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Maritimes Region

A Subtidal Marine Ecological Classification System to Represent Species Diversity and Distribution Patterns in the Maritimes Region

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The need to develop a Hierarchical Marine Ecological Classification System (HMECS) for classifying the structure and distribution of Canada's marine biota and habitats at multiple spatial scales has been recognized regionally, nationally, and internationally. An HMECS will help ensure that all habitats, communities, and ecosystems are effectively represented in Marine Protected Area (MPA) networks, and ensure that a structured approach is used to consider biodiversity at local, regional, and basin-wide scales during other marine spatial planning and oceans management applications.

A conceptual framework for an HMECS was identified for the Pacific Region, and then harmonized for applicability between the Pacific and Maritimes Regions. The harmonized HMECS contains 11 levels, and approaches for populating Levels 4–8, below the Bioregion level, are discussed.

The conceptual framework was applied in Pacific and Maritimes Regions to provide a systematic and spatially-explicit classification of ecosystems at multiple scales. A database of spatially-referenced information for identifying and locating key ecological properties was developed as part of this exercise. We also developed a set of spatially referenced information that can be integrated with other data layers (e.g., social, economic). These outputs are intended to support marine spatial planning and conservation in both the Pacific and Maritimes Regions, particularly the design of MPA networks.

This paper was presented and peer-reviewed at the September 29–October 2, 2015 zonal meeting on Evaluation of Hierarchical Marine Ecological Classification Systems for Pacific and Maritimes Regions held in Nanaimo, British Columbia. It describes the application of the classification in the Maritimes Region, with a focus on benthic ecosystem attributes two levels below the Bioregion level (Biophysical Domains and Geomorphic Units), including a separate classification for coastal areas. The environmental data used in the application were weighted by previous biological analyses in the region. Methods were proposed for populating the Biotope Level. These classifications will be used to help achieve the representativity criterion for MPA Network design in the Region.

TERMS

Biodiversity – Biodiversity is the variety of species in a particular habitat or ecosystem. This includes diversity within species, between species, and of ecosystems.

Biotope – A biotope is defined as the combination of an abiotic habitat and its associated community of species. It can be defined at a variety of scales with related corresponding degrees of similarity and should be a regularly occurring association to justify its inclusion within a classification system.

Bioregion – High-level spatial units have been identified for each of Canada's three oceans which are primarily based on oceanographic and bathymetric similarities (DFO 2009).

CHS – Canadian Hydrographic Service.

Community – A cluster of species, which has particular species at certain densities in common.

EBSA – Ecologically and Biologically Significant Area.

Environmental surrogates – Environmental factors that have a strong influence on species distribution or aspects of the species habitat. These can also be biological factors that influence species distribution, like predators or prey. Physical variables have been show to account for 25-75% of community variability depending on the system (Stevens and Connolly 2004, McArthur et al. 2010, Pitcher et al. 2012). Using physical variables to predict species diversity and distribution is particularly useful in the marine environment, where comprehensive biological data are rarely available.

Gradient Forest model – An extension of the random forest model, incorporating whole assemblages and identifying important thresholds or change points in assemblage distribution along the environmental variable.

Habitat – Defined here to encompass the substratum (rock, sediment or biogenic reefs such as mussels), its topography and the particular conditions of wave exposure, salinity, tidal currents and other water quality characteristics such as turbidity and oxygenation, which contribute to the overall nature of a place on the shore or seabed.

HMECS – A hierarchical marine ecological classification system is a framework to describe the structure of marine biodiversity.

Morphology – The form and structure of an organism.

NRCan – Natural Resources Canada.

Rugosity – The roughness of the bottom (change in slope).

Representativity – A representative network of MPAs is one that captures examples of different biogeographic subdivisions that reasonably reflect the full range of ecosystems which are present at the scale of network development, including the biotic and habitat diversity of those ecosystems (DFO 2013b).

Species distribution – the manner in which a biological taxon is spatially arranged.

Species Distribution Model (*SDM*) – Extrapolates species distribution in space and time, usually based on a statistical model. Developing a species distribution model begins with observations of species occurrences, and with environmental variables thought to influence habitat suitability and therefore species distribution. The model can be quantitative or rule-based model and, if the fit is good between the species distribution and the predictors that are examined, this can provide insight into species environmental tolerances or habitat preferences (Franklin 2009).

Species richness – Species richness is the number of different species represented in an ecological community, landscape or region.

Topography – The shape and features of the ocean bottom.

INTRODUCTION

A Hierarchical Marine Ecological Classification System (HMECS) is a framework to describe the spatial structure of marine biodiversity. The need to develop a HMECS for classifying the diversity and distribution of Canada's marine biota, and habitats at multiple spatial scales has been recognized regionally, nationally, and internationally for a variety of reasons:

1. to ensure that all habitats, communities, and ecosystems are considered and effectively represented in Marine Protected Area (MPA) networks; and
2. to ensure that a structured approach is used to consider biodiversity at local, regional, and basin-wide scales marine spatial planning and other oceans management applications.

Twelve major biogeographic units (bioregions) were identified for Canada's three oceans during a Fisheries and Oceans Canada (DFO) National Canadian Science Advice Secretariat (CSAS) peer review process (DFO 2009). Each of the major biogeographic units represents a "maximum scale" that is expected to be disaggregated/subdivided further into ecologically meaningful smaller spatial units for marine spatial planning and other oceans planning and management purposes.

DFO lacks a standardized marine ecological classification system; however, a conceptual framework for an HMECS was identified for the Pacific Region (DFO 2013a), and then harmonized for applicability between the Pacific and Maritimes Regions (DFO 2016). The conceptual framework was applied in Pacific and Maritimes Regions to provide a systematic and spatially-explicit classification of ecosystems at multiple scales. A database of spatially-referenced information for identifying and locating key ecological properties was developed as part of this exercise. These outputs are intended to support marine spatial planning and conservation in both the Pacific and Maritimes Regions, particularly the design of MPA networks.

The harmonized classification for benthic ecosystems was developed based on the Maritimes and Pacific Region results and is recommended for future benthic classification applications. The harmonized HMECS contains 11 levels, and approaches for populating Levels 4–8 below the Bioregion are discussed. The application in the Maritimes Region focused on benthic ecosystem attributes and populated two levels below the Bioregion level (Biophysical Domains, and Geomorphic Units), including coastal areas. Methods were also proposed for populating the Biotope level.

Application of the classification in the Maritimes was primarily based on environmental data that were weighted by previous biological analyses in the region. These methods were used to develop and populate Biophysical (Level 4) and Geomorphic (Level 5) units, and the resulting classification maps are presented. These units will be used to help achieve the representativity criterion for MPA Network design.

This classification did not include the intertidal zone, although this unit has been classified through other processes for MPA network planning and was discussed during a DFO Maritime CSAS Process (Greenlaw et al. 2013, DFO 2012). A pelagic classification system was not developed, but is recommended as future work. Current work on substrate, described below, could be used to help classify the Biotope unit (Level 6).

The intent of the hierarchical marine ecological classification system is to support management decision-making at multiple scales. Spatial data may be used in multiple DFO decision-making processes related to marine spatial planning and conservation.

PRIMARY MANAGEMENT OBJECTIVE

In 2011, DFO, and its federal partners, along with the provinces and territories released the "National Framework for Canada's Network of Marine Protected Areas", herein referred to as the National Framework (Government of Canada 2011). The overarching goals of Canada's National MPA network are: (1) to provide long-term protection of marine biodiversity, ecosystem function and special natural features; (2) to support the conservation and management of Canada's living marine resources and their habitats, and the socio-economic values and ecosystem services they provide; and (3) to enhance public awareness and appreciation of Canada's marine environments and rich maritime history and culture. Goal one is considered the primary goal of the MPA network. The National Framework also explains that the national network will be comprised of thirteen bioregional MPA networks that are to be developed in a manner that is consistent with the guidance provided under the Convention on Biological Diversity (CBD). The CBD guidance outlines five criteria for effective MPA networks, which include (1) ecologically and biologically significant areas, (2) representativity, (3) connectivity, (4) replication, and (5) adequacy/viability.

Guidance provided by DFO's Canadian Science Advisory Secretariat (CSAS) for planning representative MPA networks states that "...representative MPAs should capture examples of different biogeographic subdivisions that reasonably reflect the full range of ecosystems which are present at the scale of network development, including the biotic and habitat diversity of those ecosystems" (DFO 2010). The appropriate level of subdivision of bioregions will depend on the management objective(s) or policy requirements and available data since detailed species-specific [information is required to delineate smaller units. A CSAS National Advisory Process recommended that discussion and guidance on finer scales of biogeographic units should occur and come from the various DFO regions, through formal regional processes (DFO 2013b). The ecological classification described in this paper was developed to serve as a basis for meeting the representativity criterion in developing the bioregional MPA network for the Maritimes Region (or Scotian Shelf Bioregion), which includes the Bay of Fundy and the Canadian portions of the Gulf of Maine and Georges Bank. This work is an important step in fulfilling the commitment to develop an adequate representative MPA network design for the Scotian Shelf Bioregion.

The Coastal Protected Areas of Nova Scotia (CPANS) Working Group, which is a group of federal and provincial protected area practitioners, agreed that a classification for the coastal zone of Nova Scotia was required for coastal conservation planning and management. In 2010, CPANS recommended the formation of an ad-hoc sub-working group to address this issue. Representatives from DFO, Natural Resources Canada (NRCan), Nova Scotia Department of Environment, Nova Scotia Department of Natural Resources (NSDNR), and Dr. Jon Grant representing Dalhousie University are members of the sub-working group, herein referred to as the Nova Scotia Coastal Classification Working Group (NS CCWG).

Rather than adopt an existing classification, the NS CCWG recommended that two new classifications be developed for the coastal zone of Nova Scotia. These new classifications would reflect the availability of data in the region, current methods available for mapping, and the diversity of mandates of federal and provincial departments responsible for coastal management. First completed was the coastline classification which spans from the backshore to the subtidal 10 m depth isobaths (Greenlaw et al. 2013). Second, is the coastal subtidal classification, which spans to a depth of approximately 100 m. The latter classification also updates the offshore planning layers to incorporate knowledge gained regarding the influence of physical variables on biodiversity composition in the Gulf of Maine and to properly validate the coastal classification approach.

Separate offshore and coastal ecological classifications are described in this document. These classifications represent key input layers in the bioregional MPA network design process and may be incorporated into a decision support framework using tools such as MARXAN (Ball et al. 2009). Decision support tools enable the inclusion of other spatial marine information such as, Ecologically and Biologically Significant Areas (EBSAs, DFO 2004), other biological species abundance and distribution data, species at risk information, fitness data, aggregation data, and human use data (Horseman et al. 2011). A decision support framework will enable the assignment of targets for multiple data layers, and will ensure that the overall goals and objectives of the MPA network are met in an efficient manner that minimizes potential socio-economic costs. However, due to a lack of region-wide biological data in the coastal zone, other approaches may be used to identify a coastal MPA network, such as a Delphic method to rank EBSAs coupled with a GIS overlay using both the intertidal and coastal subtidal classifications, where the next candidates for protected areas should be representative of different types of ecological units that are not already protected.

Mapping species diversity and distribution can also contribute to a suite of biodiversity indicators for incorporation into an Ecosystem Approach to Management (EAM). Some examples of other applications that have and could use these data include oil spill response planning, Species at Risk Critical Habitat delineation, EBSA delineation, Sensitive Benthic Area Delineation, ecosystem status reporting, and MPA monitoring.

HIERARCHICAL MARINE ECOLOGICAL CLASSIFICATION SYSTEM

An HMECS for benthic ecosystems, including the coastal zone and offshore, was developed based on the DFO Maritimes and Pacific Regions applications (Table 1). The HMECS is based on a conceptual hierarchy from Last et al. (2010), identified by a DFO Pacific Region CSAS process (DFO 2013a), and modified to incorporate scales and biogeographic patterns important in the Maritimes and Pacific region (DFO 2016). The harmonization effort focused on Levels 4 through 8. Levels 1–3 (Realm, Province, and Bioregion) and Levels 9–11 (Species, Populations, and Genes) remain as described in the conceptual hierarchy (DFO 2013a).

Each level of the hierarchy describes attributes and surrogates to reflect the spatial scale, extent, and range of biogeographic and ecological processes. These processes determine the spatial and temporal distribution of marine biota. The upper levels (1–8) of the hierarchy, from Realm to Micro-assemblages, are ecosystem based and require environmental data to delineate, while the lower levels (6–8) biological data. Although levels 1–5 (Realms to Geomorphic Units) do not require biological data, they are preferably developed in conjunction with biological data to determine which variables are most important for structuring biological composition in the Region. In the absence of biological data, environmental variables can be used on their own. The Biotope level and levels nested within (Levels 6–8) will require in-situ sampling to delineate the class boundaries. At these levels, data are rarely available at region-wide extents due to the time consuming nature of direct surveys, using benthic sampling equipment, underwater imagery and/or acoustic representations of the sea bottom. The three basal levels (9–11) are species-based.

Subdivisions within each level may be desirable to capture specific patterns, and were identified in the Maritimes application within the Biophysical level (Level 4). When applying the framework, Last et al. (2010) describes the necessity of nesting units within levels above. This requires recognizing that the same Geomorphic Units (Level 5) within a Biophysical Unit (Level 4) combination should have a similar array of biological components. Similarly, while Geomorphic Units may nest conveniently within a single Biophysical Unit, there are exceptions; for example, a canyon extending down the continental slope will typically extend through a broad depth range crossing multiple depth regions. In such instances, the canyon, which is the Geomorphic Unit, may exceed the scale of individual Biophysical Units. Each Biophysical Unit in the canyon should have a biotic composition distinct from those adjacent, because these units typically have different biotas associated with different depths and substrata. The units should be considered independently, for example, in an MPA selection process. If any unit is excluded from this process, then representativeness of the MPA network would be compromised.

The intent of the hierarchical marine ecological classification system is to support management decision-making at multiple scales. Spatial data may be used in multiple DFO decision-making processes related to marine spatial planning and conservation (i.e., the development of indicators for implementation of an Ecosystem Approach to Management), Species at Risk Critical Habitat identification, Sensitive Benthic Area identification, oil spill response planning, and aquaculture siting. Multiple spatial scales may be used in these decisions, as illustrated in Table 2. The spatial level used to support decision-making will depend on the specific objectives to be achieved. Table 2 represents a first approximation of the present context in DFO; future application of spatial data may reflect changing priorities.

Methods were used to classify Coastal and Offshore Biophysical and Geomorphic Units (Levels 4 and 5) separately on the Scotian Shelf. Offshore areas were classified separately, due to the slightly different scale of offshore features. We propose a method to classify one component of Biotope units (substrate), but the method has not yet been published. It is recommended that this be pursued over time as classification at fine resolution will be valuable to marine spatial planning and management decisions relevant to decisions other than MPA Network planning (i.e., oil spill planning, aquaculture siting, MPA boundary delineation).

These ecological classification layers will populate the mid and lower scales of the HMECS (Table 1, Levels 4 and 5). These layers nest within already developed coarser scale ecological classification layers (DFO 2009). Guidance is provided on methods to establish appropriate finer-scale micro-habitat and species-based planning layers, including their possible management uses.

Layers will be further developed at the lower scales, when data is available, to incorporate other primary habitat components such as biology and oceanography. This is important to ensure that planned MPAs are representative of finer-scale habitat/biotope patterns within MPA planning units. A primary habitat/biotope scale is also an appropriate scale for other DFO management objectives, including management of benthic fisheries and aquaculture siting.

Biophysical and Geomorphic Units are expected to be at an appropriate scale for MPA network planning on the Scotian Shelf. Research has shown that the conservation benefits of MPAs were increased with larger MPAs (> 100 km^2, Edgar et al. 2014). Existing MPAs on the Atlantic Coast of Canada have ranged from 2 km^2 to 4300 km^2; however, larger areas including the Fundian Channel – Browns Bank in the Maritimes Region and the Laurentian Channel in the Newfoundland and Labrador Region have been proposed as Areas of Interest, the first step in potentially becoming an MPA.

