Northwest Atlantic Fisheries Organization

Serial No. N6412 **NAFO SCR Doc. 14/069**

SC WORKING GROUP ON ECOSYSTEM SCIENCE AND ASSESSMENT – NOVEMBER 2013

Application of ecoregion analysis to the identification of Ecosystem Production Units (EPUs) in the NAFO Convention Area

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Abstract

We report on the consolidation of data and analyses of ecoregion structure from coastal Labrador to the mid-Atlantic Bight and provide recommendations on the definition of appropriate Ecosystem Production Units (EPUs) in NAFO Convention Area. Nine clusters (ecoregions) were identified as the optimal solution balancing the variance within and among clusters based on an unconstrained K-means analysis of the principal component scores of the rasters along the first three principal components based on eight variables. The results revealed a high degree of geographic contiguity of ecoregions over broad spatial scales with limited fragmentation within a bioregion although there was evidence of a high degree of heterogeneity. Strong latitudinal and bathymetric gradients were apparent in the distribution of ecoregions. Because spatial heterogeneity in the distribution of ecoregions can lead to uncertainty in the delineation of management units, clustering was repeated on the first three PCs with the addition of positional (latitude, longitude) information in an attempt to include spatial proximity in the delineation of management units. This analysis also revealed the overwhelming influence of geographic proximity and distance in the definition of each cluster which appeared to overshadow the combination of environmental characteristics identified ecoregions in the unconstrained analysis. Because of the limitations associated with the analytical approaches that did or did not make use of positional information in the clustering, both sets of results served as guides for the recommendations. Overall, three nested spatial scales were identified as relevant for the development of ecosystem summaries and management plans: Bioregion, Ecosystem Production Unit (EPU), and Ecoregion. A bioregion is composed by one or more EPUs, while an EPU consists of a combination of ecoregions, which represent elements with different physical and biological characteristics based on the analytical criteria applied.The consensus results from the WG discussions identified eight major EPUs that were proposed as candidate ecosystem management areas.

Introduction

The delineation of biogeographic boundaries in the World's Oceans has been based largely on the identification of water masses, fronts and currents that influence the dispersal of plankton or that place physiological constraints on the habitats which organisms can occupy (Longhurst 2007). The physical characteristics of water masses has long been used to identify differences among major areas in which the primary production potential differs (e.g. Ryther 1969) which thereby serves to identify key ecosystems (e.g. shelf seas, upwelling, open ocean). Ideally, the delineation of marine ecosystems that would serve to assess the state of marine environments should be based on simple ecological criteria that include bathymetry, oceanography, productivity and trophic relationships (www.lme.noaa.gov). Delineation of spatial management units is prerequisite to establishment of an effective ecosystem approach to management of human activities in the marine environment. Biogeographic classification has been described as fundamental for marine spatial planning and can serve as a framework for a number of uses from assessment and monitoring to marine protected areas network design (CBD 2009). In recent years, there has been an increased need for the assessment of biogeographic classification schemes as many coastal states have moved their policies toward the implementation of Ecosystem Approaches to Management (EAM) in an attempt to recognize the interconnectedness of organisms with the environment in which they live rather than rely on single focus strategies, such as fisheries management. EAM also adds emphasis on the need to conserve biodiversity, unique habitats and sensitive or vulnerable marine ecosystems.

Ecosystem approaches to management are essentially place-based approaches; they aim to provide management provisions and advice encompassing multiple stocks which inhabit a common and geographically-defined area. These "ecosystem management" units, and the scale at which they are defined, ideally would capture the core of a functional ecosystem, though other considerations should also be taken into account in defining them (e.g. jurisdictional boundaries and legal issues, main fisheries and fleets, operational issues regarding surveillance and enforcement, etc.). A necessary starting point in the process of defining "ecosystem management" units is the delineation of ecosystem boundaries and identification of major ecosystem subunits.

From a practical perspective, society, governments and international organizations (e.g. Regional Fisheries Management Organizations – RFMOs) have had to define spatial management units in the oceans often in response to the needs associated with the conservation and exploitation of renewable marine resources well before the need to consider EAM because of the need to collect fishery statistics in order to provide scientific advice for management. Halliday and Pinhorn (1990) reviewed the history of the delimitation process of "fishing areas" in the Northwest Atlantic from the 1920s to the present circumstances following the establishment of the Northwest Atlantic Fisheries Organization (NAFO) in 1979. In their review they note:

> *"There is remarkably little documentation of the scientific knowledge which was actually utilized in decision making about the precise locations of specific statistical boundary lines. The historical record does provide accounts of the general principles used in boundary delineation. The NACFI (North American Council on Fisheries Investigations) lines were chosen 'to correspond as far as possible with natural divisions of the fish populations or with barriers to fish migrations' (Found, 1933). Barriers to migrations presumably were of topographic or oceanographic nature. Cote (MS 1953) explicitly listed topography, oceanography and stock structure (in that order) as the 'ideal' bases for subdivision of ICNAF (International Commission for the Northwest Atlantic Fisheries) subareas although, of these, ICNAF (MS 1953a) emphasized stock structure only (along with uniformity of size of subdivisions, ease of use and conformity with existing divisions). Faunal composition, or at least the distribution of commercial species, (i.e. zoogeography) also influenced some boundary decisions"*

