 2001. Benthic habitat mapping on the Scotian Shelf based on multibeam bathymetry, surficial geology and sea floor photographs. *Marine Ecology Progress Series,* Volume 219, pp. 121-137.

Kritzer, J. et al., 2016. The importance of benthic habitats for coastal fisheries. *BioScience,* 66(4), pp. 274-284.

Krivorouchko, K., 2012. *Empirical Bayesian Kriging implemented in ArcGIS Geostatistical Analyst,* Redlands: ESRI ArcUser Fall 2012 - Software and Data.

Kulka, D., Simpson, M. & Hooper, R., 2004. *Changes in distribution and habitat associations of wolffish (Anarhichidae) on the Grand Banks and Labrador Shelf,* St. John's: Canadian Science Advisory Secretariat Research Document 2004/113.

Lachance, A., Dutil, J. & Larocque, R., 2010. Shelter use and behaviour of juvenile Spotted Wolffish (*Anarhichas minor*) in an experimental context. *Environmental Biology of Fishes,* 88(3), pp. 207-215.

Larocque, R., Gendron, M. & Dutil, J., 2008. *A survey of Wolffish (Anarhichas spp.) and wolffish habitat in Les Mechins, Quebec,* Mont-Joli: Canadian Technical Report of Fisheries and Aquatic Sciences 2786.

Larue, M. et al., 2022. High-resolution satellite imagery meets the challenge of monitoring remote marine protected areas in the Antarctic and beyond. *Conservation Letters,* 15(4), p. e12884.

Lavin, C. et al., 2022. Warm and cold temperatures limit the maximum body length of teleost fishes across a latitudinal gradient in Norwegian waters. *Environmental Biology of Fishes,* 105(10), pp. 1-15.

Le Francois, N. et al., 2001. Tolerance and growth of juvenile common wolffish (Anarhichas lupus) under low salinity and hypoxic conditions: preliminary results. *Aquaculture Association of Canada Special Publications,* Volume 4, pp. 57-59.

Lecours, V., 2015. *Terrain attribute selection for spatial ecology (TASSE) v 1.0.* [Online] Available at: https://doi.org/10.13140/RG.2.2.15014.

Lecours, V. et al., 2015. Spatial scale and geographic context in benthic habitat mapping: Review and future directions. *Marine Ecology Progress Series,* Volume 535, pp. 259-284.

Lecours, V. et al., 2017. Towards a framework for terrain attribute selection in environmental studies. *Environmental Modelling Software,* Volume 89, pp. 19-30.

Lecours, V., Dolan, M., Micallef, A. & Lucieer, V., 2016. A review of marine geomorphometry, the quantitative study of the seafloor. *Hydrological and Earth Systems Science,* Volume 20, pp. 3207-3244.

Leenhardt, P. et al., 2013. The rise of large-scale marine protected areas: conservation or geopolitics. *Ocean and Coastal Management,* Volume 85, pp. 112-118.

Lee, S., Song, W. & Lee, M.-J., 2017. Habitat potential mapping of Marten (*Martes flavigula*) and Leopard Cat (*Prionailurus bengalensis*) in South Korea usign artificial neural network machine learning. *Applied Sciences,* 9(912).

Lester, S. et al., 2009. Biological effects within no-take marine reserves: a global synthesis. *Marine Ecological Progress Series,* Volume 384, pp. 33-46.

Lewis, S., Coughlan, E., Pepin, P. & Skanes, K., 2017. *An assessment of the biological indicators for the Eastport Marine Protected Area (MPA): A case study in support of an* *ecosystem goods and services valuation of,* St. John's: Canadian Science Advisory Secretariat Research Document 2017/001.

Liao, Y. & Lucas, M., 2000. Growth, diet and metabolism of common wolfish in the North Sea, a fast growing population. *Journal of Fish Biology,* Volume 56, pp. 810-825.

Liverman, D., Batterson, M., Taylor, D. & Ryan, J., 2000. Geological hazards and disasters in Newfoundland and Labrador. *Canadian Geotechnical Journal,* 38(5), pp. 936-956.

Lucieer, V. et al., 2018. User expectations for multibeam echo sounders backscatter strenth data - looking back into the future. *Marine Geophysical Research,* Volume 39, pp. 23-40.

Makowski, C. & Finkl, C., 2016. History of modern seafloor mapping. In: C. W. Finkl & C. Makowski, eds. *Seafloor Mapping along Continental Shelves: Research and Techniques for Visualizing Benthic Environments.* Heidelberg: Springer, pp. 3-49.

Malcolm, H. et al., 2016. Integrating seafloor habitat mapping and fish assemblage patterns improves spatial management planning in a marine park. *Journal of Coastal Research,* Volume 75, pp. 1291-1296.

Marshak, A. & Brown, S., 2017. *Habitat science is an essential element of ecosystem-based fisheries management.* [Online]
Available at: fisheries.org/2017/06/habitat-science-is-an-essential-element-of-ecosystem-based-fisheries-management/
[Accessed 2018].

Masson, D. et al., 2010. Efficient burial of carbon in a submarine canyon. *Geology,* Volume 38, pp. 831-834.

Mata, D., Ubeda, J. & Fernandez-Sanchez, A., 2021. Modelling of the reef benthic habitat distribution within the Cabrera National Park (Western Mediterranean Sea). *Annals of GIS,* 27(3), pp. 285-298.

Mayer, L., 2006. Frontiers in seafloor mapping and visualization. *Marine Geophysical Research,* Volume 27, pp. 7-17.

Mayer, L. et al., 2018. The Nippon Foundation GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030. *Geosciences,* 8(2), p. 63.

McCarthy, I., Moksness, E. & Pavlov, D., 1998. The effects of temperature on growth rate and growth efficiency of juvenile common wolffish. *Aquaculture International,* Volume 6, pp. 207-218.

McCusker, M. & Bentzen, P., 2010. Historial influences dominate the population genetic structure of a sedentary marine fish, Atlantic wolffish (*Anarhichas lupus*) across the North Atlantic Ocean. *Molecular Ecology,* Volume 19, pp. 4228-4241.

McDevitt-Irwin, J., Fuller, S., Grant, C. & Baum, J., 2015. Missing the safety net: evidence for inconsistent and insufficient management of at-risk marine fishes in Canada. *Canadian Journal of Fisheries and Aquatic Sciences,* Volume 72, pp. 1596-1608.

McLaren, B., Langlois, T. H. E., Shortland-Jones, H. & Stevens, R., 2015. A small no-take marine sanctuary provides consistent protection for small-bodied by-catch species, but not for large-bodied, high-risk speicies. *Journal of Experimental Marine Biology and Ecology ,* Volume 471, pp. 153-163.

Misiuk, B., Lecours, V. & Bell, T., 2018. A multiscale approach to mapping seabed sediments. *PLoS ONE,* 13(2), p. e0193647.

Misiuk, B., Lecours, V., Dolan, M. & Robert, K., 2021. Evaluating the suitability of multi-scale terrain attribute calcualtion approaches for seabed mapping applications. *Marine Geodesy,* 44(4), pp. 327-385.

Moksness, E., 1994. Growth rates of the common wolffish *Anarhichas lupus* L., and spotted wolffish, A. minor Olafson, in captivity. *Aquaculture and Fisheries Management,* Volume 25, pp. 363-371.

Moland, E. et al., 2013. Lobster and cod benefit from small-scale nothern marine protected areas: inference from an empirical before-after control-impact study. *Proceedings of the Royal Society of Biological Sciences,* Volume 280, pp. 1-9.

Monk, J. et al., 2010. Habitat suitability for marine fishes using presence-only modelling and multibeam sonar. *Marine Ecology ,* Volume 420, pp. 157-174.

Montella, R. et al., 2017. *Processing of crowd-sourced data from an internet of floating things.* Denver, Association for Computing Machinery.