SOURCES OF UNCERTAINTY

It is important to note when identifying units in each level that data aliasing (i.e., the differences in the spatial, or temporal scales, and resolution of the biological and environmental data) can impair the detection of meaningful ecological associations between biological and environmental data and thus, the location of precise boundaries between adjacent units.

A hierarchical classification relying on physical environmental "surrogates" to represent patterns in habitat and community structure may not perform as well as biological classifications at fulfilling the biodiversity representativity criterion in conservation planning. However, classifications using only biological data cannot be representative of the entire ecosystem, from micro-macrofauna.

The location and boundaries of some spatial units may change over time as a result of changing environmental processes, conditions, and interactions in response to global events such as climate change. Applications of the methods here produce a snapshot of habitat and community structure, but they do not capture temporal changes. Temporal change can be accommodated with a process to update the classifications on an ongoing basis, including components used to define biophysical units.

HIERARCHICAL LEVELS

Levels 2 and 3 Province and Bioregion

First-order and second-order subdivisions of Canadian marine biogeographic units, herein referred to as Provinces and Bioregions, were delineated by DFO Science (DFO 2009). It was agreed by the Canadian Council of Resource Ministers (CCRM) that three Bioregions were appropriate for the coarsest provincial scale of the Atlantic Ocean (Figure 1); the Scotian Shelf, the Newfoundland-Labrador Shelves, and the Gulf of St. Lawrence. The criteria given for subdivision were the marked differences in the fish and plankton communities between the core areas of the Scotian Shelf and the Newfoundland-Labrador Shelves. The exact line between the two biogeographic units was uncertain. The respective slopes down to the Laurentian Channel were suggested to be part of the respective shelf units. However, the trough itself was cautioned to be best viewed as a permanent transition zone, with its greater depth contributing to unique features (DFO 2009).

On the south end of the Scotian Shelf biogeographic unit, the Bay of Fundy-Georges Bank areas have biogeographic affinities with the Gulf of Maine and the Scotian Shelf. It was suggested, by those identified by the CCRM, that this boundary would be best represented as a first-order subdivision of the larger Scotian Shelf biogeographic unit, which has been incorporated into regional planning. For regional planning, the Scotian Shelf Bioregion was further subdivided into three planning regions (Greenlaw et al. 2013) to acknowledge the coarsest scale Oceanographic and Geomorphic Units. This was done to facilitate consultations with different stakeholder groups, and to reflect data availability. These units are the Atlantic Coast of Nova Scotia, the Offshore Scotian Shelf, and the Bay of Fundy. The boundaries between the Bay of Fundy and Atlantic Coast planning areas were determined through the coastline classification process and then re-examined though the creation of the coastal subtidal classification (Figure 2).

To demonstrate these biogeographic divisions, the Gulf of St. Lawrence is used as an example. The Gulf of St. Lawrence contains differences in fish, plankton, and benthic communities when comparing the southern Gulf and the northern Gulf; there are also some affinities of those communities in the southern Gulf with those in the Scotian Shelf biogeographic unit. The dominant oceanographic processes provide coherence to the Gulf of St. Lawrence as a distinct biogeographic unit, but more investigation of benthic communities and their affinities for the Scotian Shelf and Gulf of St. Lawrence Bioregions might reveal some different patterns in the benthos than reflected in these major subdivisions (DFO 2009).

For administrative and practical purposes, MPA network planning for the Scotian Shelf Bioregion will take place within the boundaries of DFO’s Maritimes Region (Figure 1), which contains the entire Scotian Shelf Bioregion, but overlaps with the Gulf of St. Lawrence Bioregion in the Sydney Bight area.

Level 4 Biophysical Units

Biophysical units were delineated using two environmental component layers: oceanography and depth. Biological relationships were previously demonstrated for the variables making up these components, for 2/3 of the study area, and used to assign weightings to these components (Pitcher et al. 2012).

The oceanographic layer was created using benthic temperature, benthic salinity, and benthic current stress which were readily available as modeled variables across the Scotian Shelf, and were identified as important explanatory variables of benthic biodiversity in Pitcher et al.'s (2012) Gradient Forest in the Gulf of Maine and over 2/3 of the Scotian Shelf. These variables were weighted by their 'importance', a metric from the Gradient Forest analysis, extracted for the portion of the analysis over the Scotian Shelf, for structuring biodiversity composition.

Depth was derived from a high resolution (approx. 50 m) bathymetry, described below. Breakpoints defining bathymetric zones were also identified from the Scotian Shelf portion of Pitcher et al.'s (2012) Gradient Forest analysis, as the most important regions along the depth gradient for influencing changes in species diversity and distribution.

The oceanography and bathymetry components were overlaid to define Biophysical Units and boundaries in this layer were smoothed where overlaps of the components were slightly spatially separated, up to a maximum of 500 m. Although the resolution of the oceanographic and bathymetric layers is finer than 500 m (35 m for oceanography and 50 m for bathymetry), the underlying data used to create the layers was of variable resolution and, beyond well surveyed areas, does not achieve a native density of less than 500 m.

Future work could pursue a species-based approach to create a classification layer for Levels 4 and 5 of the offshore component, incorporating biological data, similar to Pitcher et al. (2012). A species-based approach, however, could not be used for the coastal component of the classification due to the lack of region-wide biological data. A comparison between offshore approaches is recommended, as the approach presented in this report is designed to account for community patterns from micro- to macrofauna. Incorporating biological data would leave the final layer biased towards those species that we are able to measure.

The main difference between the HMECS applied to the Scotian Shelf Bioregion and Pacific Northern Shelf Bioregion lies in the generation of the levels of the framework starting at the Biophysical Unit level. Although they are at approximately the same spatial extent (100 – 1000s km), to operationalize the PMECS Biophysical (Level 4), Rubidge et al. (2016) take a traditional biogeographical approach using species composition to define areas where clusters of similar species occur, whereas the Maritimes layers use a physiographic approach to create Oceanographic and Bathymetric Units, and then use biological data to validate the abiotic units. Both approaches are valid and are driven by the needs of the region, previous existing classifications in the region, and the availability of data.

Level 4a – Oceanographic Units

Oceanographic Units were not included in Last et al. (2010)'s classification system, or in the Pacific Region's delineation of Biophysical units, but they have been included in the Biophysical Units on the Scotian Shelf due to overwhelming evidence that oceanographic factors structure biodiversity at a meso-scale on the Scotian Shelf. There are a variety of oceanographic variables that generally affect species diversity and distribution. Productivity and temperature have been historically ascribed as the greatest direct influence over benthic organisms. On the Scotian Shelf, oceanographic differences between the eastern and western Scotian Shelf have long been recognized; the eastern shelf experiences colder bottom temperatures and lower base productivity than the western shelf due to different levels of input from the Labrador

Current and Gulf Stream. Regional differences in oceanographic conditions result in communities dominated by small demersal and pelagic fish species, and benthic macroinvertebrates on the eastern Scotian Shelf. The similarity in species composition of the east and west reflects their geographic proximity, while differences in growth rates between the east and west reflect the climatological temperature and base productivity differences (Shackell and Frank 2007). The Western Scotian Shelf is expected to have greater resiliency, due to higher average summer bottom temperatures, which result in high biological productivity sufficient to stabilize the system. The east and west are separated by Emerald Basin, which has been considered an impediment to the migration of some species (Shackell and Frank 2007). Over the Scotian Shelf, the Nova Scotia Current has been recognized as a strong localized flow adjacent to the coast, bringing in cold, less saline water from the north and the Gulf of St. Lawrence, as well as much of its *Calanus* supply (Herman et al. 1991).

Variables were chosen to be included in the Oceanographic Units layer based on the results of a Gradient Forest analysis applied over 2/3 of the Scotian Shelf. The analysis was applied over both the Gulf of Maine and 2/3 of the Scotian Shelf; however, for classification, results were extracted from the Scotian Shelf portion only. This analysis provided a ranking of physical and oceanographic variables on the structure of benthic biodiversity composition (Pitcher et al. 2012).

Benthic temperature, sea surface temperature, benthic salinity, surface chlorophyll, and benthic current stress were the oceanographic variables shown to explain the most variability in biodiversity composition on the Western Scotian Shelf by Pitcher et al. 2012 (Figure 3). Of these variables, only benthic variables were chosen to be included in the Oceanographic Units layer (benthic temperature, benthic salinity and benthic current stress). Even though pelagic variables showed high predictive capability in the Gradient Forest analysis, they are not expected to be direct drivers of benthic biodiversity composition (variables with a physiological influence on a species; indirect surrogates correlate with direct drivers, but have no physiological connection to the species (McArthur et al. 2010)). Ideally, variables describing direct and resource gradients would always be used as predictors to develop a classification representative of biological community patterns. Moreover, pelagic variables included in the Gradient Forest analysis are expected to show a high correlation to benthic variables important for structuring species composition on the Western Scotian Shelf (e.g., stratification, and upwelling and tidal mixing). For example, Sea Surface Temperature shows a large change where the tidal amplitude begins to increase as you enter into the Bay of Fundy. Benthic irradiance and stratification were included in the analysis. Benthic irradiance came out as highly important. Stratification did not come out highly ranked; however, the stratification layer was based on low density sampling data from the water column. These factors are only expected to show a structuring force on the Western Scotian Shelf, where higher tides dominate the ecosystem structure. A sensitivity analysis was suggested to evaluate the influence of removing pelagic variables from the Oceanographic Units; however, this was not performed due to reasons described above and timing constraints.

The variables included were normalized (from 0–1) and combined into a single layer (Figure 4) using weightings based on their approximate ‘importance’ (a metric output from the Gradient Forest analysis) for structuring biodiversity composition. These included benthic temperature (40%), salinity (35%), and benthic current stress (25%), based on the results of Pitcher et al. 2012. From this layer, nine Oceanographic Units were identified (Figure 4, Figure 5 and inset Figure 6):

Region 1 - Bay of Fundy and Eastern Nova Scotia Inshore: High benthic Temperature (T), low benthic salinity, high Chla, high Root Mean Square (RMS) currents

Region 2 - Gulf of Maine: High benthic T, high benthic salinity, med. Chla, med RMS currents

Region 3 - Baccaro and LaHave Bank: High benthic T, med. benthic salinity, med. Chla, low RMS currents

Region 4 - Atlantic Inshore: Low benthic T, low benthic salinity, high Chla, low RMS currents

Region 5 - LaHave and Emerald Basin: High benthic T, high benthic salinity, high Chla, low RMS currents

Region 6 - Western and Sable Island Banks: High benthic T, med. benthic salinity, med. Chla, low RMS currents

Region 7 - Eastern Scotian Shelf: Low benthic T, med. benthic salinity, high Chla, med. RMS currents

Region 8 - Characteristics of Laurentian Slope

Region 9 - Characteristics of the Slope, Rise, and Abyss

Oceanographic layers were derived from numerous sources. Their compilation is described in an unpublished report by Smith (2005) detailing the creation of many layers to derive an offshore habitat template model (Kostylev and Hannah 2004, DFO 2005) for the Gulf of Maine.

Benthic salinity and benthic temperature layers (Figure 7A and 7B) were derived using data compiled for the publication of Naimie et al. (1994). The original data collected by Naimie et al. (1994) were obtained from historical temperature/salinity databases assembled from Canadian national archives and cruises, although it was not made clear which specific databases were used. Climatological mean density fields were calculated for each of the six bimonthly periods (January–February, March–April, May–June, July–August, September–October and November–December). The temporal range of the data was from 1912 to 1991, with the highest data density from 1964 onward. When oceanographic models including current data become available, this layer could be redone to compare boundary changes over time, especially in light of climate change.

For each period, all bottle and conductivity-temperature-depth (CTD) data from a four-month rolling interval centered on the middle of a given bi-monthly time-period, which passed standard quality control, were used as input. The number of input stations/profiles over the greater Gulf of Maine-Scotian Shelf region ranged from about 11000 for January–February to about 21000 for September–October. The fields were interpolated to the nodes of a finite element mesh covering the Gulf of Maine in its entirety and features length scales ranging from 10–500 m (Lynch and Naimie 1993). The values are assumed to be one meter above the seafloor.

Mean annual benthic temperature and salinity data from Naimie et al. (1994) was used by Smith (2005) to compute the temperature and salinity averages, while temperature and salinity variability was calculated as the seasonal maximum and minimum. Seasonal benthic temperature layers were created by Hannah et al. (2001), using data from 1950–1994. Although it was not stated how variability was calculated, the interpolation of seasonal layers smooths variability due to river plume movement, shelf break variations, and warm core rings, leading to artificially low variability in frontal and nearshore regions. Interannual and super-seasonal variability is also ignored. For use in the nearshore, these layers can only define a general offshore condition, rather than actual nearshore values. The resolution of the seasonal benthic temperature layers is 500 m^2/pixel.

The bottom stress (Figure 7C) for tidal and subtidal currents was also derived by Smith (2005) using Root Mean Square (RMS) of the tidal and seasonal circulation described by Lynch and Naime (1993) and Lynch et al. (1997).

All oceanographic variables compiled are representations from historical data sources (1992 and earlier). These data were chosen as they represent a model of the oceanographic environment, rather than an interpolated one. The density, resolution, and error associated with the original data used to create this model were not available. Work is currently underway to produce interpolated layers of benthic temperature and salinity for current periods.

Level 4b – Bathomes

Depth has been shown to be one of the strongest environmental correlates of fish and benthic community structure globally and on the Scotian Shelf/Gulf of Maine (MacArthur 2010, Pitcher at al. 2012). Bathomes were described by Last et al. (2010) as finer-scale subdivisions of Bioregions that are characterized primarily by the bathymetric distribution of the biota. Last et al. (2010) describes the governing factors at this level as temporally evolving, depth-related processes such as depth-layering of water masses, contemporaneous physiological constraints on species depth distributions, and depth-related differentiation in habitat distribution defined by geophysical constraints. Similar to provinces, the spatial scales of Bathomes are large relative to units at lower levels of the hierarchy. Bathomes often exceed 1000 km^2 and even more at abyssal depths. Historically the sea has been divided by ecologists into neritic and oceanic zones, with the boundary between them demarcated at the Continental Shelf margin, which is often defined by the point of greatest gradient change between the shelf and slope. The dramatic depth change here is illustrated by a representative depth profile of the Scotian Shelf (Figure 8). Bathomes are often different from each other due to the biotic compositions of demersal species, and need to be treated as independent ecological units.

Bathomes were created for the Scotian Shelf using guidance from a Gradient Forest analysis, which determined the most transitory depth zones for community composition patterns on the Gulf of Maine and 2/3 of the Scotian Shelf (Pitcher et al. 2012).

The bathymetry layer (Figure 9A) was derived using a combination of contour, sounding, and multibeam data (Figure 9B) obtained from the Canadian Hydrographic Service and the University of New Brunswick Ocean Mapping Group. The multibeam data layers used were at a resolution of 10 m, with exceptions in Passamaquoddy Bay, Grand Manan and the Saint John area of the Bay of Fundy, which were at a resolution of 1 m. Incorporated sounding data were at an average nearest neighbor of 64.2 m between soundings. An average nearest neighbour (ESRI, 2013) calculation was run on the sounding data to determine the optimal resolution for the output layer (Figure 9C). The nearest neighbour calculation computes the average distance from each sounding point to its closest neighbouring point. Table 3 provides the resolution of the original data sources.

The contour and sounding data were converted from the vertical datum, Chart Datum, to Mean Water Level and interpolated using a Triangular Irregular Network (TIN) (ESRI, 2012), before being converted to a raster grid. Creating a TIN allows contour lines to be incorporated into the model, using a “soft line” method for contour data, and a “hard point” method for sounding data. Using these two methods together allows for flexibility using contour lines when they overlap with the sounding data. Sounding data dominate and maintain their depth values, as they are expected to be more accurate.

Breakpoints were selected as the most important regions along the depth gradient for influencing change in species diversity and distribution patterns, using DFO and National Marine Fisheries Service Centre (NMFSC) current and historical benthic trawl and grab data (Pitcher et al. 2012) including breakpoints at (Figures 10 and 6): 50 m, 110 m, 200 m, 300 m, 500 m, 1000 m, 1500 m, 2000 m, 3000 m, and 4000 m.

