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SC WORKING GROUP ON ECOSYSTEM SCIENCE AND ASSESSMENT – NOVEMBER 2017

Report of the 10th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA)

NAFO Headquarters, Dartmouth, Canada
8 - 16 November 2017

Contents

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09-17 November 2017

INTRODUCTION

The NAFO SC Working Group on Ecosystem Science and Assessment (WG-ESA), formerly known as SC Working Group on Ecosystem Approaches to Fisheries Management (WG-EAFM), had its 10th meeting on 8-16 November 2016 at NAFO Headquarters, Dartmouth, Canada.

The work of WG-ESA can be described under two complementary contexts:

a) work intended to advance the Roadmap, which typically involves medium to long-term research, and

b) work intended to address specific requests from Scientific Council (SC) and/or Fisheries Commission (FC), which typically involves short to medium-terms analysis, aligned to roadmap priorities.

WG-ESA revised and up-dated its long-term ToRs in 2016 to be implemented at its 2017 meeting and thereafter, accordingly:

Theme 1: Spatial considerations

> **ToR 1.** Update on identification and mapping of sensitive species and habitats in the NAFO area. In support of the Roadmap develop research and summarize new findings on the spatial structure and organisation of marine ecosystems with an emphasis on connectivity, exchanges and flows among ecosystem units in the NAFO Convention Area.

Theme 2: Status, functioning and dynamics of marine ecosystems

> **ToR 2.** Develop research and summarize new findings on the status, functioning, productivity of ecosystems (including modelling multi-species interactions) in the NAFO Convention Area.

Theme 3: Practical application EAFM

> **ToR 3.** Develop research and summarize new findings on long-term monitoring of status and functioning of ecosystem units (including ecosystem summary sheets) and the application of ecosystem knowledge for the assessment of impacts and management of human activities in the NAFO Convention Area.

Theme 4: Specific requests

> **ToRs 4+.** As generic ToRs, these are place-holders intended to be used when addressing expected additional requests from Scientific Council or Fisheries Commission that don't fit in to the standing ToRs above.

The following ToRs were addressed at the 10th meeting of WG-ESA:

THEME 1: SPATIAL CONSIDERATION

ToR 1.1. Update of Vulnerable Marine Ecosystem Indicator Taxa in the NAFO Conservation and Enforcement Measures

The last assessment of deep-water marine invertebrate taxa found in the NAFO Regulatory Area (NRA) against the FAO criteria for vulnerable marine ecosystem (VME) indicator designation occurred in 2011 (see Murillo et al., 2011). In the 2011 assessment, over 500 benthic taxa recorded in the NRA from rock dredge and trawl surveys were assessed against the criteria for functional significance, fragility, and life history characteristics that make recovery difficult, and revealed three additional taxa that constitute VME: erect bryozoans, sea lilies (crinoids), and sea squirts. Since the assessment in 2011, additional information has become available on the taxonomy, presence, ecological function, and life history characteristics of benthic marine fauna found in the NRA, calling for a review of the current List of VME Indicator Species in Annex 1.E of the NAFO Conservation and Enforcement Measures (NCEM).

Currently, the list of VME Indicator Species in the NCEM encompasses only those taxa that are caught or likely to be retained in trawl gear. However, the use of camera and video systems in the NRA has revealed the presence of VME Indicator Species not previously observed in the trawl surveys. For instance, xenophyophores, which are considered a VME indicator by the FAO (FAO, 2009) were recorded during a camera survey of Kelvin Seamount (NAFO, 2016) of the NAFO New England Seamount Closure. This group is unlikely to be recorded in trawl gears as their tests are fragile and easily disintegrate. As NAFO moves towards the use of non-destructive sampling alternatives such as camera systems to monitor the status of VME in the NRA, a review of the current list of VME Indicator Species is warranted.

WG-ESA **recommends** that *Scientific Council examine the current format and inclusion of species in the List of VME Indicator Species in Annex 1.E of the NCEM and determine whether:*

a) The list should include only those VME Indicator Species likely to be encountered in trawl gear, or whether:

b) The list be revised to include a full list of VME Indicator Species in the NRA that could be encountered or recorded by use of non-destructive or alternative sampling gears such as camera/video surveys, as well as trawl gear.

Similarly, the list of VME Indicator Species in the NCEM should be revised to reflect the current scientific nomenclature. For instance, small gorgonian coral *Acanella eburnea* (Poutalès, 1868) requires removal from the list of VME Indicator Species in the NCEM as it has recently been synonymized with *Acanella arbuscula* (Cordeiro et al 2018a). Similarly, *Keratoisis ornata* (Verrill, 1868) is no longer valid and is a synonymized name for *Keratoisis grayi* (Wright, 1869) (Cordeiro et al 2018a).

Advancements in the identification of fauna caught in scientific trawl surveys in the NRA have revealed the presence of VME Indicator Species not current listed in the NCEM. For instance, the large sponge *Mycale* (*Mycale*) *loveni* (Fristedt, 1887) has recently been identified from Canadian multispecies trawl surveys in the NRA (Wareham Hayes, pers. comm.). This species is relatively large compared to other VME sponge taxa, reaching heights of at least 35 cm and widths of 40 cm (see Fristedt, 1887; Wareham Hayes pers. comm.) and should be included as a Large-Sized Sponge VME Indicator Species. Similarly, a sponge species new to science, *Cladorhiza kenchingtonae*, was recently described from a sample collected with an ROV from the southern Flemish Cap slope (Hestetun et al., 2017).

As NAFO prepares for the reassessment of the VME fishery closures in 2020, WG-ESA will plan to conduct a complete review of taxa occurring in the NRA that were *not previously assessed against the FAO criteria for VME designation* (see Murillo et al. (2011) and Fuller et al. (2008)). This would allow for consideration and inclusion of new taxonomic records for the NRA. Similarly, new evidence to support VME status for those taxa previously excluded (e.g. soft corals) should also be reviewed and those taxa reconsidered. In the example of soft corals, this group has been shown to dominate the biomass within the sea pen VME on the eastern Flemish Cap (See Fig. 1.33, NAFO, 2013).

i) New preliminary data on VME encounters in NAFO Regulatory Area (Divs. 3LMNO) from EU and EU-Spain Groundfish Surveys (2017), and Canadian Multispecies Surveys (2016-2017).

During the 10th NAFO Working Group on Ecosystem Science and Assessment (WG-ESA) meeting new preliminary data on deep-water corals and sponges were presented from the 2017 EU and EU-Spain bottom trawl groundfish surveys, and 2016-2017 Canadian multispecies surveys. The data was made available to the NAFO WG-ESA to improve mapping of Vulnerable Marine Ecosystem (VME) species in the NAFO Regulatory Area (Divs. 3LMNO).

During the 6th meeting of the NAFO Scientific Council WG-ESA, quantitative spatial analyses were applied for corals and sponges for all the available data within the NAFO Regulatory Area (NAFO SCS, 2013). Outcomes from these analyses produced the following thresholds for VME species groups: 75 kg per tow for sponges, 0.6 kg per tow for large gorgonians, 0.15 kg per tow for small gorgonians, and 1.4 kg per tow for sea pens. Based on these thresholds deep-water coral and sponge data were identified and mapped, overlaid with the current closed areas, polygons for kernel density of sea pens and modified kernel density polygons for sponge grounds and large gorgonian VMEs.

Data used in the 2017 WG-ESA analysis were collected from four surveys:

1. The EU-Spain 3NO groundfish survey, conducted by the Instituto Español de Oceanografía (IEO), sampled the Grand Banks of Newfoundland (NAFO Divs. 3NO) between 41 - 1389 m depth with a total of 114 tows.
2. The EU-Spain and Portugal Flemish Cap groundfish survey, conducted by the IEO together with the Instituto de Investigaciones Marinas (IIM) and Instituto Português do Mar e da Atmosfera (IPMA), sampled the Flemish Cap (NAFO Div. 3M) between 132 -1434 m, with a total of 184 tows.
3. The EU-Spain Fletán Negro-3L groundfish survey, conducted by the IEO, sampled northeast Grand Banks of Newfoundland (NAFO Div. 3L) between 106 - 1433 m depth, with a total of 103 tows.
4. The Canadian Multispecies Surveys, conducted by Fisheries Oceans Canada, sampled the Grand Banks of Newfoundland (NAFO Divs. 3LNO) between 36 - 694 m depth, with a total of 259 tows.

There were 660 (401 EU + 259 CAD) bottom trawl tows carried out during 2017 EU Groundfish and 2016-2017 Canadian Multispecies surveys in the NRA for this report.

Following previous methodologies used by WG-ESA, deep water corals were grouped by VME species groups and include; large gorgonians (Order: Alcyonacea), small gorgonians (Order: Alcyonacea), sea pens (Order: Pennatulacea), and sponges (Phylum: Porifera).

Distribution maps of presence (non-significant and significant catches) for large gorgonians, small gorgonians, sea pens, and sponges are presented below (Figs. 1.1.1-1.1.8). Locations of each coral and sponge records were assigned by start position of each tow for 2017 EU-Spain Surveys, and 2016-2017 Canadian survey tows. Coordinates and weights of the significant catches are provided in Table 1.1.1.

Table 1.1.1 Significant catches of corals and sponges in the NRA (Divs. 3LMNO) with their corresponding depth and weight. Note tow positions are in decimal degrees. * CAD survey tows.

VME Indicator Species	Year	Survey	Start position Lat (N)	Start position Long (W)	Depth (m)	Weight (kg)
SPONGES ≥ 75 kg	2017	3M	47.60	-43.63	1106	7113.44
	2017	3M	46.95	-43.50	965	1432.34
	2017	3M	46.72	-44.04	721	3220.97
	2017	3NO	45.45	-48.18	1324	203.04
	2017	3NO	45.66	-48.13	1323	145.04
LARGE GORGONIANS ≥ 0.6 kg	2017	3L	46.53	-47.12	601	1.48
	2017*	3N	45.98	-47.65	658	2.08
	2017*	3O	43.12	-51.40	631	1.52
SMALL GORGONIANS ≥ 0.15 kg	2017	3NO	43.18	-49.05	1369	0.18
	2017	3NO	42.74	-50.04	831	2.03
	2017	3NO	42.75	-50.11	611	0.15
SEAPENS ≥ 1.4 kg	2017	3M	48.23	-44.40	829	1.52
	2017	3M	48.37	-44.87	661	2.21
	2017	3M	46.72	-46.32	391	1.80
	2017*	3O	43.12	-51.40	631	2.26

Sponges

EU-Spain 2017 Data: Sponges were recorded in 142 of the total tows (35.4% of the total tows analyzed), with depths ranging between 54 - 1338 m and average depth of 494 m (Fig. 1.1.1).

Significant catches of sponge (≥ 75 kg/tow) were found in five EU tows (see Table 1.1.1 and Fig. 1.1.1). Three of these catches were located in the eastern part of the Flemish Cap; the other two were located in Flemish Pass area inside the KDE sponge polygon. Sponge catches for these tows ranged between 145 - 7113 kg.

Canadian 2016-2017 Data: Sponges were recorded in 103 of the total tows (42.6% of total tows analyzed), with depths ranging between 52 - 694 m and average depth of 377.8 m (Fig. 1.1.2). There were no significant catches of sponge (≥ 75 kg/tow) encountered in Canadian 2016-2017 data.

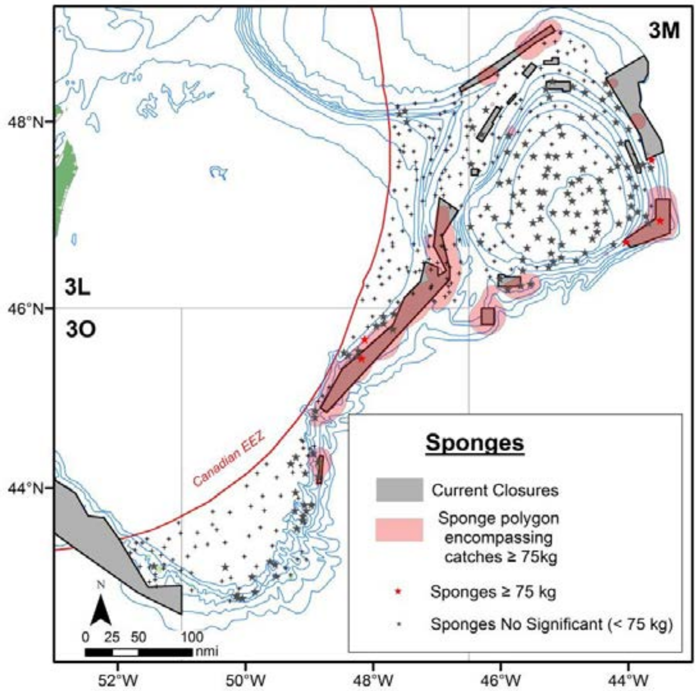

Fig. 1.1.1. Distribution of significant and non-significant catches of sponges in the study area from 2017 EU-Spain surveys (NAFO Divs. 3LMNO). Black crosses represent tows with no sponge bycatch recorded.

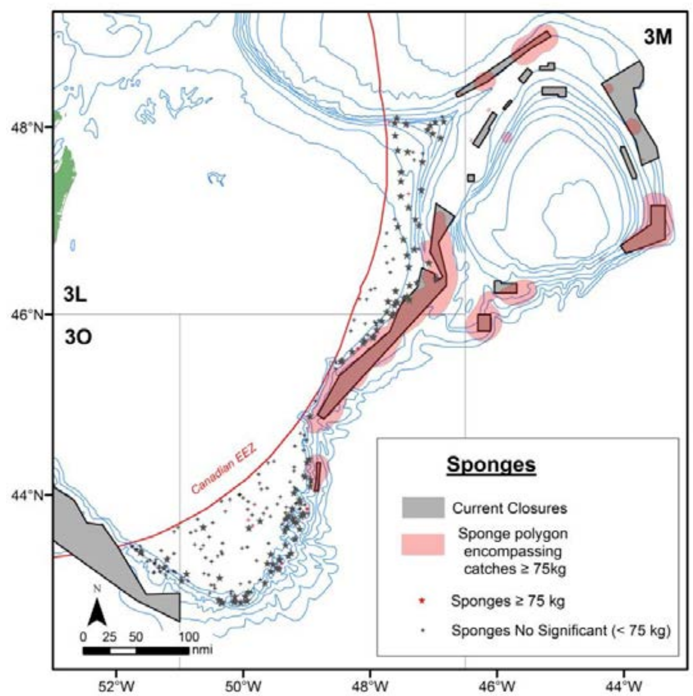

Fig. 1.1.2. Distribution of non-significant catches of sponges in the study area from 2016-2017 Canadian surveys (NAFO Divs. 3LNO). There were no significant sponge catches documented. Black crosses represent tows with no sponge bycatch recorded, and red crosses represent unsuccessful tows.

<u>Large Gorgonians</u>

EU-Spain 2017 Data: Large gorgonians were recorded in 12 tows (3% of total tows analyzed), with depths ranging between 342 - 1285 m and average depth of 845 m (Fig. 1.1.3).

Significant catches of large gorgonians (≥ 0.6 kg/tow) were found in one EU tow (see Table 1.1.1 and Fig. 1.1.3). This catch was located in the Flemish Pass area inside the corresponding KDE polygon but outside the actual closed area number 2.

Canadian 2016-2017 Data: Large Gorgonians were recorded in 19 tows (7.9% of total tows analyzed) with depths ranging between 50 - 694 m and average depth of 350.5 m (Fig. 1.1.4).

There were two tows with significant catches of large gorgonians (≥ 0.6 kg/tow) documented in Canadian surveys (see Table 1.1.1 and Fig. 1.1.4). Both catches were located outside of the KDE polygons and existing closures. One catch had 1.52 kg (NAFO Div. 3O) of bamboo coral (Family Isididae) located on the Tail of the Grand Banks. The other consisted of 2.08 kg of bubble gum coral (*Paragorgia arborea*) located on the edge of the continental shelf adjacent to closed area number 2.

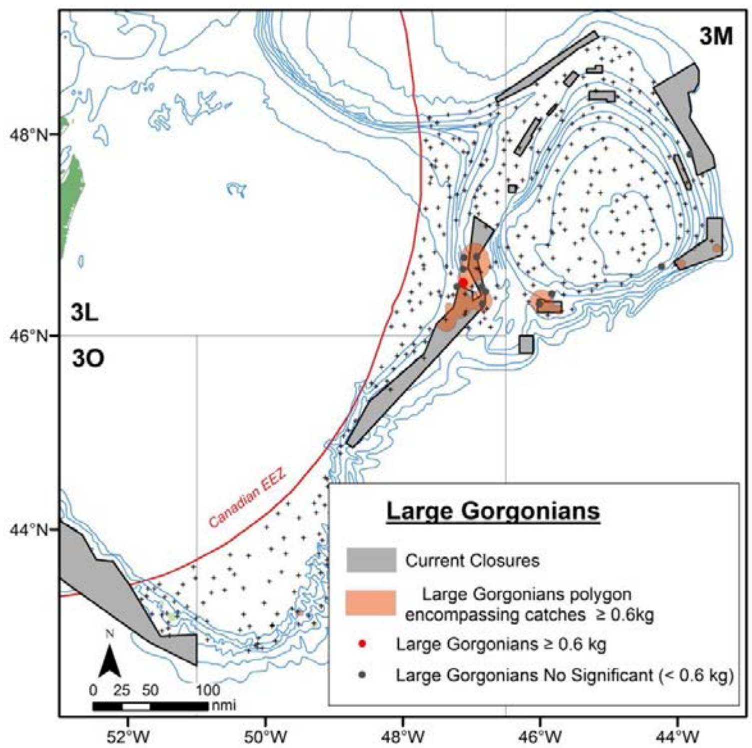

Fig. 1.1.3. Distribution of significant and non-significant catches of large gorgonians in the study area from EU-Spain 2017 surveys (NAFO Divs. 3LMNO). Black crosses represent tows with no large gorgonians bycatch recorded.

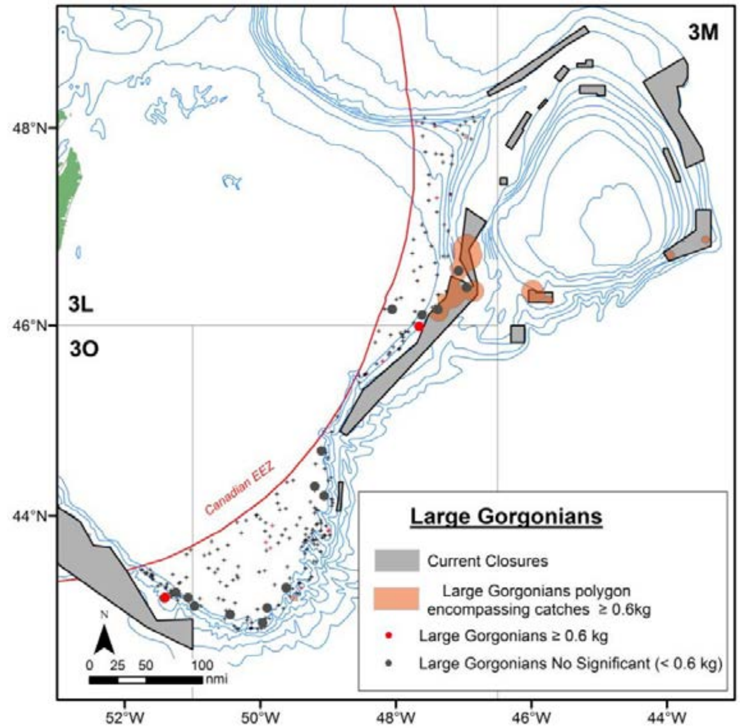

Fig. 1.1.4. Distribution of significant and non-significant catches of large gorgonians in the study area from Canadian 2016-2017 surveys. Black crosses represent tows with no large gorgonian bycatch recorded, and red crosses represent unsuccessful tows.

Small Gorgonians

EU-Spain 2017 Data: Small gorgonians were recorded in 55 tows (13 % of total tows analyzed), with depths ranging between 224 - 1434 m and average of 927 m (Table 1.1.1; Fig.1.1.5).

Significant catches ($\geq$ 0.15 kg/tow) were recorded in three tows (0.75% of the total tows) located at the Tail of the Grand Banks, outside of the actual closed areas with depths between 611 - 1369 m.