Moore, C., Drazen, J., Radfor, B. & Kelley, C. N. S., 2016. Improving essential fish habitat designation to support sustainable ecosystem-based fisheries management. *Marine Policy,* Volume 69, pp. 32-41.

Moussaoui, A. & Auger, P., 2015. Simple fishery and marine reserve models to study the SLOSS problem. *ESAIM Proceedings and Surveys,* Volume 49, pp. 78-90.

Muntoni, M., Devillers, R. & Koen-Alonso, M., 2019. Science should not be left behind during the design of a marine protected area: meeting conservation priorities while integrating stakeholder interests. *Facets,* 4(1).

Naselli-Flores, L. & Padisak, J., 2022. Ecosystem services provided by marine and freshwater phytoplankton. *Aquatic Ecosystem Services,* Volume 850, pp. 2691-2706.

Neat, F. & Righton, D., 2007. Warm water occupancy by North Sea cod. *Proceedings of the Royal Society of London B: Biological Sciences,* 274(1611), pp. 789-798.

Nelson, G. & Ross, M., 1992. Distribution, growth and food habits of the Atlantic wolffish (*Anarhichas lupus*) from the Fulf of Maine-Georges Bank Region. *Journal of Northwest Atlantic Fisheries Science ,* Volume 13, pp. 53-61.

Nemani, S. et al., 2022. A multi0scale feature selection approach for predicting benthic assemblages. *Estuarine, Coastal and Shelf Science,* 277(31), p. 108053.

Novaczek, E., Devillers, R. & Edinger, E., 2019. Generating higher resolution regional seafloor maps from crowd-sourced bathymetry. *PlosOne,* 14(6), p. e0216792.

Novaczek, E., Devillers, R., Edinger, E. & Mello, L., 2017. High-resolution seafloor mapping to describe coastal denning habitat of a Canadian species at rik: Atlantic wolffish (*Anarhichas lupus*). *Canadian Journal of FIsheries and Aquatic Sciences,* 74(12).

Novaczek, E. et al., 2017. Limited contribution of small marine protected areas to regional biodiversity: the example of a small Canadian no-take MPA. *Frontiers in Marine Science,* Volume 4.

OceanDTM, 2014. *Olex global bathymetry database.* [Online]
Available at: www.oceandtm.com/olexdata.html
[Accessed May 2019].

Odum, E. & Kroodsma, R., 1976. *Fundamentals of Ecology.* Philadelphia: Saunders.

O'Hara, C., Frazier, M. & Halpern, B., 2021. At-risk marine biodiversity faces extensive, expanding and intensifying human impacts. *Science,* 372(6537), pp. 84-87.

Olsgard, F. et al., 2008. Effects of bottom trawling on ecosystem functioning. *Journal of Experimental Marine Biology and Ecology,* 366(1-2), pp. 123-133.

Pavlov, D. & Moksness, E., 1994. Reproductive biology, early ontogeny, and effect of temperature on develeopment in wolffish: comparison with salmon. *Aquaculture International,* Volume 2, pp. 133-153.

Pavlov, D. & Moksness, E., 1995. Development of wolffish eggs at different temperature regimes. *Aquaculture International,* 3(4), pp. 315-335.

Pavlov, D. & Novikov, G., 1993. Life history and peculiarities of common wolffish (*Anarhichas lupus*) in the White Sea. *ICES Journal of Marine Science,* Volume 50, pp. 271-277.

Pearce, B., Tappin, D., Dove, D. & Pinnion, J., 2012. Benthos supported by the tunnel-valley of the souther Norther Sea. In: P. B. E. Harris, ed. *Seafloor Geomorphology as Benthic Habitat.* London: Elsevier, pp. 597-612.

Pickrill, R. & Kostylev, V., 2007. Habitat mapping and national seafloor mapping strategies in Canada. *Geological Association of Canada Special Paper,* Volume 47, pp. 483-495.

Pickrill, R. & Todd, B., 2003. The multiple roles of acoustic mapping in integrated ocean management, Canadian Atlantic continental margin. *Ocean & Coastal Management,* 46(6-7), pp. 601-614.

Piper, D. et al., 2012. Erosional and depositional features ofglacial meltwater discharges on the eastern Canadian continental margin. *Society for Sedimentary Geology,* Volume 99, pp. 61-80.

Poloczanska, E. et al., 2016. Response of marine organisms to climate change across oceans. *Frontiers in Marine Science,* Volume 3.

Pörtner, H. & Knust, R., 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science,* Volume 315, pp. 95-96.

Powles, P., 1967. Atlantic wolffish (*Anarhichas lupus L.*) eggs off southern Nova Scotia. *Journal of Fisheries Research Board of Canada,* 24(1), pp. 207-208.

Proudfoot, B., Devillers, R. & Brown, C., 2020. Integrating fine-scale seafloor mapping and spatial patter metrics into marine conservation prioritization.. *Aquatic Conservation,* Volume 30, pp. 1613-1625.

Proudfoot, B., Devillers, R. & Brown, C., 2020. Seafloor mapping to support conservation planning in an ecologically unique fjord in Newfoundland and Labrador, Canada.. *Journal of Coastal Conservation,* 24(36).

Radic, T., Pavic, I. & Miskovic, J., 2023. Comparison of hydrographic survey data with crowdsourced bathymetry data. *Nase more,* 70(2), pp. 115-125.

Rao, A. et al., 2014. *Eelgrass (Zostera marina) locations in Newfoundland and Labrador,* St. John's: Canadian Technical Report on Fisheries and Aquatic Science.

Rauchenstein, K. et al., 2022. LiDAR metrics predict suitable forest foraging areas of endangered Mouse-eared bats (*Myotis myotis*). *Forest Ecology and Management,* Volume 515, p. 120210.

Raymond, E., 1999. The cathedral and the bazaar. *Knowledge, Technology, & Policy,* 12(3), pp. 23-49.

Rengstorf, A., Grehan, A., Yesson, C. & Brown, C., 2012. Towards high-resolution habitat suitability modelling of vulnerable marine ecosystems in the deep sea: Resolving terrain attribute dependencies.. *Marine Geodesy,* Volume 35, pp. 343-361.

Rennie, S. et al., 2009. Physical properties and processes in the Perth Canyon, Western Australia: Links to water column production and seasonal pygmy blue whale abundance. *Journal of Marine Systems,* Volume 77, pp. 21-44.

Rinehart, R. et al., 2004. *ArcGIS8.x Benthic Terrain Modeler: analysis in American Samoa.* San Diego, Proceedings of the 24th Annual ESRI User Conference.

Robert, K. et al., 2014. Finding the hotspots within a biodiversity hot-spot: fine scale biological predictions within a submarine canyon using high-resolution acoustic mapping techniques. *Marine Ecology,* Volume 36, pp. 1256-1276.

Rodriguez-Perez, D. & Sanchez-Carnero, N., 2022. Multigrid/Multiresolution Interpolation: Reducing Oversmoothing and Other Sampling Effects. *Geomatics,* 2(3), pp. 236-253.

Roff, C. & Evans, S., 2002. Frameworks for marine conservation -- non-hierarchical approaches and distinctive habitats. *Aquatic Conservation: Marine and Freshwater Ecosystems Journal,* Volume 12, pp. 635-648.

Rosenberg, A., Jencks, J., Robertson, E. & Reed, A., 2017. *Mapping the gaps: Building a pipeline for contributing and accessing crowdsourced bathymetry data.* New Orleans, American Geophysical Union.

Ross, L., Ross, R., Stewart, H. & Howell, K., 2015. The influence of data resolution on predicted distribution and estimates of extent of current protection of three 'listed' deep-sea habitats. *PLoS ONE,* Volume 10, p. e0140061.

Rovere, M., Gamberi, F., Mercorella, A. & Leidi, E., 2014. Geomorphometry of a submarine mass-transport complex and relationships with active faults uplifting margin (Gioia Basin, NE, Sicily margin). *Marine Geology,* Volume 356, pp. 31-43.