Level 5 Geomorphic Units

Geomorphic Units are based primarily on geomorphology, and typically smaller in size than Bathomes and Oceanographic Units. They are assumed to be surrogates for distinctive biological assemblages (Last et al. 2010) responding to ecological niches provided by aspects of their physical environment.

Surrogate relationships for some Geomorphic Units, such as estuaries, are well documented, but remain largely invalidated for others, such as those differentiated in the deep sea (Heap and Harris 2008). On the Scotian Shelf, the deep sea has distinct community types within its basins and banks. Deep Scotian Shelf basins harbor large populations of zooplankton during autumn and winter. This storage mechanism is the dominant supply of young copepods in surface waters during the spring. Weak circulation within the basins ensures that the copepod populations are not displaced throughout the year (Herman et al. 1991). Banks on the Scotian Shelf, such as Georges Bank, often experience higher current stress. On Georges Bank, strong tidal currents over steep topography lead to a tidal mixing front along the northern flank (Dale et al. 2003). Primary production on this bank has been estimated to be about 40% greater than the surrounding shelf regions and fish production is also twice the surrounding regions (Cohen et al. 1982).

The Scotian Shelf also contains unique Geomorphic Units such as the Gully. The Gully is a highly productive Geomorphic Unit, with high diversity, and due to its depth has a high density of cetacean species. It is also expected to have high finfish diversity due to immense habitat heterogeneity expanding over several depth ranges. Another unique geomorphological feature is The Bay of Fundy; it is a large estuarine bay with a shape and topography that contribute to an extremely macro-tidal environment, resulting in the highest tides in the world. Species composition is known to change from the Gulf of Maine and Scotian Shelf upon entering the bay.

Geomorphic Units were defined based on Fader's (2007) original seabed feature units for the Gulf of Maine and Scotian Shelf, and reworked to incorporate additional coastal and offshore geomorphic features such as: coastal inlets, topographically complex areas in the coastal regions and offshore area, slope and plain features, and canyons. Nomenclature was also transferred to standard descriptions normally used to identify geomorphic units from the work of Greene et al. (1999).

The resulting classification includes 12 geomorphic units at two distinct scales (Figures 6 and 11):

Level 5a – Geomorphic Level 1 – Higher-level geomorphic units including Inland Seas, Inner Shelf, Shelf, Slope, Continental Rise and Abyssal Plain. These also correspond to Oceans and Coastal Management Division's Planning Regions (Figure 2).

Level 5b – Geomorphic Level 2 – Finer scale geomorphic units including Inlets, Banks, Basins, Flats, Channels, Topographically Complex Area, Topographically complex Banks, Topographically Complex Basins, Canyons.

COASTAL CLASSIFICATION

DEFINING THE COAST

The Oceans and Coastal Management Division requested that coastal data be separated from the offshore data; this requires defining the coast, which can be complicated for several reasons. First, the term "coastal zone" is widely used and is often defined according to the issue or task. For the purpose of DFO's MPA network planning within the Scotian Shelf Bioregion, the seaward limit of the coastal zone was defined as the 110 m depth contour (Figure 2). The landward limit was defined as the high-water mark in accordance with the National Framework (Government of Canada 2011).

The coastal zone layer was further subdivided into large and smaller scale sub-divisions along the coast. These subdivisions were established using along shore oceanography and geology. Divisions were manually drawn, with underlying geological and oceanographic layers.

COASTAL HIERARCHICAL LEVELS

Coastal Biophysical Units (Figure 12 inset) and Geomorphic Units (Figure 11) were developed using similar environmental data sources to those used for the offshore Scotian Shelf. The Biophysical and Geomorphic Units developed offshore Scotian Shelf are expected to be sufficient for MPA Network planning in the coastal zone, and for most other DFO uses.

Level 4 – Biophysical Units

Level 4a – Oceanographic Units

Oceanographic units in the Coastal Zone are a combination of the Biophysical Unit scale and the Biotope scale. Units were developed using a weighted average of environmental factors (Figure 7); a combined overlay of a Principal Component Analysis (PCA) of oceanographic factors (40%; oceanographic factors were described in the offshore section) and phi scale substrate (60%; substrate data layer described below). This combined layer was classified into 9 distinct classes of oceanography and substrate (Figure 13).

Coastal Oceanographic units (Figures 12 and 13: whole numbers):

1. Bay of Fundy
2. Quoddy Region
3. Grand Manan and Environs
4. German Bank and Environs
5. South Shore
6. Eastern Shore
7. Southern Cape Breton
8. Eastern Cape Breton
9. Bras D'Or Lakes

Level 4b – Bathomes

Bathomes are the same as those in the offshore. In the Coastal regions bathymetric breaks were at 50 and 110 m (Figure 10).

Level 5 – Geomorphic Units

Geomorphic units in the coastal zone were included with the offshore layer presented above. Coastal Geomorphic units include (Figure 11):

Level 5a – Geomorphic Level 1 – Bay of Fundy and Inner Shelf

Level 5b – Geomorphic Level 2 – Inlet, Flat, Bank

Level 6 – Biotopes

Finer scale (10s m to 100s km) variables are becoming available for the coastal portion (< 110 m) of the Scotian Shelf. Substrate is one of three components necessary to develop a complete picture of Biotopes (Table 1; Substrate, Biology and Oceanography). Finer scale substrate units have been developed, including a variety of habitat attributes such as: surficial grain size, dominant grain size, range of grain sizes, primary benthic type (hard, mixed, soft) and secondary benthic types (Greenlaw et al. Unpublished[1]) to begin to populate Biotope levels of the ecological classification hierarchy. These layers have been used to develop a preliminary Biotope Units using only substrate for the coastal zone (Figure 13). Finer scale layers are useful for coastal MPA Network Planning, as the size of MPAs in the coastal zone are also expected to be smaller, coastal areas include less migratory species, and smaller regions will protect a larger proportion of species.

Coastal Biotopes include (Figure 13: lettered numbers):

1a. Chignecto Bay Soft Substrates

1b. Minas Basin Soft Substrates

2. Bay of Fundy Sand and Gravel

3a. SW New Brunswick Soft Substrates

3b. Owen Basin Gravel

4a. Passamaquoddy Islands Bedrock

4b. Inner Passamaquoddy Soft Substrates

5a. West Grand Manan Gravel

5b. Grand Manan Bedrock and Soft Substrates

6. Outer Bay of Fundy

7a. Metaghan Mixed Substrates

7b. Meteghan Offshore Mixed Substrates

8a. Lobster Bay/German Bank Inshore Mixed Substrates

8b. German Bank Offshore

9a. Shelburne Mixed Substrates

9b. Port Mouton Bedrock and Mixed Sediments

9c. Mahone Bay Islands and Soft Sediments

9d. Sambro Bedrock Ledges

9e. Shelburne Port Mouton Offshore Mixed Sediments

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[1] Greenlaw, M.E., Schumacher, M., King, E., McCurdy, Q., Smith, K., Doon, M., Page, F. and Kostylev, V. Unpublished. A substrate classification for the inshore Scotian Shelf, Maritimes Region. Can. Tech. Rep. Fish Aquat. Sci. xxxx. iv + 46 p

10. Soft Substrate Inlets and Sand/Gravel Offshore

10b. Musquodoboit Offshore Sand and Gravel

11a. Eastern Shore Islands Bedrock and Fine Substrates

11b. Eastern Offshore Mixed Substrates

12a. Country Harbour Sedimentary Inlets

12b. Tor Bay Mixed Substrates

12c. Canso Bedrock Ledges

12d. Tor Bay Offshore Mixed Substrates

13a. Chedabucto Bay and Isle Madam Mixed Substrates

13b. Gabarus Sand and Bedrock

13c. Southern Cape Breton Offshore Mixed Substrates

14a. Eastern Cape Breton Mixed Substrates

14b. Eastern Cape Breton Offshore Mixed Substrates

15. Bras D'Or Fine Substrates

Substrate Layer

Substrate has many characteristics that biological organisms respond to but many are difficult to map for habitat classification purposes. Common substrate characteristics that could be mapped include average substrate grain size, the range of substrates present, sediment organic matter content, microbial abundance and microbial composition (Snelgrove and Butman 1994). It is especially difficult to determine these aspects of the surficial sediment layer from traditional geological characterizations.

Geologists (NRCan) have a different mandate when characterizing geology, with more focus on resource development verses habitat mapping, resulting in characterizations concerning the underlying geology rather than the surficial sediment. In the Maritimes Region, the surficial geology is often determined by glacial history and characterizations can include a wide variety of surficial substrate grain sizes. It is common practice to identify five surficial sediment units: Scotian Shelf Drift, Emerald Silt, Sambro Sand, Sable Island Sand and Gravel, and LaHave Clay (Fader et al. 1977).

These geological descriptors are used to acknowledge the dominant processes determining surficial substrate where shelf wide glaciations existed. This has provided a widely used conceptual framework for understanding the distribution and character of sediments on the Scotian Shelf. Over 60% of sediments on the continental shelf are predominantly relict, exhibiting dominant characteristics of past environments with little modern influence. However, this can be problematic for biologically based habitat descriptions as we see with the classification of till. The classification of glacial till (Scotian Shelf Drift) allows for a wide variety of mud, sand, and gravel mixtures to be summarized within a coherent depositional unit (till) directly deposited by glacial ice as a moraine.

To make these original geological descriptors into something useful for biologists, a framework is being created (Greenlaw et al. Unpublished) to translate and map original geological descriptors into those of use for a wide variety of projects and management decisions within DFO. A map of the substrate classification is included (Figure 14).

Currently, biological and oceanographic data layers at a similar scale are not available as region-wide datasets to be incorporated into coastal Biotope layers. Data describing accurate patterns of oceanography and biology would need to be available at the resolution of tens of meters to hundreds of kilometers. They also do not include data from coastal areas that sufficiently captures the variety of oceanographic conditions in the coastal zone. The coastal zone is a highly transitional area, which is influenced by the terrestrial environment as well as the open ocean.

DISCUSSION

VALIDATING THE OFFSHORE CLASSIFICATION LAYERS

The ecological classification was planned to initially cover only the coastal zone (< 110 m); however, the classification was extended to cover the offshore component of the Bioregion for two reasons. The first being that knowledge could be incorporated from a Gradient Forest analysis applied in the Gulf of Maine (Pitcher et al. 2012). The Gradient Forest analysis provided better knowledge of the variables expected to be the most important influences on species diversity and distribution patterns in the Gulf of Maine and similar influences are expected on the Scotian Shelf. This knowledge was learned subsequent to the creation of previous offshore planning layers (Kostylev and Hannah 2004, Fader 2007).

The second reason the classification was extended to the offshore is that the offshore has a wide variety of biological survey data that can be used to validate the ecological classification layers. Such a validation will provide evidence that the approach is appropriately incorporating variables that contribute to biodiversity composition patterns in the coastal zone. Once more detailed biological data becomes available, the coastal portion of the classification can also be validated to ensure its accuracy.

A preliminary validation of the Oceanographic, Bathymetric, and Geomorphic Units was completed using a Principal Component Analysis (PCA) of individual species distribution layers from the DFO Ecosystem Survey (Figure 15). The PCA of species distribution layers is overlaid onto the combined Oceanographic, Bathymetric, and Geomorphic Units. This provides a limited visual validation (visual comparison of whether patterns in the PCA layer of species distributions corresponds to the distribution of classification units).

Species included in the PCA layer were ecologically significant, depleted, rare or dominant. The analysis included a total of 32 fish species. Fish distributions were interpolated using Inverse Distance Weighting (IDW). For more information on how species layers were categorized, or created, consult Smith (2005).

In the future, the classification units could be validated using more quantitative methods. Validating the layer using multidimensional scaling of ecosystem survey data would ensure that each unit captures a unique species make-up (are significantly different from one another). With this approach, the classification could be simplified if classes are found to be statistically similar.

A preferred approach to create the classification layer would be to use a community distribution modeling method, similar to the one used by Ferrier and Guisan (2006), or Pitcher et al. (2012). A Gradient Forest analysis would be the most appropriate method, as it accounts for non-linear patterns, and importance of each variable. Using a Gradient Forest analysis would also incorporate the portion(s) along the gradient of each variable that are most important for influencing biodiversity composition patterns.

EXAMPLE MPA NETWORK OBJECTIVES

Biophysical Units are an appropriate starting point for considering representativity in preliminary MPA network planning. However, the classification will be further developed as a hierarchical classification so finer-scale ecological units can be delineated to determine whether planned MPAs within each region are truly representative. Within each Biophysical and Geomorphic Unit there will be a variety of primary habitats/biotopes. The protected areas that cover each Unit should capture the variety of primary habitats/biotopes within that unit. To accomplish this, further classification at finer scales incorporating biological data should be pursued over time. However, this is a long-term process that is not required to move forward with MPA network planning. Layers can be used in their current state, and adapted as necessary.

There are various possible configurations for a comprehensive network of MPAs in the coastal zone depending on conservation priorities, data availability, funding, personnel availability, political will, and public support. Example MPA network objectives for the Scotian Shelf/Bay of Fundy Bioregion, which ensure representation at the minimum starting scale of Oceanographic Units are listed below. It is recommended that representation be incorporated at progressively finer scales as an iterative process, as more MPAs are added to the Network. An eventual goal of MPA Network planning should be to incorporate representation at the primary habitat/biotope scale. Classification of primary habitats would require physical factors at the resolution of at least 10s of kilometers and the classification of substrate-based units at the same scale for coastal and offshore habitats. These scales are not yet approachable in many of the ecoregions of Canada, especially the Arctic.

Example MPA network objectives for the Scotian Shelf Bioregion that first ensure representation at a minimum starting scale of Oceanographic Units, would be:

1. Protect a percentage of each Level 4a - Oceanographic Unit; Offshore: Figure 5, Coastal Region: Figure 12. Ensure that these are nested within the coarser scale layers (Provinces and Bioregions).
2. Protect a percentage of each Level 4 - Biophysical Unit (Oceanographic Units and Bathomes; Offshore: Figures 5 and 10, Coastal Region: Figures 10 and 12. Ensure that these are nested within coarser scale layers (Provinces and Bioregions).
3. Protect a percentage of each Level 5 - Geomorphic Unit; Offshore and Coastal Region: Figure 6. Ensure that these are nested within the coarser scale layers (Level 5 - Biophysical Units).
4. Protect a percentage of each Level 6 – Biotope. Only available in the Coastal Region: Figure 13. Ensure these are nested within Biophysical and Geomorphic Units.

Iterations of examples one or two above are likely to be the primary objectives for MPA Network planning until ample data are available to incorporate features at finer scales in the HMECS.

COMPARISON TO PREVIOUS ECOLOGICAL CLASIFICATION LAYERS CREATED FOR MPA NETOWRK PLANNING ON THE SCOTIAN SHELF

The classification units build on previous ecological classification layers created for MPA network planning. Previously, Oceans and Coastal Management Division incorporated the Kostylev and Hannah (2004, 2007) Habitat Template Model, and Geomorphic Units created by Fader (2007) for World Wildlife Fund. Kostylev's framework adapts Southwood's (1988) habitat template theory to characterize seabed habitats. The template is based on the ecological theory that habitat properties, and consequently life history strategies of benthic organisms, are thought to be determined by two major forces – Disturbance (habitat stability) and Scope for

Growth (severity of environmental conditions). Although theoretical approaches to mapping species diversity and distribution are often used in absence of measured statistical relationships between species' and their environment, the degree and ranking of structuring environmental variables is expected to differ between regions.