Canadian 2016-2017 Data: Small gorgonians were recorded in only one tow (0.4% of total tows analyzed) at a depth of 161 m and the catch was not significant (Fig. 1.1.6).

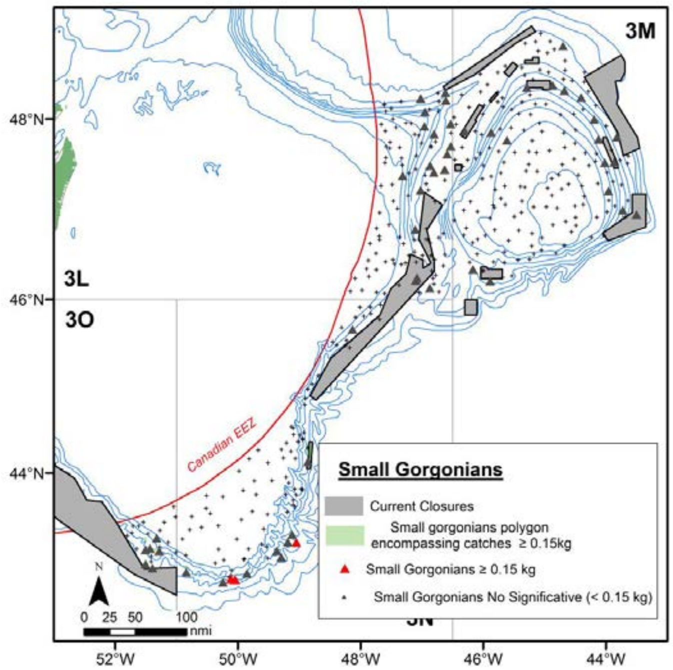

Fig. 1.1.5. Distribution of significant and non-significant catches of small gorgonians in the study area from EU-Spain 2017 surveys (NAFO Divs. 3LMNO). Black crosses represent tows with no small gorgonian bycatch recorded.

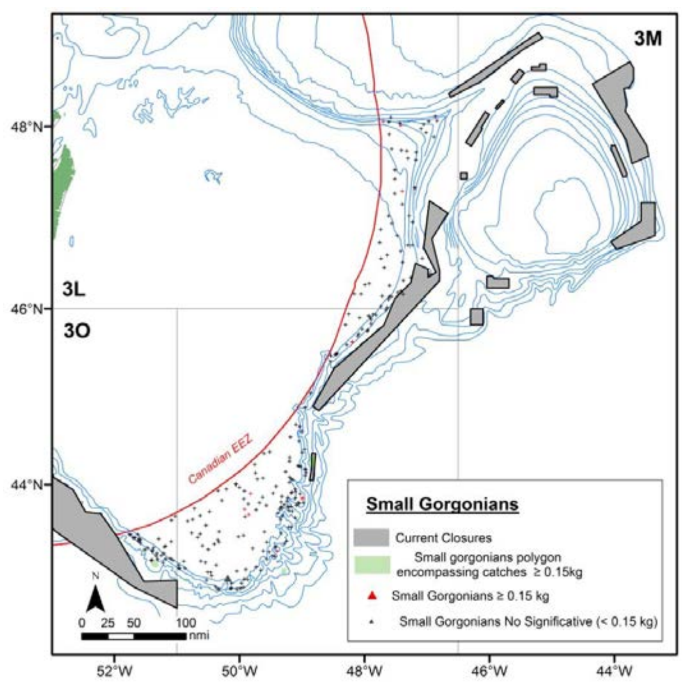

Fig. 1.1.6. Distribution of one non-significant catch of small gorgonians in the study area from Canadian 2016-2017 surveys. Black crosses represent tows with no small gorgonian bycatch recorded, and red crosses represent unsuccessful sets.

Sea Pens

EU-Spain 2017 Data: Sea pens were recorded in 140 tows (34.9% of total tows analyzed), with depths ranging between 242 - 1434 m and average depth of 884 m (Table 1.1.1; Fig. 1.1.7).

Significant catches (≥ 1.4 kg/tow) were recorded in three tows (1.52- 2.21 kg), two of them were located north of Flemish Cap and inside the corresponding VME KDE polygon. The other one was located southwest of the Flemish Cap, outside the KDE polygon.

Canadian 2016-2017 Data: Sea pens were recorded in 17 tows (7% of total tows analyzed), with depths ranging between 272 – 661 m and average depth of 248 m (Fig. 1.1.8).

There was only one tow recorded with a significant catch of sea pens (≥ 1.4 kg/tow) from the Canadian surveys (see Table 1.1.1; Fig. 1.1.8). The catch had 2.26 kg of an unspecified Pennatulacean, and was located outside of KDE polygon on the Tail of the Grand Banks of Newfoundland in NAFO Div. 3O.

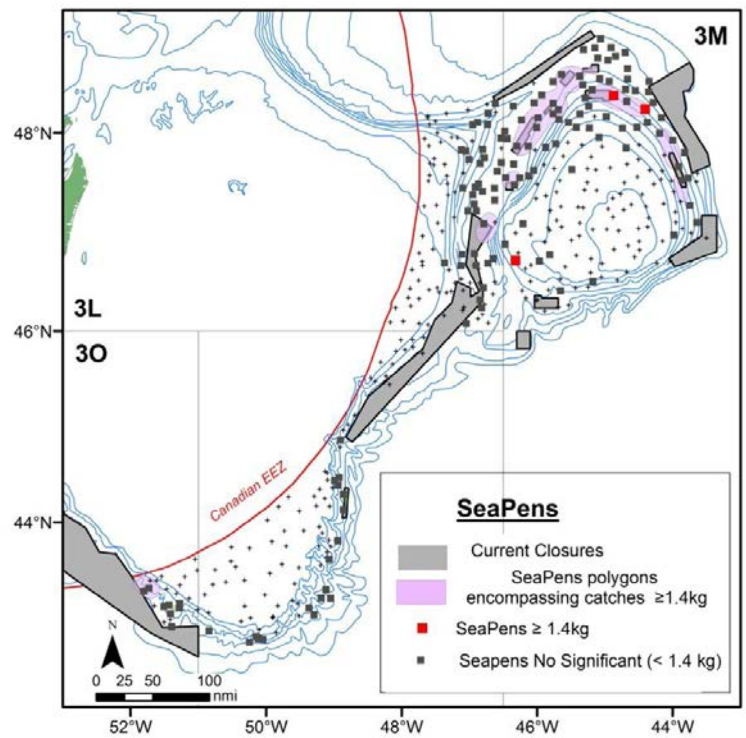

Fig. 1.1.7. Distribution of significant and non-significant catches of sea pens in the study area from EU-Spain 2017 surveys (NAFO Divs. 3LMNO). Black crosses represent tows with no sea pen bycatch recorded.

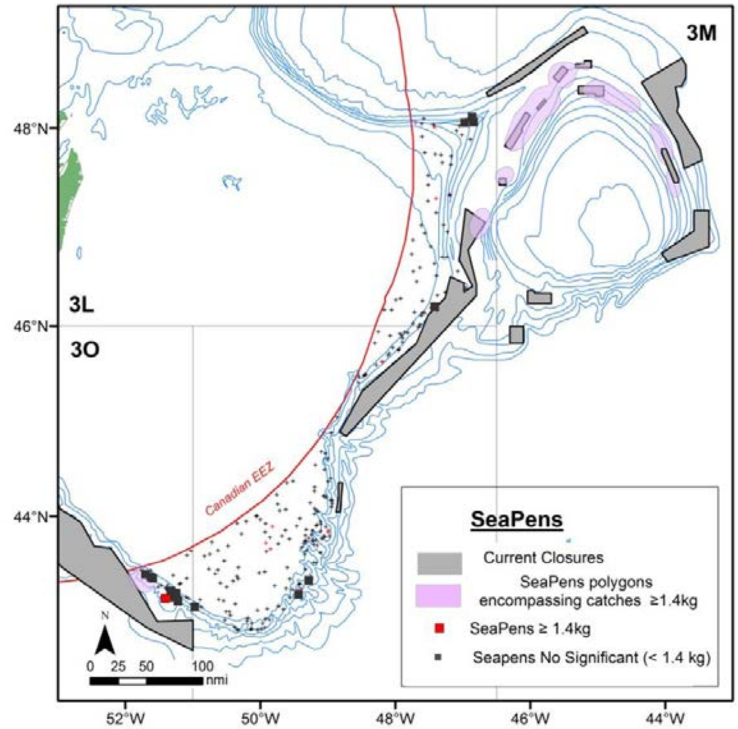

Fig. 1.1.8. Distribution of one significant catch of sea pens in the NRA study area from Canadian 2016 -2017 survey. Black crosses represent tows with no sea pen bycatch recorded, and red crosses represent unsuccessful sets.

Table 1.1.2. Summary of deep-water corals and sponges records for the NRA from EU-Spain 2017 data and Canadian 2016-2017 survey data. For Canadian data only successful tows (n=242) were analyzed.

EU-Spain data 2017	Presence Significant and Non- Significant (# of tows)	Total Tows (%)	Significant Concentrations (# of tows)	Significant Concentrations (% of tows)	Significant Concentrations inside KDE corresponding polygon
Sponges	142	35.4%	5	1.2%	3
Large Gorgonians	12	3%	1	0.25%	1
Small Gorgonians	55	13.7%	3	0.75%	0
Sea Pens	140	34.9%	3	0.75%	2

Canadian data 2016-2017	Presence Significant and Non- Significant (# of tows)	Total Tows (%)	Significant Concentrations (# of tows)	Significant Concentrations (% of tows)	Significant Concentrations inside KDE corresponding polygon
Sponges	103	42.6	0	0%	0
Large Gorgonians	19	7.9	2	0.82%	0
Small Gorgonians	1	0.4	0	0%	0
Sea Pens	17	7	1	0.41%	0

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ToR 1.2 Discussion on up-dating Kernel Density Analysis and SDMs for VME indicator species especially for sea pens

i) Re-Analyses of KDE Estimation of Sea Pen VMEs in the NAFO Regulatory Area

Kernel density estimation (KDE) utilizes spatially explicit data to model the distribution of a variable of interest within a given search radius and grid size. It is a simple non-parametric neighbour-based smoothing function that relies on few assumptions about the structure of the observed data. It has been used in ecology to identify hotspots from lower level background distributions, that is, areas of relatively high biomass/abundance. The kernel surface is a sum of the values under each Gaussian curve fitted over each data point in areas of overlap. With respect to marine benthic invertebrate species, it was first applied to the identification of significant aggregations of sponges in the NAFO Regulatory Area in 2009 (Kenchington *et al*., 2009) and published in the primary literature applied to VME indicators in 2014 (Kenchington *et al*., 2014). Canada has used this method, combined with species distribution modelling to identify significant benthic areas of coral and sponge in five biogeographic zones in eastern Canada (Kenchington et al., 2016). An overview of the method with a breakdown of the steps involved is found in Kenchington *et al.* (2016).

By constructing equal-density polygons using different catch levels, the minimum catch weight which corresponds to the main sponge or coral aggregations can be determined (catch here is research vessel catch). Polygons are then constructed around those concentrations and can be used to give a measure of "habitat area". These polygons are considered by NAFO to be vulnerable marine ecosystems when applied to sponge, sea pens, large and small gorgonian corals (NAFO, 2013). Kenchington *et al*. (2016) compared updated analyses performed with additional survey data to those produced previously and found that the KDE analyses produced very similar locations to those previously identified (Kenchington et al., 2010), despite the large increase in the number of data points used in the 2016 re-analysis. However, polygons will change if the survey point density is low in a given area. Kenchington *et al*. (2012) proposed and tested metrics that could be constructed from individual polygons (e.g., mean polygon area and shape) using attributes of their statistical distribution (e.g., mean, maximum, variance) of the corresponding polygon variable (e.g., size, shape). The spatial relationship among polygons, or patch configuration was also quantified using nearest neighbour and other statistics capturing information on the relative position of the patches within the survey landscape. They found that polygon area was a good metric while nearest neighbour and other metrics could be influenced by the identification of new polygons over time in under-sampled areas.

Significant concentrations of sea pens have been identified previously in the NRA using kernel density analyses and an evaluation of the expansion of the area covered by successive density polygons (Murillo *et al*., 2010), although this was done for all the 3LMNO Divisions, including Canadian waters. These analyses were updated in 2013, using all available data from the RV trawl surveys and applied to the NRA area only. Specifically data from the Spanish 3NO survey (2002-2013), EU Flemish Cap Survey (2003-2013), the Spanish 3L Survey (2003-2013) and the DFO-NL Multi-species Surveys (1995-2012) were assessed. These data sources yielded 1310 sea pen records (183 from the Canadian surveys and 1127 from the EU-Spanish surveys). However, there were significant differences among the catch series for each survey ($P < 0.001$) with the Campelen catches being more similar to one another than with the Lofoten catches. These dissimilarities were driven by differences in the number of small catch weights. When all records less than 0.2 kg were removed, there was no significant difference among the catch distributions ($P=0.087$). Therefore the analyses were performed on 262 catches ≥ 0.2 kg (35 Canadian records and 227 EU-Spanish records). Species distribution modelling was then done to support the decision process (NAFO, 2013). Despite these detailed analyses, fisheries managers remain concerned over the stability of the polygons used to inform the area (Area 14) closed to protect sea pens on the eastern aspect of Flemish Cap and have asked for the KDE analysis to be re-evaluated.

Here we present a re-analysis of the kernel density estimation of sea pen VMEs in the NRA. Also, for the first time, KDE analysis was applied to sea pen abundance data to provide further information on the VME formed by these species (see Appendix 1). Sea pen biomass from Canadian and EU surveys from 2005 to 2017 were assessed and included the 262 records used in the 2013 analysis and 123 new sea pen records at or above the 0.2kg weight value. The total number of records is 385. Following previously established methods and assessment criteria (NAFO, 2013), a kernel density surface was created (Fig. 1.2.1) and the area of successive density polygons calculated (Table 1.2.1). The search radius was 21.6 km, cell size was 2.90 km, and the contour interval for constructing equal density polygons was 0.00001 kg. These were the values used in the 2013 analysis. The kernel density distribution identified sea pen fields on the western, northern and eastern portions of Flemish Cap and on the Tail of Grand Bank in 3O (Fig. 1.2.1).

The area of sea pen habitat encompassed by the polygons increases first between the 3 kg and 2 kg catch thresholds (Table 1.2.1, Fig. 1.2.2). This increase in area was 403% and was created through the addition of 9 data points. The lower threshold is picking up sea pen areas that were not included in the area covered by the 3 kg threshold (Fig. 1.2.3), indicating that the area is still being delineated. The next largest change in area occurs between 1.4 and 1.2 kg (Table 1.2.1, Fig. 1.2.2), where the increase in area is 97%. This increase occurs through joining polygons formed by higher thresholds on the Flemish Cap. Following previously established guidelines (Kenchington et al., 2016) the 1.4 kg/ RV tow threshold emerged as defining significant concentrations of sea pens (i.e., sea pen field VME). This is the same threshold value established previously (NAFO, 2013). When superimposed on the kernel density surface (Fig. 1.2.3B), the 1.4 kg density polygon captures all of the highest density areas (red and orange colour on Fig. 1.2.1) from the kernel analysis.

The reanalysis to determine the location of sea pen significant concentrations in the NRA has identified a number of sea pen fields on Flemish Cap and the slopes of Grand Bank (Fig. 1.2.4). When compared with the previous analysis (NAFO, 2013), there is very little change in the overall picture (Fig. 1.2.4B). A new area has been identified on the Tail of Grand Bank where one catch over the threshold occurred in the new data series. In this area there are many smaller catches of sea pens (Fig. 1.2.1). On Flemish Cap, sea pen VMEs on the northern aspect have merged, with new data linking the previously separate polygons there. On the eastern aspect, the wasp-waist configuration of the two VME areas identified in 2013, are now separated. Fig. 1.2.5 shows the data that affected this change in relation to Closed Area 14. There were no new catches above the 1.4 kg RV catch threshold used to delineate the polygons (Fig. 1.2.5A), however there were some lower catches made in the area which adjusted the contours of the VME (Fig. 1.2.5 B,C). These lower catches could represent the presence of smaller species that form the significant concentrations, or juveniles of the same species. This is examined in detail in Appendix 1.

Table 1.2.1. Characteristics of Equal-density Polygons of Sea Pen Biomass Constructed for Successive Density Thresholds.

No. Points Defining Polygon	Polygon Area (km^2)	Density Threshold Weight (kg)	Percent Change in Area
3	37.5	9.0	
6	791.5	5.0	79.0
9	1416.6	4.0	0.7
12	1426.0	3.0	403.2
21	7176.2	2.0	2.2
27	7334.2	1.9	1.4
34	7439.0	1.6	7.6
44	8003.4	1.4	97.0
53	15763.8	1.2	0.4
71	15825.0	1.0	2.1
82	16161.5	0.9	28.7
97	20796.5	0.8	2.5
108	21315.8	0.7	0.5
126	21427.8	0.6	20.3
151	25783.6	0.5	5.5
188	27204.4	0.4	32.4
255	26013.9	0.3	23.5
385	44487.3	0.2	

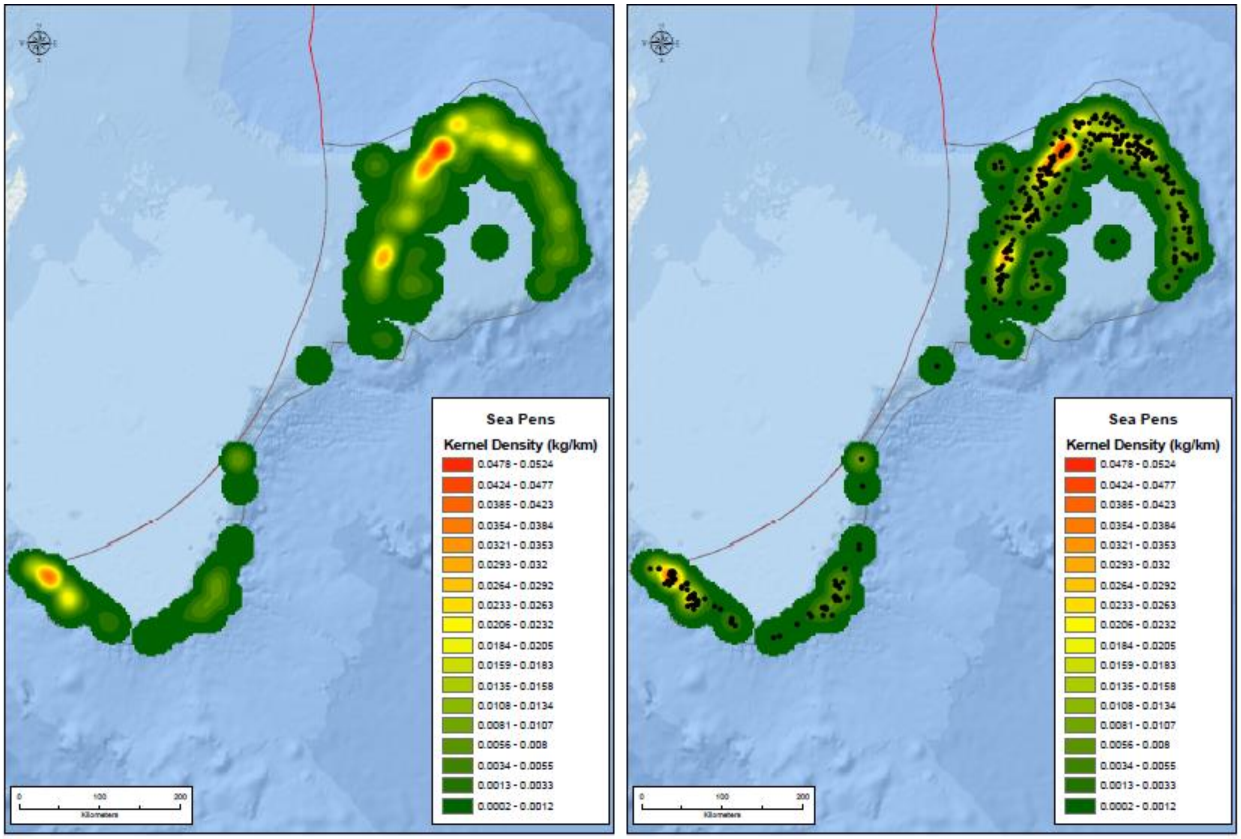

Fig. 1.2.1. Kernel density distribution of sea pens in the NAFO Regulatory Area (Left panel) with the location of the 385 data points used in the analysis (Right panel).