Rowden, A. et al., 2017. High-resolution habitat suitability models for the conservation and management of vulnerable marine ecosystems on the Louisville Seamount Chain, South Pacific Ocean. *Frontiers in Marine Science,* 4(335), pp. 1-19.

Rowe, S. & Feltham, G., 2000. Eastport Peninsula lobster conservation: integrating harvester's local knowledge and fisheries science for resource co-management. In: B. Neis & L. Felt, eds. *Finding Out Sea Legs: Linking FIshery People and Their Knowledge with Science and Management.* St. John's: ISER Books, pp. 236-245.

Russel, I. & Wright, R., 2017. Navigation sonar: more that underwater radar - Realizing the full potential of navigation and obstacle avoidance sonar. *The International Hydrographic Review,* Volume 17, pp. 41-60.

Rutterford, L. et al., 2015. Future fish distributions constrained by depth in warming seas. *Nature Climate Change,* 5(6), pp. 569-573.

Ryan, W. et al., 2009. Global multi-resolution topography synthesis. *Geochemistry, Geophysics, Geosystems,* Volume 10, pp. 1526-2027.

Sanderson, P. & Jorgensen, F., 2017. Buried tunnel vallers in Denmark and their impact on the geological architecture of the subsurface. *Geological Survey of Denmark and Greenland Bulletin,* Volume 38, pp. 13-16.

Scheibling, R., 1996. The role of predation in regulating sea urchin populations in eastern Canada. *Oceanologica Acta,* Volume 19, pp. 421-430.

Schlaginweit, G., 1993. *Real-time acoustic bottom classification for hydrography: A field evaluation of Rox-Ann.* Victoria, IEEE.

Schultz, J., Darling, E. & Cote, I., 2013. What is an endangered species worth? Threshold costs for protecting imperilled fishes in Canada. *Marine Policy,* Volume 42, pp. 125-132.

Sedaghat, L., Hersey, J. & McGuire, M., 2013. *Detecting spatio-temporal outliers in crowdsourced bathymetry data.* New York, Association for Computing Machinery.

Shaw, J. et al., 2011. New evidence for widespread mass transport on the Northeast Newfoundland Shelf revealed by Olex single-beam echo-sounding.. *Geo-Marine Letters,* 32(1), pp. 5-15.

Shaw, J. et al., 2014. Continental shelves of Atlantic Canada. In: F. Chiocci & A. Chivas, eds. *Continental Shelves of the World: Their evolution during the last glacio-eustatic cycle.* London: Geological Society of London, pp. 7-19.

Sherman, K. & Hempel, G., 2008. *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's regional seas,* Nairobi: UNEP Regional Seas Report and Studies.

Simpson, M. et al., 2013. *An update on the biology, population status, distribution, and landings of wolffish (Anarhichas denticulartus, A. minor, and A. lupus) in the Canadian Atlantic and Arctic Oceans,* St. John's: Canadian Science Advisory Secretariat Research Document 2013/089.

Simpson, M., Mello, L., Holloway, C. & Maddigan, T., 2015. *A preliminary analysis of habitat use and movement patterns of wolffish (Anarhichas spp) in coastal Newfoundland waters,* St. John's: Canadian Science Advisory Secretariat Research Document 2014/033.

Simpson, M., Mello, L., Miri, C. & Treble, M., 2012. *A pre-COSEWIC assessment of three species of wolffish (Anarhichas denticulatus, A. minor, and A. lupus) in the Canadian Atlantic and Arctic Oceans,* St. John's: Canadian Science Advisory Secretariat Research Document 2011/122.

Smith, W. & Sandwell, D., 2004. Conventional bathymetry, bathymetry from space, and geodetic altimetry. *Oceanography,* 17(1), pp. 8-23.

Snelgrove, P., 2010. *Discoveries of the Census of Marine Life: makign ocean life count.* Cambridge: Cambridge University Press.

Soykan, C. & Lewison, R., 2015. Using community-level metrics to monitor the effects of marine protected areas on biodiversity. *Conservation Biology,* Volume 29, pp. 775-783.

Spagnolo, M. & Clark, C., 2009. A geomorphological overview of glacial landforms on the Icelandic continental shelf. *Journal of Maps,* 5(1), pp. 37-52.

Stanley, R. et al., 2018. The efficcacy of small closures: A tale of two Marine Protected Areas in Canada.. In: R. Brinkmann & S. Garren, eds. *The Palgrave Handbook of Sustainability.* Cham: Palgrave Macmillan.

Steneck, R., Cavrinec, J. & Leland, A., 2004. Accelerating trophic-level dysfunction in kelp forest ecosystems of the western North Atlantic. *Ecosystems,* Volume 7, pp. 323-332.

Stewart, M., 2017. Assemblage of buried and seabed tunnel valleys in the central North Sea: from morphology to ice-sheet dynamics. *Journal of the Geological Society of London,* Volume 46, pp. 317-320.

Stow, D. et al., 2009. Benform-velocity matrix: The estimation of bottom current velocity from bedform observations. *Geology,* 37(4), pp. 327-330.

Tanaka, K. & Chen, Y., 2015. Spatiotemporal variability of suitable habitat for American lobster (*Homarus americanus*) in Long Island Sound. *Journal of Shellfish Research,* Volume 34, pp. 531-543.

Templeman, W., 1984. Migrations of wolffish, *Anarhichas* sp., from tagging in the Newfoundland area. *Journal of Northwest Atlantic Fisheries Science,* Volume 5, pp. 93-97.

Templeman, W., 1985. Stomach contents of Atlantic wolffish (*Anarhichas lupus*) from the Northwest Atlantic. *NAFO Scientific Council Studies,* Volume 8, pp. 49-51.

Thorson, J., Clarke, M., Stewart, I. & Punt, A., 2013. The implications of spatially varying catchiability on bottom trawl surveys of fish abundance: a proposed solution involving underwater vehicles. *Canadian Journal of Fisheries and Aquatic Sciences ,* 70(2), pp. 294-306.

UNEP-WCMC, I., 2016. *The world database on protected area (WDPA).* [Online] Available at: www.protectedplanet.net [Accessed December 2016].

Vasques, J., 2010. *Methods used to evaluate MPA proposals in the MLPA North Coast study region.* Eureka: California Department of Fish and Game.

Verfaillie, E. et al., 2007. *The bathymetric position index (BPI) as a support tool for habitat mapping,* Gent: Worked example for the Mapping European Seabed Habitats (MESH) Final Guidance.

Wahle, R. & Steneck, R., 1992. Habitat restrivtions in early benthic life: experiments on habitat selection and in situ predation with the American lobster. *Journal of Experimental Marine Biology and Ecology ,* Volume 157, pp. 91-114.

Walbridge, S., Slocum, N., Pobuda, M. & Wright, D., 2018. Unified geomorphological analysis workflows with Benthic Terrain Modeler. *Geoscience,* 8(3), p. 94.

Weatherall, P. et al., 2015. A new digital bathymetris model of the world's oceans. *Earth Space Science,* Volume 2, pp. 331-345.

Wolfl, A.-C.et al., 2019. Seafloor mapping - The challenge of a truly global ocean bathymetry. *Frontiers in Marine Science,* Volume 6.

Woo-Durand, C. et al., 2020. Increasing importance of climate change and other threats to at-risk species in Canada. *Environmental Reviews,* Volume 28, pp. 449-456.

Xu, N. & Dabiri, J., 2022. Bio-inspired ocean exploration. *Oceanography,* 35(2), pp. 35-48.

Yan, H. F. et al., 2021. Overfishing and habitat loss drives range contraction of iconis marine fishers to near extinction. *Science Advances,* 7(eabb6026), pp. 1-10.

Young, M. & Carr, M., 2015. Assessment of habitat representation across a network of marine protected areas with implications for the spatial design of monitoring. *PLoS ONE,* Volume 10, p. e0116200.