In essence, Halliday and Pinhorn (1990) indicated that although knowledge based, the approaches to the delineation of management units in the Northwest Atlantic had been largely qualitative and the result of a myriad of political, scientific, and somewhat arbitrary recommendations applied by a succession of decision-making entities. More recently, the Scientific Council of NAFO agreed that any ecoregion mapping of the Convention Area (NCA) must be consistent with similar mapping done by other coastal states in their respective Exclusive Economic Zones (EEZs) and tasked the Working Group on Ecosystem Approach to Fisheries Management (WGEAFM, now the Scientific Council Working on Ecosystem Science Advice WGESA) to identify regional ecosystems across the entire jurisdictional area of the organization. To this end, WGEAFM members undertook a series of analyses based on the application of multivariate methods that served to synthesize knowledge of the bathymetry, oceanography, biological, and in some instances geological conditions to which a variety of clustering approaches could be applied to identify areas that were statistically more similar (NAFO 2008, 2010, 2012).

The different sources of data available to describe the ocean can represent important challenges to the application of quantitative methods for the delineation of spatial management units. Most data are obtained using some form of remote sensing, whether it is fishing nets that can bias which organisms are being collected, satellites that only represent conditions in surface layers, or conductivity-temperature-depth (CTD) sensors that provide high degree of vertical resolution but have limited horizontal resolution owing to survey constraints on slow moving ships. Furthermore, there is considerable vertical structure in the distribution of physical, chemical and biological properties that may be difficult to capture fully across broad geographic areas. These factors can result in differences in the quality and representativeness of different data sources which may, depending on the data sources available in different parts of the region of interest, affect the outcome of any quantitative delineation process. This may have particularly important implications if the nature, extent and quality of information vary over time.

During previous meetings (NAFO 2008, 2010, 2012, 2013), extensive work had been reported on that consolidated multivariate data sets that reflected the physiographic, environmental, oceanographic and demersal resource base throughout each of the four major biogeographic regions (bioregions) on the east coast of North America (i.e. Newfoundland & Labrador Shelf, Flemish Cap, Scotian Shelf, and US northeast continental Shelf [Gulf of Maine (GoM)/Georges Bank/Mid-Atlantic Bight]). Here, we report on the outcome of the analyses based on the consolidated information and provide recommendations on the definition of appropriate Ecosystem Production Units (EPUs) in NAFO Convention Area, as well as on spatial scales representing levels or spatial organization of these ecosystems that can be useful for developing ecosystem management plans.

Results of the ecoregions analysis

Geographic Information Systems (GIS) served to develop consistent data layers within each bioregion which were then summarized using a combination of multivariate analyses, based primarily on principal components analysis (PCA) to reduce the dimensionality of the information layers. The information derived from those analyses, in the form of scores along principal axes, was then grouped using clustering algorithms to identify areas with common combinations of characteristic and geographically distinct features that represent ecoregions within each bioregion (Fogarty et al. 2011; Pepin et al. 2010, 2012; Pérez-Rodriguez et al. 2010; Zwanenburg et al .2010). The degree of definition of ecoregions within each bioregion was, to some extent, dependent on the number of distinct information layers available in each bioregion. For example, there were a large number of data sources for the analyses of both the US northeast continental Shelf (Fogarty et al. 2011) and the Scotian Shelf (Zwanenburg et al .2010) that resulted in a high degree of differentiation of among ecoregions in each locale. In contrast, there was less information available on the Newfoundland Shelf and Flemish Cap, which resulted in a lower degree of resolution to identify distinct ecoregions (Pepin et al. 2010; Pérez-Rodriguez et al. 2010). The contrast in results based on differences in the level of information available highlights the potential significance of knowledge in identifying features that may require different considerations and/or approaches in the provision of scientific advice and decision making.

To identify areas appropriate for EAM, we undertook to consolidate the information from all bioregions. The analytical approach was essentially identical to that applied at the scale of the bioregion (Figure 1) but carried out at the scale of the western north Atlantic (Labrador to mid-Atlantic Bight). However, some modifications had to be applied. Because of differences in data availability, the number of variables used in the analysis had to be limited to the eight data types (Table 1), which provide some information physiographic, environmental, oceanographic and demersal resource base. However, following preliminary analyses, the presence/absence of coral was dropped from the consolidation effort because the uniqueness of those ecosystem elements resulted in sites (rasters) with coral being grouped separately without consideration of geographic contiguity. It is clear that these elements are important features that define habitats within bioregions, and their occurrence within the broader context of ecosystem management units necessitates special consideration, but the information was not helpful in the delineation at large scales.

The results of the PCA explained 59% of the variance in the first three axes (PC) in the seven variables (PC1 23.2%; PC2 18.4%; PC3 17.2%), and highlighted the gradient in conditions from coastal areas to the deep ocean (1000 m isobath) and the contrast between warm bottom waters that also have higher biomasses of demersal fish, and colder areas having generally lower biomass. The analysis indicated the existence of some degree of non-linearity in the relationships between variables but this may reflect the influence of observations or conditions that are at the extremes of the range for certain variables. This was not considered to significantly affect the overall outcome of the analyses. Nine clusters (ecoregions) were identified as the optimal solution balancing the variance within and among clusters based on an unconstrained K-means analysis of the raster scores along the first three principal components. The results revealed a high degree of geographic contiguity of ecoregions over broad spatial scales with limited fragmentation within a bioregion although there was evidence of a high degree of heterogeneity (Figure 2). Strong latitudinal and bathymetric gradients were apparent in the distribution of ecoregions across the NAFO area but each ecoregion was not restricted to a single bioregion or portion thereof. For example, the ecoregion that occurs over the central Grand Banks also occurs over much of the eastern Scotian Shelf as well as on the southern flank of Georges Bank and in the central mid-Atlantic Bight (Figure 2). Similarly, conditions that predominate over much of the western Scotian Shelf can also be found over parts of the Flemish Cap, along the southwestern edge of the Grand Banks and in the northern portion of the mid-Atlantic Bight (Figure 2). The occurrence of ecoregions among bioregions likely reflects our use of composite (e.g. biomass) metrics in the analyses to describe the biological elements considered in the delineation assessment. Incorporating descriptors of phytoplankton and/or demersal community composition could have enhanced the analyses by giving greater consideration to species-habitat relationships, although this by itself has not always yielded clear correspondence between biogeographic and community boundaries (e.g. Mahon et al. 1998).