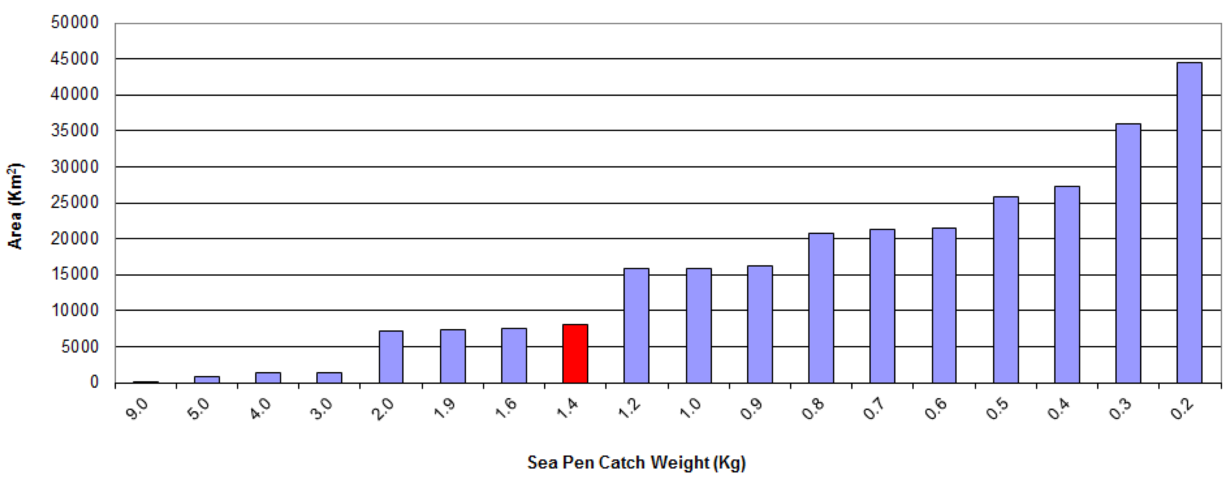

Fig. 1.2.2. Area occupied by successive equal density thresholds (sea pen catch weight in kilograms). Red bar indicates the density threshold used to identify significant concentrations of sea pens.

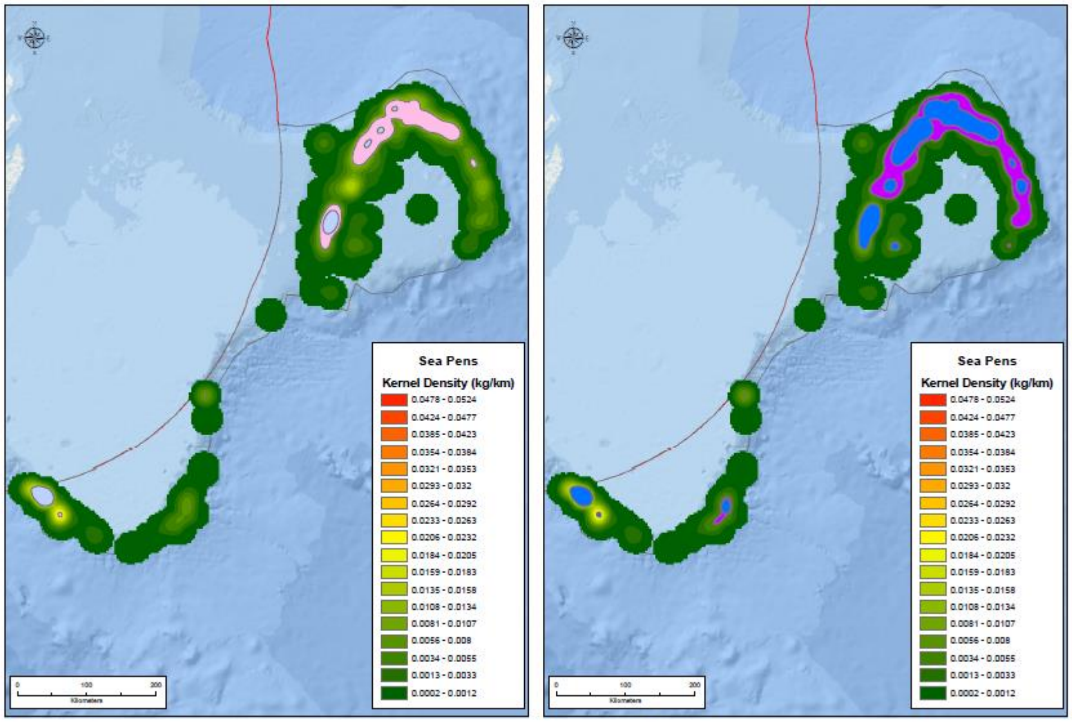

Fig. 1.2.3. Spatial configuration of KDE-derived polygons showing difference in area between polygons calculated with thresholds of A) 3 kg sea pen catch (light blue) and 2 kg sea pen catch (light pink); and B) 1.4 kg sea pen catch (blue) and 1.2 kg sea pen catch (purple), overlain on KDE surfaces.

Fig. 1.2.4. A) Sea pen VMEs (blue polygons) identified on Flemish Cap and the slopes of Grand Bank in the NAFO Regulatory Area from the present analysis, and B) Comparison of sea pen VMEs determined from the present analysis (blue) with those produced from the earlier analysis (purple; NAFO, 2013). The fishing footprint is shown in outline.

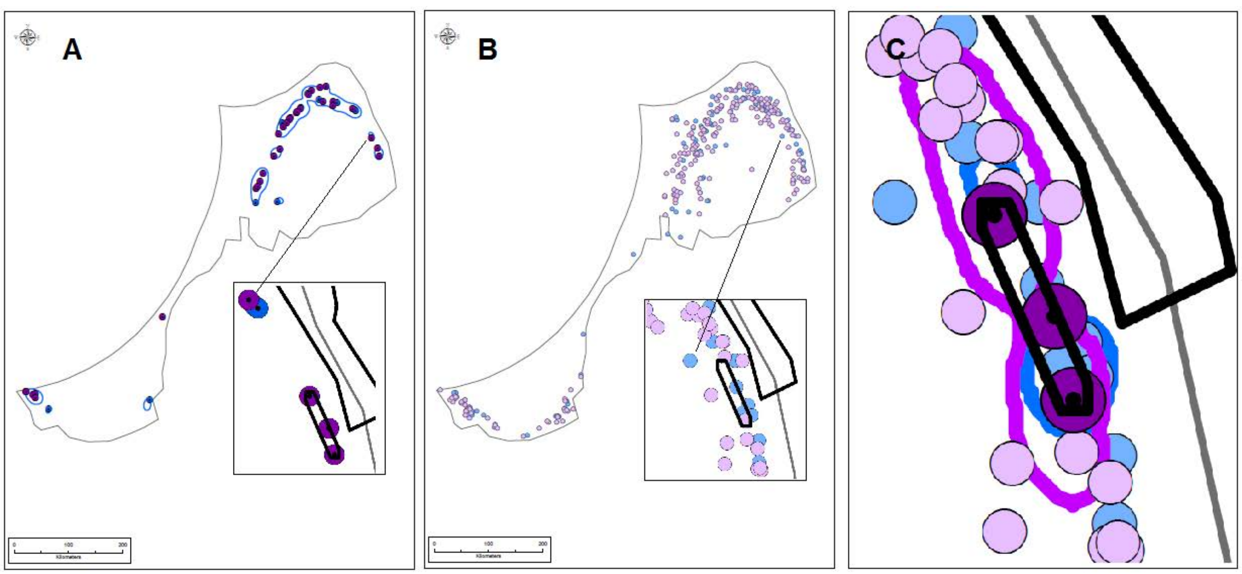

Fig. 1.2.5. A) Location of catches ≥ 1.4 kg/tow RV catches from the 2013 analysis (purple) and the current 2017 analysis (blue) with an inset of data around Closed Area 14; B) Location of catches ≤ 1.4 kg/tow RV catches from the 2013 analysis (purple) and the current 2017 analysis (blue) with an inset of data around Closed Area 14; C) Location of catches ≥ 1.4 kg/tow RV catches from the 2013 analysis (purple) and the current 2017 analysis (blue), catches ≤ 1.4 kg/tow RV catches from the 2013 analysis (purple) and the current 2017 analysis (blue) showing the current sea pen VME polygons (blue) compared to the previous sea pen VME polygons (purple) in relation to the Closed Area 14 boundary.

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ii) Appendix 1 – KDE Analysis of Sea Pen Abundance

During the meeting WG-ESA explored additional data sources to assist with the advice on protecting sea pen VMEs on Flemish Cap. Sea pen abundance data from EU surveys from 2014 to 2017 were assessed and included 309 records. Abundance data were available only for the EU Flemish Cap survey using Lofoten gear, therefore this analysis is not directly comparable to the KDE analysis using biomass. Following previously established methods and assessment criteria (NAFO, 2013), a kernel density surface was created (Fig. 1.2.6) and the area of successive density polygons calculated (Table 1.2.2). The search radius was 20 km, cell size was 2.90 km, and the contour interval for constructing equal density polygons was 0.0005 kg. The kernel density distribution identified sea pen fields on the western, northern and eastern portions of Flemish Cap (Fig. 1.2.6).

The area of sea pen habitat encompassed by the polygons increases first between the 30 and 20 catch thresholds (Table 1.2.2 Figs 1.2.6, 1.2.7). This increase in area was 59% and was created through the addition of 21 data points (Table 1.2.2). Following previously established guidelines (Kenchington et al., 2016) the 30 individuals/RV tow threshold emerged as defining significant concentrations of sea pens (i.e., sea pen field VME) based on abundance. The final KDE polygons are shown against the data distribution in Fig. 1.2.8. When superimposed on the kernel density surface created from biomass for this area (1.4 kg density polygon; Fig. 1.2.9, left panel) there is good congruence between the areas identified except for one polygon adjacent to Area 2 where no abundance data were available (Fig. 1.2.9, right panel). These results suggest that the KDE analysis using biomass data is sufficient to define the habitat of these sea pens.

Table 1.2.2 Characteristics of Equal-density Polygons of Sea Pen Abundance Constructed for Successive Density Thresholds.

No. Points Defining Polygon	Polygon Area (km²)	Density Threshold Weight (kg)	Percent Change in Area
1	36.2	300	935.1
7	374.3	100	1439.7
13	5763.2	60	36.0
22	7837.1	40	1.7
34	7971.4	30	59.0
55	12672.5	20	31.0
86	16598.5	10	7.1
101	17780.2	8	18.8
129	21120.9	6	0.0
148	21120.9	5	30.1
187	27474.4	3	23.9
219	34037.4	2	25.2
309	42597.9	1	

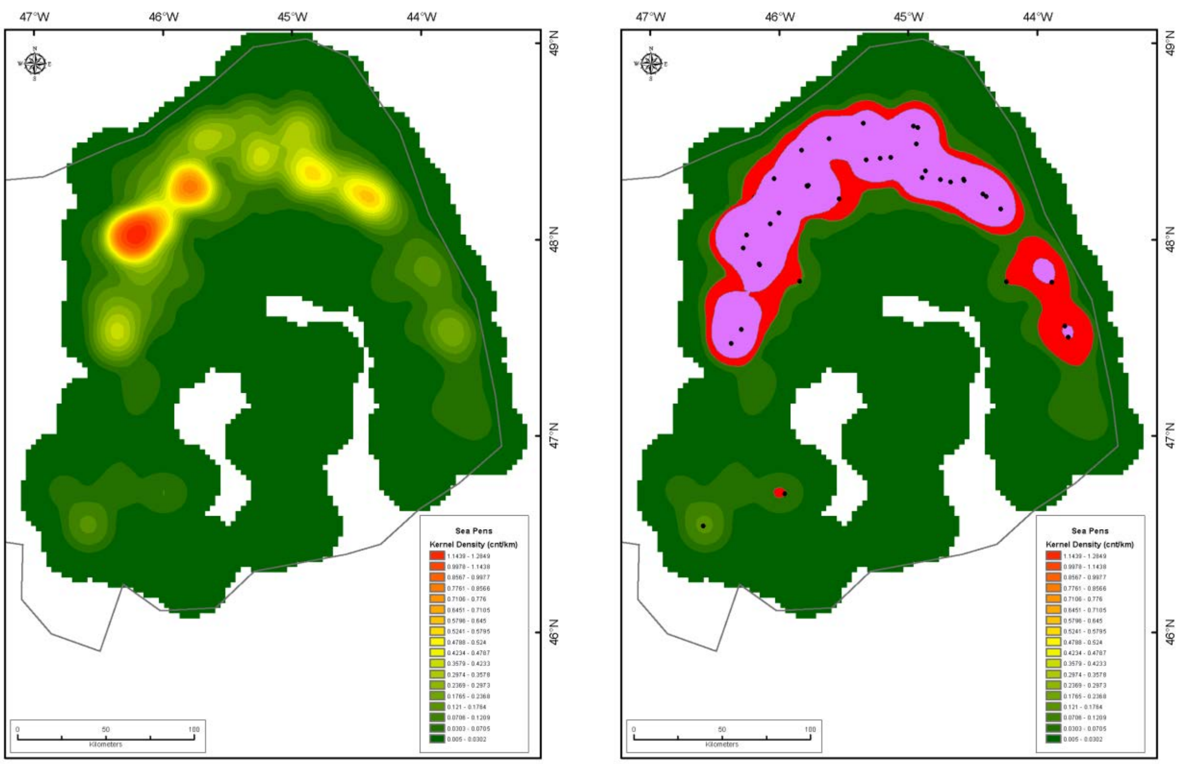

Fig.1.2.6. Kernel density distribution of sea pens in the NAFO Regulatory Area based on abundance (Left panel) ith the location of the 30 (purple) and 20 (red) abundance polygons overlain (Right panel). Individual points show the catch locations for the abundance data above the 20 individuals/tow threshold.

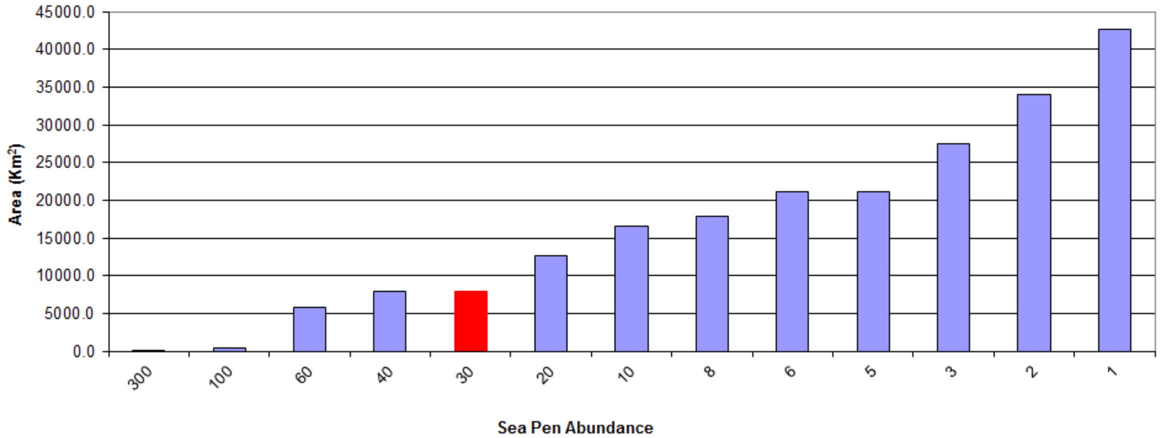

Fig. 1.2.7. Area occupied by successive equal density thresholds (sea pen catch numbers). Red bar indicates the ensity threshold used to identify significant concentrations of sea pens.

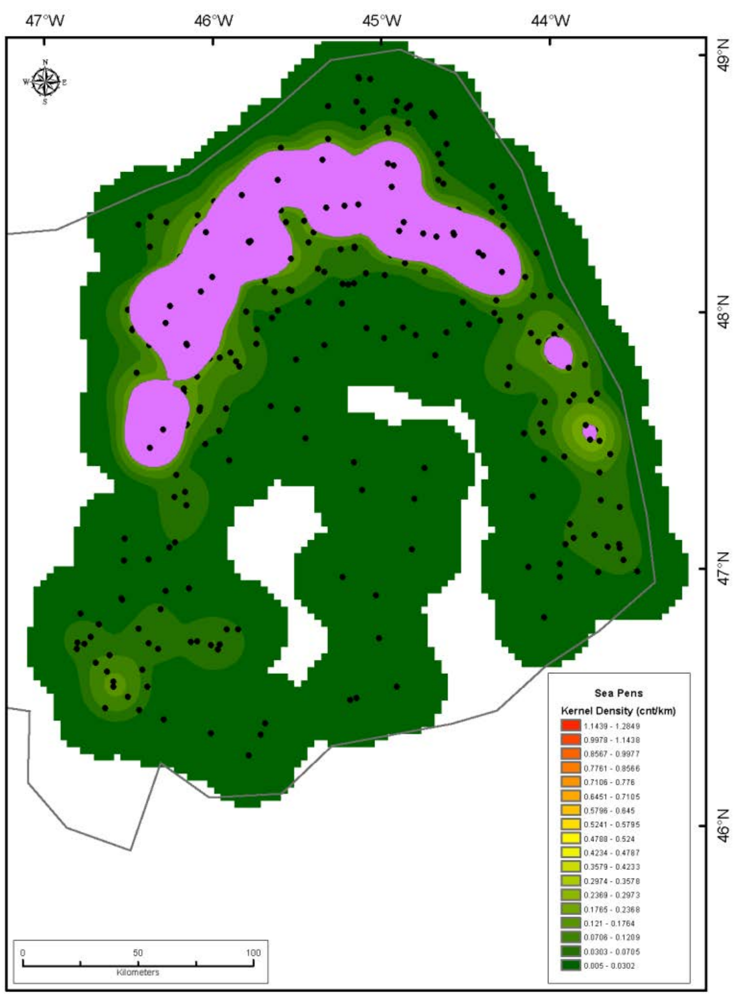

Fig.1.2.8. Sea pen VMEs based on abundance (purple polygons) identified on Flemish Cap in relation to the data distribution.

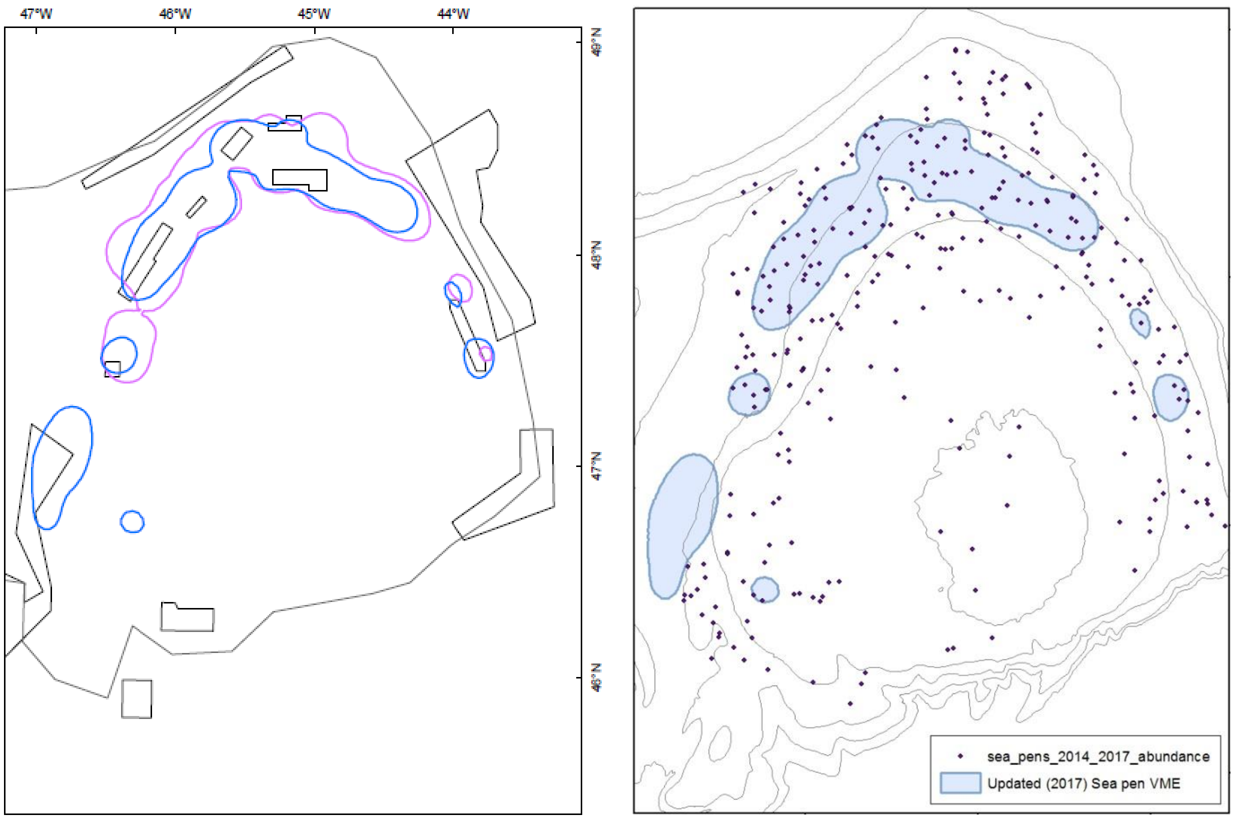

Fig. 1.2.9. Sea pen VMEs based on biomass (blue polygons) and abundance (pink polygons) identified on Flemish Cap (left panel). The fishing footprint is shown in outline. Closed areas are shown in black. Right panel shows the distribution of tow sets with abundance information used in the KDE analysis.