Young, M., Iampietro, P., Kvitek, R. & Garza, C., 2010. Multivariate bathymetry-derived generalized linear model accurately predicts rockfish distribution on Cordell Bank, California, USA. *Marine Ecology Progress Series,* Volume 415, pp. 247-261.

Young, M. et al., 2022. *Statewide assessment of Victorian marine protected areas using existing data,* Melbourne: Parks Victoria Technical Series 118.

Supplementary materials

Table S2.1 Analysis of Similarity and Similarity Percentages Analysis of species occurrence and abundance across six acoustically distinct substrates.

Pairwise test (A, B)	ANOVA		SIMPER Dissimilarity (%)	Contributing species	Average Abundance (per m^2)	
	R	P			A	B
1, 2*	0.028	0.462	46.56	Green urchin (19%)	2.51	1.59
				Blue mussel (12%)	1.93	1.62
				Northern sea star (12%)	1.62	0.50
				Cunner (10%)	0.58	0.78
1, 3	0.917	0.036	74.30	Brittle star (22%)	0.00	3.24
				Blue mussel (13%)	1.93	0.00
				Northern sea star (11%)	1.62	0.00
				Amphipod (7%)	0.00	1.09
1, 4	0.956	0.005	76.02	Blue mussel (13%)	1.93	0.00
				Brittle star (13%)	0.00	2.09
				Northern sea star (11%)	1.62	0.00
				Whelk (10%)	0.00	1.39
				Green urchin (8%)	2.51	1.92
1, 5	0.897	0.001	98.70	Green urchin (15%)	2.51	0.00
				Blue mussel (12%)	1.93	0.00
				Northern sea star (10%)	1.62	0.00
				Arrow worm (7%)	0.00	1.09
				Coralline algae (7%)	1.00	0.00
1, 6	0.957	0.002	88.15	Green urchin (13%)	2.51	0.73
				Brittle star (13%)	0.00	2.06
				Blue mussel (12%)	1.93	0.00
				Northern sea star (9%)	1.62	0.20
				Northern red anemone (7%)	0.51	1.35
2, 3	0.321	0.200	71.03	Brittle star (20%)	0.73	3.24
				Blue mussel (13%)	1.62	0.00
				Green urchin (10%)	1.59	2.30
				Amphipod (9%)	0.00	1.09

2, 4	0.604	0.057	75.09	Blue mussel (13%)	1.62	0.00
				Brittle star (13%)	0.73	2.09
				Whelk (11%)	0.00	1.39
				Green urchin (9%0	1.59	1.92
				Northern red anemone (9%)	0.49	1.30
2, 5	0.853	0.022	98.00	Blue mussel (13%)	1.62	0.00
				Green urchin (11%)	1.59	0.00
				Arrow worm (8%)	0.00	1.09
				Coralline algae (8%)	1.00	0.00
				Cunner (7%)	0.78	0.00
				Macroalgae (6%)	0.75	0.00
2, 6	0.656	0.016	84.21	Brittle star (13%)	0.73	2.06
				Blue mussel (13%)	1.62	0.00
				Green urchin (10%)	1.59	0.73
				Northern red anemone (9%)	0.49	1.35
				Coralline algae (8%)	1.00	0.00
3, 4*	0.214	0.267	42.80	Brittle star (19%)	3.24	2.09
				Whelk (18%)	0.00	1.39
				Amphipod (12%)	1.09	0.25
				Northern red anemone (10%)	0.50	1.30
3, 5	0.759	0.022	89.42	Brittle star	3.24	0.00
				Green urchin	2.30	0.00
				Arrow worm	0.00	1.09
3, 6*	0.127	0.429	57.16	Green urchin (19%)	2.30	0.73
				Brittle star (14%)	3.24	2.06
				Amphipod (9%)	1.09	0.20
				Northern red anemone (8%)	0.50	1.35
4, 5	0.669	0.002	81.63	Green urchin (17%)	1.92	0.00
				Brittle star (17%)	1.09	0.00
				Arrow worm (10%)	0.00	1.09
				Northern red anemone (9%)	1.30	0.27

4, 6*	0.275	0.095	54.01	Green Urchin (18%)	1.92	0.73
				Brittle star (15%)	2.09	2.06
				Whelk (12%)	1.39	0.58
				Atlantic cod (7%)	0.66	0.20
5, 6	0.566	0.001	77.84	Brittle star (21%)	0.00	2.06
				Northern red anemone (11%)	0.27	1.35
				Arrow worm (9%)	1.09	0.48
				Whelk (8%)	0.78	0.58

* indicates substrates what were combined into biologically similar habitats.

Table S3.1 Species observed and identified in Eastport MPA video survey

Common Name	**Phylum**	**Taxa**
Fan Worm	Annelida	Sabellidae Spp.
Toad Crab	Arthropoda	*Hyas araneus*
Snow Crab	Arthropoda	*Chionoectes opilio*
Rock Crab	Arthropoda	*Cancer irroratus*
Pout	Chordata	Zoarcidae spp.
Sculpin	Chordata	Myoxocephalus spp.
Cunner	Chordata	*Tautogolabrus adspersus*
Atlantic Cod	Chordata	*Gadus morhua*
Flatfish	Chordata	Pleuronectidae spp.
Green Urchin	Echinodermata	*Strongylocentrotus droebachiensis*
Smooth Sunstar	Echinodermata	*Solaster endeca*
Spiny Sunstar	Echinodermata	*Crossaster papposus*
Bloodstar	Echinodermata	*Henricia sanguinolenta*
Seastar	Echinodermata	*Asterias rubens*
Juvenile Starfish	Echinodermata	

Brittlestar	Echinodermata	*Ophiopholis aculeata*
Sanddollar	Echinodermata	*Echinarahnius parma*
Orange-footed Sea Cucumber	Echinodermata	*Cucumaria frondosa*
Blue Mussel	Mollusca	*Mytilus edulis*
Sea Scallop	Mollusca	*Placopecten magellanicus*
Bay Scallop	Mollusca	*Argopecten irradians*
Frilled Anemone	Cnidaria	*Metridium senile*
Burrowing Aneome	Cnidaria	*Pachycerianthus borealis*
Stalked Jelly	Cnidaria	*Lucernaria quadricornis*
Clam	Mollusca	
Finger Sponge	Porifera	*Haliclona oculata*
Kelp	Phaeophyta	*Laminaria spp.*
Sea Colander	Phaeophyta	*Agarum spp.*
Fucoid Seaweed	Phaeophyta	*Fucales spp.*
Filamentous Brown Algae	Phaeophyta	
Rhodolith	Rhodophyta	*Lithothamnion glaciale*
Encrusting Coralline Algae	Rhodophyta	Corallinales spp.
Northern Sea Fern	Rhodophyta	*Ptilota serrata*
Leafy Red Algae	Rhodophyta	*Coccotylus truncatus*
Dulse	Rhodophyta	*Palmaria palmata*
Irish Moss	Rhodophyta	*Chondrus crispus*
Filamentous Red Algae	Rhodophyta	
Unknown Red Algae	Rhodophyta	
Sea Lettuce	Chlorophyta	Ulva spp.
Filamentous Green Algae	Chlorophyta	

Table S3.2 ANOSIM analysis of observed species composition and abundance on substrate classes (Bray Curtis similarity matrix).