The Biophysical and Geomorphic Units are made up of physical environmental variables including many of the same layers that were included in the Kostylev and Hannah (2004) Habitat Template Model. In comparison to the Habitat Template Model, environmental variables were chosen to be included in the make-up of the Biophysical Units based on their importance for structuring species diversity and distribution on the Western Scotian Shelf (Pitcher 2012). A table is provided comparing the original layers included in the Kostylev and Hannah (2004) approach, and their importance in the Gradient Forest analysis (Table 4). In a comparison of Gradient Forest analyses in three regions, the Gulf of Maine, Gulf of Mexico and on the Great Barrier Reef, Pitcher et al. (2012) did not find that the three regions had similar structuring variables. For the Gulf of Maine and Western Scotian Shelf, the Gradient Forest analysis provided detailed knowledge of the best environmental predictors of species diversity and distribution in the region. However, these relationships are only based on the species data where available, which are biased towards the large components of the ecosystem that we can measure (species measured by the ecosystem survey). It would be beneficial to compare and contrast the both methods, when a Gradient Forest layer for the entire Scotian Shelf is developed.

FURTHER DEVELOPMENT OF THE ECOLOGICAL CLASSIFICATION HIERARCHY

Through scientific consensus, eventually a standardized ecological classification system should be developed for National use. This HMECS represents a zonal approach that could be used to further flesh out an inclusive classification approach nationally. Developing a standardized Ecological Classification System is data intensive and will involve DFO and numerous partners contributing to provide and analyze data, data products, and models, which constitute essential elements of the system.

A classification of pelagic habitats and communities using the HMECS is needed in both Pacific and Maritimes Regions. Because biological and environmental processes, and interactions, in benthic and pelagic systems may differ in scale and distribution, a hierarchical marine ecological classification system for pelagic ecosystems may differ from the structure of the HMECS developed here for benthic ecosystems.

PARALLEL PROCESS FOR DEVELOPMENT OF A STANDARIZED ECOLOGICAL CLASSIFICATION HIERARCHY

A conceptual framework for a HMECS was harmonized between the Pacific and Maritimes Regions to disaggregate/subdivide Bioregions into smaller hierarchical spatial units based on their ecological attributes. The application of the conceptual framework in the Pacific and Maritimes Regions provides a systematic and spatially-explicit classification of ecosystems at multiple scales. The population of the Biophysical and Geomorphic Unit levels in the HMECS fills gaps in our descriptions of species, habitat diversity, and distribution patterns on the Scotian Shelf; however, there are still multiple gaps to fill before a complete standard ecological classification hierarchy is completed. The HMECS framework can be used to create other layers for the Scotian Shelf to fill these gaps to be used in multiple applications beyond MPA Network planning. Recognition of the current gaps in layers available would also help direct science proposals.

By populating the HMECS further, a system would begin to emerge with data at a variety of scales, which could be used for quick decisions, in the absence of new funding. As shown from the development of this classification, progress can be made with little or zero funds. Much of the biological and physical data simply need to be assembled at the appropriate scale to provide more appropriate outputs for management decisions.

The first step in using the HMECS is deciding on the scale and resolution of output data that would meet the need of the required management objective. This is a crucial and non-trivial decision, which can save valuable time and money for uses that do not require fine scale and high resolution data. In most cases, detailed acoustic-based marine habitat mapping layers are not available. They are also not the most appropriate data in some cases, as many decisions do not require fine scale data. Guidance on the common scales and resolutions of output data for popular decisions and management objectives is provided in Table 2. Some of these gaps could be filled with limited resources, while some will take large amounts of resources.

By translating the variety of data available on species diversity and distribution patterns into a standardized ecological classification scheme (scales, resolutions, input data), we can begin to understand what we know about species diversity and distribution patterns in the Maritimes Region. We have begun to develop a common language for marine habitat mapping data, and could continue this process through further development of the HMECS, ensuring that translations are not required between data products.

There are many methods available for mapping, predicting, or inferring species diversity and distribution patterns (Table 5) that can be used to populate the HMECS, depending on the scale, resolution, and accuracy of the data required for decision-making. A better understanding of these methods within DFO would lead to less confusion when making decisions (e.g., species distribution models, community distribution models, surrogate-based methods). Many of these methods have been applied in the Maritimes Region, at a variety of scales, creating an unclear and patchy suite of methods and maps available. It is necessary at some point to compare and contrast the methods for specific management needs, including a discussion of trade-offs required when choosing the appropriate method.

The overall process of mapping species diversity and distribution also involves data acquisition, data development, data management and data rescue. These steps involve dataset publication, decisions that data are authoritative, standards for incorporation of data from contractors, and the assurance that they are saved and incorporated into DFO databases. Data management involves archiving in Maritimes Science’s Geospatial Data Repository, which includes dataset storage processes. Having these data inventoried and stored in one place aids decision makers as they are more accessible to managers. Access will also ensure that scientists are not duplicating data and data gaps are more visible.

Finally, a critical attribute in the implementation of a framework is the ability to incorporate new data, new model outputs, and new knowledge in an ongoing manner. Moving forward with this process will require guidance on the process for incorporating new information and regenerating appropriate outputs. An overview of the parallel processes involved for further development of the HMECS is depicted in Figure 16.

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TABLES

Table 1. The operational hierarchical marine ecological classification scheme, based on DFO Maritimes and Pacific Region's applications of the conceptual framework (DFO 2013). Text in grey was inherited from the conceptual framework and not updated during the review of the applications. A dash (-) indicates not applicable.

Level	Unit	Spatial extent	Spatial resolution	Benthic Description
1	Realm	10,000's km	1,000 km^2	Broad-scale geographic units such as the north Pacific Ocean.
2	Province	1,000's km	Approx. 100 km^2	Broad-scale geological units such as continental blocks, basins and abyssal plains.
3	Bioregions	1,000's km	Approx. 10–100 km^2	Distinctive, recurring and small-scale physical oceanographic processes (e.g., separation between California Current and Alaska Current regions). Research and analysis is required to understand how marine species diversity differs among these Bioregions.
4	Biophysical	100's–1,000's km	Approx. 10–100 km^2	Distinct physiographic and oceanographic conditions/processes, including bathymetry, related to biotic composition if data are available or evidence in the literature.
5	Geomorphic	100s km	1–10 km^2	Discrete geomorphological structures assumed to have distinctive biological assemblages; Individually defined by shape, size and topographic variation. May span other levels of hierarchy.
6	Biotopes (Habitats and Communities)	100's m–100's km	100's m^2 – 1 km^2	Discrete taxonomic assemblages characterized by associated substrate and environmental factors.
7	Biological Facies	100's m	< 10 m^2	Groups of biogenic or foundation species identified by one or more indicator species. BFs are patchy and nested within biotopes. Most examples are biogenic habitats, e.g., glass sponge reefs, cold-water corals, eelgrass beds, kelp forest.
8	Micro-assemblage	10's m	< 1 m^2	Distinct assemblages of often highly specialized species. For example, kelp forest holdfast community.
9	Species	-	-	Operational taxonomic units
10	Populations	-	-	Spatially structured subgroups of a species; includes phenotypes, evolutionary significant units, CUs
11	Genes	-	-	Alleles and DNA sequences

Table 2. Proposed scales of data (extent and resolution) for some of the management issues encountered within DFO at present. The management issues shown here do not constitute an exhaustive list of marine spatial planning needs. Specific objectives related to decision making will determine necessary spatial level. Dark grey indicates that spatial information at a particular level is expected to be used in decision making and light grey indicates that there is less certainty among meeting participants in the use of spatial information for decision-making. White indicates that a level is not expected to be used in decision-making. A dash (-) indicates not applicable.

	Level	Unit	Spatial Extent	Spatial Resolution	MPA Network Planning	Representation Criterion – MPA Network Design	Environmental Assessment for Project Siting	Delineating Critical Habitat (SARA)	Ecological Restoration	Species Management	Marine Spill Response	Cumulative Effects for Planning
ECOSYSTEM-BASED	1	Realm	10,000s km	1000s km^2	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used
	2	Province	1000s km	Approx. 100s km^2	High certainty will be used	High certainty will be used	Not used	Not used	Not used	Not used	Not used	Not used
	3	Bioregion	1,000s km	Approx. 10–100 km^2	High certainty will be used	High certainty will be used	Not used	High certainty will be used	Not used	Not used	Not used	Not used
	4	Biophysical	100s-1000s km	10–100 km^2	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Not used	Not used	Lower certainty will be used	Lower certainty will be used
	5	Geomorphic	100s km^2	1–10 km^2	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Not used	Not used	High certainty will be used	Lower certainty will be used
	6	Biotope	100s m–100s km	< 1 km^2	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Lower certainty will be used
	7	Biological Facies	10s–100s m	< 100 m^2	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Lower certainty will be used
	8	Micro-assemblage	10s m	< 1 m^2	High certainty will be used	Not used	Low certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Lower certainty will be used
SPECIES-BASED	7	Species	-	-	High certainty will be used	Not used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Lower certainty will be used
	8	Populations	-	-	High certainty will be used	Not used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	High certainty will be used	Lower certainty will be used
	9	Genes	-	-	High certainty will be used	Not used	Not used	Low certainty will be used	Low certainty will be used	High certainty will be used	Lower certainty will be used	Not used

Table 3. Data inputs used to create the background bathymetry layer; a Scotian Shelf Digital Elevation Model. N/A = not available.

Data Inputs	Data Type	Resolution (m^2/pixel)	Date(s)	Type of multibeam	Data Source
Coastal Series Soundings	shapefile	N/A	N/A	N/A	CHS
Coastal Series Contours	shapefile	N/A	N/A	N/A	NS Geomatics Centre
CHS Soundings	shapefile	N/A	N/A	N/A	CHS
Bay of Fundy Multibeam	raster	10	1993, 1994, 1996, 2006, 2007, 2008, 2009	Creed EM1000, Creed EM1002, Matthew EM710, Pipit EM3002, Plover EM3002	CHS
St Ann's Bank multibeam	raster	23	2010, 2012	Matthew EM710, Pipit EM3002, Plover EM3002, Creed EM1002	CHS
German Bank multibeam	raster	23	1997, 2000	Anne S Pierce EM1002, Creed EM1000	CHS
Georges Bank multibeam	raster	23	1999, 2000	Anne S Pierce EM1002, Creed EM1000	CHS
Browns Bank multibeam	raster	23	1996, 1997	Creed EM1000	CHS
Musquash and Saint John multibeam	raster	1	1992, 1994, 1996, 2000, 2001, 2004, 2005, 2006, 2007, 2008	Creed EM1000, HarbQ EM3002, Hawk EM3002, Heron EM3000, Heron EM3002, Plover EM3000	UNB Ocean Mapping
Passamaquoddy Bay multibeam	raster	1	1992, 1995, 2000, 2002, 2004, 2005, 2006, 2008	Creed EM1000, Heron EM3000, Heron EM3002, Plover EM3000	UNB Ocean Mapping
Maces Bay multibeam	raster	1	2005, 2007, 2008	Heron EM3000, Heron EM3002	UNB Ocean Mapping
Grand Manan multibeam	raster	1	2002, 2006, 2007	Heron EM3000, Heron EM3002, Plover EM3000	UNB Ocean Mapping

Table 4. Comparison of the variables included in the Kostylev and Hannah (2004) Habitat Template Model for the Scotian Shelf, and their rank in the Gradient Forest Analysis (for 2/3 of the Scotian Shelf) designed to measure the importance of 29 variables at structuring species diversity and distribution on the Western Scotian Shelf and through the Gulf of Maine. n/a = not applicable.

Kostylev and Hannah (2004) Variable	Rank in GF Analysis (out of 28 variables)
	Scope for Growth
Mean Benthic Temperature	12
Primary Productivity	3 (Chlorophyll Average)
Mean Benthic Salinity	7
Benthic Temperature Variation	17 (Seasonal Range of Temperature)
Mixed Layer Depth	22 (Stratification Average)
Disturbance	
Grain Size	9, 10, 14 (Gravel, Sand and Mud Percentage)
RMS Current	4, 13 (Benthic Current Stress, tides and waves then tides only)
Orbital Velocity	n/a

Table 5. Methods available to populated the different levels of the HMECS, the level of the HMECS which the method could contribute data towards, the EAM indicators the layers generated would inform, an example of popular approaches used for these methods, and the variables required as input data. A dash (-) indicates not applicable.

Method	**HMECS Scale**	**EAM Indicator**	**Approaches**	**Variables Required**
Biophysical habitat mapping	Habitat/Biotope	Habitat Distributional Range Habitat Distributional Pattern Habitat Area	EUNIS Valentine et al.	Biological Environmental
Clustering techniques (biological information)	Physiographic Units	Composition and Relative Proportion of Ecosystem Components (Habitats and Species)	-	Biological (multiple species)
Species Distribution Modeling	Species/Populations	Species Distributional Range Species Distributional Pattern Area Covered by Species	General Additive Models Random Forest Maxent	Biological (single species) Environmental
Community Distribution Modeling	Physiographic Units Habitat/Biotope	Composition and Relative Proportion of Ecosystem Components (Habitats and Species) Species Diversity	Gradient Forest	Biological (multiple species) Environmental
Interpolation techniques	Species/populations	Species Distributional Range Species Distributional Pattern Area Covered by Species	Kreiging IDW	Biological (single species)
Abiotic Habitat Classification	Physiographic Units	Composition and Relative Proportion of Ecosystem Components (Habitats and Species)	Clustering Manual Delineation	Environmental
Substrate Mapping	Habitat/Biotope	Habitat Distributional Range Habitat Distributional Pattern Habitat Area	Manual Delineation Clustering	Substrate
Rule-based	Species/Populations	Species Distributional Range Species Distributional Pattern Area Covered by Species	-	Environmental

FIGURES

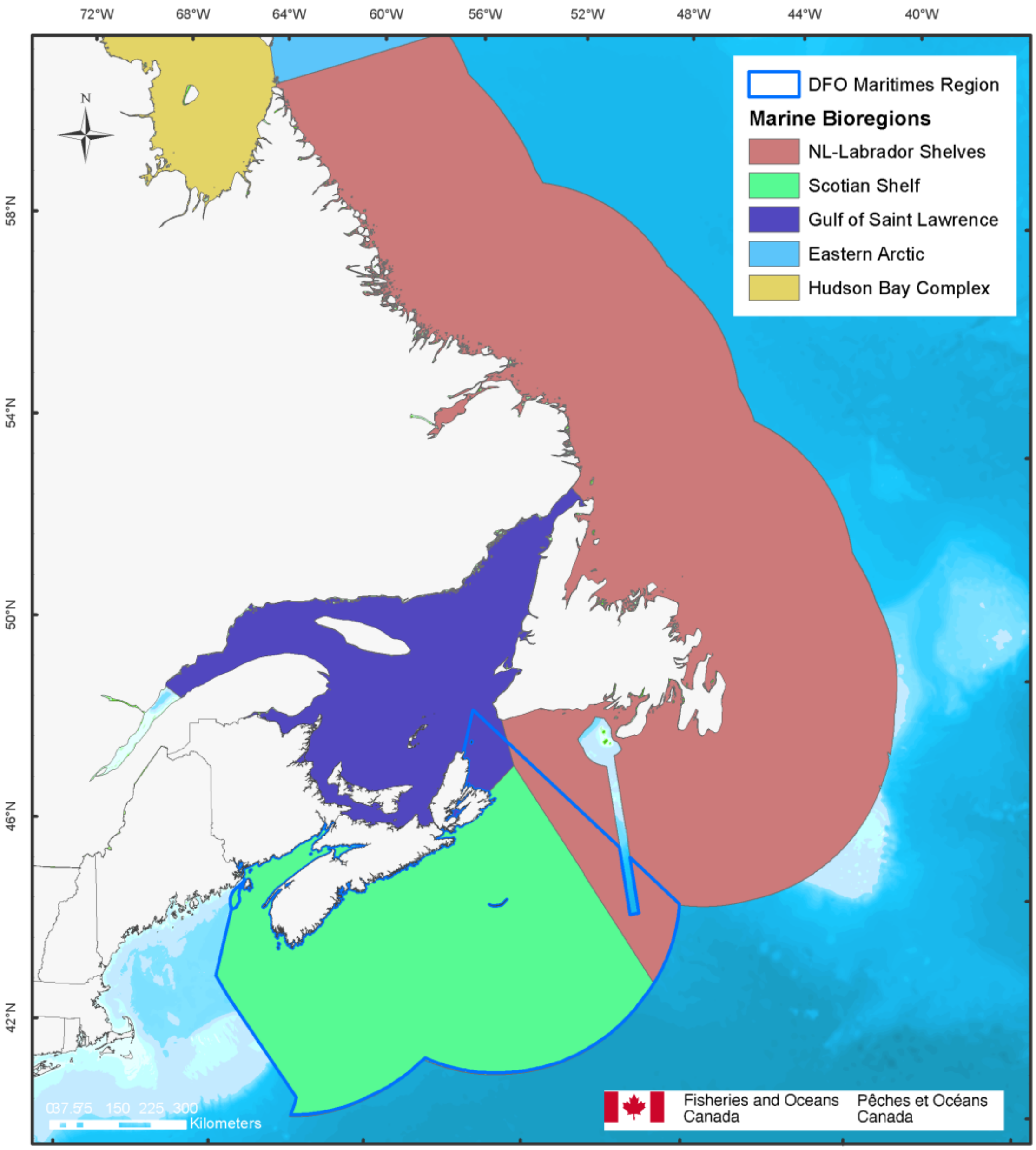

Figure 1. Level 3 – Bioregion - DFO Atlantic Canadian Marine Bioregions, established from a national advisory process, compared to the DFO Maritimes Region.