Mean individual biomass of the different sea pen species present in the Flemish Cap survey was examined to determine whether catches in the eastern portion of the cap represent juveniles of the same species which form the significant concentrations in the Area 14 closure. EU survey data from inside the KDE sea pen polygons was examined, and the data were divided by geographic region (east, northeast, northwest, west; Fig. 1.2.10; Table 1.2.3). Two statistical tests were carried out to examine differences in biomass between the two dominant species, *Anthoptilum grandiflorum* and *Halipteris finmarchica* (see Table 1.2.3): the non-parametric Kruskal-Wallis test between all geographic units together, and the Mann-Whitney U test between pairs of groups. For *A. grandiflorum*, significant differences were found in mean individual biomass all geographic units combined, and between east and west regions, with mean individual biomass being larger in the east (see Table 1.2.4 and Fig. 1.2.11). For *H. finmarchica* no significant differences in mean individual biomass were found (Table 1.2.5. and Fig. 1.2.12). Fig. 1.2.13 shows a pie chart diagram of the biomass distribution between species per tow, depicting no real differences in biomass distribution by species in the NAFO Regulatory Area.

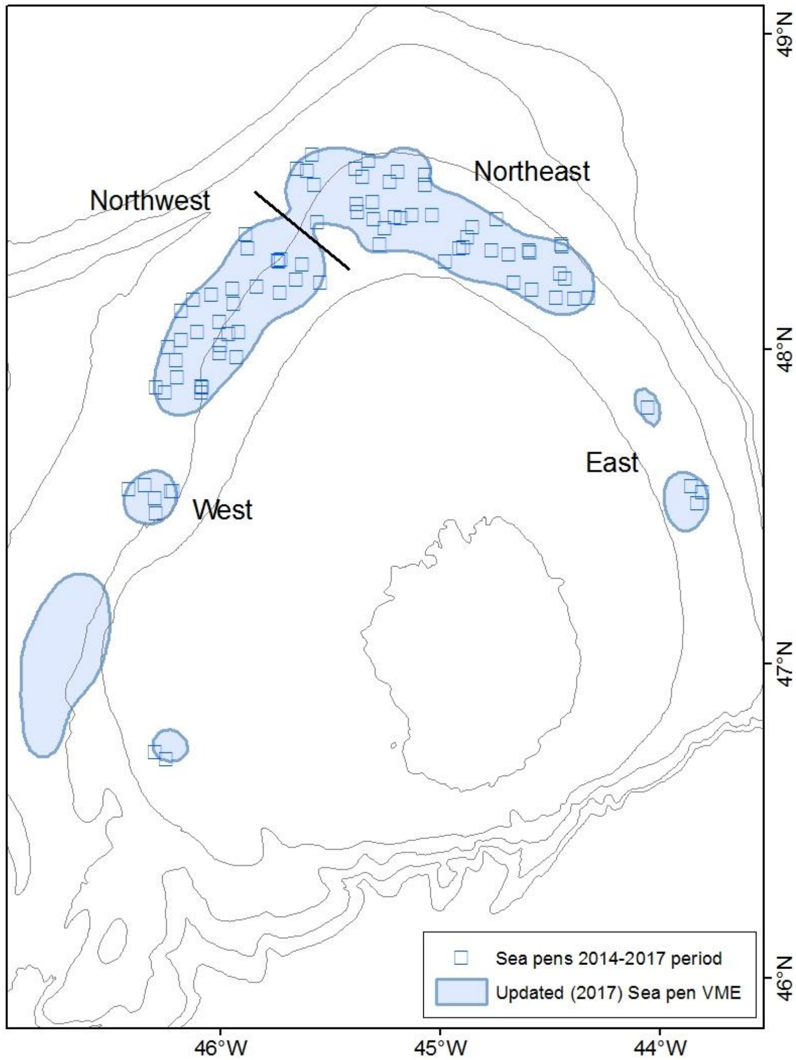

Fig. 1.2.10. Sea pens catches for the period 2014-2017 considered to study the mean individual biomass for sets inside the updated sea pen VME areas.

Table 1.2.3. Summary of data sets studied by taxa and area considered. E, east; NE, northeast; NW, northwest; W, west.

	E	NE	NW	W
Anthoptilum grandiflorum	4	39	30	6
Distichoptilum gracile	0	2	4	0
Funiculina quadragularis	0	13	10	4
Halipteris christii	0	0	1	0
Halipteris finmarchica	4	30	15	3
Pennatula grandis	0	2	0	0
Pennatula spp.	0	1	2	0
Pennatulacea	1	0	0	0
Umbellula spp.	1	7	4	0

Table 1.2.4. Mean ± SD individual biomass of *Anthoptilum grandiflorum* per trawl set inside the sea pen VMEs and per geographic area (2014-2017 period). Number of sets (N) and maximum individual biomass (Max) are also indicated. Two tests were carried out, the non-parametric Kruskal-Wallis test between all units group together (NE, NW, E and W), and the Mann-Whitney U test between pairs of groups. Asterisks indicate significant differences at 95% level. E, east; NE, northeast; NW, northwest; W, west.

					Comparison			
					All areas	E vs NE	E vs NW	E vs W
	Mean	SD	N	Max	*P* value	*P* value	*P* value	*P* value
NE	0.016	0.008	39	0.038	0.018*	0.161	0.065	0.038*
NW	0.016	0.015	30	0.073				
E	0.023	0.008	4	0.028				
W	0.010	0.002	6	0.012				

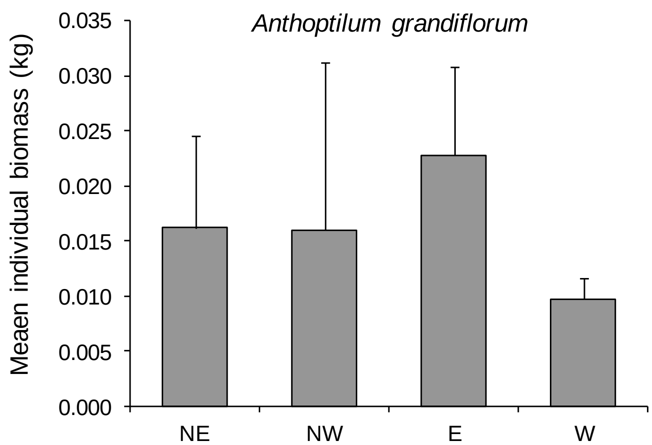

Fig.1.2.11. Mean individual biomass of *Anthoptilum grandiflorum* per geographic area. E, east; NE, northeast; NW, northwest; W, west.

Table 1.2.5. Mean ± SD individual biomass of *Halipteris finmarchica* per trawl set inside the sea pen VMEs and per geographic area (2014-2017 period). Number of sets (N) and maximum individual biomass (Max) are also indicated. Two tests were carried out, the non-parametric Kruskal-Wallis test between all units group together (NE, NW, E and W), and the Mann-Whitney U test between pairs of groups. E, east; NE, northeast; NW, northwest; W, west.

					Comparison			
					All areas	E vs NE	E vs NW	E vs W
	Mean	SD	N	Max	*P* value	*P* value	*P* value	*P* value
NE	0.031	0.023	30	0.110	0.310	0.669	0.736	0.400
NW	0.020	0.009	15	0.038				
E	0.023	0.009	4	0.036				
W	0.017	0.009	3	0.027				

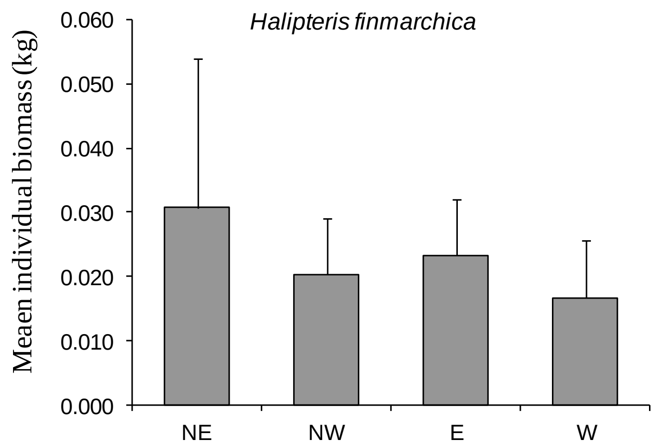

Fig. 1.2.12. Mean individual biomass of *Halipteris finmarchica* per geographic area. E, east; NE, northeast; NW, northwest; W, west.

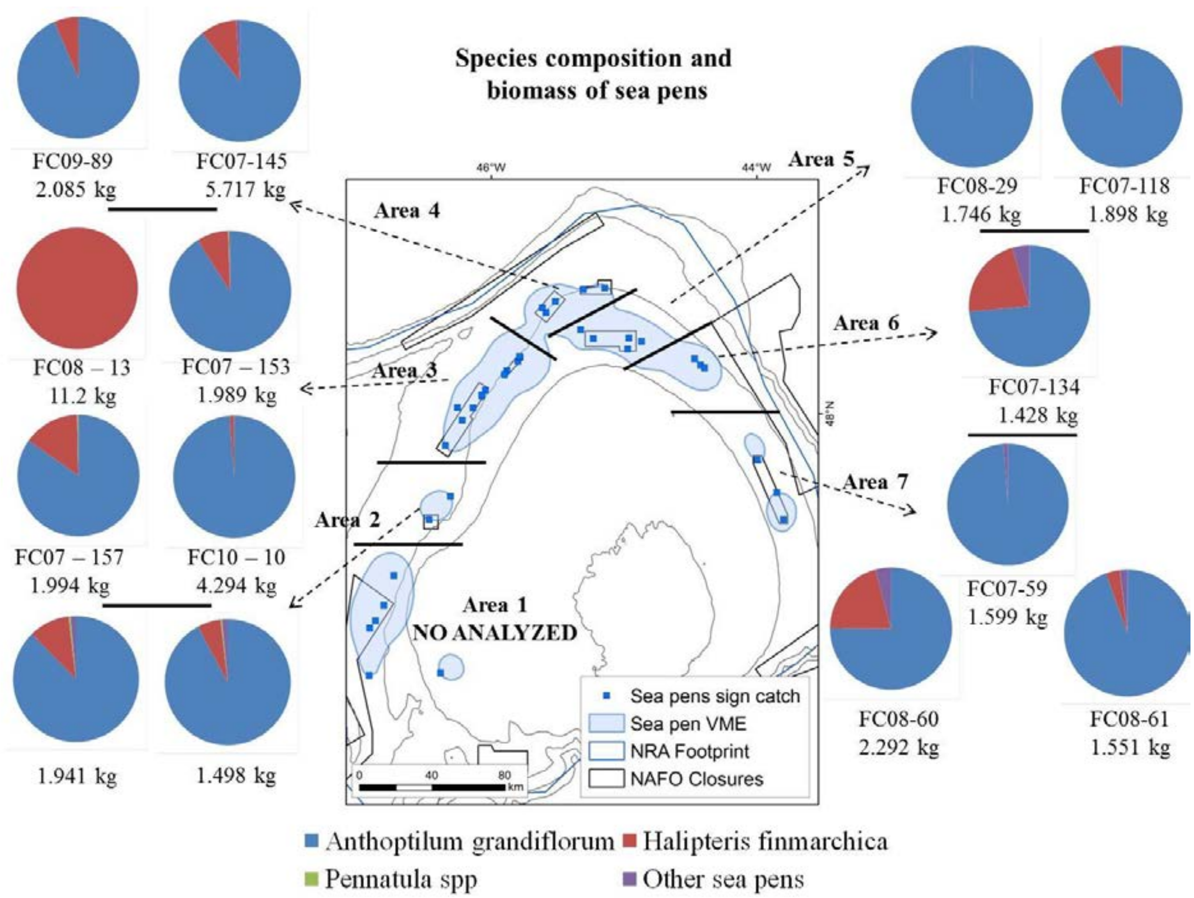

Fig. 1.2.13. Species composition and biomass of sea pens from EU survey tows located inside the KDE polygons for sea pens.

iii) Update on the Research Activities Related to EU-funded Horizon 2020 ATLAS Project: Flemish Cap Case Study.

During the 10th NAFO WG-ESA meeting, EU ATLAS project was presented giving updated information regarding work packages WP6 and WP3: Identification of "context setting" for Marine Spatial Planning (MSP-WP6) using the MESMA framework (Monitoring and Evaluation of Spatially Managed Areas) together with Species Distribution Models (SDMs-WP3) for the *Anthoptilum sp.* deep-water pennatulacean coral for Flemish Cap Case Study.

This is a four-year EU-funded Horizon 2020 project (www.eu-atlas.org) that started in May 2016 and aims to gather diverse new information on sensitive Atlantic ecosystems (including Vulnerable Marine Ecosystems and Ecologically or Biologically Sensitive Areas) to produce a step-change in our understanding of their connectivity, functioning and responses to future changes in human use and ocean climate. This is possible because ATLAS takes innovative approaches to its work and interweaves its objectives by placing business, policy and socio-economic development at the forefront with science.

ATLAS not only uses trans-Atlantic oceanographic arrays to understand and predict future change in living marine resources, but enhances their capacity with new sensors to make measurements directly relevant to ecosystem function. Research activities are focusing on waters 200-2000 m deep, where the greatest gaps in our understanding lie and certain populations and ecosystems are known to be under pressure. 25 deep sea cruises are already planned with more in development and several already having taken place in 2016. These cruises are providing data to study a network of 12 case studies spanning the Atlantic from the LoVe observatory located off the Lofoten and Vesterålen islands, Norway to the Davis Straight, Eastern Artic. Ecosystems to be studied include sponge, cold-water coral, seamount and mid-ocean ridge systems.

The 4 overarching objectives of ATLAS are to:

1.- ADVANCE our understanding of deep Atlantic marine ecosystems and populations;

2.- IMPROVE our capacity to monitor, model and predict shifts in deep-water ecosystems and populations;

3.- TRANSFORM new data, tools and understanding into effective ocean governance;

4.- SCENARIO-TEST and develop science-led, cost-effective adaptive management strategies that stimulate Blue Growth.

Species Distribution Models (SDMs) for the *Anthoptilum sp.* deep-water pennatulacean coral for Flemish Cap Case Study has been carried out by Centro Oceanográfico de Vigo (Flemish Cap Case Study coordinator) in close collaboration with Centro Oceanográfico de Murcia (iSEAS project).

The main partners involved in this Case Study (Fig. 1.2.14) are the Instituto Español de Oceanografía (IEO), Centro Oceanográfico de Vigo, and Fisheries and Oceans Canada (DFO), Bedford Institute of Oceanography. Both have extensive experience (e.g. NEREIDA project) and have plans to develop future research in the area.

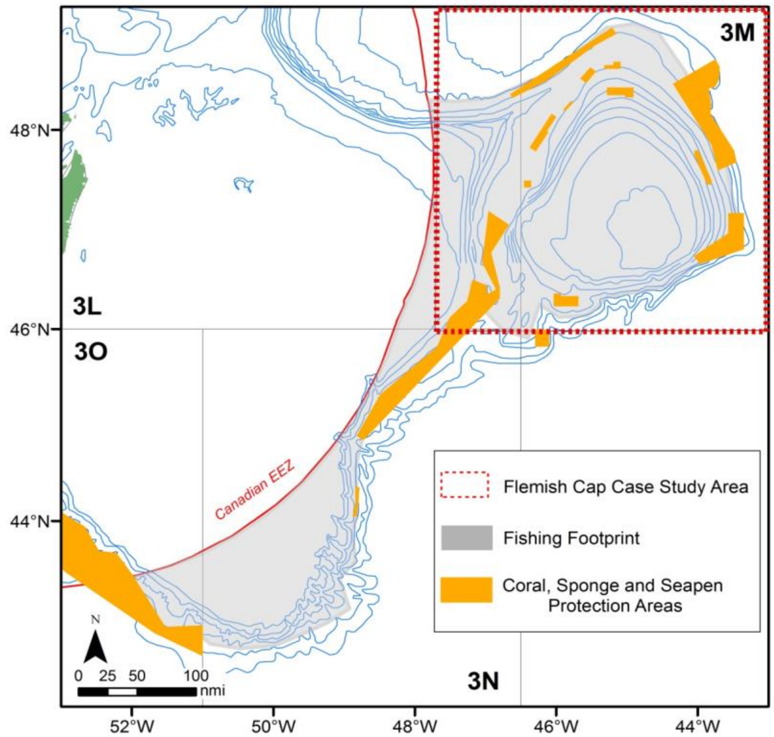

Fig. 1.2.14 Flemish Cap Case Study spatial extent (red dashed line)

Regarding SDMs, different modeling algorithms were presented to classify the probability of habitat suitability for *Anthoptilum sp.* as a function of a set of environmental variables. SDMs contribute to improve the understanding of biodiversity and biogeography of VME indicator species and will be integrated in the MSP activities related with the Flemish Cap Case Study.

Environmental variables used to implement these Species Distribution Models (SDMs) were:

I. Oceanographic variables: Sea Bottom Temperature and sea Bottom Salinity.
II. Bathymetric features: bathymetry, slope and orientation of the seabed.

Preliminary tests using different models such as GLMs and GAMs (mixed and not mixed models), BRT (boosted regression trees), BIOCLIM (bioclimatic model), MAXENT(maximum entropy model) and bayesian models were run. While BIOCLIM and MAXENT use only presence records the other models run with presence/absence data.

The objective to pursue was identifying potentially complex linear and non-linear relationships in multi-dimensional environmental space and predicting the distribution of *Anthoptilum* sp. deep-water pennatulacean in unsampled locations of Flemish Cap Case Study area.

To tackle this task, we have implemented different modeling approaches built in the free spatial statistical computing software R (R development Core Team, 2016) using the necessary packages for each case. Only for the Maximum Entropy method, freely available software was used: MAXENT 3.4.1 (MAXENT, 2017). MAXENT results were after introduced in R software to make the mean of all models.

Maps below show preliminary Species Distribution Modeling (SDM) results obtained for the *Anthoptilum* sp. deep-water pennatulacean coral in the Flemish Cap area together with presence records (black dots).