Although the distribution and spatial arrangement of ecoregions helped to qualitatively identify broad areas that included one or several ecoregions (e.g. Flemish Cap or Grand Banks), the spatial heterogeneity in the distribution of ecoregions can lead to uncertainty in the delineation of management units. To overcome the concern, K-means clustering was repeated on the first three PCs with the addition of positional (latitude, longitude) information in an attempt to include spatial proximity in the delineation of management units. The optimal solution identified 7 clusters across the NAFO area (Figure 3). Although generally informative, the analysis also revealed the overwhelming influence of geographic proximity and distance in the definition of each cluster which appeared to overshadow the combination of environmental characteristics identified ecoregions in the unconstrained analysis. For example, the cluster centered over the Georges Bank/GoM area (Figure 3) extends onto the western Scotian Shelf in an apparent disregard of the distinct environmental conditions that separated the two areas in the unconstrained analysis (Figure 2), and also does not correspond accurately to the spatial separation of major fish stocks in the region. Exploration of other proximity constrained solutions around the optimal number of clusters revealed that that a greater number of clusters could serve to delineate smaller management units on the Scotian and US northeast continental Shelves but again, the solution did not appear to be a realistic reflection of several regional biological aspects that were not included in the analytical assessment of the information.

Discussion

Because of the limitations associated with the analytical approaches that did or did not make use of positional information in the clustering, both sets of results served as guides for the WG discussions, along with expert knowledge that would include and consider the location of ecoregions, knowledge of the distribution of major marine resources and fish stocks, as well as geographic proximity in the delineation/definition of potential management units. This was based on the clear understanding that ecoregions in themselves do not define all ecologically important elements but that instead represent an intermediate level of delimitation of ecosystem elements in a hierarchy of spatial scales pertinent to the provision of management advice and action. Furthermore, the WG acknowledged that the current assessment does not explicitly take into consideration the functional nature of the ecological elements that are necessary for ecosystem integrity, stability and resilience. The process of unit delineation is iterative to some degree as results and observations are combined. The spatial extent of the units identified through this process essentially reflected the major features of the analytical results (Figure 4), with only details about the location of the boundaries for practical management units being the source of discussion.

The final consensus results from the WG discussions identified eight major Ecosystem Production Units (EPUs) that can serve as practical candidate management units (from the coast seaward to the 1500 m isobath) that consist of the Labrador Shelf (NAFO subareas 2GH), the northeast Newfoundland Shelf (subareas 2J3K), the Grand Banks (subareas 3LNO), Flemish Cap (subarea 3M), the Scotian Shelf (subareas 4VnsWX), Georges Bank (parts of subareas 5Ze and 5Zw), the Gulf of Maine (subarea 5Y and part of 5Ze) and the mid-Atlantic Bight (part of subarea 5Zw and subareas 6ABC) (Figure 5). The boundaries were adjusted only modestly to correspond with the with the current subarea boundaries on the Newfoundland Shelf. This is likely because Halliday and Pinhorn's (1990) conclusion that "*NACFI (North American Council on Fisheries*

Investigations) lines were chosen to correspond as far as possible with natural divisions of the fish populations or with barriers to fish migrations. Barriers to migrations presumably were of topographic or oceanographic nature." proved to be apparent in the more quantitative approach used in the WG's analyses. It is important to note, however, that Mahon et al. (1998) concluded that oceanographic barriers were not limitations to the distribution of groundfish species assemblages. This raises the possibility that biophysical features that control different taxa's ability to achieve life history closure may contribute to the defining production units.

The WG noted that the consensus solution represents a compromise that aims to define management units based on the boundaries of existing NAFO subareas. This may not exactly reflect the production areas that contribute to the Ecosystem and Fishery Production Potential (EPP and FPP, respectively) management units but the differences are considered subtle, so that application of models to estimate EPP and FPP should essentially focus on the proposed EPUs.

Spatial scales for ecosystem summaries and candidate ecosystem-level management units

Based on the full suite of ecoregion analyses, and in the context of developing and implementing ecosystem approaches to fisheries management, three major spatial scales were identified as relevant for the development of ecosystem summaries and management plans (Table 2). The broadest scale corresponds to bioregions, which are conceptually equivalent to Large Marine Ecosystems (Sherman and Alexander 1989), and correspond to Newfoundland and Labrador Shelves, Flemish Cap, Scotian Shelf, and US northeast continental Shelf (Gulf of Maine/Georges Bank/Mid-Atlantic Bight) (Figure 6).