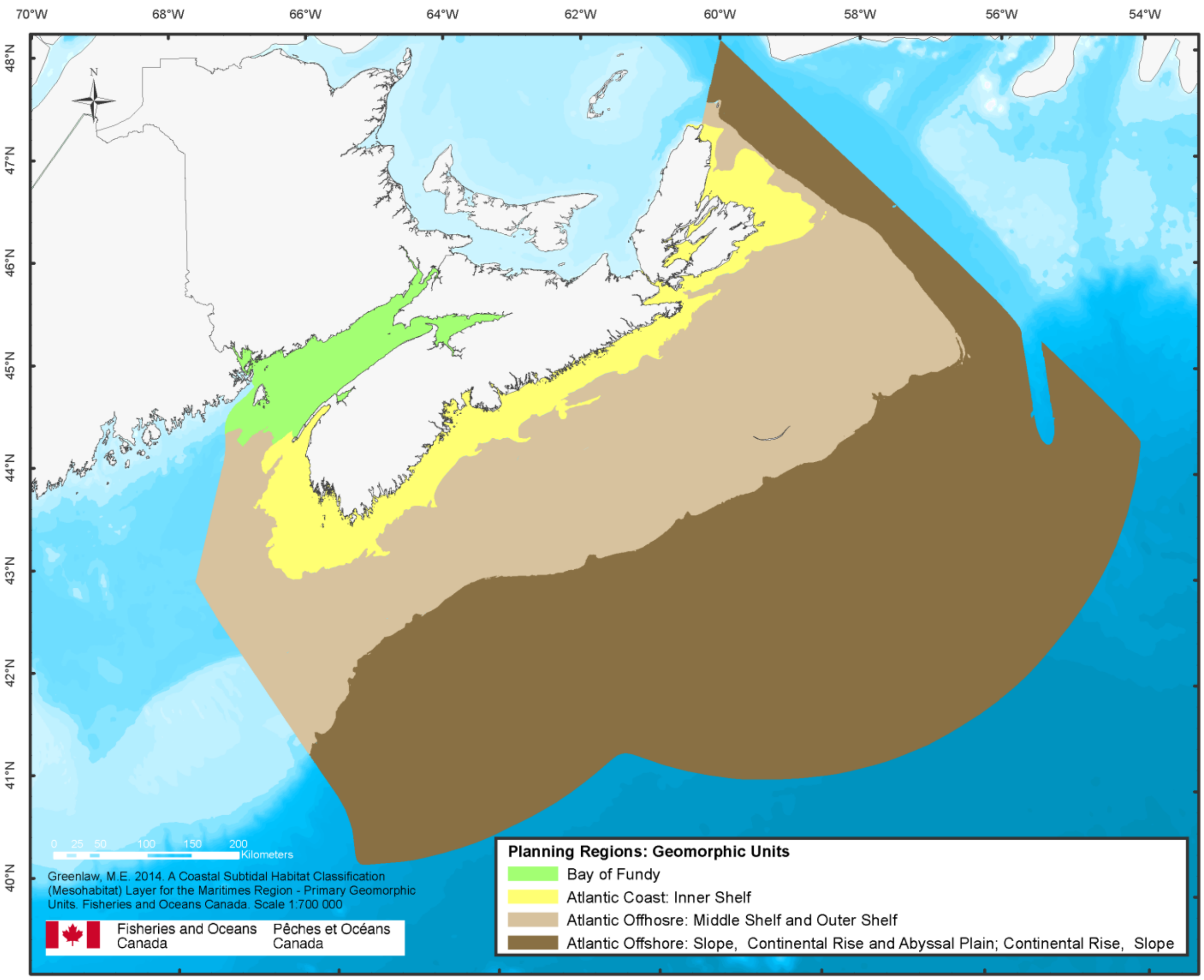

Figure 2. Level 5 – Geomorphic Units - GeoLevel1 - Higher-level geomorphic units including Inland Seas, Inner Shelf, Shelf, Slope, Continental Rise and Abyssal Plain. These also correspond to Oceans and Coastal Management Division's Planning Regions.

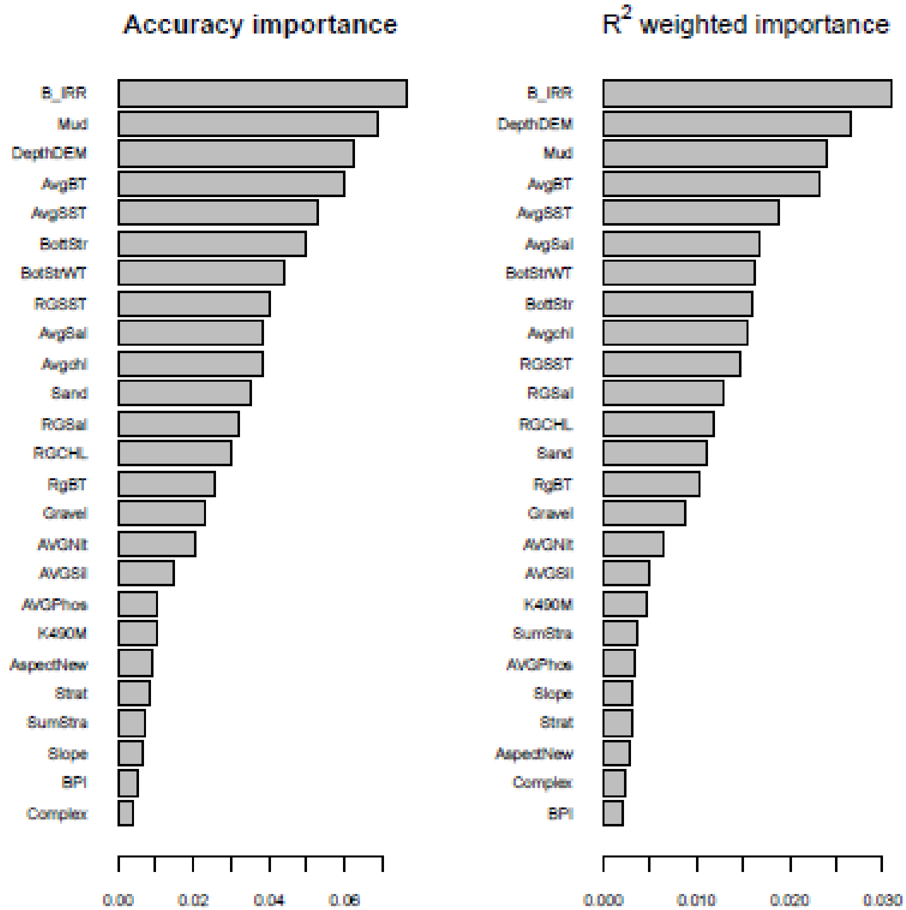

Figure 3. Benthic temperature, sea surface temperature, benthic salinity, surface chlorophyll and benthic current stress were the oceanographic variables shown to explain the most variability in biodiversity composition (Figure 4; on 2/3 of the Scotian Shelf). Of these variables, only benthic variables were chosen to be included in the Oceanographic Units layer (benthic temperature, benthic salinity and benthic current stress). Even though pelagic variables showed high predictive capability in the Gradient Forest analysis, they are not expected to be direct drivers of benthic biodiversity composition. Variable explanations can be found in Greenlaw et al. 2010 (B_IRR – benthic irradiation, DepthDEM – depth, Mud - % Mud, AvgBT – average yearly benthic temperature, AvgSST – average yearly sea surface temperature, AvgSal – average yearly benthic salinity, BotStrWT – benthic current stress with tides, BottStr – benthic current stress without tides, Avgchl – average surface chlorophyll, sand - % sand, RgBT – yearly range of benthic temperature, Gravel - % Gravel, AVGNit – average yearly benthic nitrogen, AVGSi – Average yearly benthic silicate, K490 – Mean Diffuse Attenuation Coefficient, Sumstrat – summer stratification, AVGPhos – yearly average benthic phosphate, slope – slope, strat – yearly stratification, complex, benthic complexity, BPI – benthic position index).

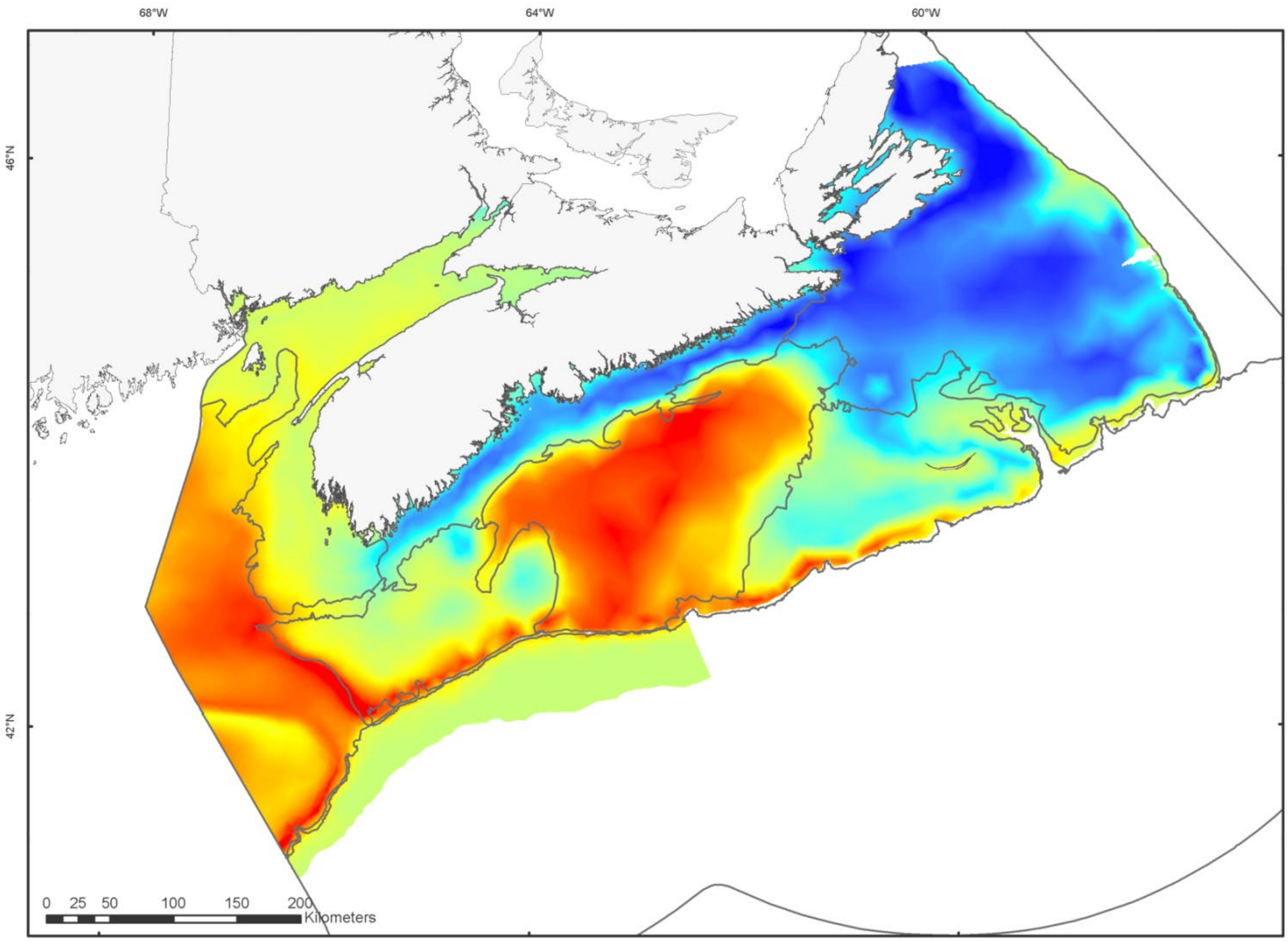

Figure 4. The oceanography layer was created using benthic temperature, benthic salinity, and benthic current stress, which were identified as important benthic explanatory variables of benthic biodiversity on the Western Scotian Shelf, during Pitcher et al.'s (2012) Gradient Forest analysis. Results were extracted from the Scotian Shelf portion of the analysis only. The variables were weighted by their "importance" (a metric from the Gradient Forest analysis) for structuring biodiversity composition; benthic temperature 40%, salinity 35%, and benthic current stress 25%, when creating the oceanography layer, which identified nine oceanography domains. The oceanographic variables compiled for the oceanography layer are from historical data sources (1992 and earlier) and the original density, resolution, and error associated with these data are not known at present.

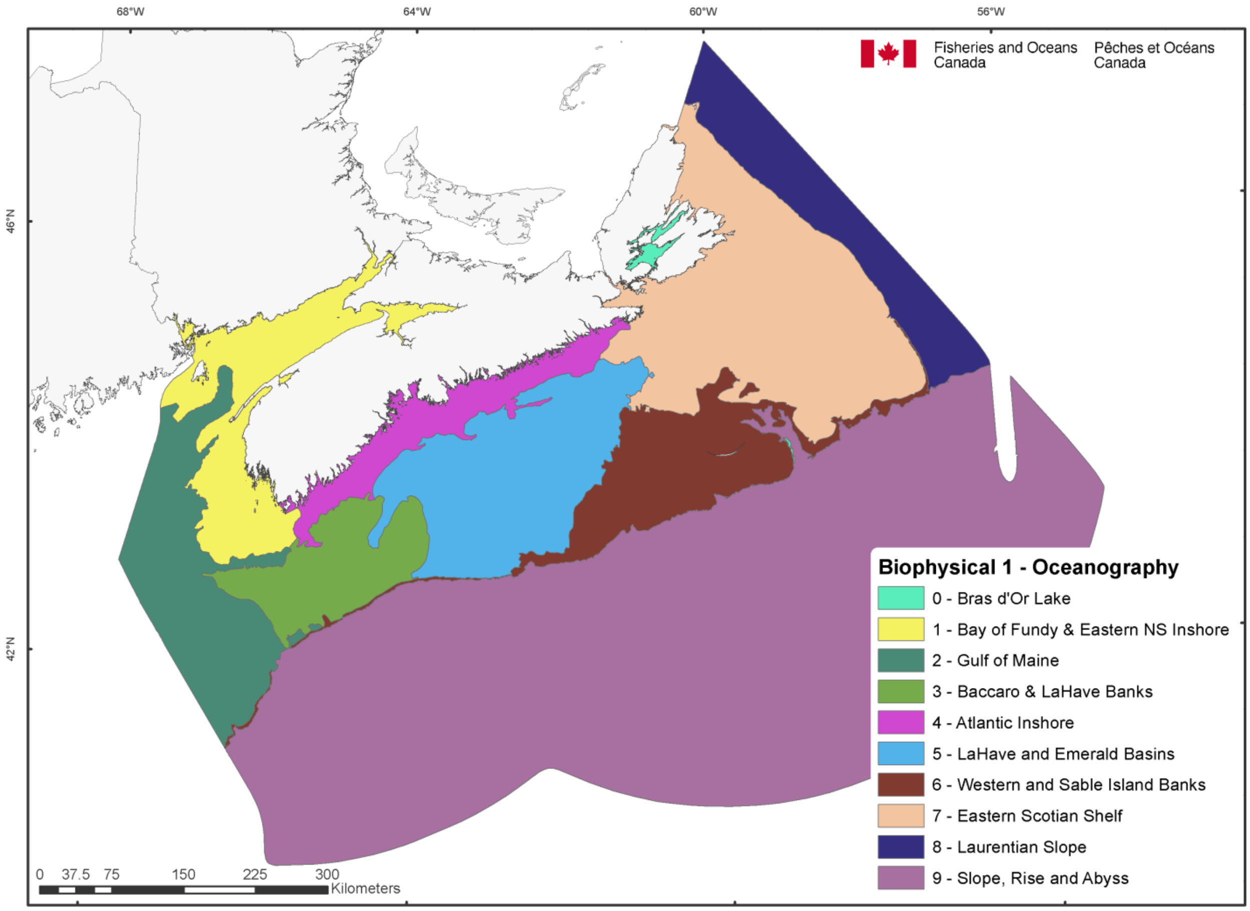

Figure 5. Level 4a – Biophysical Units - Oceanography – Distinct physiographic and oceanographic conditions/processes related to biotic composition. The oceanography layer was created using benthic temperature, benthic salinity and benthic current stress, which were identified as important benthic explanatory variables of benthic biodiversity on the Western Scotian Shelf, during Pitcher et al.'s (2012) Gradient Forest analysis. Results were extracted from the Scotian Shelf portion of the analysis only. These variables were weighted by their "importance" (a metric from the Gradient Forest analysis) for structuring biodiversity composition; benthic temperature 40%, salinity 35%, and benthic current stress 25%, when creating the oceanography layer, which identified nine oceanographic domains. The oceanographic variables compiled for the oceanography layer are from historical data sources (1992 and earlier) and the original density, resolution, and error associated with these data are not known at present.