Every map (Fig.1.2.15 to Fig. 1.2.17) shows the probability of habitat suitability for *Anthoptilum sp.* using different algorithms*.*

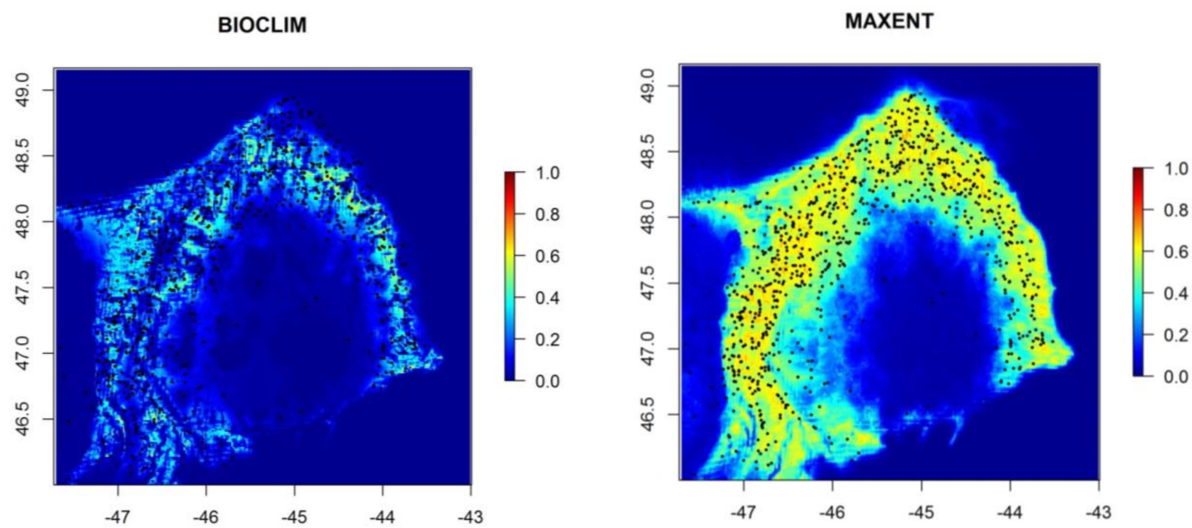

Fig. 1.2.15. BIOCLIM and MAXENT model result for *Anthoptilum sp.* in Flemish Cap area

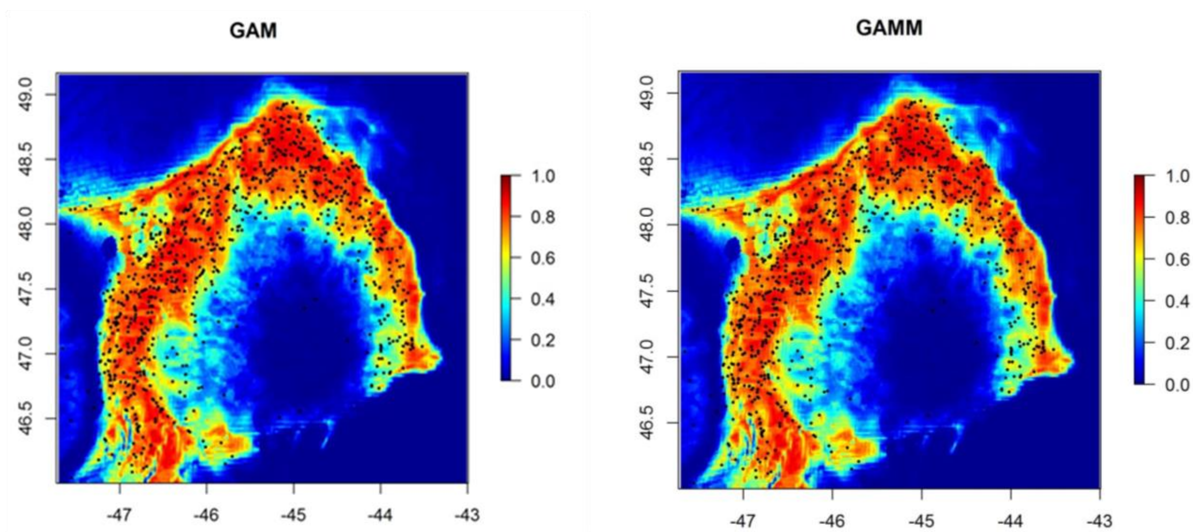

Fig. 1.2.16. GAM and GAMM model result for *Anthoptilum sp.* in Flemish Cap area

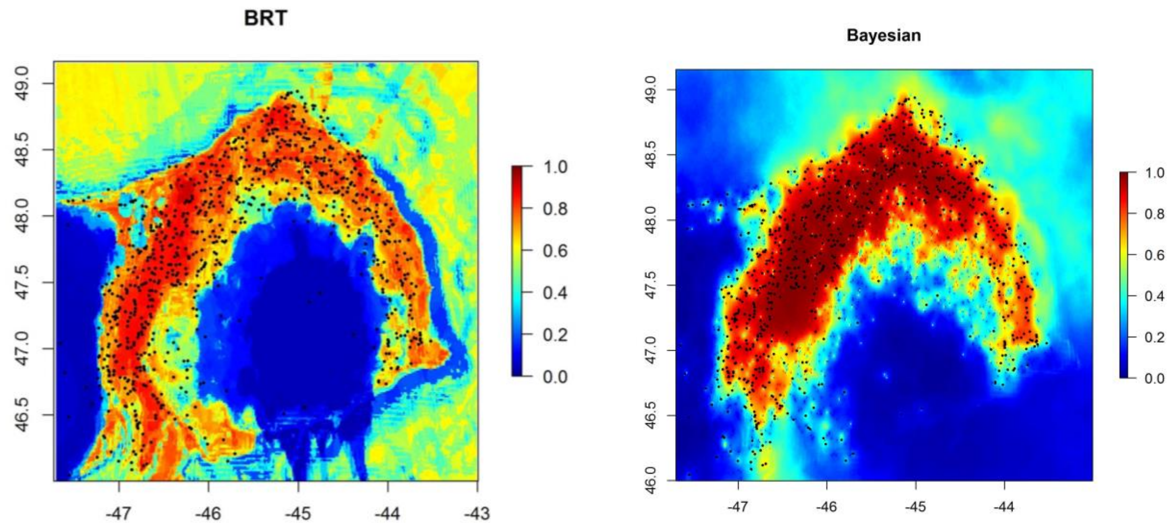

Fig. 1.2.17. BRT and B-HDM model result for *Anthoptilum sp.* in Flemish Cap area

The dataset was randomly split into two main subsets: a training dataset including 80% of the total observations, and a validation dataset containing the remaining 20% of the data. The relationship between occurrence data and the environmental variables was modelled by using the training dataset and the quality of predictions was then assessed by using the validation dataset. We repeated validation 10 times for the best model and results were averaged over the different random subsets.

We performed a validation procedure to formally evaluate overall model prediction using the area under the receiver-operating characteristic curve (AUC), specificity and sensitivity to calculate the True Statistic Skills (TSS) value, where:

- AUC measures the ability of a model to discriminate between those sites where a species is present and those where it is absent, and has been widely used in the species distribution modeling literature (Elith *et al*., 2006). AUC ranges from 0 to 1, with values below 0.6 indicating a performance no better than random, values between 0.7 and 0.9 considered as useful, and values >0.9 as excellent.

- Specificity is the proportion of True Negatives correctly predicted and reflects a model's ability to predict an absence given that a species in fact does not occur at a location.

- Sensitivity is the proportion of True Positives correctly predicted and reflects a model's ability to predict a presence given that a species in fact occurs at a location.

- The TSS measures the accuracy of the model (Allouche *et al*., 2006) and is calculated as sensitivity + specificity – 1 and ranges from -1 to +1, where +1 indicates perfect agreement and values of zero or less indicate a performance no better than random.

Table 1.2.6 shows the AUC, TSS and correlation of the different models in order to assess the accuracy of the different SDM implemented.

All models have achieved AUC values greater than 0.80, which indicates an excellent degree of discrimination between those locations where *Anthoptilum sp*. is present and those where it is absent. According to AUC values, the most accurate model for this deep-water pennatulacean coral was the Bayesian (B-HDM).

Table 1.2.6. AUC, TSS and correlation of the models used in SDM implemented.

Model	AUC	TSS	r
MAXENT	0.83	-	-
GAM	0.82	0.32	0.51
GAMM	0.82	0.32	0.46
BRT	0.83	0.33	0.56
B-HDM	0.85	0.36	0.6

This work should be considered as a preliminary approach for the creation of VME species maps and habitat distribution models (SDMs and HSMs) used to improve the understanding of biodiversity in the Flemish Cap area.

References

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- Elith, J., Graham, C.H., Anderson, R.P., Dudık, M., Ferrier, S., Guisan, A., Hijmans, R.J., Huettmann, F., Leathwick, J.R., Lehmann, A., et al., 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography 29, 129-151

ToR 1.3. Continue to work on non-sponge and coral VMEs (e.g. bryozoan and sea squirts) to prepare for the next reassessment of bottom fisheries.

i) Re-Analyses of KDE estimation of Bryozoans and Ascidians on the Nose and Tail of Grand Bank

Significant concentrations of the VME indicators bryozoans and the ascidian *Boltenia ovifera* (Large Sea Squirts) have been determined previously in the NRA using kernel density analyses and an evaluation of the expansion of the area covered by successive density polygons (NAFO, 2013). Given that nothing was known of the catchability of trawl gear for these taxa, in 2013 WG-ESA recommended that *in situ* camera surveys be done to groundtruth these areas prior to their adoption as VME. In 2015 a benthic survey using camera gear was conducted by Fisheries and Oceans Canada to groundtruth these polygons. Five camera transects were conducted inside the bryozoan and *Boltenia* significant concentrations, but neither taxa were observed in the collected imagery and thus the polygons could not be validated (NAFO, 2015). WG-ESA determined that the patch size of these VME indicator species is less than 1 km and recommended that the location of significant catches within the KDE polygons be adopted as Significant Concentrations of VME Indicators rather than the full polygon areas (NAFO, 2015). As these taxa require hard substrate to attach to, it was posed that surficial geology from RoxAnn or other sources be examined to better define the habitat formed by these taxa.

In 2017 the KDE analyses for Bryozoa and *Boltenia* were updated using data from the EU RV trawl surveys from 2006-2017 for bryozoans and from 2007-2017 for *Boltenia* to determine whether more information could be provided on these VME prior to the next bottom fisheries assessment in 2020. Additionally, species distribution models (SDMs) were generated for each taxa to provide more information content to the KDE polygons and assist with advice on protecting these VME in the NAFO Regulatory Area.

After reviewing the updated analyses during the meeting, WG-ESA deliberated that all analyses (i.e. KDE and SDM) point to a contiguous habitat being formed by the significant catches of these non-coral and sponge VME, particularly by the sea squirts (*Boltenia*), but that additional information on the distribution of fishing in relation to the KDE polygons and other habitat data (e.g. surficial geology layers) be examined to support adoption of the KDE-derived significant concentrations as VME. WG-ESA will continue to review additional information to support these non-coral and sponge VME prior to the reassessment of the VME fishery closures in 2020.

ii) Boltenia ovifera

KDE Analysis of Boltenia ovifera

Following previously established methods and assessment criteria (NAFO, 2013), a kernel density surface was created (Fig. 1.3.1) and the area of successive density polygons calculated (Table 1.3.1) for *Boltenia* (recorded as *Boltenia ovifera* and 'Boltenia_o' in the surveys). The search radius was 15 km, cell size was 0.53 km, and the contour interval for constructing equal density polygons was 0.0005 kg. These values differ from those used in the 2013 analysis because we changed the spatial extent to include only the Tail of Grand Bank where this species was found with higher biomass. Both search radius and cell size are functions of the spatial extent and are optimized accordingly in the defaults of the ArcGIS program. Consequently some changes to the perimeters of the KDE polygons are expected. The kernel density distribution identified *Boltenia* habitats on the Tail of Grand Bank (Fig. 1.3.1) close to the canyon heads.

The area of *Boltenia* habitat encompassed by the polygons increases first between the 0.3 kg and 0.2 kg catch thresholds (Table 1.3.1, Fig. 1.3.2). This increase in area was 89% and was created through the addition of 10 data points. Following previously established guidelines (Kenchington et al., 2016) the 0.3 kg/ RV tow threshold emerged as defining significant concentrations of *Boltenia*). The 0.2 kg threshold joins up the other areas without supporting data. When superimposed on the kernel density surface (Fig.1.3.3), the 0.3 kg density polygon captures all of the highest density areas (red and orange colour on Fig. 1.3.1) from the kernel analysis. Comparing these results with those produced in 2013 (Fig. 1.3.4) the areas to the south have not changed and those to the north, opposite Area 2 have amalgamated. The large polygon to the southwest of Area 2 is not well supported in its current configuration.

Table 1.3.1. Characteristics of Equal-density Polygons of *Boltenia* Biomass Constructed for Successive Density Thresholds. Shaded rows indicate potential thresholds for identification of significant concentrations.

No. Points Defining Polygon	Polygon Area (km^2)	Density Threshold Weight (kg)	Percent Change in Area
1	0.9	100	10595.6
5	96.6	4	1846.8
17	1880.1	2	26.0
28	2369.7	1	7.4
33	2545.4	0.8	2.0
37	2597.3	0.6	10.9
45	2880.6	0.4	19.8
54	3451.6	0.3	88.8
64	6515.3	0.2	36.2
85	8876.7	0.1	0.0
87	8876.7	0.08	0.0
90	8876.7	0.07	0.0
93	8876.7	0.06	0.0
98	8876.7	0.04	0.0
101	8876.7	0.03	0.0
103	8876.7	0.02	0.0
107	8876.7	0.01	0.0
111	8876.7	0.002	

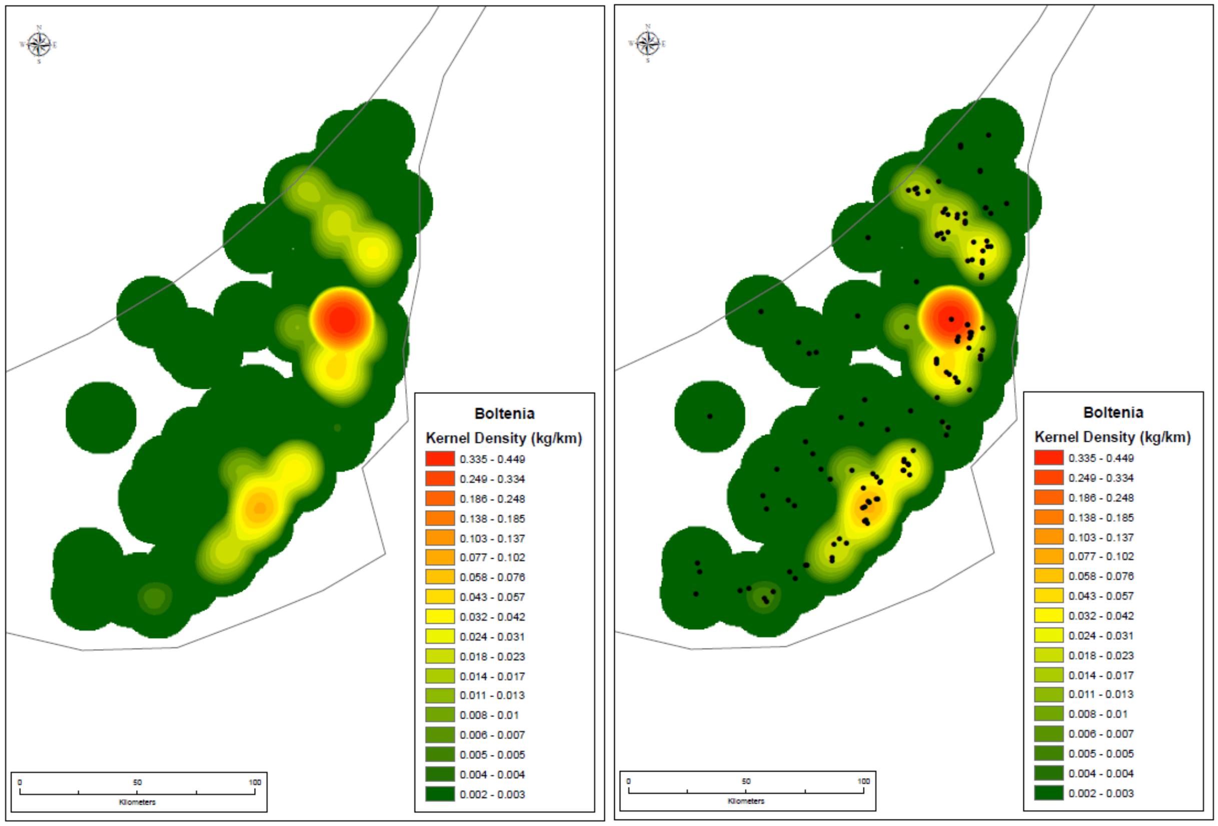

Fig. 1.3.1. Kernel density distribution of Boltenia on the Tail of Grand Bank in the NAFO Regulatory Area (Left panel) with the location of the 131 data point used in the analysis (Right panel).

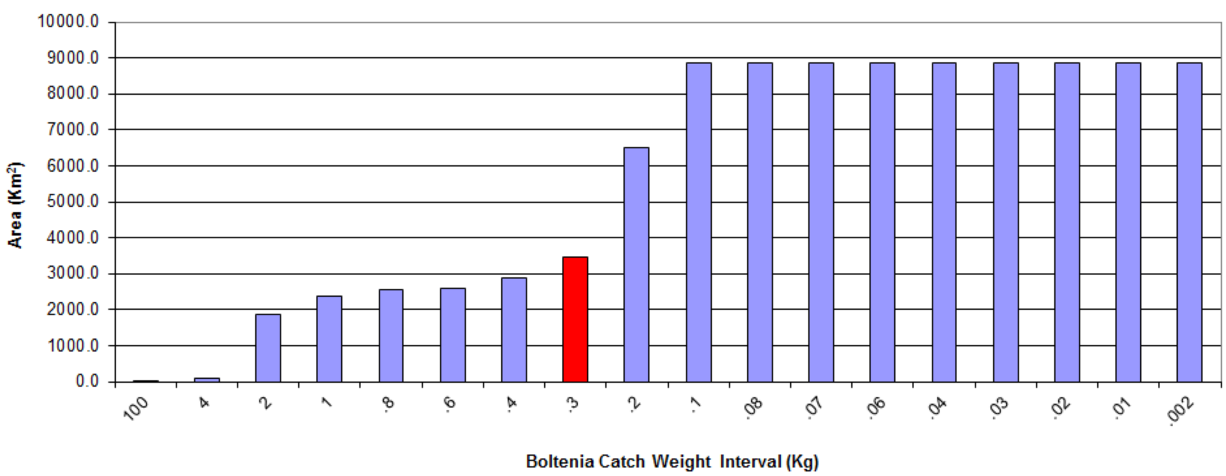

Fig. 1.3.2. Area occupied by successive equal density thresholds (*Boltenia* catch weight in kilograms). Red bar indicates the density threshold used to identify significant concentrations of *Boltenia*.