The proposed candidate management units correspond to the Ecosystem Production Units (EPUs) that define major areas within the bioregions which contain a reasonably well defined food web/production system (Figure 5); these areas provide the spatial scale with which to estimate fishery production potential. Although EPUs are proposed as candidate management units, it should not be assumed that they are fully closed systems; transfer of production across EPU boundaries within a bioregion is to be expected. Furthermore, these proposed management units correspond closely with the initial consensus Ecosystem Production Units (Figure 4), differing only in terms of the boundaries between the northeastern Newfoundland Shelf, the Grand Banks and the Flemish Cap (Figures 4 and 5), but nonetheless still represent a compromise between ecological considerations and management practicality.

Each of the EPUs consists of a combination of ecoregions, which represent elements with different physical and biological characteristics based on the analytical criteria applied. Ecoregions in themselves do not define all ecologically important elements. Instead they represent an intermediate level of delimitation of ecosystem elements (e.g. Figure 2) in a hierarchy of spatial scales pertinent to the provision of management advice and action. However, it is the ecoregion scale which is expected to provide the context for defining more precise habitats, including Vulnerable Marine Ecosystems (VMEs).

More detailed knowledge of a broader range of elements than was considered in the synthesis as well as greater spatial resolution of the input data would provide greater scope to identify important or significant ecosystem elements. WGESA therefore recommends that careful consideration be assigned to the results of earlier the regional analyses (Fogarty et al. 2011; Pepin et al. 2010, 2012; Pérez-Rodriguez et al. 2010; Zwanenburg et al. 2010) in the development and implementation of ecosystem management measures within the proposed EPUs to ensure that decisions are based on the best available information.

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Table 1. The variables used as input for the PCA and clustering analysis showing their original data type, source, units, and time period.

Variables	Data Source	Units
Bathymetry	GEBCO (1' Grid)	Meters
Sea Surface Temperature	NOAA AVHRR Satellite (4km Grid)	^{0}C annual average
Bottom Temperature	Temperature at fishing	^{0}C from multi-species surveys
Chlorophyll-a	SeaWiFS Satellite (4 km)	mg/m^3 (annual average)
Primary Production	SeaWiFS Satellite (1.5 km)	mg/m^3/year (cumulative)
Demersal Biomass	Multi-species Survey	kg/standard tow
Demersal Diversity	Multi-species Survey	Shannon's evenness index

Table 2. Basic spatial scales identified as relevant and useful for ecosystem summaries and management plans in the context of developing and implementing Ecosystem Approaches to Fisheries Management.

Name	General operational description	Examples in NAFO Convention Area
Bioregion	Large geographical area characterized by distinct bathymetry, hydrography, and which contains one or more reasonably well defined (but still interconnected) major marine communities/food web systems.	• Newfoundland and Labrador Shelves • Flemish Cap • Scotian Shelf • US northeast continental Shelf
Ecosystem Production Unit (EPU)	Within a bioregion, a major geographical subunit characterized by distinct productivity and a reasonably well defined major marine community/food web system.	• Northeast Newfoundland Shelf (2J3K) • Grand Bank (3LNO) • Flemish Cap (3M) • Georges Bank
Ecoregion	Within an EPU, geographical area with consistent physical and biological characteristics. Often corresponds to a broadly defined seascape and/or major habitat type/class; its precise delineation and extent can vary depending on data availability and the analytical criteria applied. It is within this spatial scales that more precise habitats can be identified (e.g. VMEs).	• Inshore areas in the Northeast Newfoundland Shelf • North region of the Grand Bank (~3L) • Top of the bank in Flemish Cap • Slope areas