Groups	**R Statistic**	**Significance Level (%)**

S2, S3	0.28	0.1
S2, S5	0.091	22.7
S2, S4	0.215	0.1
S2, S1	0.35	0.1
S3, S5	0.363	0.7
S3, S4	0.054	5.5
S3, S1	0.618	0.1
S5, S4	0.209	6
S5, S1	0.03	32.9
S4, S1	0.536	0.1
Global Test Sample statistic (R): 0.255 Significance level of sample statistic: 0.1%		

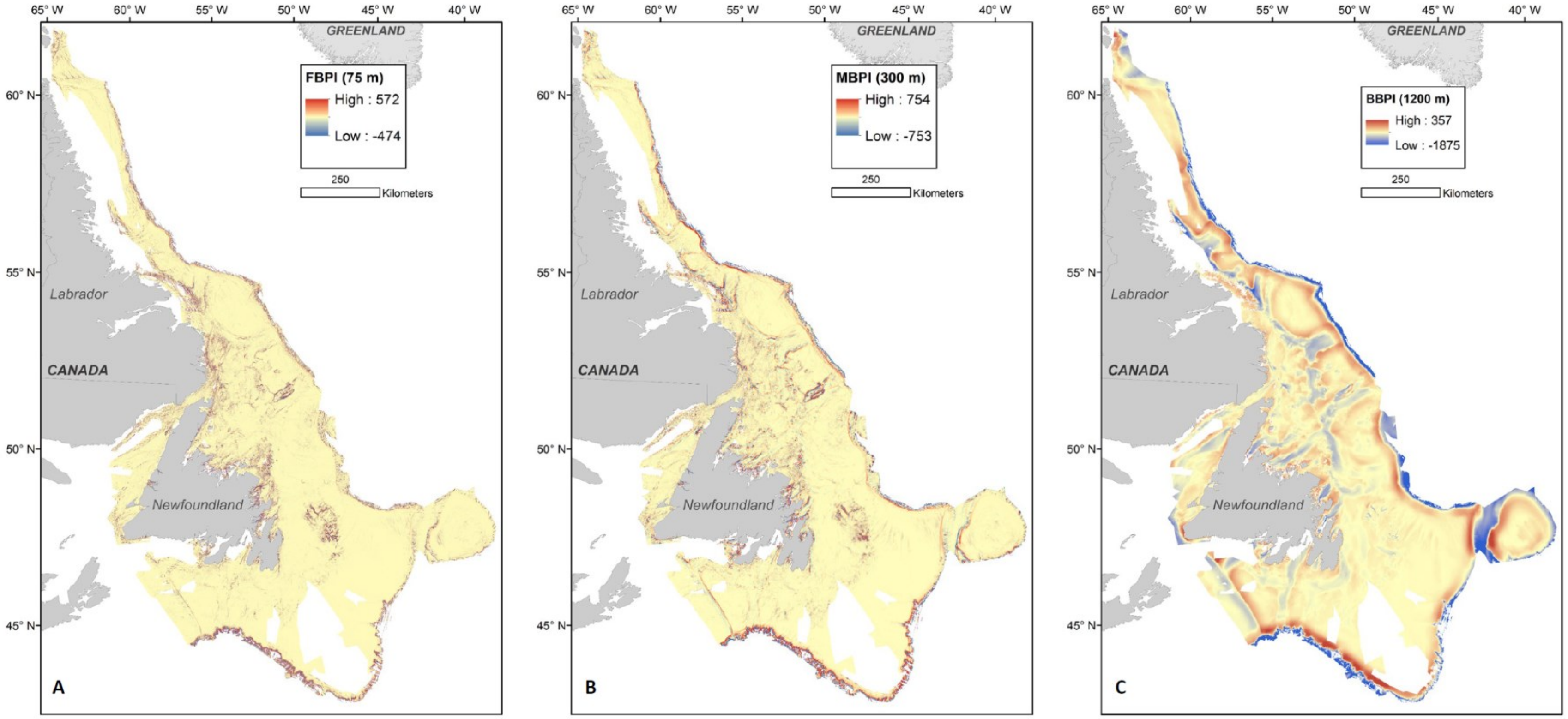


Figure S4.1. Benthic Position Index (BPI). BPI was calculated in Benthic Terrain Modeler 2.0 at multiple scales; (a) an 8 cell inner radius and 16 cell outer radius applied to the 75m interpolated bathymetry, (b) a 25 cell inner radius and 50 cell outer radius applied to the mean interpolated bathymetry within a 300 m neighbourhood, and (c) a 100 cell inner radius and 500 cell outer radius applied to the mean interpolated bathymetry within a 1200 m neighbourhood.

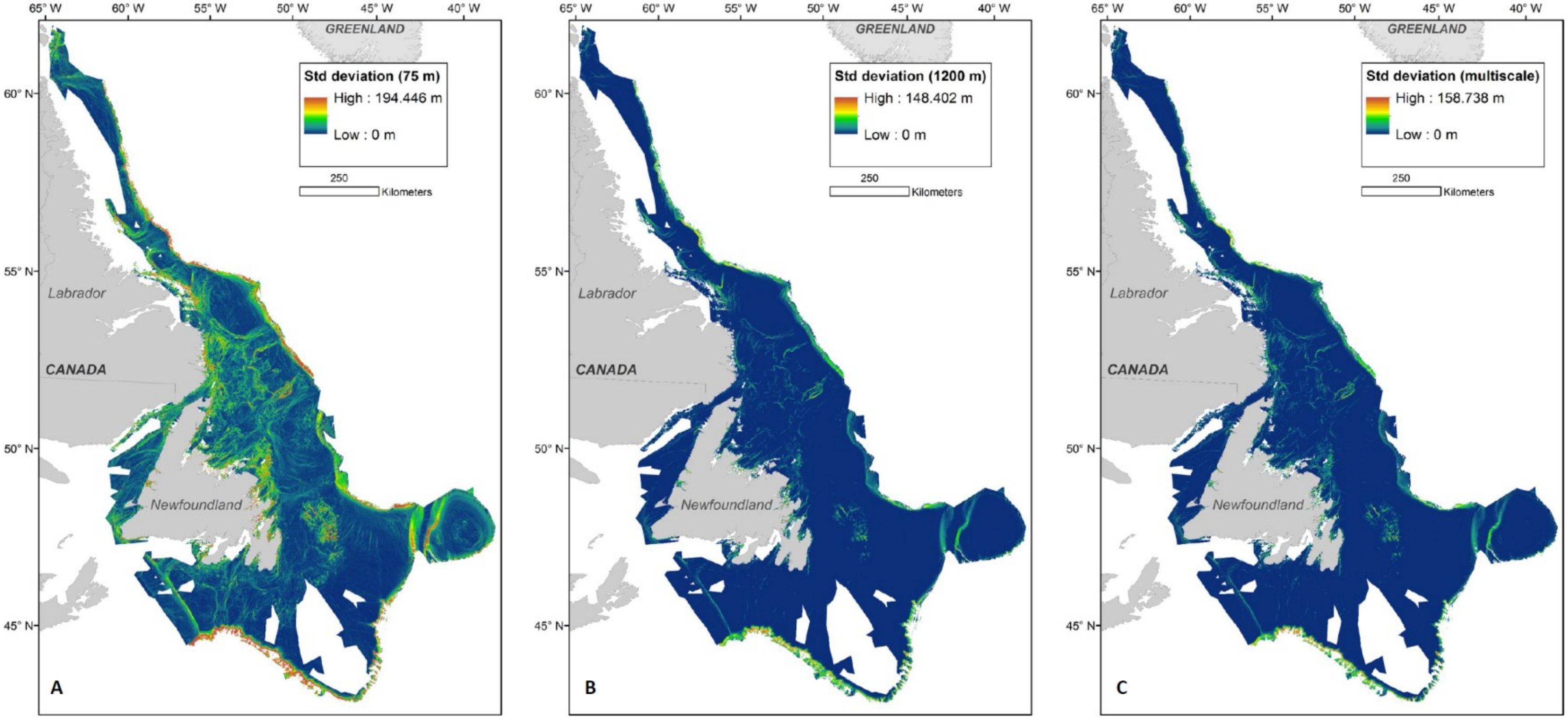


Figure S4.2. Bathymetric standard deviation. Standard deviation within a 9 cell analysis window was calculated in Benthic Terrain Modeler 2.0 at multiple scales: (a) 75m interpolated bathymetry, (b) the mean interpolated bathymetry within a 1200m neighbourhood, and (c) the mean was taken of 5 standard deviation rasters derived from the interpolated bathymetry (75m grid and local mean bathymetry within 150m, 300m, 600m, and 1200m neighbourhoods).