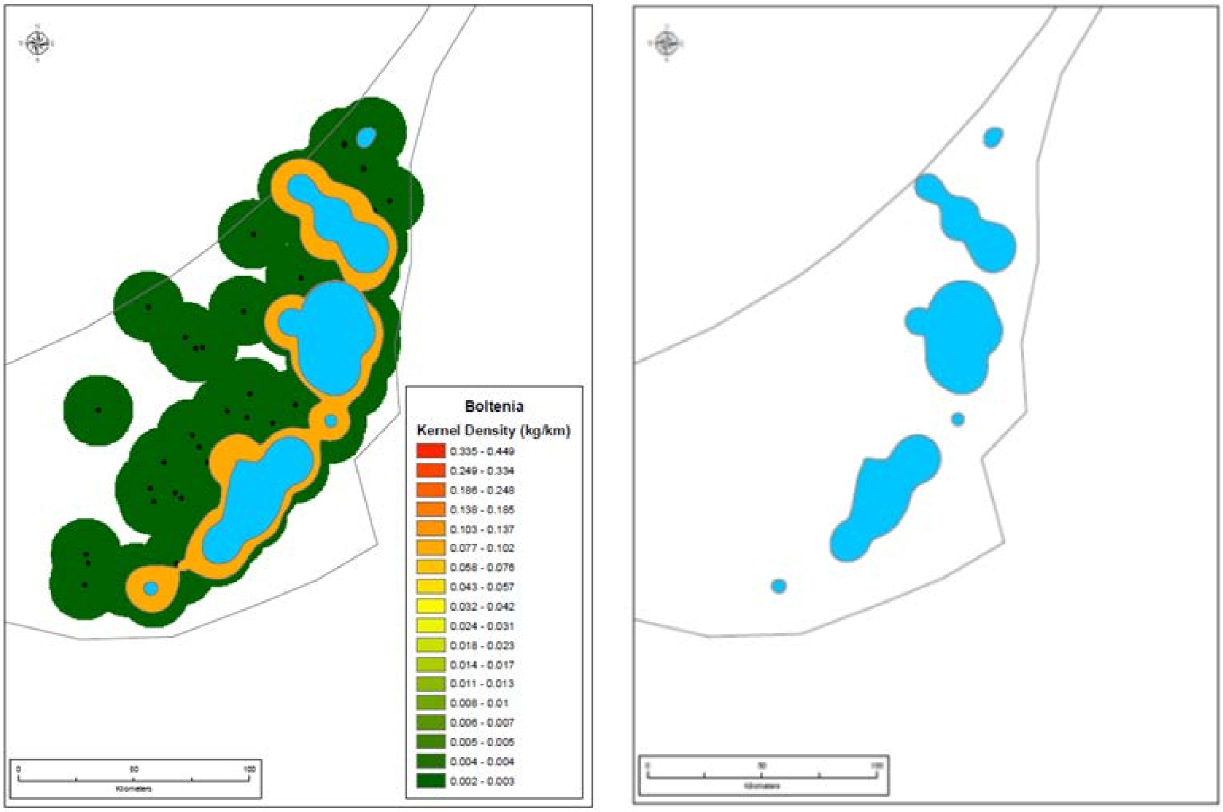

Fig. 1.3.3. Spatial configuration of KDE-derived polygons showing difference in area between polygons calculated with thresholds of the 0.2 kg *Boltenia* catch (orange) and 0.3 kg *Boltenia* catch (light blue). The 0.3 kg threshold was chosen as the threshold denoting the *Boltenia* habitat (right panel).

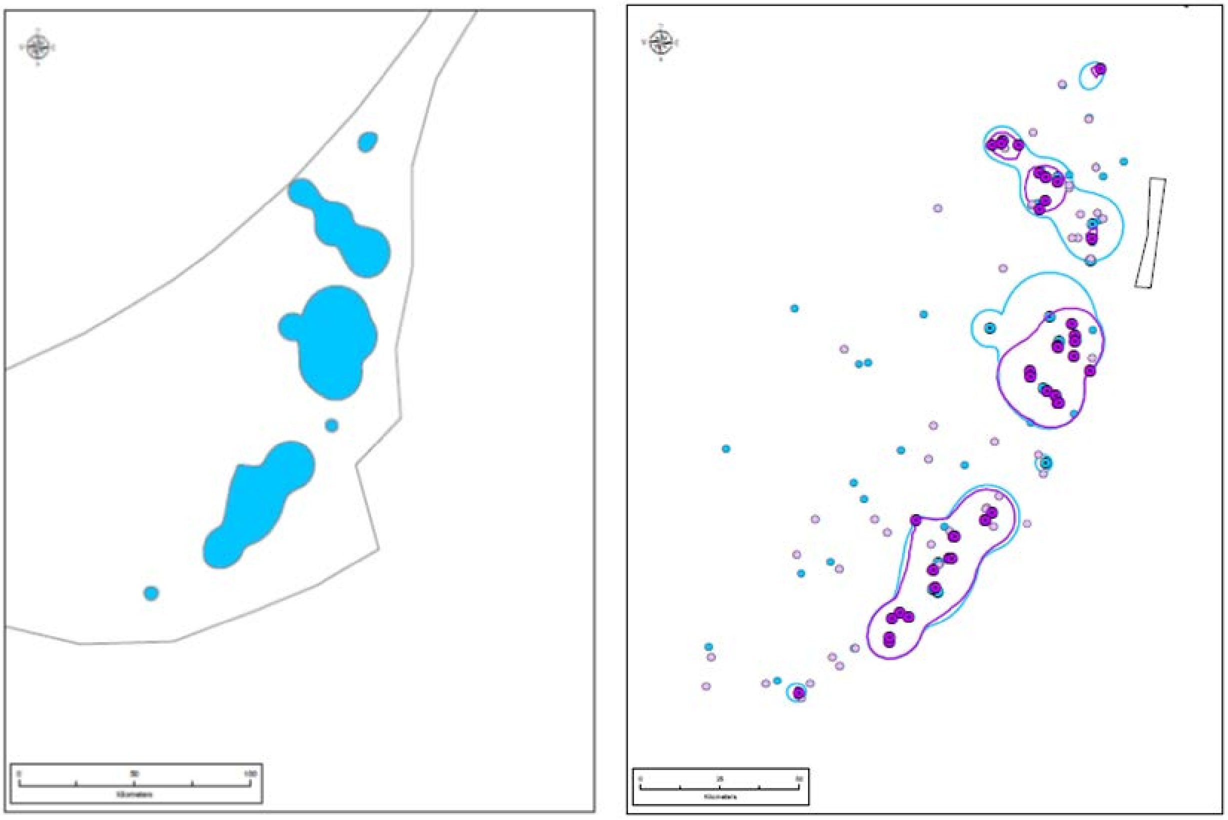

Fig.1.3.4. *Boltenia* KDE polygons from the 2017 analyses on Grand Bank in the NAFO Regulatory Area (left) and in comparison between the 2013 (purple) and the 2017 analyses (blue) identified in relation to the closed areas (right) with the location of catches equal to or above the threshold of 0.3 kg from previous (purple) and additional (blue) data used in the current analyses.

Species Distribution Modelling of Boltenia ovifera

A species distribution model (SDM) based on the presence and absence of *Boltenia ovifera* was generated using the non-parametric, machine-learning technique random forest (Breiman, 2001) following the same methodology used for species distribution models of corals, sponges, and other taxa including bryozoans and sea squirts in Fisheries and Oceans Canada's (DFO) Biogeographic Regions in Eastern Canada (see Beazley et al. 2016a,b; Guijarro et al. 2016a,b; Murillo et al. 2016). A total of 66 environmental predictor variables from various sources and native spatial resolutions were used in the models. The response data were catches of *Boltenia ovifera* from the Spanish and Canadian multispecies trawl surveys conducted on the Tail and Nose of Grand Bank and in Flemish Pass. Absence data were created from null catches from the same surveys. A total of 152 presences and 1873 absences of *Boltenia* across both the Canadian and Spanish surveys were included in the model (see Table 1.3.2; Fig. 1.3.5). Note that the study extent of model predictions was based on the NAFO fishing footprint extended to the 2000 m contour to encompass the NAFO closure areas.

Table 1.3.1. Number of presences and absences of *Boltenia* from the Canadian and Spanish multispecies trawl surveys occurring in the NAFO Regulatory Area and used for species distribution modelling of *Boltenia*.

	Presences	Absences
Canadian Multispecies Trawl Survey (2016-2017)	35	117
Spanish Groundfish Trawl Survey (2007-2017)	144	1729

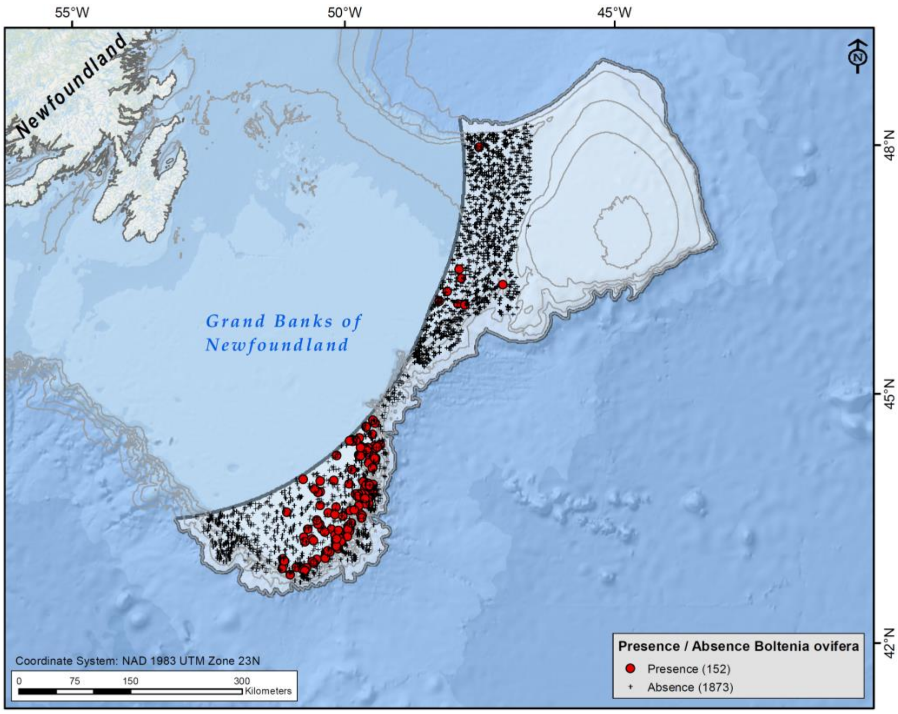

Fig.1.3.5. Distribution of *Boltenia* presences (red circles) and absences (black crosses) used in the random forest species distribution model. Grey polygon indicates the model's predictive extent.

The random forest model performance had excellent performance, with a cross validated mean AUC value of 0.928 ± 0.027, and Sensitivity and Specificity values of 0.855 and 0.847, respectively. Fig. 1.3.6 shows the predicted presence probability surface of *Boltenia*. Predicted presence probability of *Boltenia* was high in patches on the Tail of Grand Bank and was low on the Nose. *Boltenia* was predicted to be absent in the Flemish Pass and along the slope of the Grand Bank. The areas of high presence probability coincided with the location of presence observations (Fig. 1.3.7). The top environmental predictor variables were Minimum Fall Chlorophyll *a* and Surface Salinity Range.

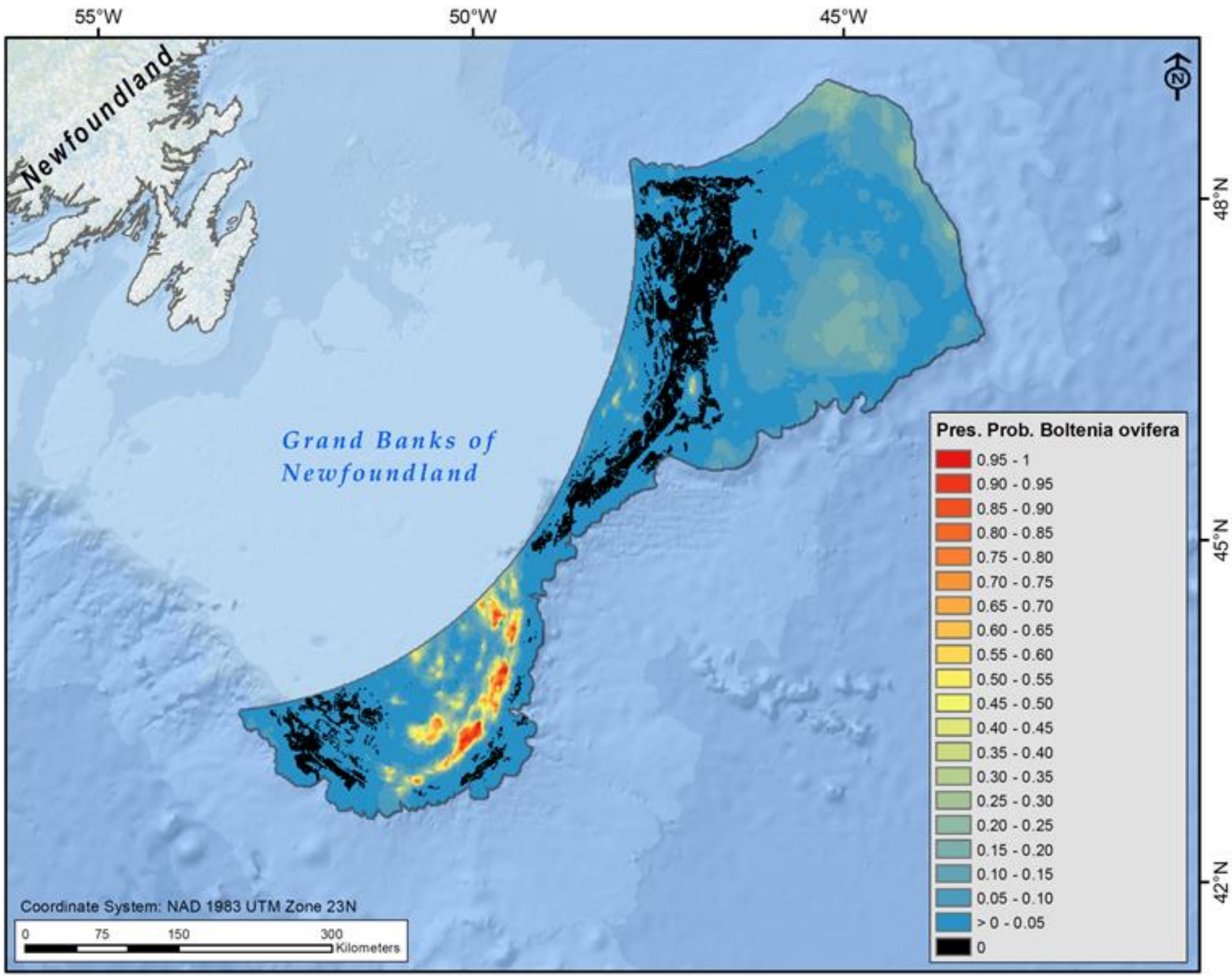

Fig. 1.3.6. Predicted presence probability of *Boltenia* from a random forest species distribution model on *Boltenia* presence and absence data from Canadian and Spanish multispecies trawl surveys conducted in the NAFO Regulatory Area between 2007 and 2017.

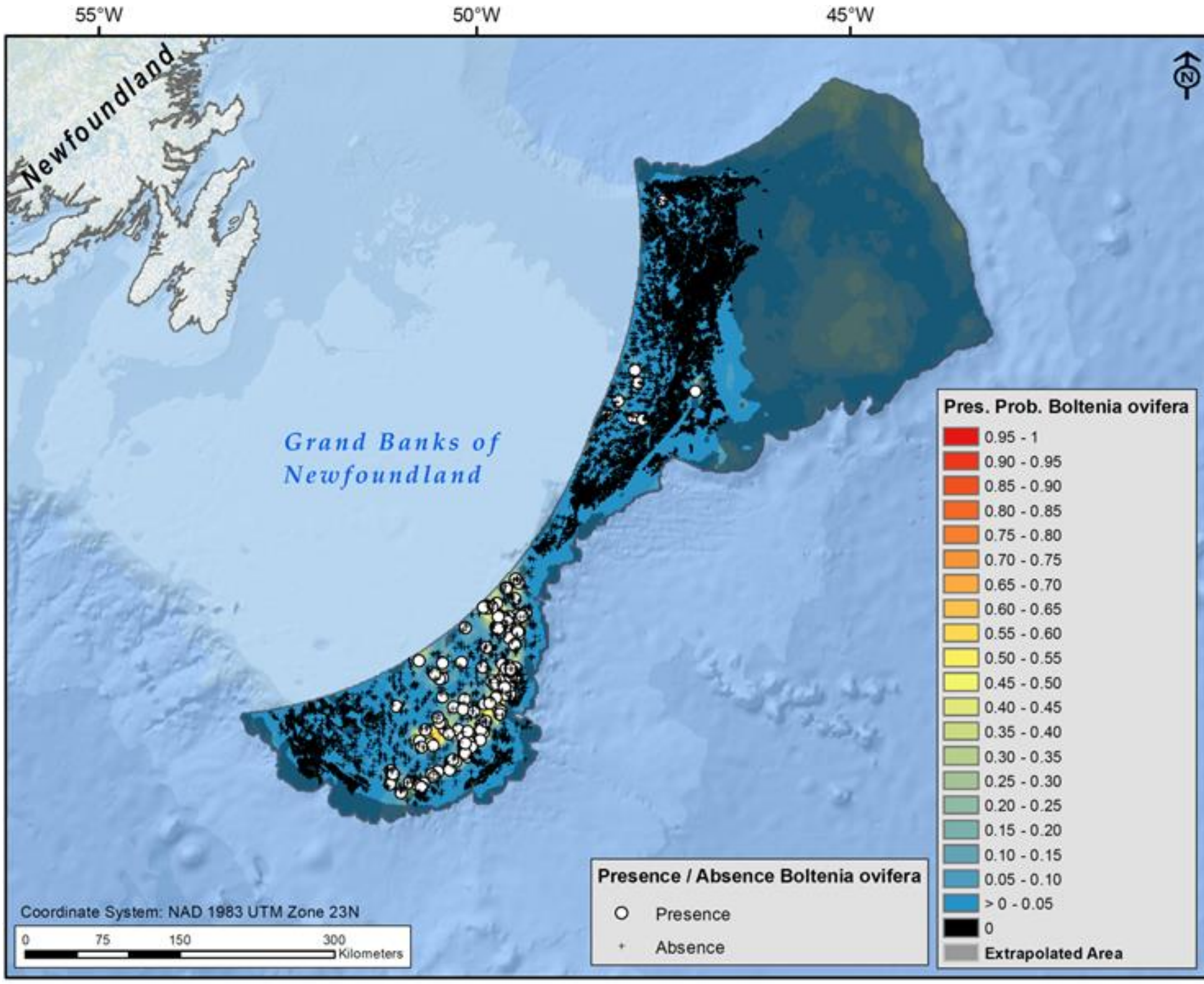

Fig. 1.3.7. Predicted presence probability of *Boltenia* overlain with presence and absence data points and areas of model extrapolation (i.e. areas where at least one environmental predictor variable is outside the environmental envelope used to train the model. These highlight areas where model predictions and require validation).

There was good congruence between the KDE-derived significant concentrations of *Boltenia* and areas of high predicted presence probability of *Boltenia* as indicated by the random forest model (Fig. 1.3.8, left panel). Predicted probability was lower along the edges of the KDE polygons. Most of the polygon area was predicted as suitable *Boltenia* habitat when considering species prevalence (Fig. 1.3.9, right panel).

The northern portion of the KDE polygon that was not well supported by data observations was predicted with low probability of occurrence of *Boltenia* by the random forest model (Fig. 1.3.8). This portion of the polygon could be clipped using the boundary denoting suitable versus unsuitable habitat from the prevalence surface (see Fig. 1.3.9 for example).

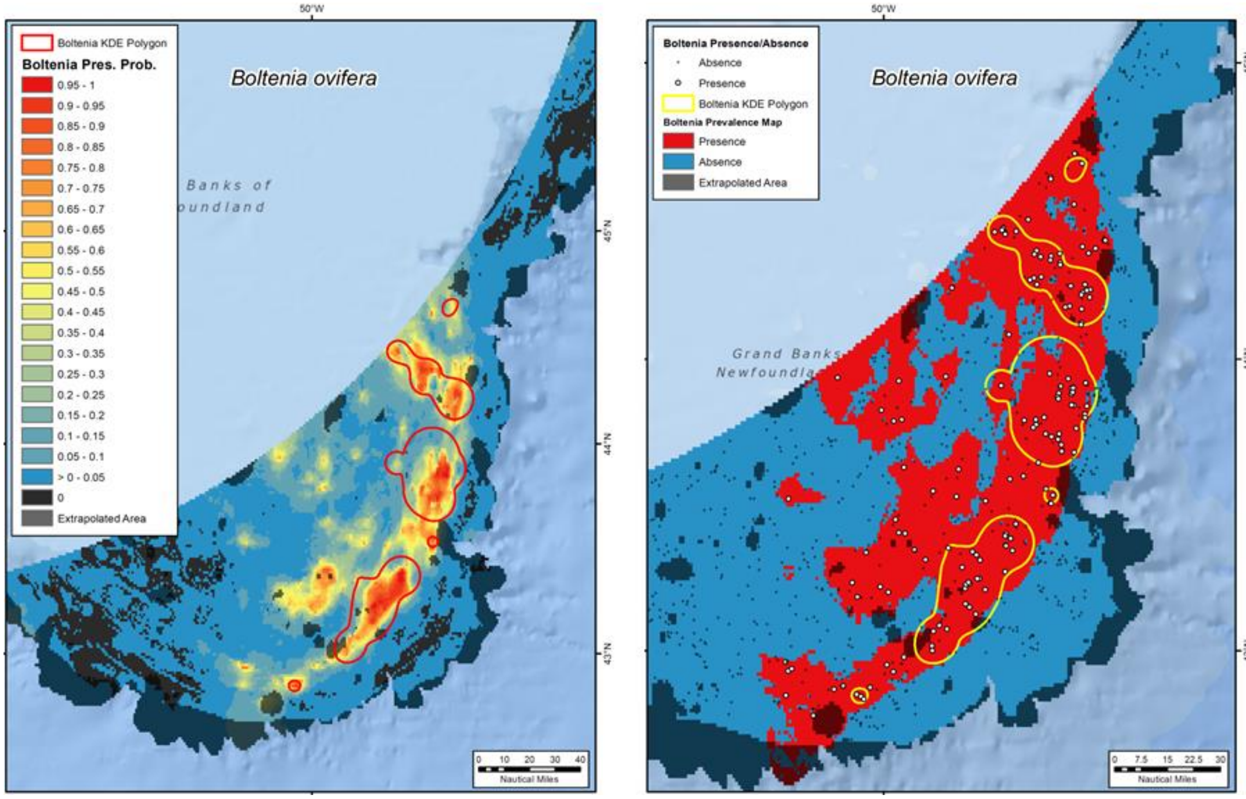

Fig. 1.3.8. KDE polygons denoting significant concentrations of *Boltenia* overlain on the predicted presence probability (left) and binary presence-absence map (right) of *Boltenia* based on the random forest model of *Boltenia* presence-absence from Canadian and Spanish multispecies trawl survey data from 2006 to 2017. The binary presence-absence map was created by reclassifying the predicted presence probability values into presence (suitable habitat) and absence (unsuitable habitat) of *Boltenia* using species prevalence (i.e. the proportion of presences in the dataset).