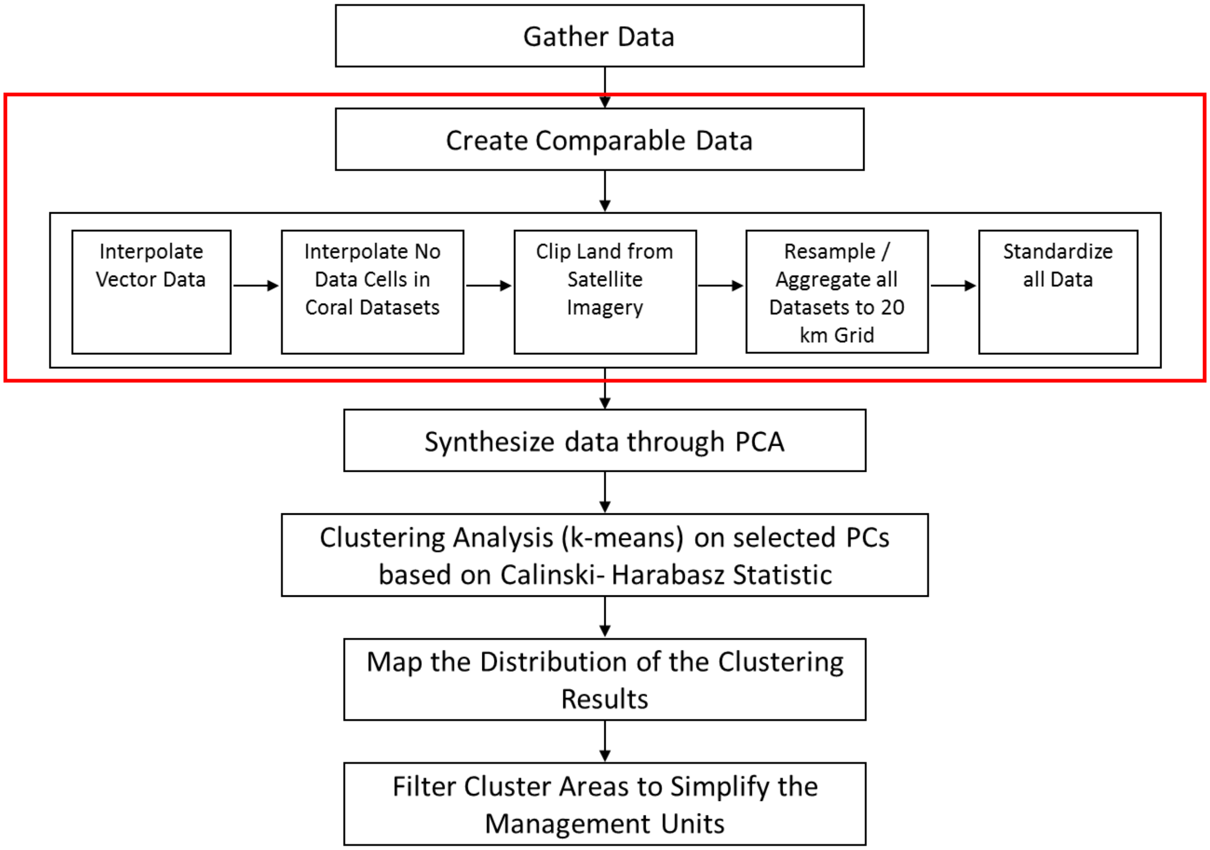

Fig. 1. Flow chart of the analytical approach used to consolidate the data.

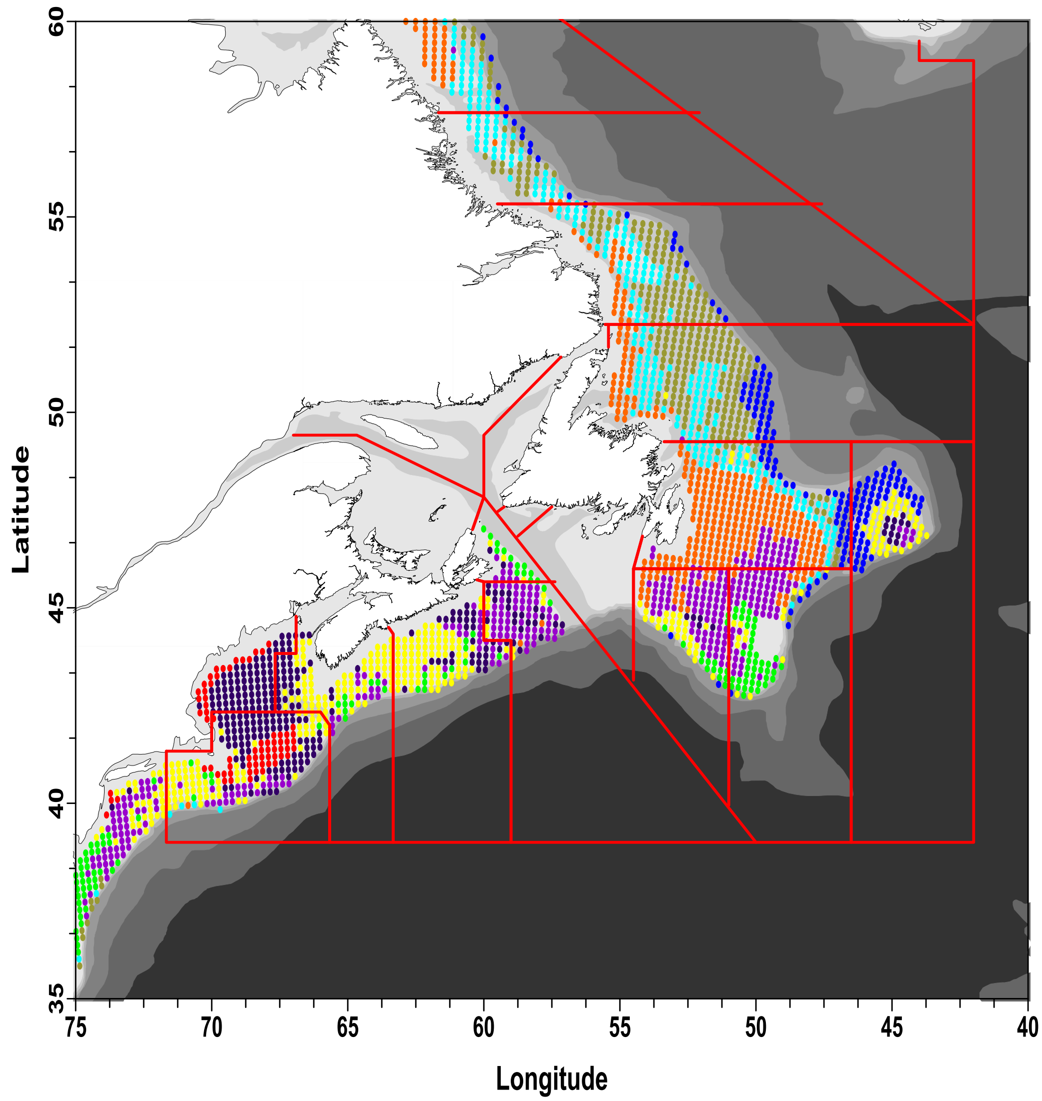

Fig. 2. Map of unconstrained k-means clustering results of the first three principal components. Each colour represents a different cluster.