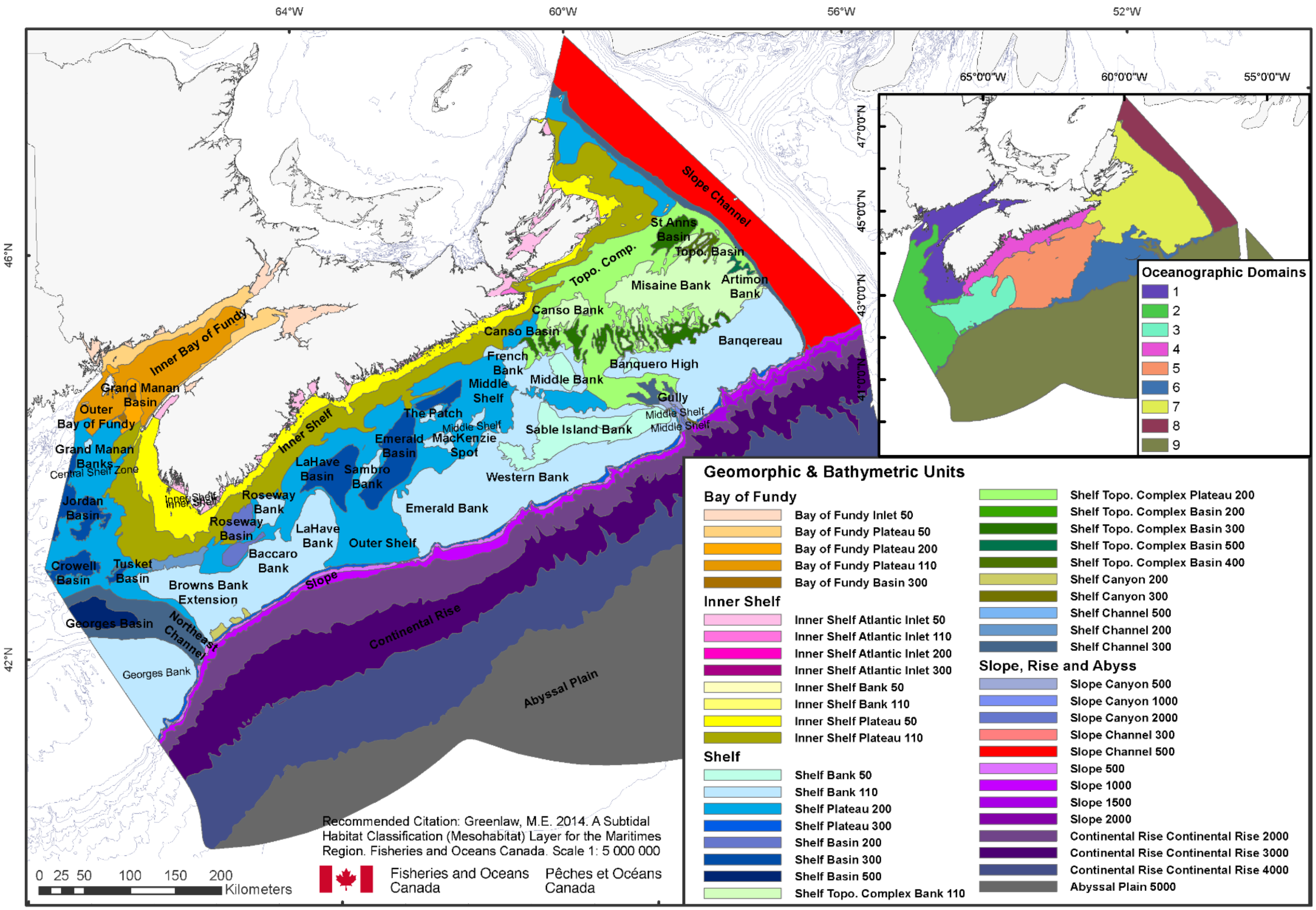

Figure 6. Levels 4 & 5 – Biophysical and Geomorphic Units of the ecological classification. Biophysical Units are derived from the combination of Oceanographic Units and Bathomes. For ease of visualization, Geomorphic Units and Bathomes have been combined as they are often similar boundaries. Oceanographic Units on their own are shown in the top right inset. Biophysical and Geomorphic Units are expected to represent homogeneous distributions of species diversity and distribution patterns at a mesoscale (1–100 km^2).

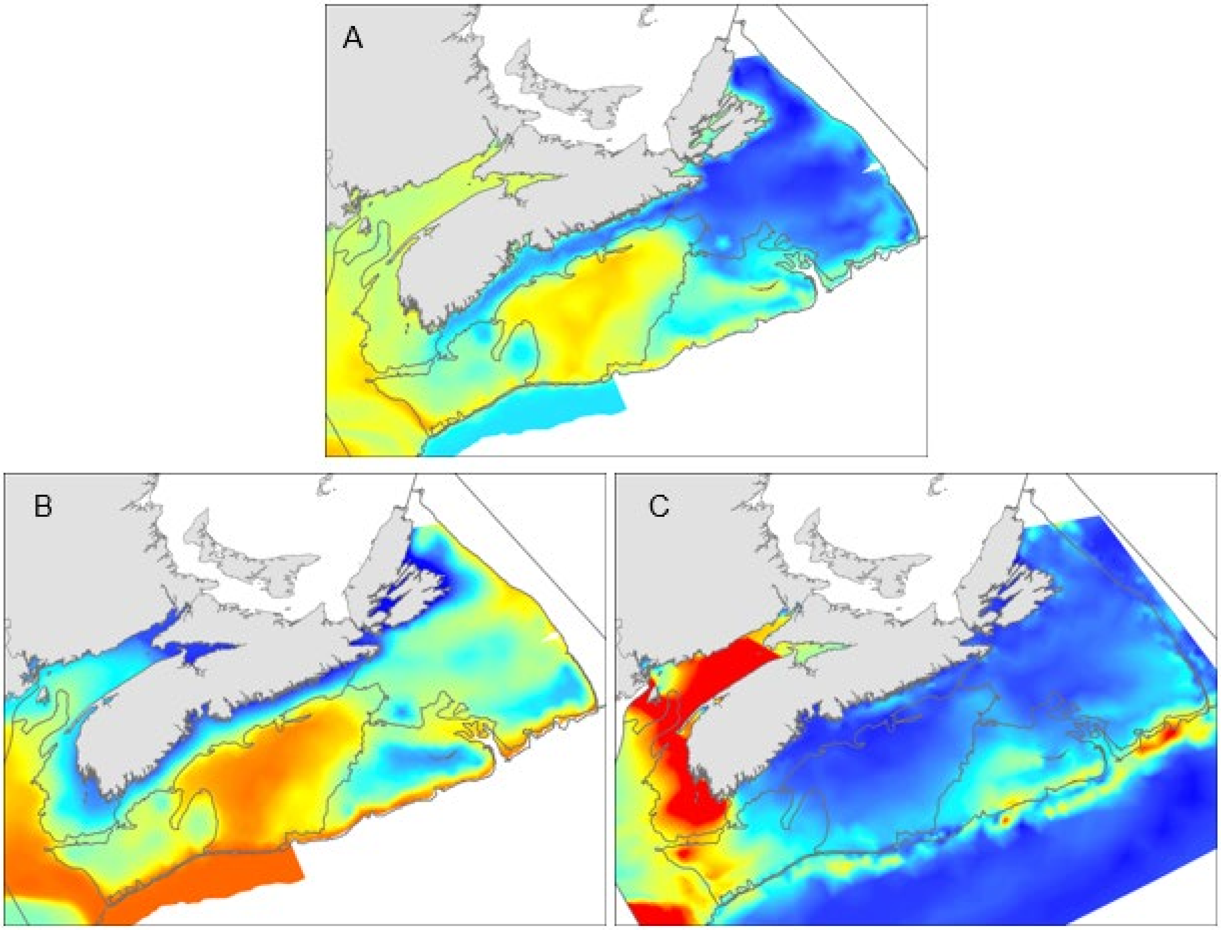

Figure 7. The variables used to create the Oceanographic Units layer. A. benthic temperature B. benthic salinity and C. root mean square current stress. The individual layers were normalized (from 0–1) and combined into a single layer (Figure 4) using weightings based on their approximate 'importance' (a metric output from the Gradient Forest analysis) for structuring biodiversity composition; benthic temperature 40%, salinity 35%, benthic current stress 25%, based on the results of Pitcher et al. 2012. From this layer, nine Oceanographic Units were identified (Figure 4 & inset Figure 6).

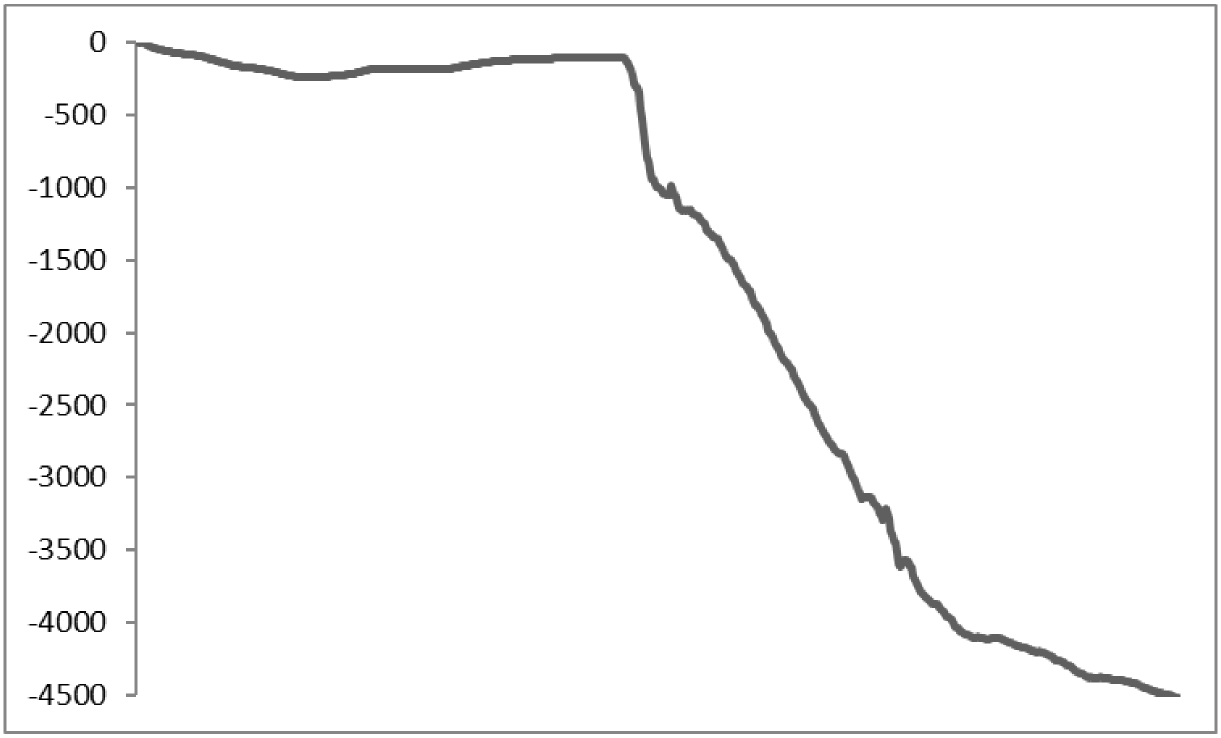

Figure 8. The dramatic depth change is illustrated by a representative depth profile of the Scotian Shelf.

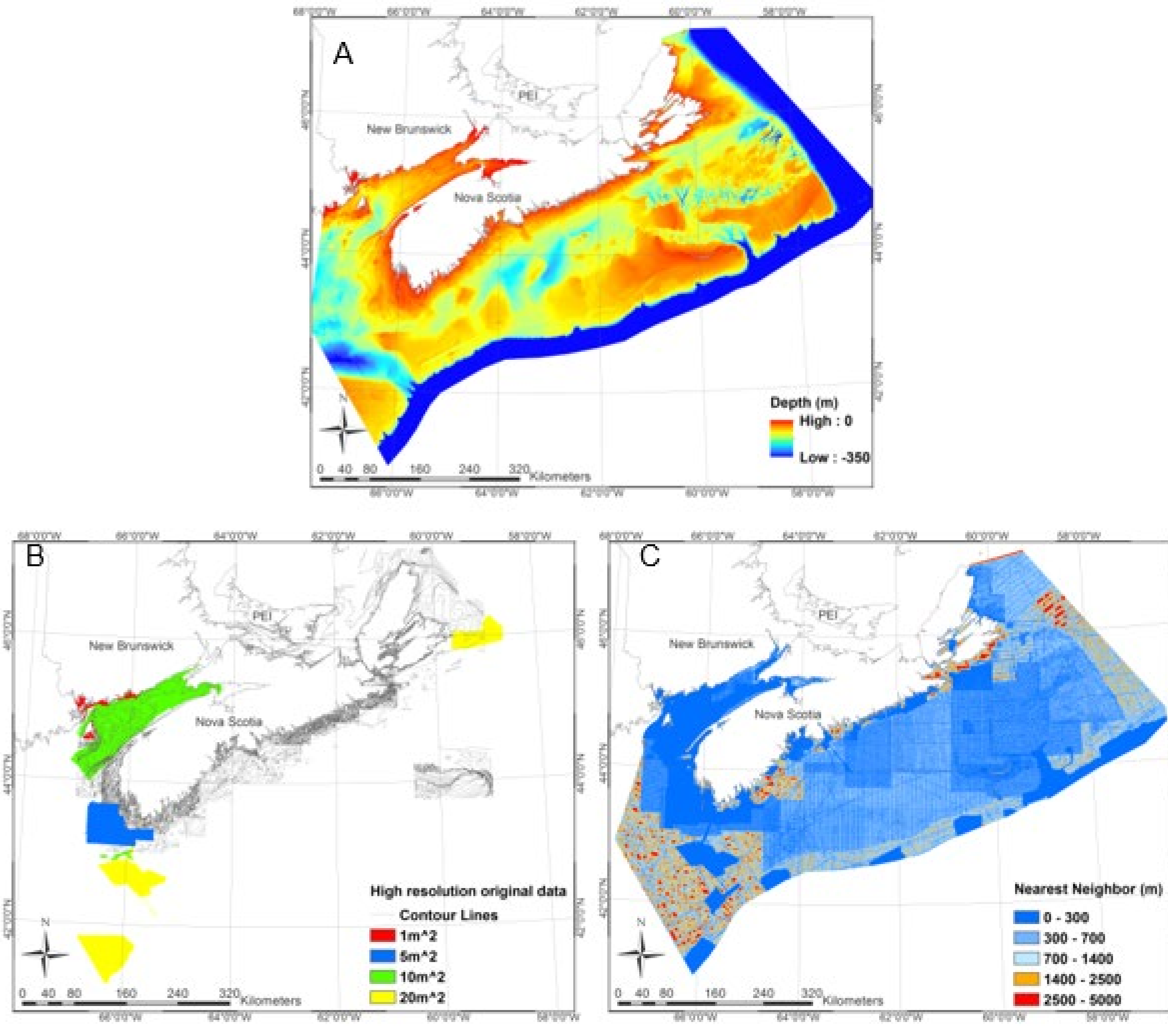

Figure 9. A) The 35 m^2 per/pixel bathymetry layer used to create the Bathymetric Units in the HMECS B) The location of multibeam and contour data (Table 3) used to create the Scotian Shelf DEM. Contour lines surround Nova Scotia, Cape Breton, Sable Island, and the Bay of Fundy. The 1 m^2 multibeam data covers coastal southwestern New Brunswick, and Grand Manan Island. 5 m^2 multibeam data covers German Bank off southwest Nova Scotia. 10 m^2 multibeam data covers the entire Bay of Fundy, and a small portion of Browns Bank. 20 m^2 multibeam data covers Browns Bank, a portion of Georges Bank, and St. Anns Bank off Eastern Cape Bretton. C) A nearest neighbour surface calculated using the Euclidian distance tool in ArcGIS, which calculates the proximity of points relative to one another. The output resolution of the surface is 35 m^2/pixel.