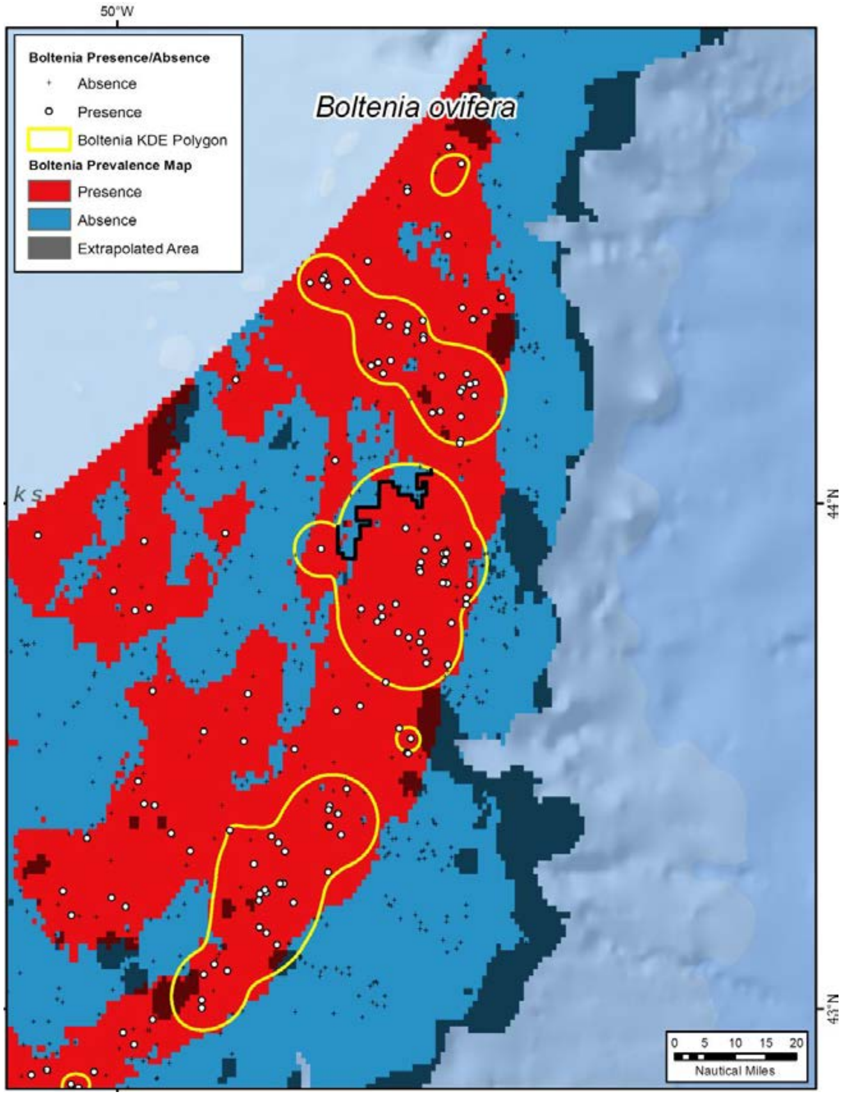

Fig. 1.3.9. Example of how the *Boltenia* KDE polygon that was not well supported by data points could be clipped using the boundary of suitable and unsuitable habitat denoted by the random forest model (black line following the 'prevalence' boundary).

In addition to the KDE and SDM analyses, available information on the surficial geology of the Tail of Grand Bank was reviewed in order to better inform the former analyses and help deduce patterns between the small-scale distribution of *Boltenia ovifera* and its preferred substrate. Fig. 1.3.10 shows the location of track lines from RoxAnn collected on the Tail of Grand Bank between 1994 and 2005 in relation to the large *Boltenia* KDE polygon to the southwest of Area 2. RoxAnn is an ultrasonic processor that gives real-time classification of seabed features by processing the signals from a vessel's echo-sounder (Caddel, 1998). The data distinguishes between mud, sand, gravel, small rock, and rock events within the *Boltenia* KDE polygon. RoxAnn track lines passing over the location of tow sets which recorded *Boltenia* indicate that hard substrate (small rocks and rocks) is present in those areas. This hard substrate is patchy in its distribution throughout the polygon which is consistent with previous conclusions that patch sizes for this species are on scales of less than 1 km.

The presence of hard and patchy substrate within the *Boltenia* KDE polygons is further supported by the failed or unsuccessful tow sets indicating torn nets from the Canadian multispecies trawl survey present in those polygons (Fig. 1.3.11). In these surveys, unsuccessful sets are coded as 3, 4, or 5. Sets coded as 3 indicate that the net is torn and catch compromised, and usually occurs when the net impacts hard bottom, but can also indicate when large catches of sponges are made (V. Wareham, pers. comm.). As large catches of sponges are not frequently made in this area (NAFO, 2015), these unsuccessful sets likely represent encounters with hard substrate.

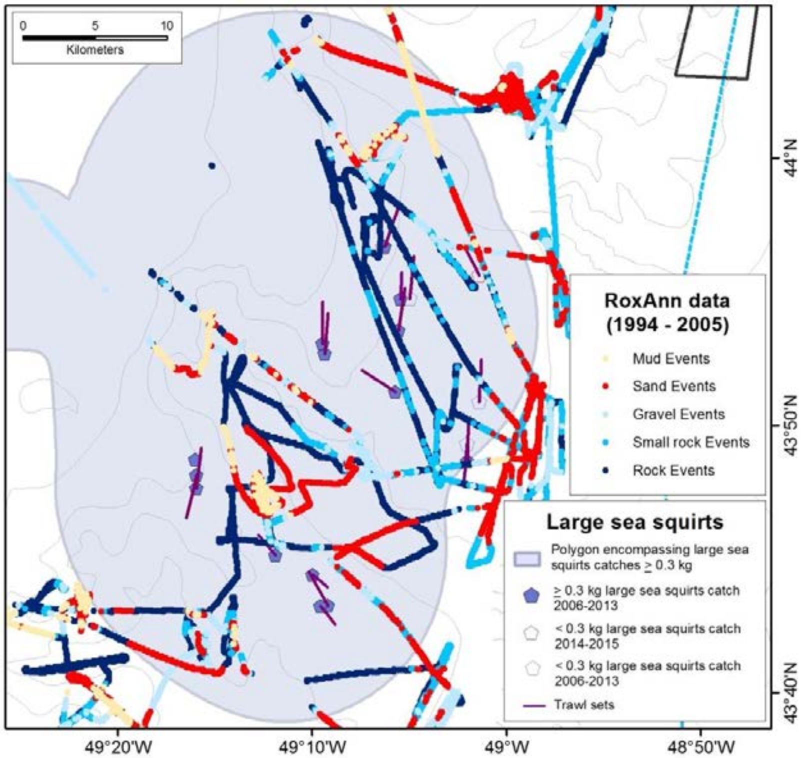

Fig.1.3.10. Seabed classification from RoxAnn track lines collected between 1994 and 2005 on the Tail of Grand Bank in relation to the KDE *Boltenia* polygon. Tow sets containing significant concentrations of large sea squirts (*Boltenia*) and their associated trawl lines are plotted.

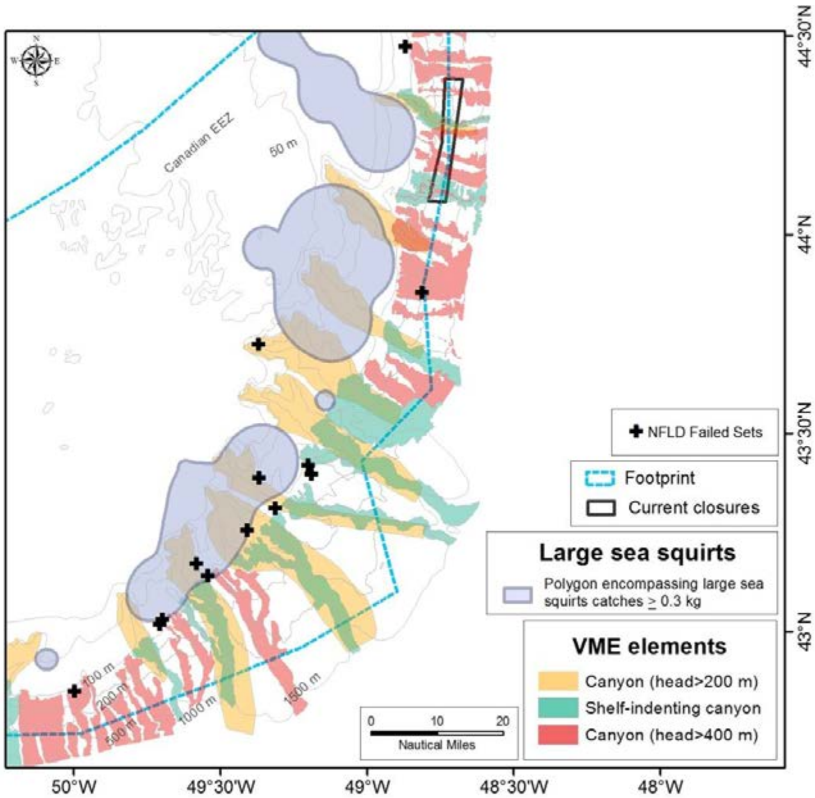

Fig. 1.3.11. Location of failed or unsuccessful tow sets for the period 2006 to 2017 from the Canadian multispecies trawl survey on the Tail of Grand Bank in relation to the *Boltenia* KDE polygons and VME elements.

iii) Bryozoa

KDE analysis of Bryozoa

A kernel density surface was created (Fig. 1.3.12) and the area of successive density polygons calculated (Table 1.10) for bryozoans in the NRA. The search radius was 14 km, cell size was 1.68 km, and the contour interval for constructing equal density polygons was 0.0005 kg. These values differed from those used in the 2013 analysis because we changed the spatial extent to include only the Nose and Tail of Grand Bank where these species were found with higher biomass. The Flemish Cap recorded presence of very low biomass only (NAFO, 2013). Both search radius and cell size are functions of the spatial extent and are optimized accordingly in the defaults of the ArcGIS program. Consequently some changes to the perimeters of the KDE polygons are expected. The kernel density distribution identified bryozoan habitats on the Tail of Grand Bank in 3O (Fig. 1.3.12).

The area of bryozoan habitat encompassed by the polygons increased first between the 1 kg and 0.6 kg catch thresholds (Table 1.3.3, Fig. 1.3.13). This increase in area was 116% and was created through the addition of 6 data points. The lower threshold picked up bryozoan areas that were not included in the area covered by the 1 kg threshold (Fig. 1.3.14), indicating that the area is still being delineated. The next largest change in area occurred between 0.2 and 0.1 kg (Table 1.3.3, Fig. 1.3.13), where the increase in area was 142%. This increase occurred through 22 additional data points. Following previously established guidelines (Kenchington et al., 2016) the 0.2 kg/RV tow threshold emerged as defining significant concentrations of bryozoans). This is the same threshold value established previously (NAFO, 2013). When superimposed on the kernel density surface (Fig. 1.3.14), the 0.2 kg density polygon captures all of the highest density areas (red and orange colour on Fig. 1.3.12) from the kernel analysis. The difference in area circumscribed by the KDE analyses in 2013 and 2017 are compared in Figs. 1.3.14 and 1.3.16. The tighter boundaries in the present analyses are due to the smaller search radius and analysis optimized for the Tail of Grand Bank. The final locations of significant concentrations of bryozoans from the current analysis are shown in Fig. 1.3.16.

Table 1.3.3. Characteristics of Equal-density Polygons of Bryozoan Biomass Constructed for Successive Density Thresholds. Shaded rows indicate potential thresholds for identification of significant concentrations.

No. Points Defining Polygon	Polygon Area (km^2)	Density Threshold Weight (kg)	Percent Change in Area
1	0.5	70	101420.2
6	477.7	3	121.7
8	1059.1	2	34.7
16	1426.3	1	115.8
22	3078.4	0.6	13.6
33	3497.5	0.3	9.3
39	3823.4	0.2	141.8
61	9245.5	0.1	5.7
66	9769.5	0.08	4.9
81	10252.1	0.06	18.4
98	12140.8	0.04	89.0
141	22945.7	0.02	41.4
210	32434.2	0.01	0.0
226	32434.2	0.008	0.0
260	32434.2	0.006	1.0
310	32747.0	0.004	0.5
414	32917.2	0.002	0.0
478	32917.2	0.001	

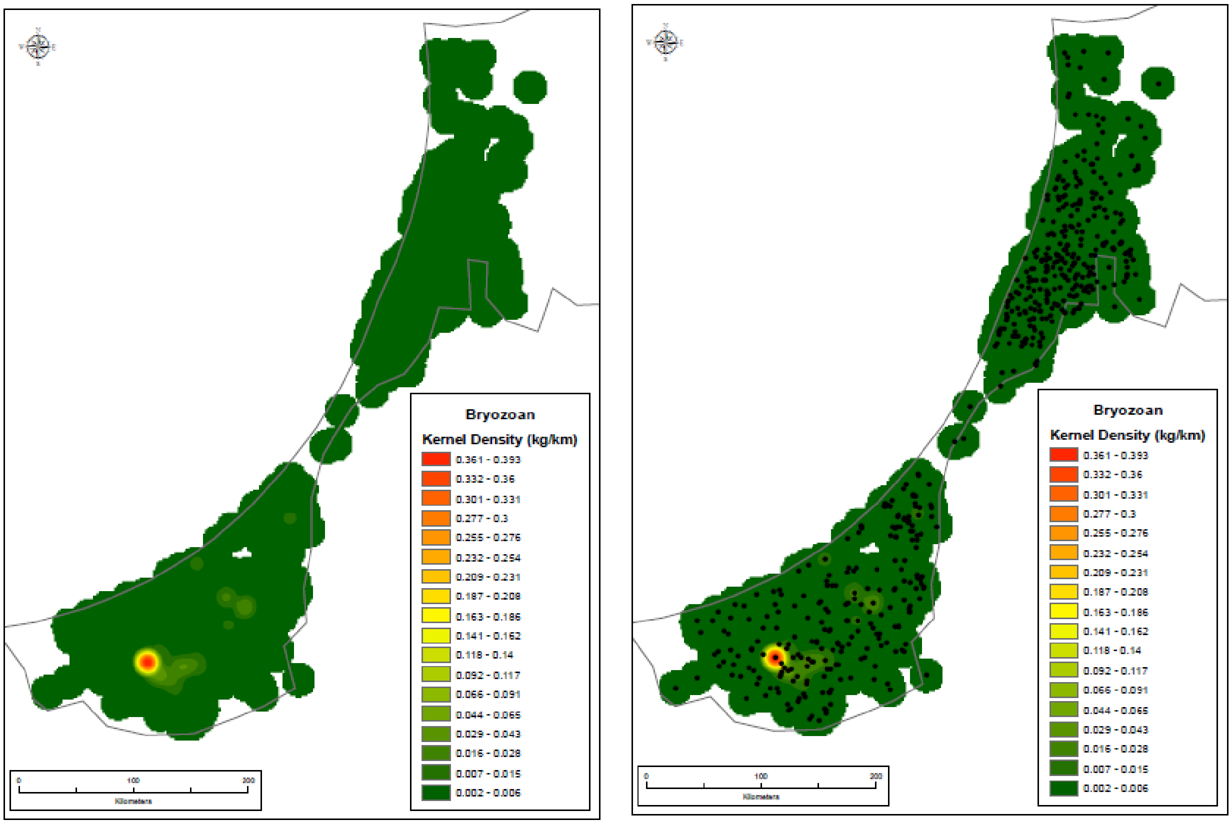

Fig. 1.3.12. Kernel density distribution of bryozoans on the Nose and Tail of Grand Bank in the NAFO Regulatory Area (Left panel) with the location of the 546 data points used in the analysis (Right panel).

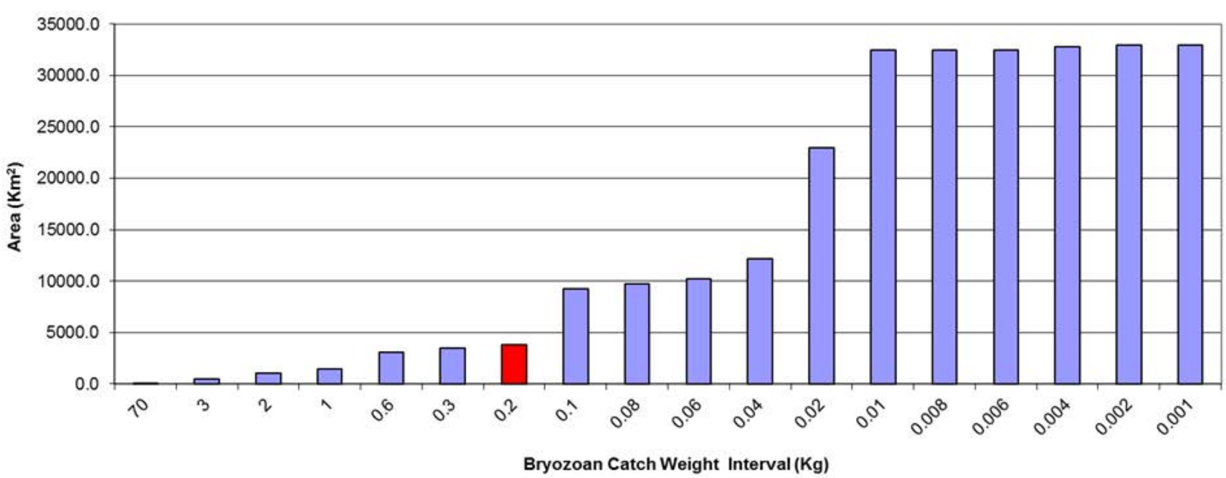

Fig. 1.3.13. Area occupied by successive equal density thresholds (bryozoan catch weight in kilograms). Red bar indicates the density threshold used to identify significant concentrations of bryozoans.