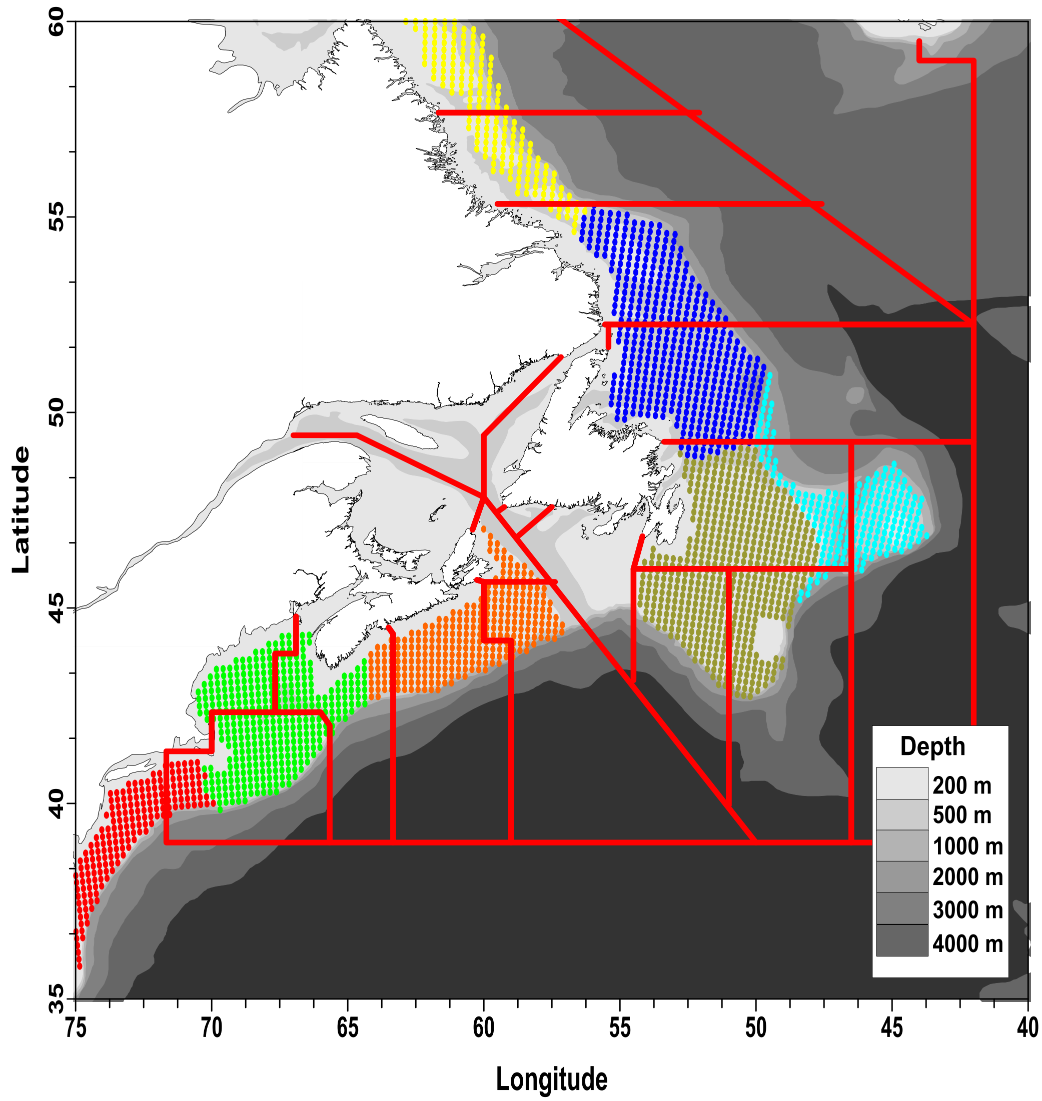

Fig. 3. Map of geographically constrained k-means clustering results of the first three principal components. Each colour represents a different cluster.