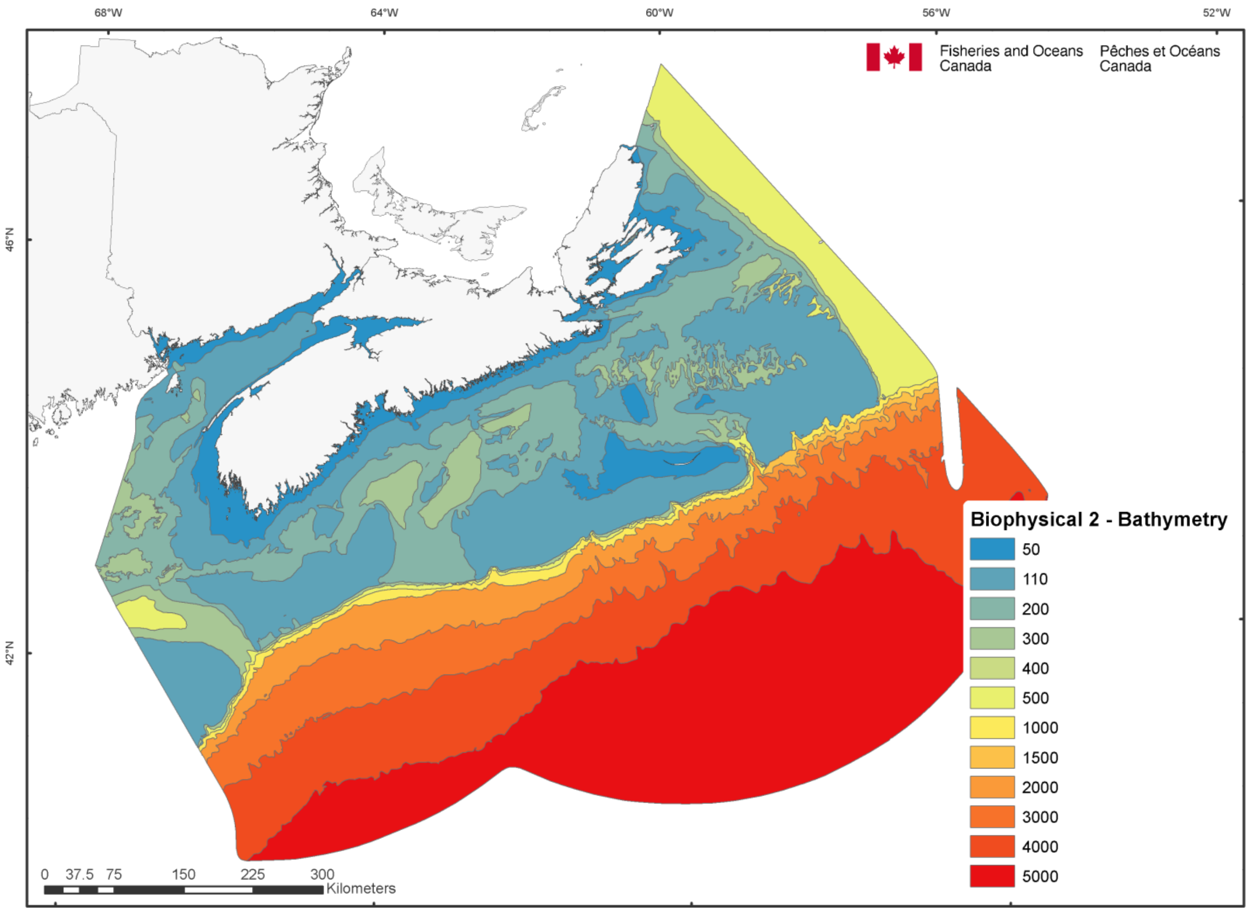

Figure 10. Level 4b – Biophysical Units - Bathomes – were derived from high resolution (1–10 m) bathymetry data. Breakpoints defining were identified as the most important regions along the depth gradient, influencing changes in species and habitat diversity and distribution patterns based on the results of a Gradient Forest (Pitcher et al. 2012) analysis using data from the Gulf of Maine and two-thirds of the Scotian Shelf.

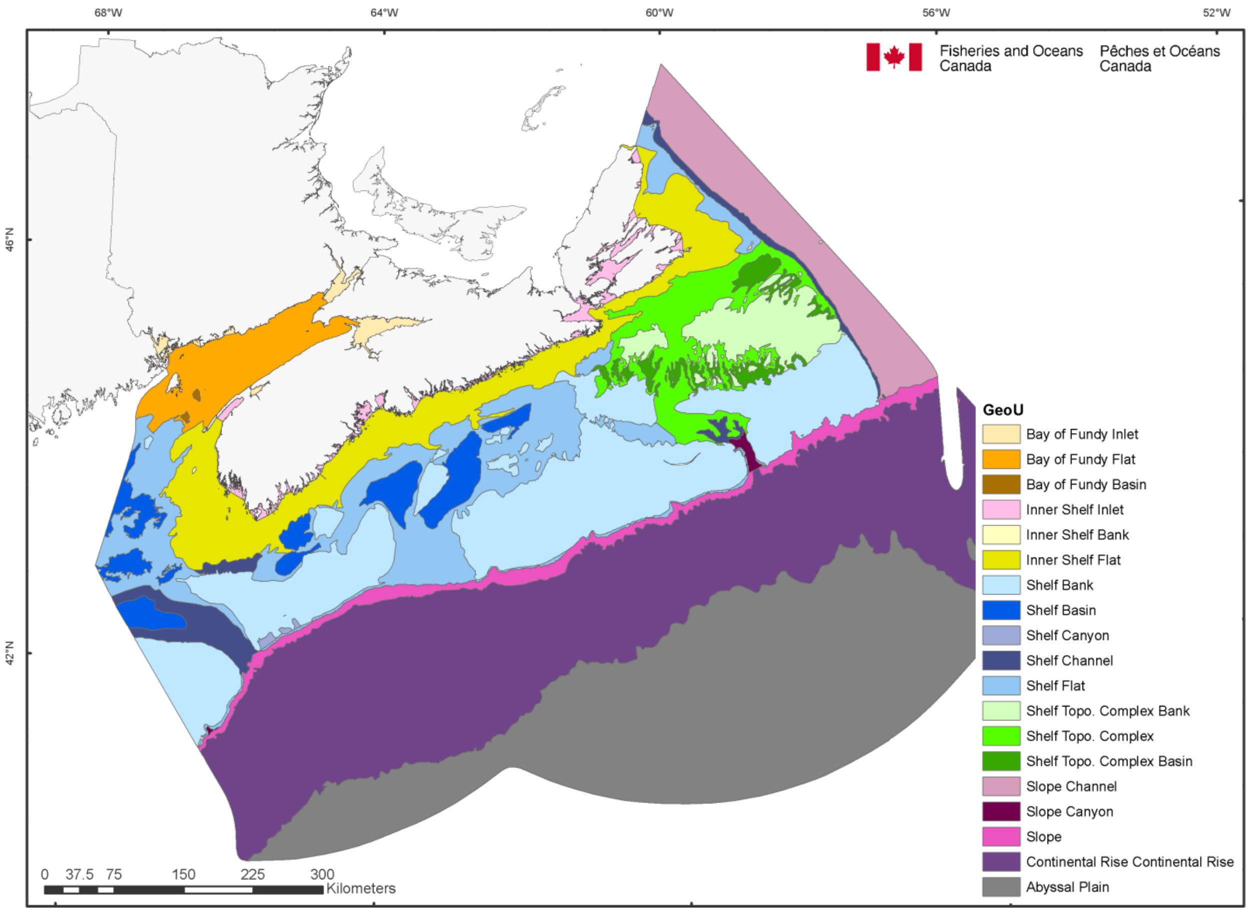

Figure 11. Level 5 – Geomorphic Units - identified in the Scotian Shelf Bioregion using a modified version of Fader's (2007) classification of geomorphic features for the Gulf of Maine and Scotian Shelf.

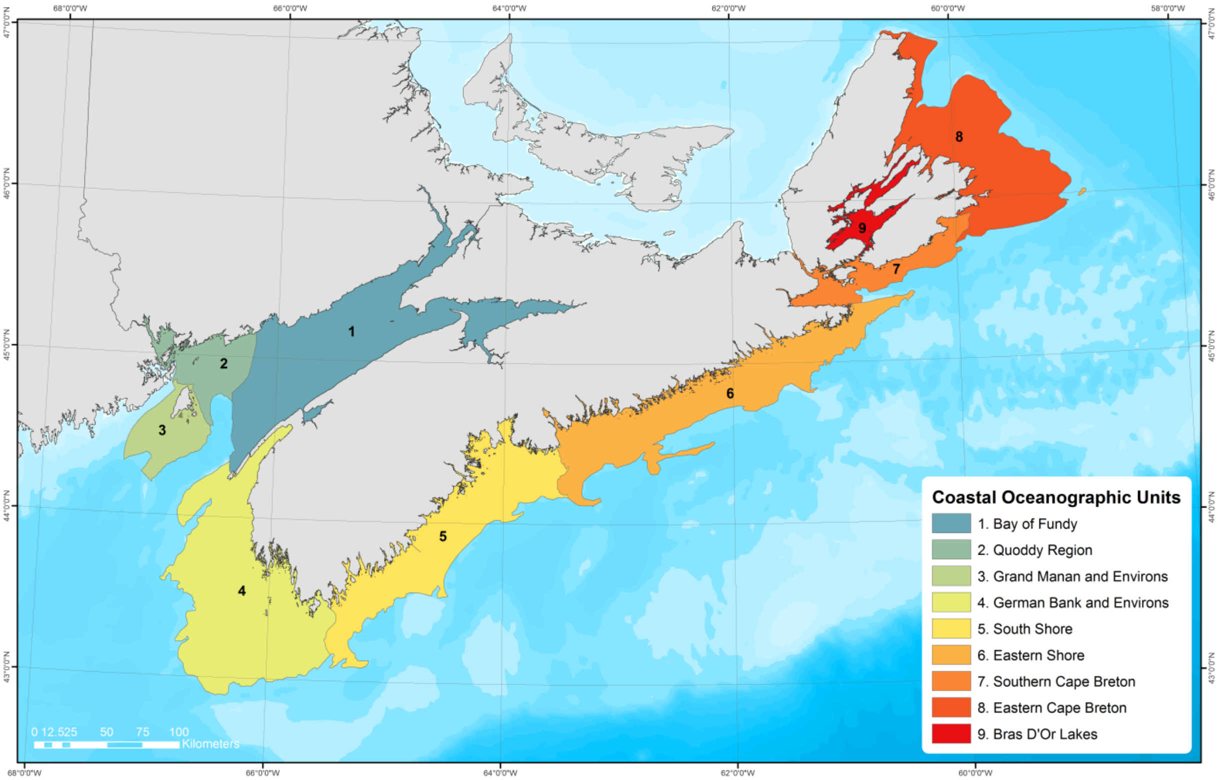

Figure 12. Level 4a – Biophysical Units - Coastal Oceanographic Units - Oceanographic units in the Coastal Zone are a combination of the Biophysical Unit scale and the Biotope scale. Units were developed using a weighted average of environmental factors; a combined overlay of a principal component analysis (PCA) of oceanographic factors (40%; oceanographic factors were described in the offshore section) and phi scale substrate (60%; substrate data layer described below). This combined layer was classified into 9 distinct classes of oceanography and substrate.

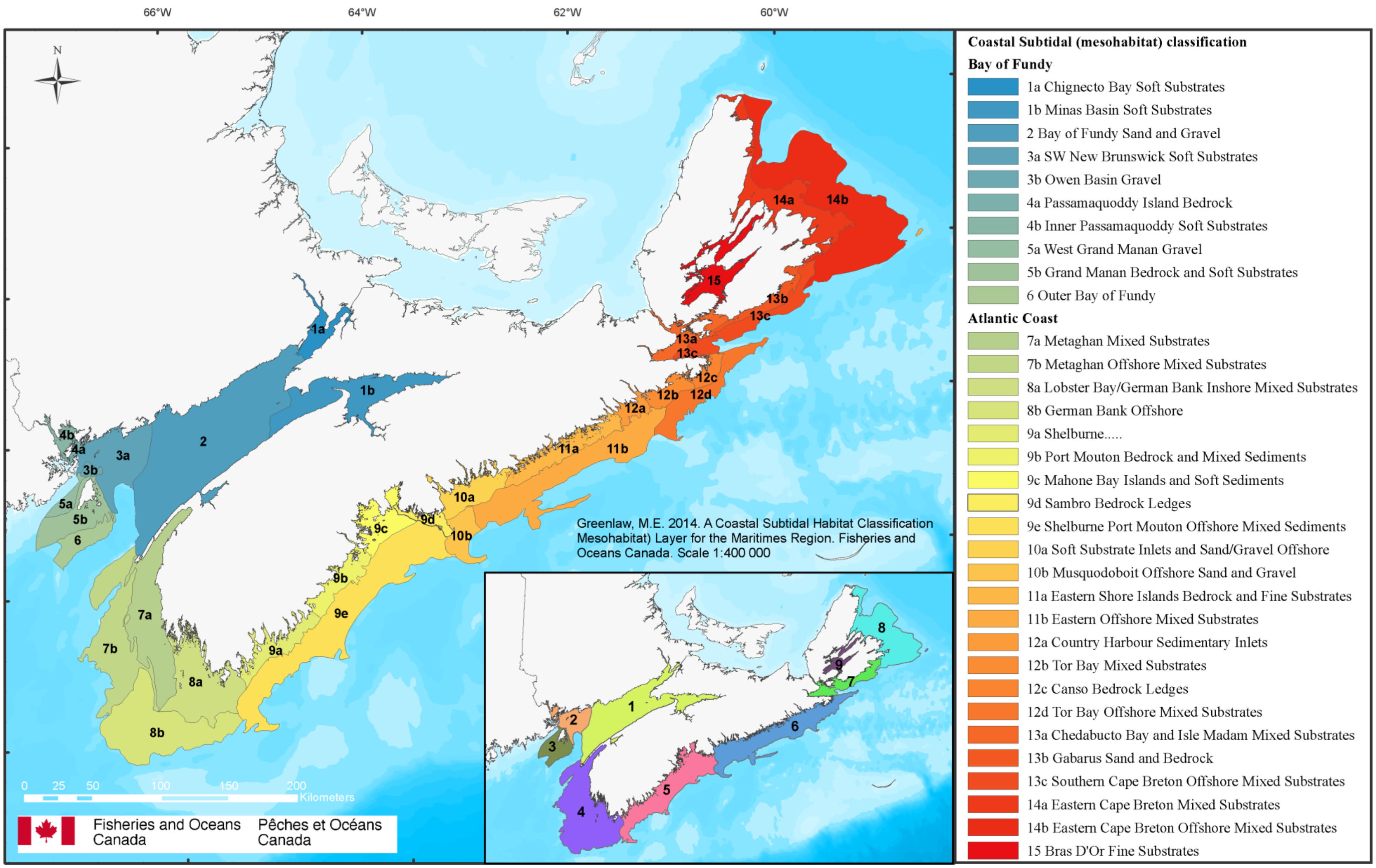

Figure 13. Levels 4, 5 & 6 – Coastal Biophysical and Geomorphic Units, and Biotopes - Coastal Oceanographic and Geomorphic Units (whole numbers) and Biotopes with Bathome breaks (lettered numbers). Bathomes in the offshore included coastal breaks, including breaks 50 and 110 m. Geomorphic units in the coastal zone were included with the offshore layer. Coastal Geomorphic units include: Geolevel1 - Bay of Fundy and Inner Shelf. Geolevel2 is not shown on this figure.