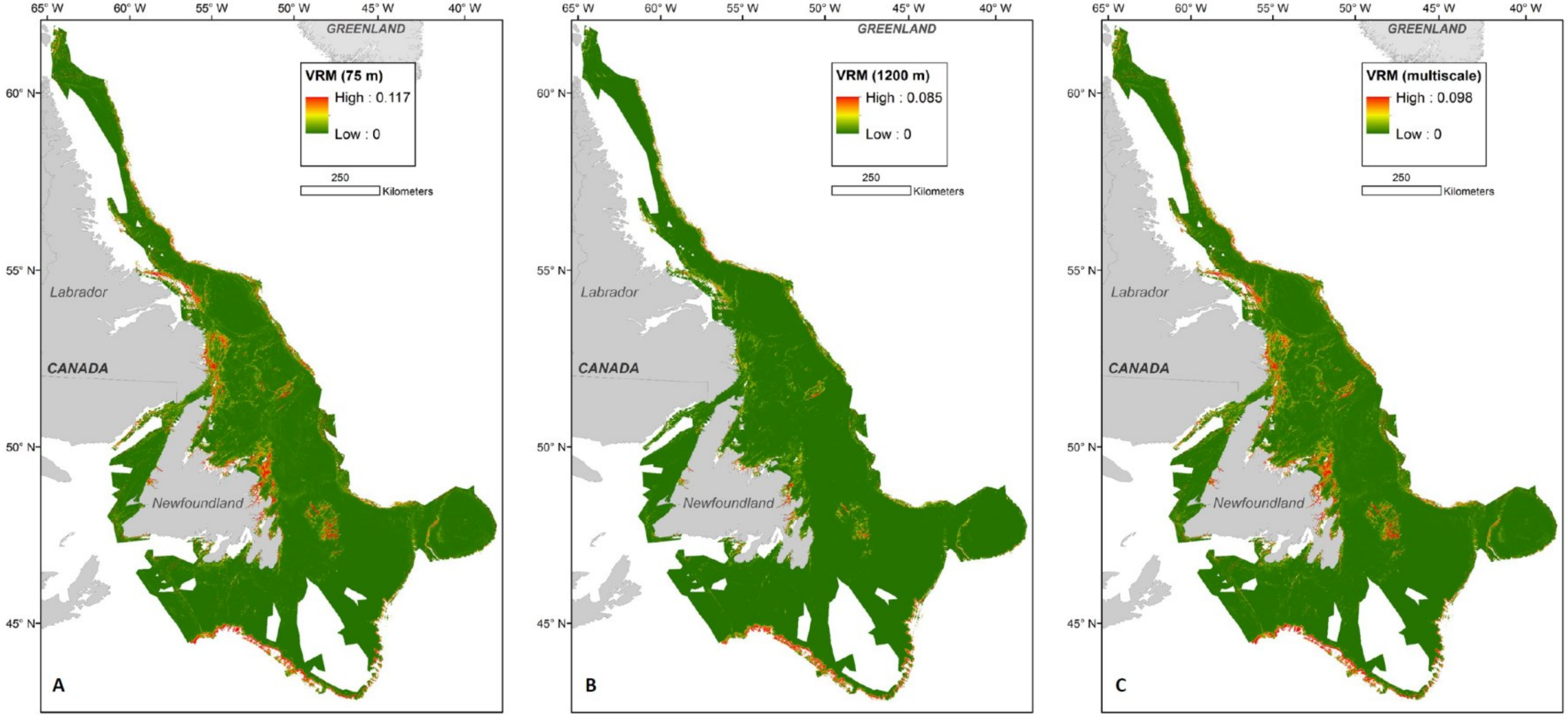


Figure S4.3 Vector Ruggedness measure. VRM was calculated in Benthic Terrain Modeler 2.0, for a 21 cell analysis window at multiple scales: (a) 75m interpolated bathymetry, (b) the mean interpolated bathymetry within a 1200m neighbourhood, and (c) the mean was taken of 5 VRM rasters derived from the interpolated bathymetry (75m grid and local mean bathymetry within 150m, 300m, 600m, and 1200m neighbourhoods).

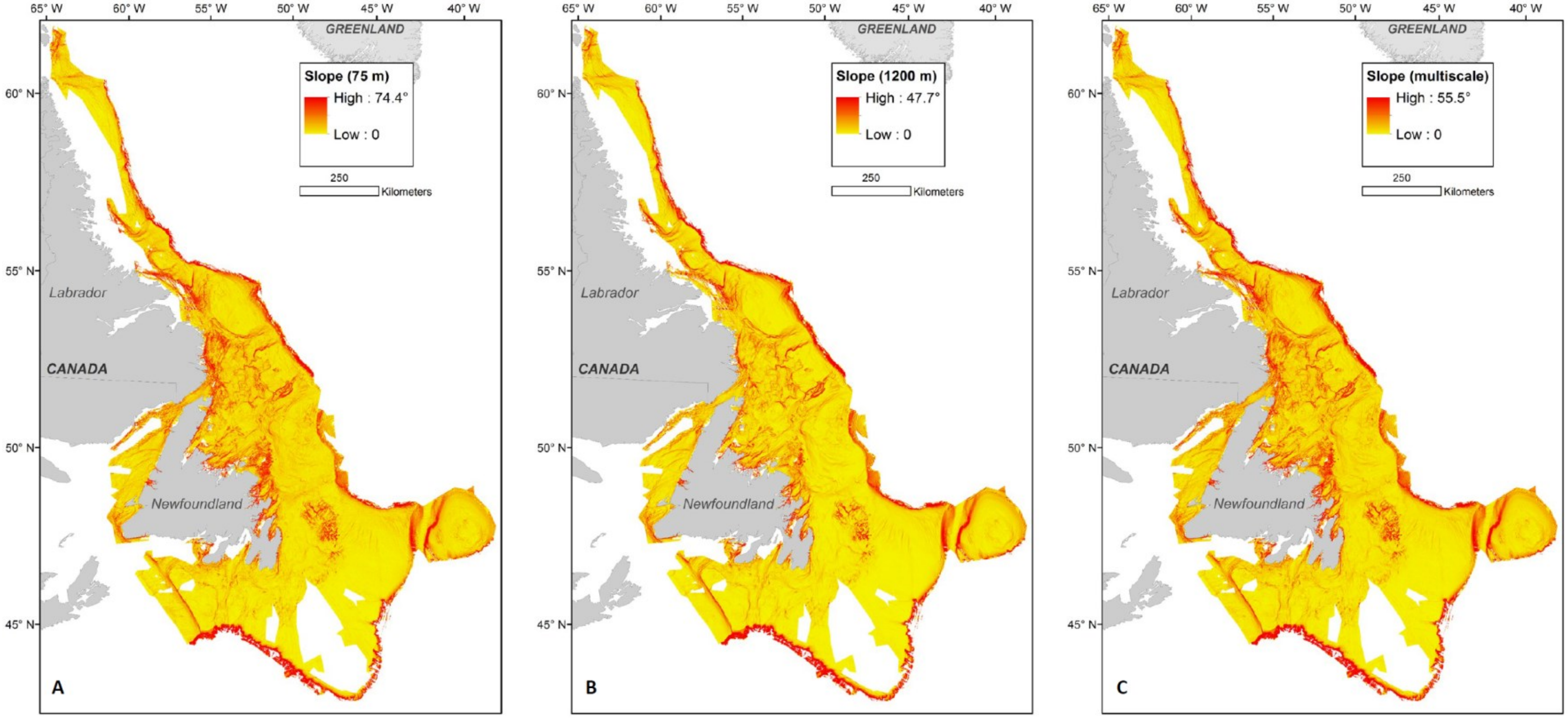


Figure S4.4 Slope. Slope was calculated in Benthic Terrain Modeler 3.0 within a 9 cell analysis window at multiple scales: (a) 75m interpolated bathymetry, (b) the mean interpolated bathymetry within a 1200 m neighbourhood, and (c) the mean was taken of 5 slope rasters derived from the interpolated bathymetry (75 m grid and local mean bathymetry within 150 m, 300 m, 600 m, and 1200 m neighbourhoods).