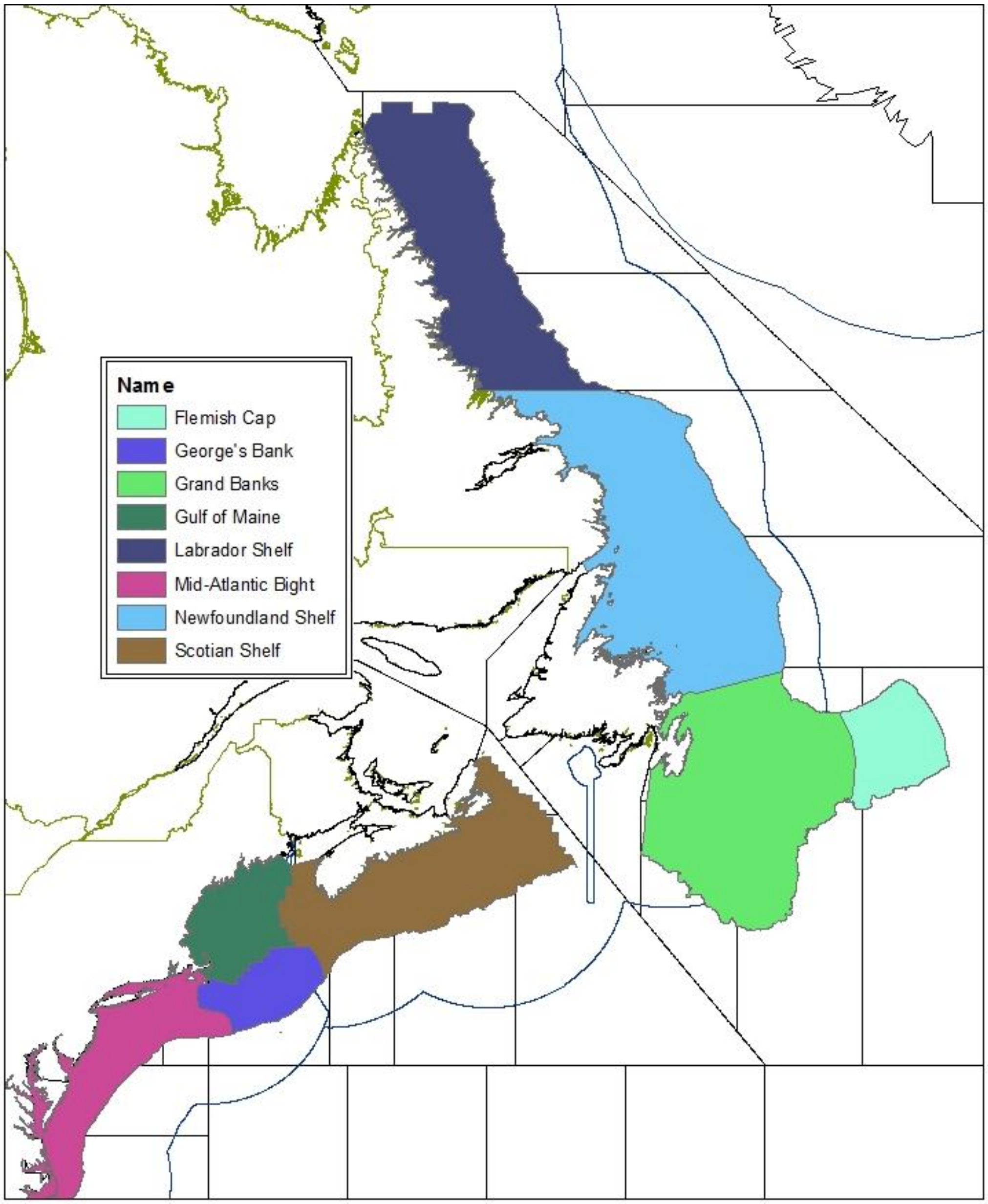

Fig. 4. Initial consensus map of Ecosystem Production Units identified as a result of ecoregion analysis and expert opinion.