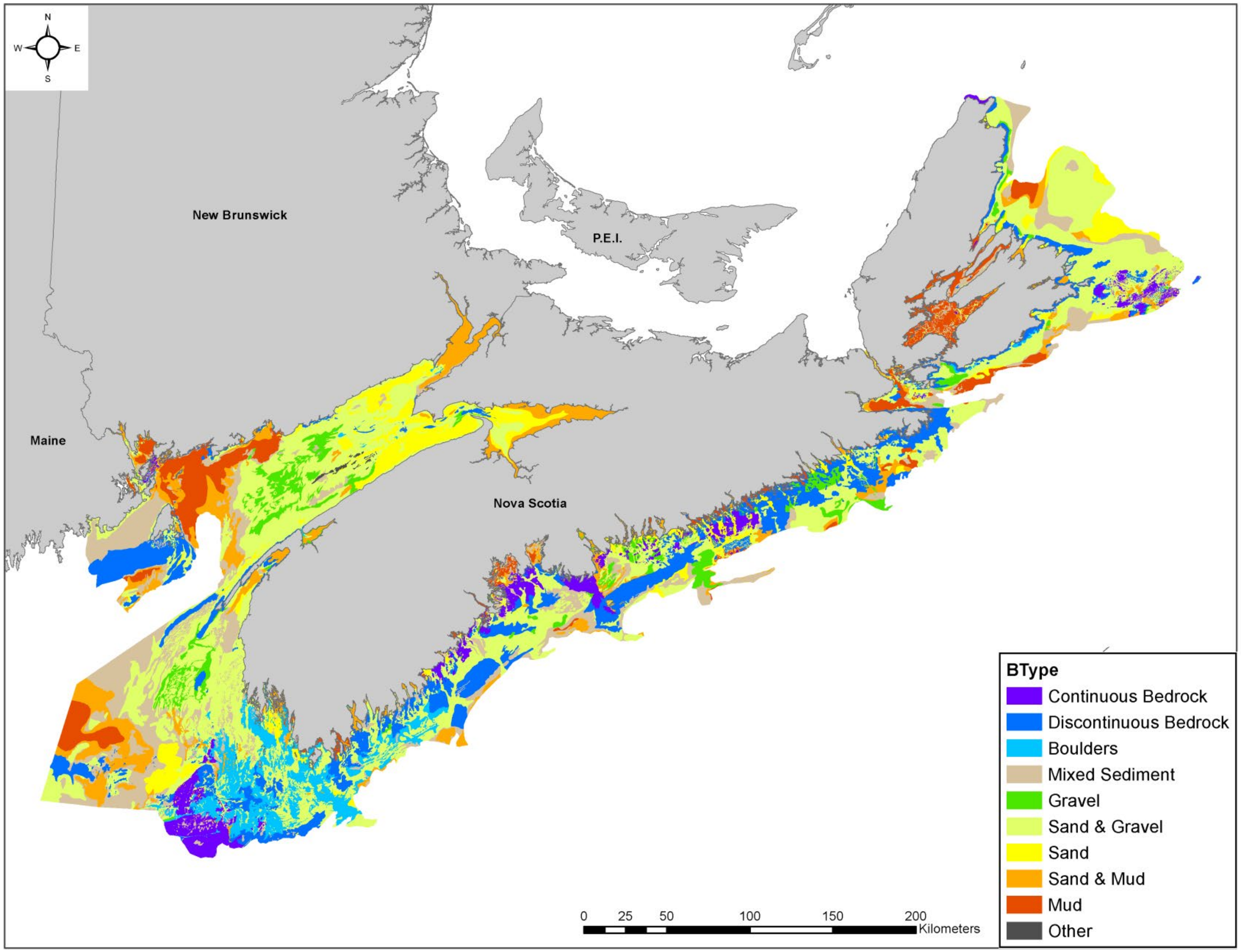

Figure 14. Substrate grain size of the coastal macro-habitat classification, intended to be used as a first approximation of finer scale biotopes, however the data are currently unpublished and there has been no consensus on whether these data would be suitable to begin planning at the biotope level (Greenlaw et al. Unpublished).

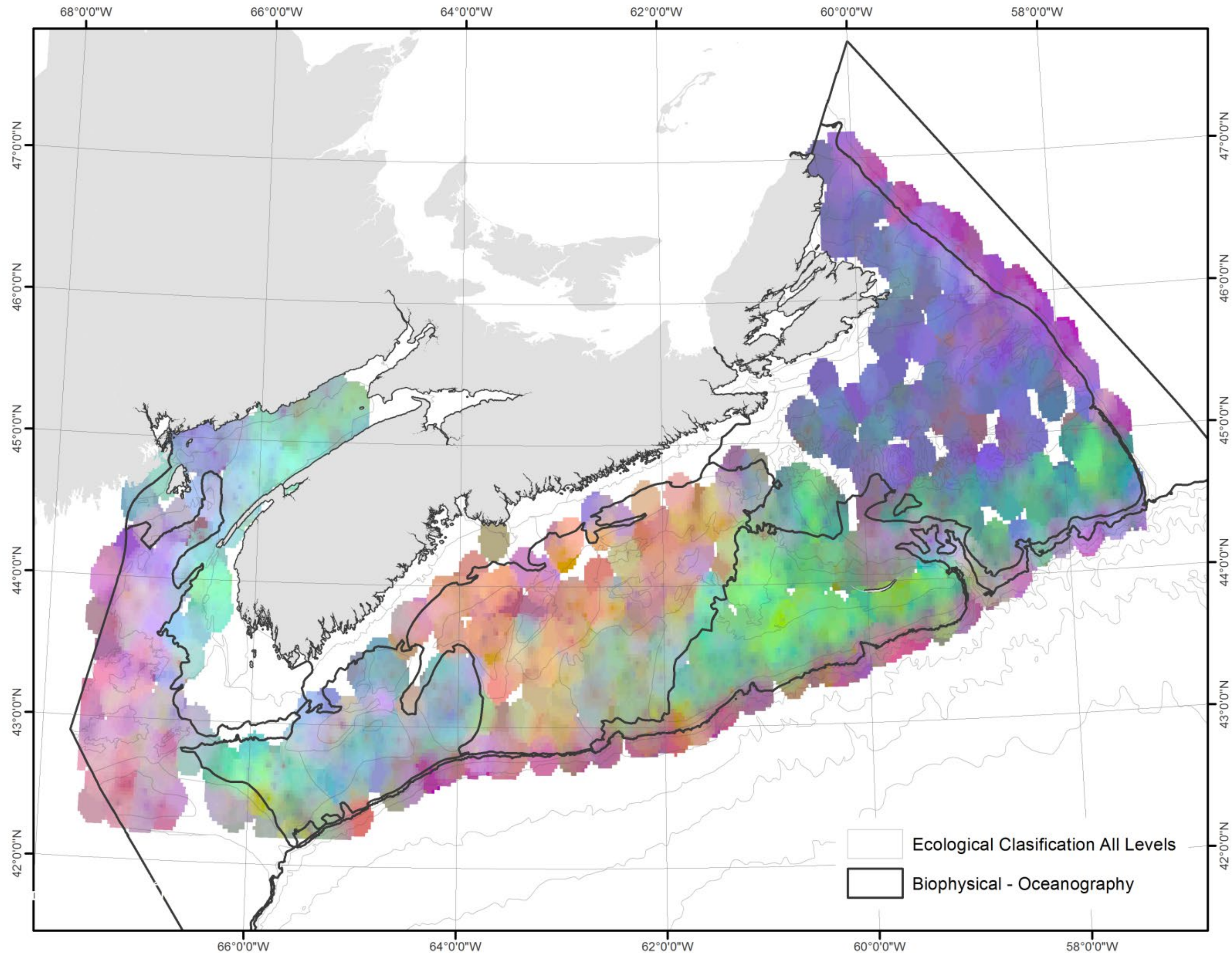

Figure 15. Oceanographic (thick line), Biophysical and Geomorphic units (thin lines) overlaid onto the first three principal components of the combination of 32 fish distributions extracted from the ecosystem surveys on the Scotian Shelf.

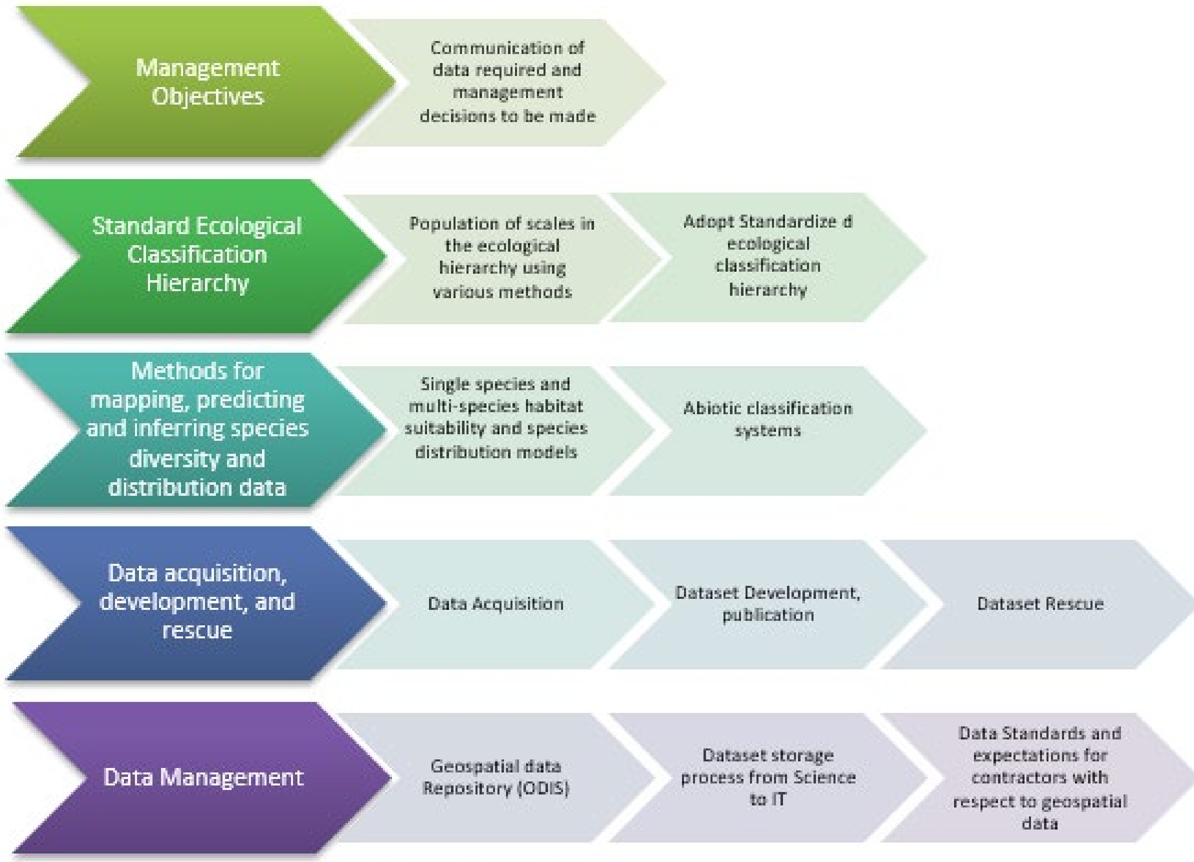

Figure 16. Parallel processes required for project planning and continual development of the ecological classification, including populating the ecological classification levels in the Maritimes Region.

APPENDIX: GIS LAYER ATTRIBUTES

Name – Common Name

Biophys1_O – Level 4a - Biophysical Units – Oceanography – Distinct physiographic and oceanographic conditions/processes related to biotic composition. The oceanography layer was created using benthic temperature, benthic salinity and benthic current stress, which were identified as important benthic explanatory variables of benthic biodiversity on the Western Scotian Shelf, during Pitcher et al.'s (2012) Gradient Forest analysis. Results were extracted from the Scotian Shelf portion of the analysis only. These variables were weighted by their "importance" (a metric from the Gradient Forest analysis) for structuring biodiversity composition; benthic temperature 40%, salinity 35%, and benthic current stress 25%, when creating the oceanography layer, which identified nine oceanographic domains. The oceanographic variables compiled for the oceanography layer are from historical data sources (1992 and earlier) and the original density, resolution, and error associated with these data are not known at present.

Biophys2_B – Level 4b – Biophysical Units - Bathomes – were derived from high resolution (1–10 m) bathymetry data. Breakpoints defining were identified as the most important regions along the depth gradient, influencing changes in species and habitat diversity and distribution patterns based on the results of a Gradient Forest (Pitcher et al., 2012) analysis using data from the Gulf of Maine and two-thirds of the Scotian Shelf.

GeoLevel1 – **Level 5a** – Geomorphic Level 1 – Higher-level geomorphic units including Inland Seas, Inner Shelf, Shelf, Slope, Continental Rise and Abyssal Plain. These also correspond to Oceans and Coastal Management Division's Planning Regions.

GeoLevel2 – **Level 5b** - Geomorphic Level 2 – Finer scale geomorphic units including Inlets, Banks, Basins, Flats, Channels, Topographically Complex Area, Topographically complex Banks, Topographically Complex Basins, Canyons.

GeoU – Level 5 - Geomorphic Units – The combination of Geomorphic Level 1 & 2 Units, which make up the Geomorphic Units layer.

Geo_Batho – **Levels 4b & 5** - Level 4b Biophysical Units (Bathymetric Units) and Geomorphic Units – The combination of Geomorphic and Bathymetric Units.

PhysioU – **Levels 4 & 5** - The combinations of Geomorphic and Biophysical Units.

Coastal Name – Common Coastal Names.

Coast1 – **Level 4a** - Coastal Oceanographic Units - Oceanographic units in the Coastal Zone are a combination of the Biophysical Unit scale and the Biotope scale. Units were developed using a weighted average of environmental factors (Figure 7); a combined overlay of a principal component analysis (PCA) of oceanographic factors (40%; oceanographic factors were described in the offshore section) and phi scale substrate (60%; substrate data layer described below). This combined layer was classified into 9 distinct classes of oceanography and substrate.

Coast2 – Level 6 - Coastal Biotopes – Substrate layers have been used to develop a preliminary Biotope Units using only substrate for the coastal zone.

Coast3 – **Levels 6 & 4b** - Coastal Biotopes broken into the two coastal Bathomes (50 and 110 m).

Coast Class – **Levels 6 & 4b** - Names and numbers in Figure 13 corresponding to Coastal Biotopes broken into the two coastal Bathomes (50 and 110 m).