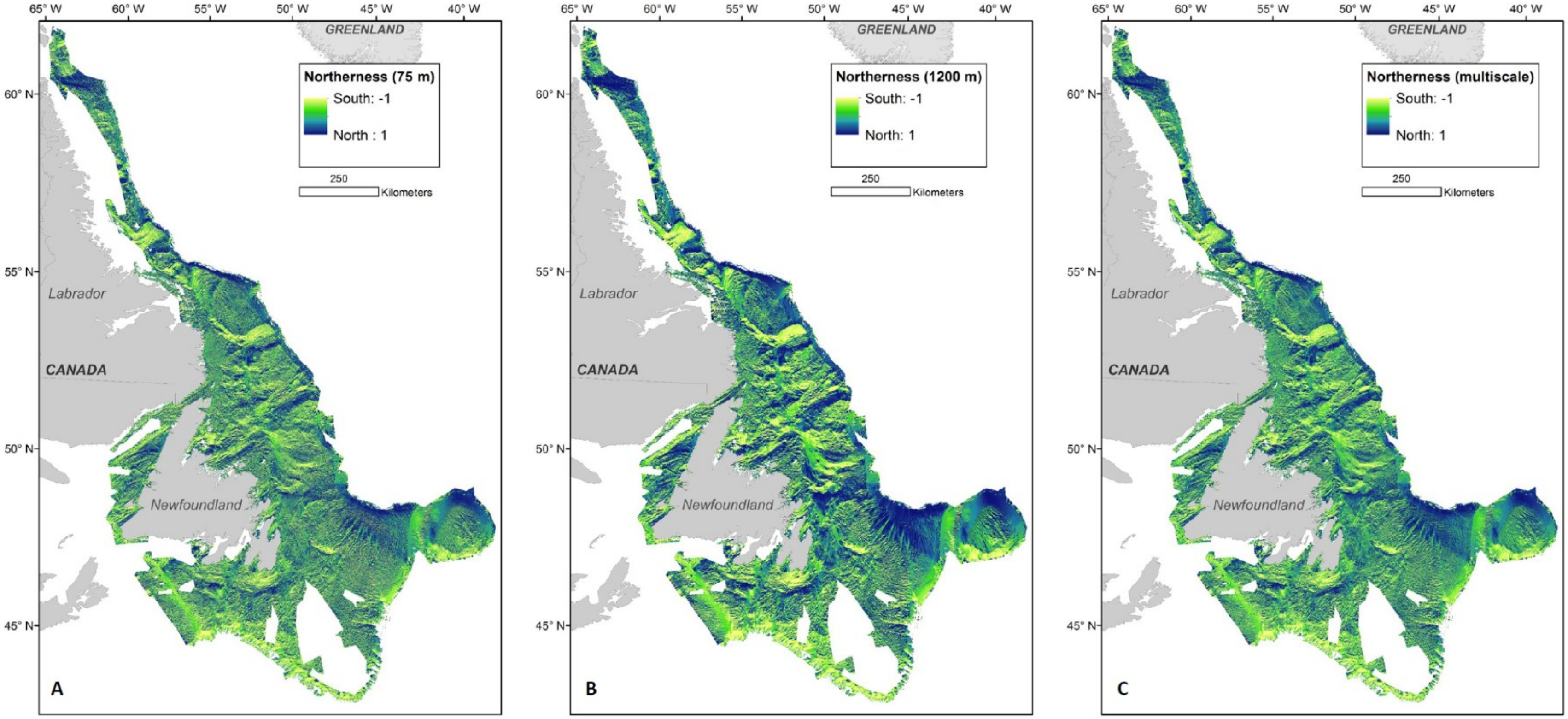


Figure S4.5 Aspect (Northerness). Statistical aspect (i.e. slope orientation) was calculated in Benthic Terrain Modeler 3.0 for a 3x3 cell analysis window at multiple scales: (a) 75m interpolated bathymetry, (b) the mean interpolated bathymetry within a 1200 m neighbourhood, and (c) the mean was taken of 5 northerness rasters derived from the interpolated bathymetry (75m grid and local mean bathymetry within 150 m, 300 m, 600 m, and 1200 m neighbourhoods).

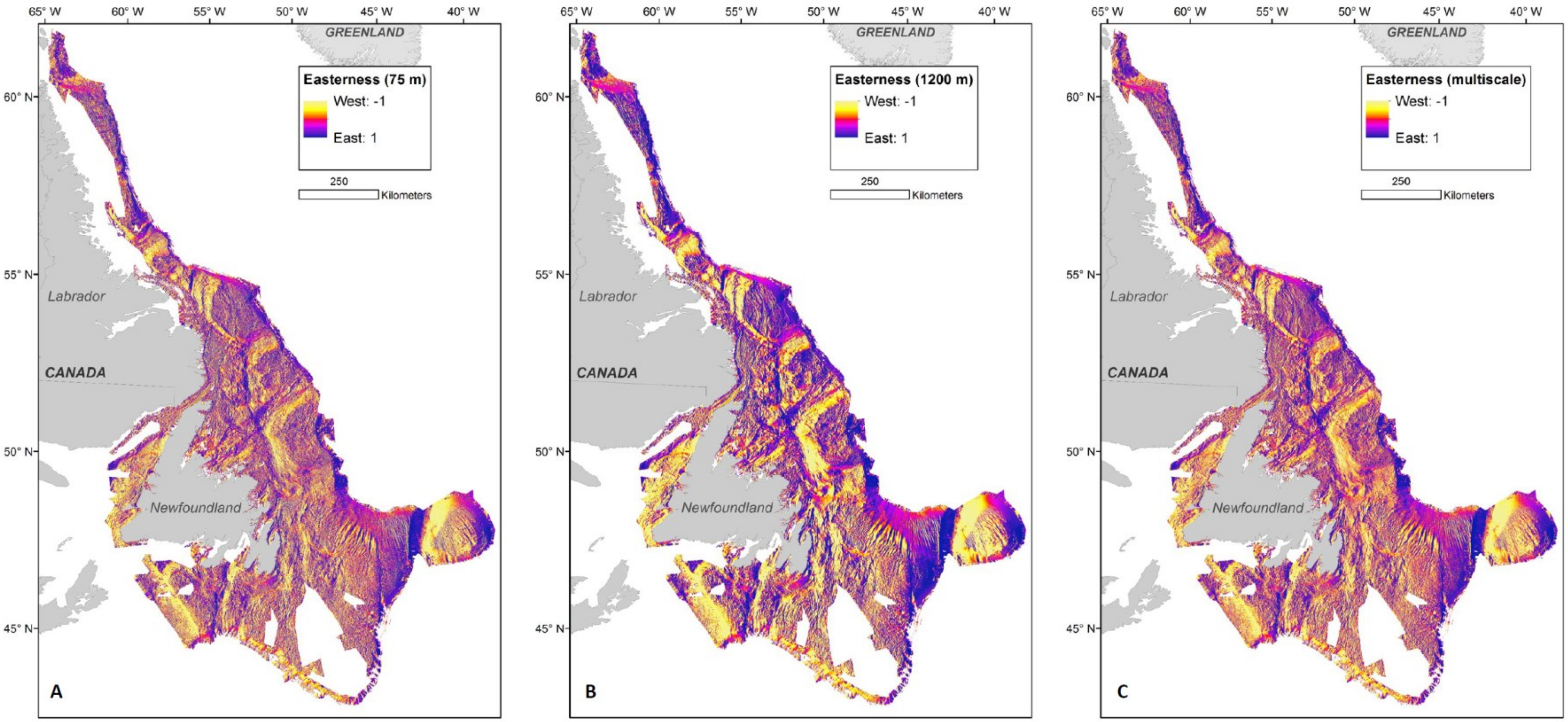


Figure S4.6 Aspect (Easterness). Statistical aspect (i.e. slope orientation) was calculated in Benthic Terrain Modeler 3.0 for a 3x3 cell analysis window at multiple scales: (a) 75m interpolated bathymetry, (b) the mean interpolated bathymetry within a 1200 m neighbourhood, and (c) the mean was taken of 5 easterness rasters derived from the interpolated bathymetry (75m grid and local mean bathymetry within 150 m, 300 m, 600 m, and 1200 m neighbourhoods).