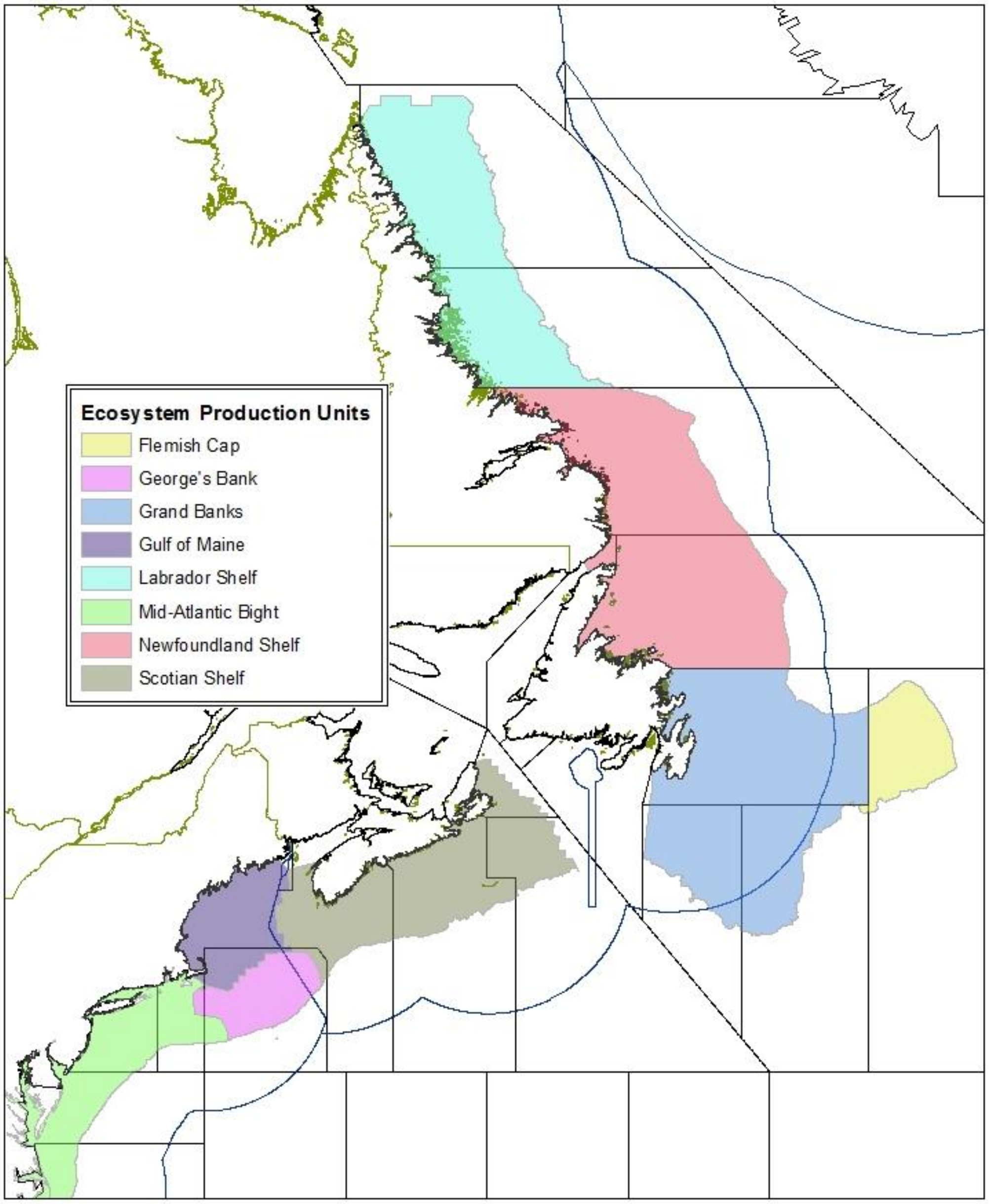

Fig. 5. Final consensus map of Ecosystem Production Units that can serve as practical Ecosystem Management Areas identified as a result of ecoregion analysis and expert opinion.

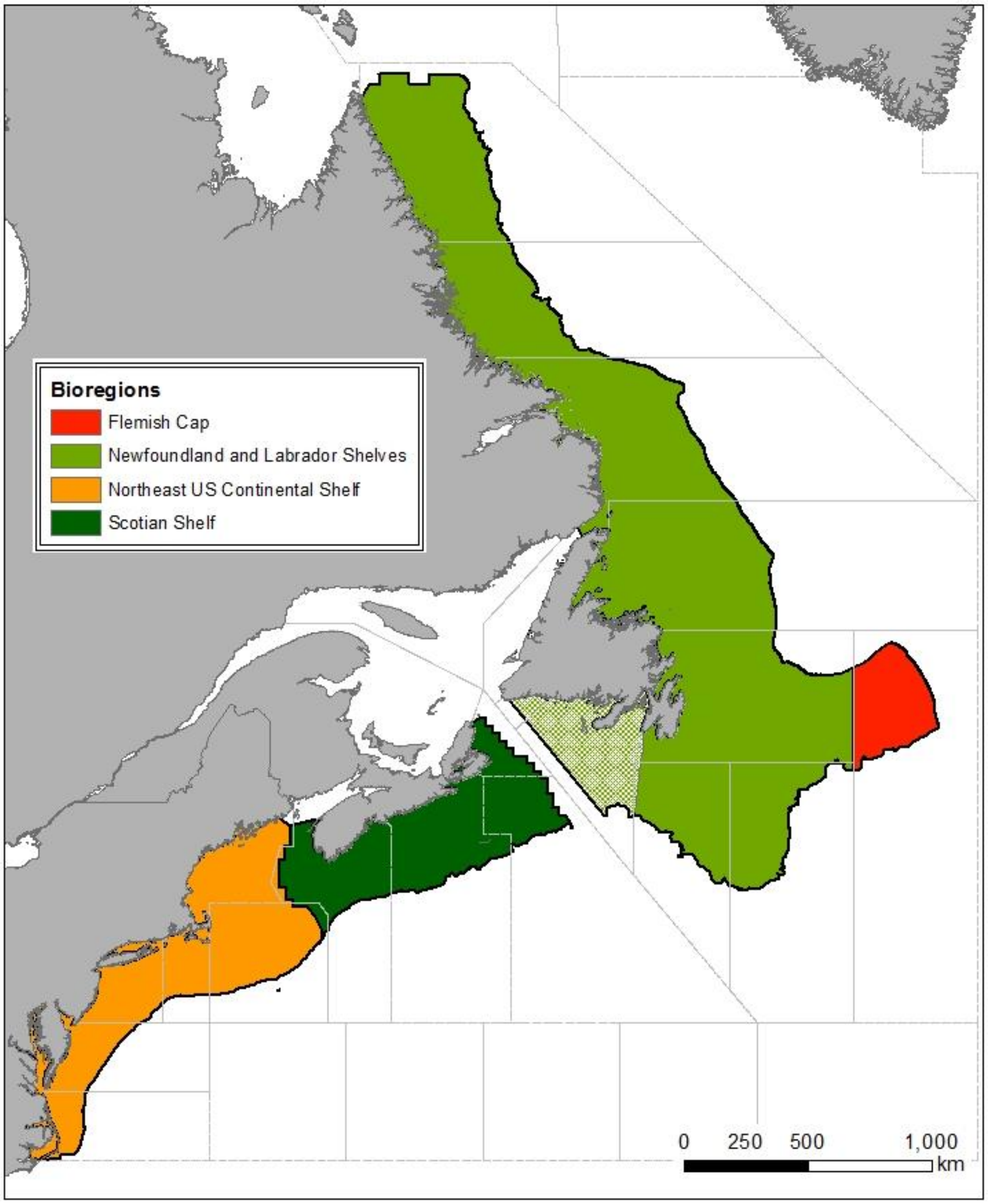

Fig. 6. Bioregions identified by multiple "ecoregion analyses", as well as expert opinion. NAFO Div. 3P appears shaded because it is considered part of the NL shelves, but data for this area were not included in the ecoregion analyses.