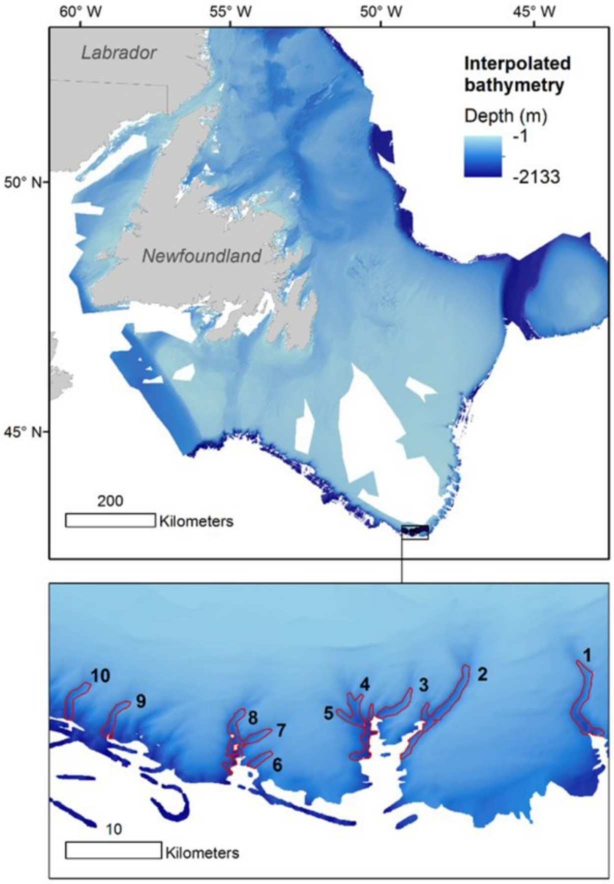


Figure S4.7. Manually identified canyons. Ten shelf edge canyons were identified from visual assessment of the interpolated 75m bathymetric grid and measured to inform the parameters for canyon classification across the shelf edge of the entire study area.

Table S4.1 Measurements of 10 visually identified canyon features

Canyon #	Length (m)	Width at head (m)	Width at middle (m)	Width at mouth (m)
1	8753	748	1599	2185
2	8673	1852	1706	2026
3	6199	817	1199	2128
4	3041	393	558	758
5	4613	440	897	933
6	2232	910	1468	1041
7	3277	443	619	1013
8	4761	460	840	1157
9	5037	388	984	1227
10	6374	587	1052	1488

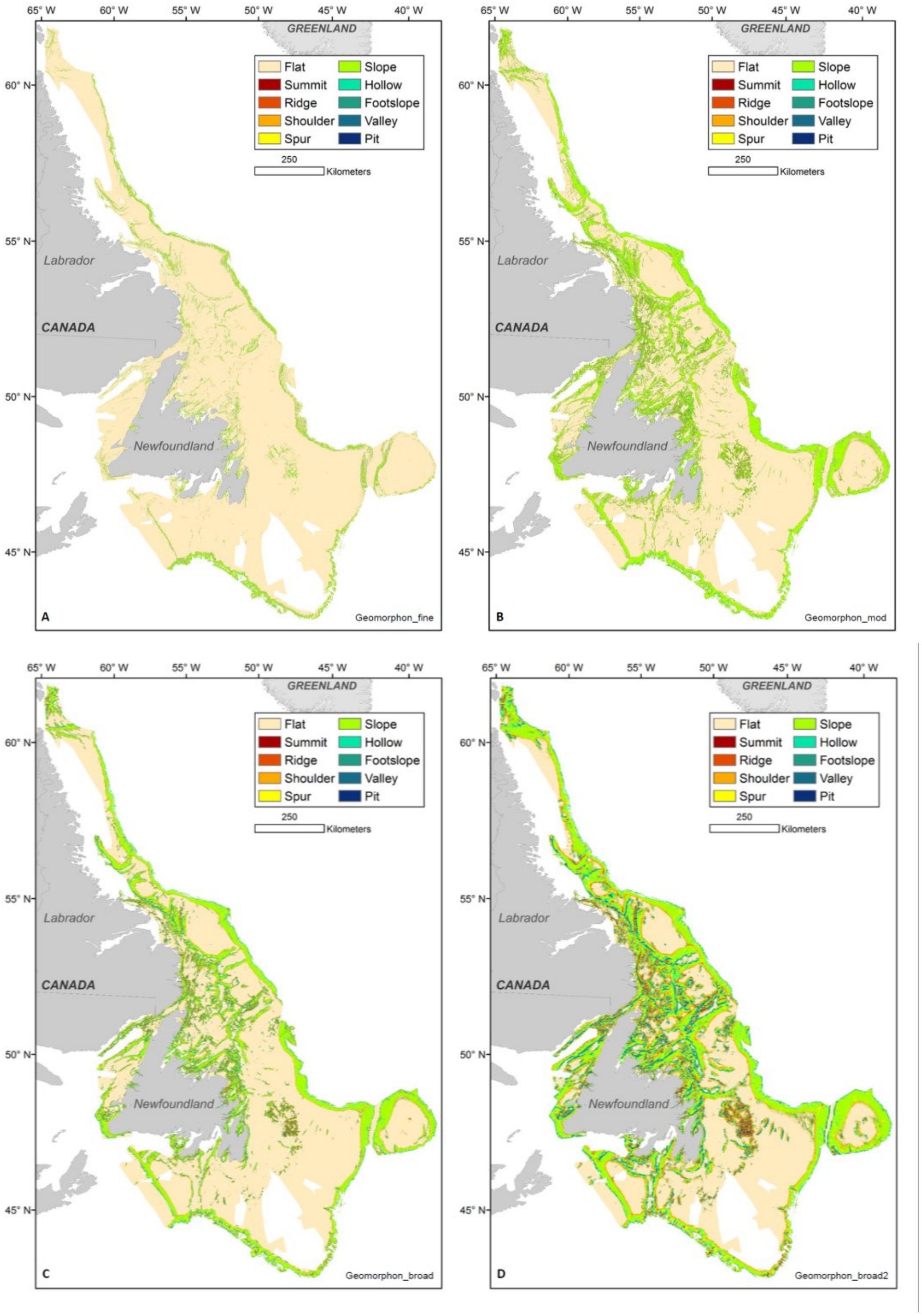


Figure S4.8 Specific geomorphometry. The r.geomorphons model was applied in GRASS GIS 7.4 to classify specific geomorphometry at multiple scales, based on (a) 75m interpolated bathymetry (inner search radius of 0m and an outer search radius of 225m), (b) the mean interpolated bathymetry in a 150m neighbourhood (inner search radius of 300m and an outer search radius of 1200m), (c) the mean interpolated bathymetry in a 1200mneighbourhood (inner search radius of 900m and an outer search radius of 3300m), and (d) the mean interpolated bathymetry in a 1200 m neighbourhood (inner search radius of 1875m and an outer search radius of 7500m).