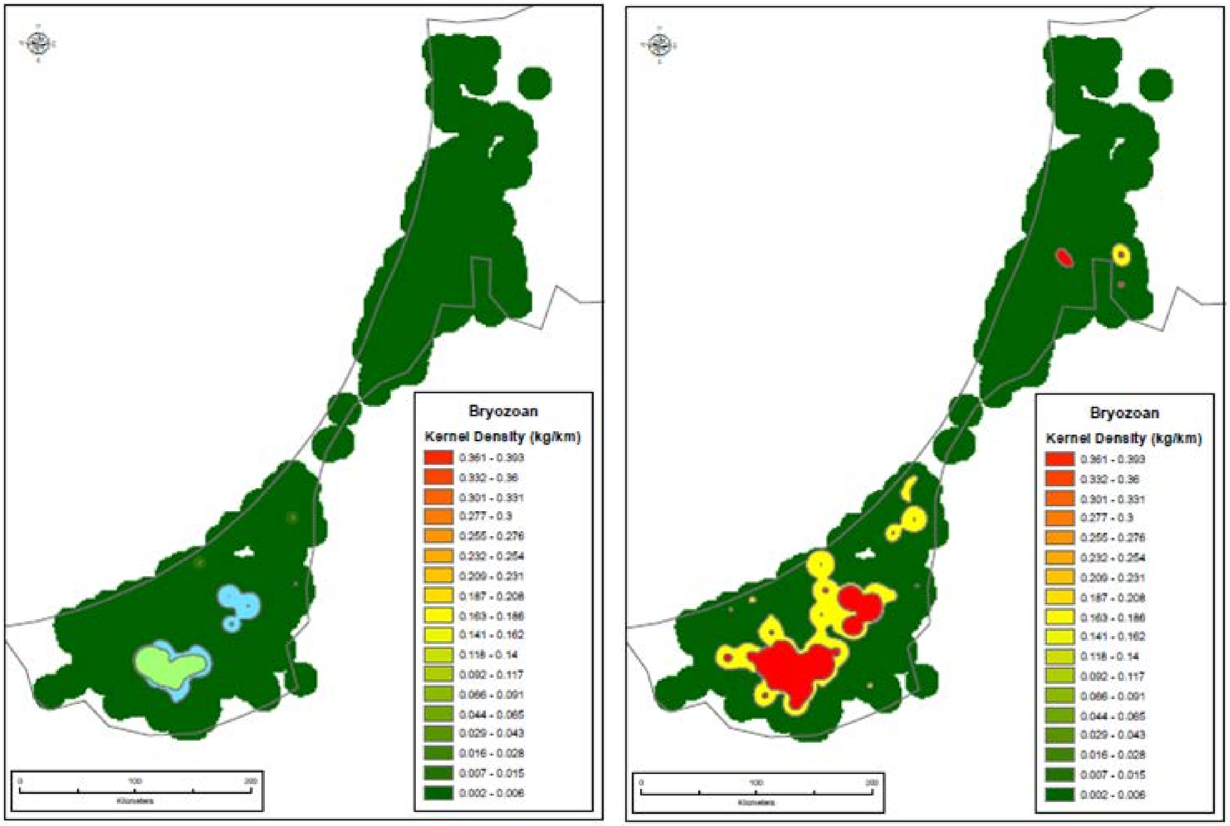

Fig. 1.3.14. Spatial configuration of KDE-derived polygons showing difference in area between polygons calculated with thresholds of A) 1 kg bryozoan catch (light green) and 0.6 kg bryozoan catch (light blue); and B) 0.2 kg bryozoan catch (red) and 0.1 kg bryozoan catch (yellow), overlain on KDE surfaces.

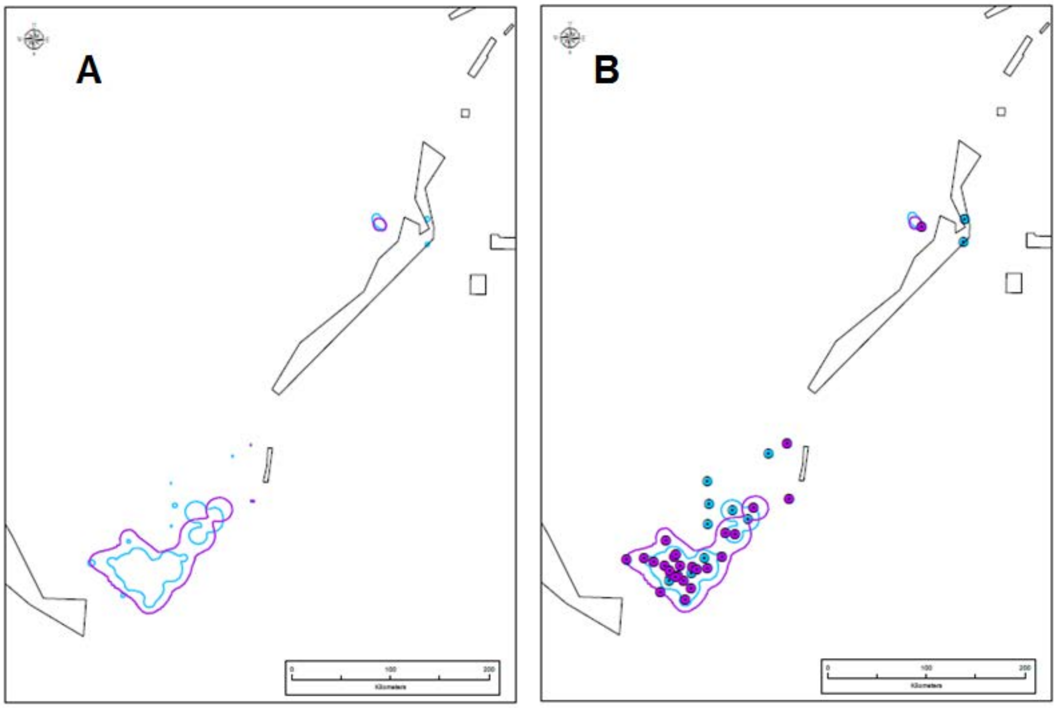

Fig. 1.3.15. A) Bryozoan KDE polygons from the 2013 analyses (purple polygons) and the 2017 analyses (blue polygons) identified on Grand Bank in the NAFO Regulatory Area in relation to the closed areas; B) with the location of catches equal to or above the threshold of 0.2 kg from previous (purple) and additional (blue) data used in the current analyses.

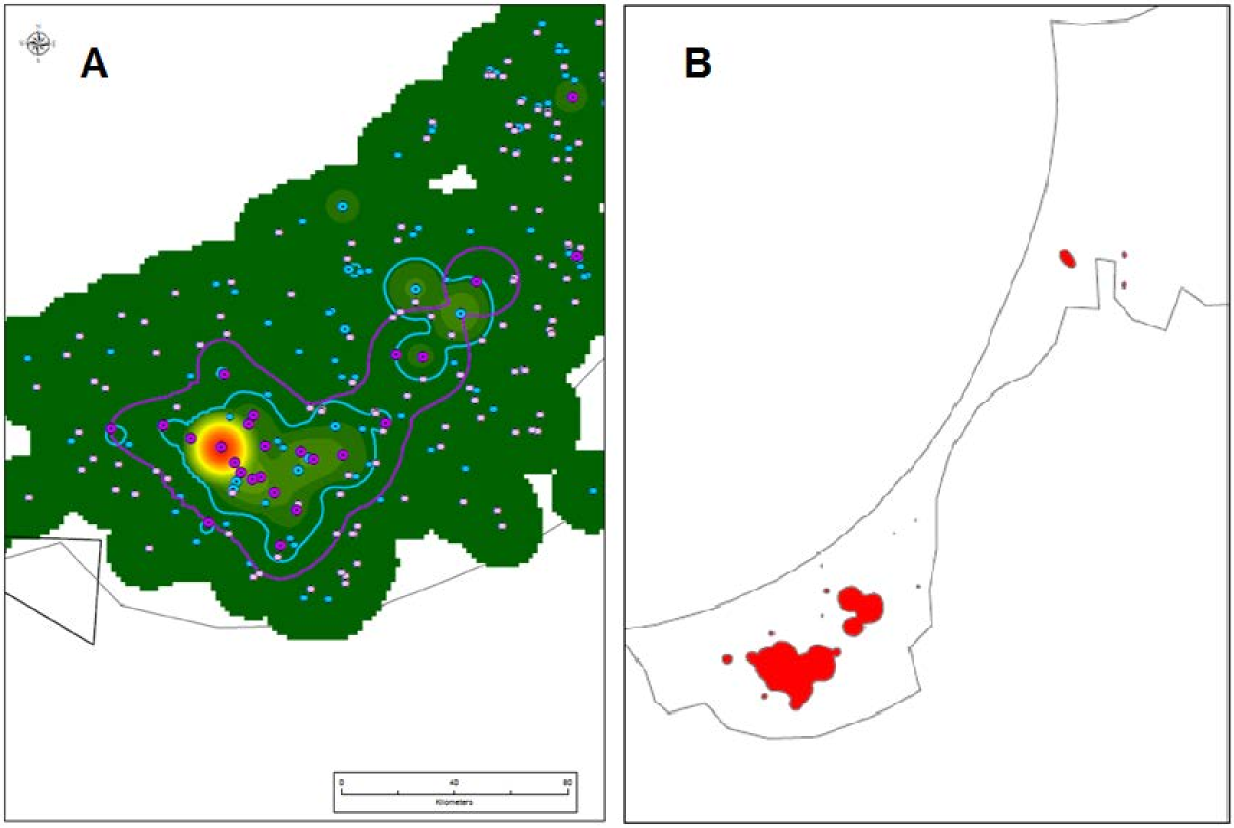

Fig. 1.3.16. A) Close up of bryozoan KDE polygons from the 2013 analyses (purple polygons) and the 2017 analyses (blue polygons) identified on Grand Bank in the NAFO Regulatory Area in relation to the closed areas; B) Significant concentrations of bryozoans as identified through the 2017 (current) KDE analyses.

Species Distribution Modelling of Bryozoa

A species distribution model based on the presence and absence of bryozoans was generated using random forest following the same methodology as used for *Boltenia ovifera*. The response data were catches of bryozoans (recorded as either Bryozoa, or Bryozoa Ent. Or Ect. in the surveys) from the Spanish and Canadian multispecies trawl surveys conducted on the Tail and Nose of Grand Bank and in Flemish Pass. Absence data were created from null catches from the same surveys. Although Spanish surveys conducted recorded bryozoans on the Flemish Cap, these data were excluded in the SDM as the composition of species is different than those dominating on the Tail and Nose of Grand Bank and in the Flemish Pass (J. Murillo, pers. comm.), making it less comparable to the KDE analysis of this group. A total of 548 presences and 1854 absences of bryozoans across both the Canadian and Spanish surveys were included in the model (see Table 1.3.4; Fig. 1.3.17).

Table 1.3.4. Number of presences and absences of bryozoans from the Canadian and Spanish multispecies trawl surveys occurring in the NAFO Regulatory Area and used for species distribution modelling.

	Presences	Absences
Canadian Multispecies Trawl Survey (2016-2017)	15	91
Spanish Groundfish Trawl Survey (2006-2017)	533	1763

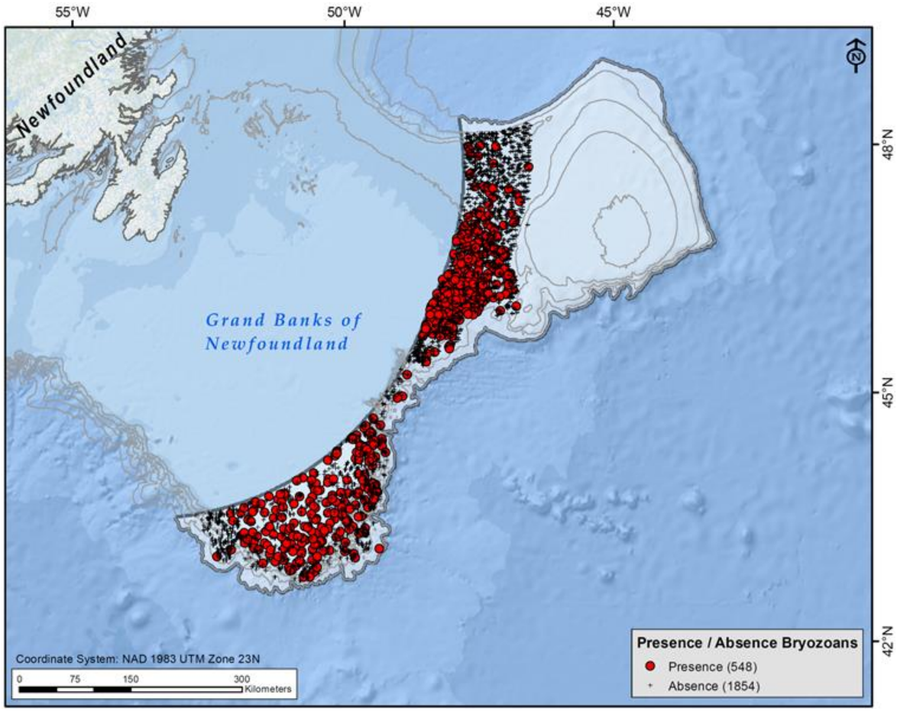

Fig. 1.3.17. Distribution of Bryozoa presences (red circles) and absences (black crosses) used in the random forest species distribution model. Grey polygon indicates the model extent.

The random forest model performance was considered good, with a cross validated mean AUC value of 0.757 ± 0.037, and Sensitivity and Specificity values of 0.673 and 0.690, respectively. The lower performance of this model could be attributed to the coarse taxonomic resolution of the bryozoan identifications in the survey and the inclusion of multiple species with a preference for different environmental requirements, as noted for random forest models of Bryozoa in adjacent Canadian waters (Guijarro et al., 2016b). Alternatively, the current distribution of bryozoans in the NRA may have been impacted by fishing, which was not included as a predictor variable in the model.

Fig. 1.3.18 shows the predicted presence probability surface of Bryozoa. Predicted presence probability of Bryozoa was patchy on the Tail and Nose of Grand Bank. These areas of higher presence probability coincided with the location of presence observations (Fig. 1.3.19). The top environmental predictor variable was Maximum Summer Mixed Layer Depth, followed by Mean Bottom Temperature.

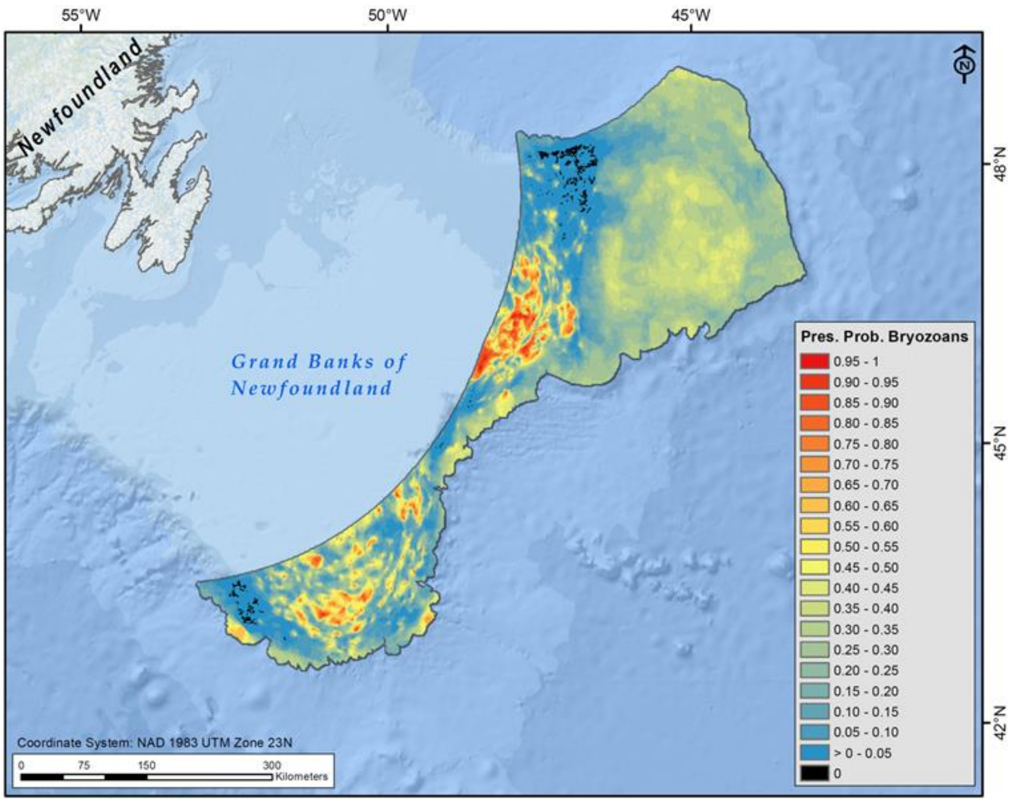

Fig. 1.3.18. Predicted presence probability of Bryozoa from a random forest species distribution model on Bryozoa presence and absence data from Canadian and Spanish multispecies trawl surveys conducted in the NAFO Regulatory Area between 2006 and 2017.

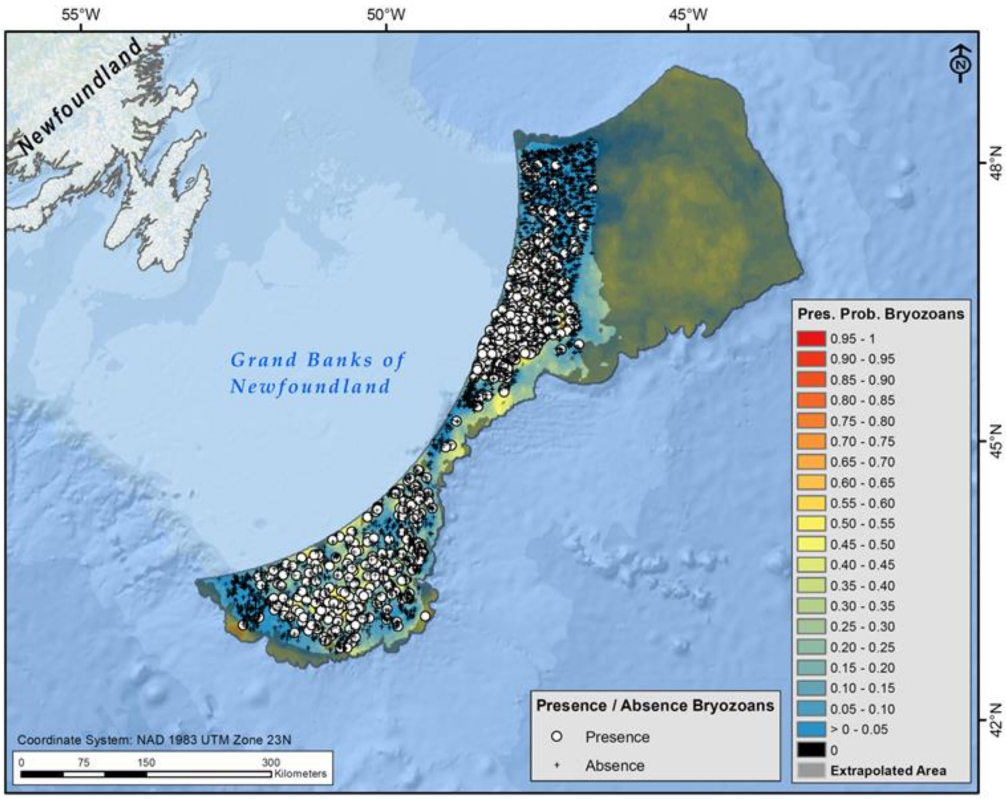

Fig. 1.3.19. Predicted presence probability of Bryozoa overlain with presence and absence data points and areas of model extrapolation (i.e. areas where at least one environmental predictor variable is outside the environmental envelope used to train the model. These highlight areas where model predictions require validation).

Areas of high predicted presence probability of Bryozoa as indicated by the random forest model were patchy inside the KDE-derived Bryozoa polygons (Fig. 1.3.20, left panel). The majority of area within the polygons was predicted as suitable habitat by the model when considering the 'prevalence' surface (Fig. 1.3.20, right panel). Presence and absence observations and areas of unsuitable habitat for Bryozoa were found inside the polygons on the Tail of Grand Bank, however the pattern was not clear enough to consider clipping the polygon's extent.

The main species of bryozoa that constitutes the significant catches of this group is *Eucratea loricata*, which is commonly found attached to shells and other hard substrate in the NRA (J. Murillo, pers. comm.). The presence of shells inside the Bryozoa KDE polygon was indicated by the RoxAnn data collected here (Fig. 1.3.21) and was patchy inside the polygon. This is also consistent with the patch size for these species being less than 1 km (or the tow length) and associated with hard bottom.

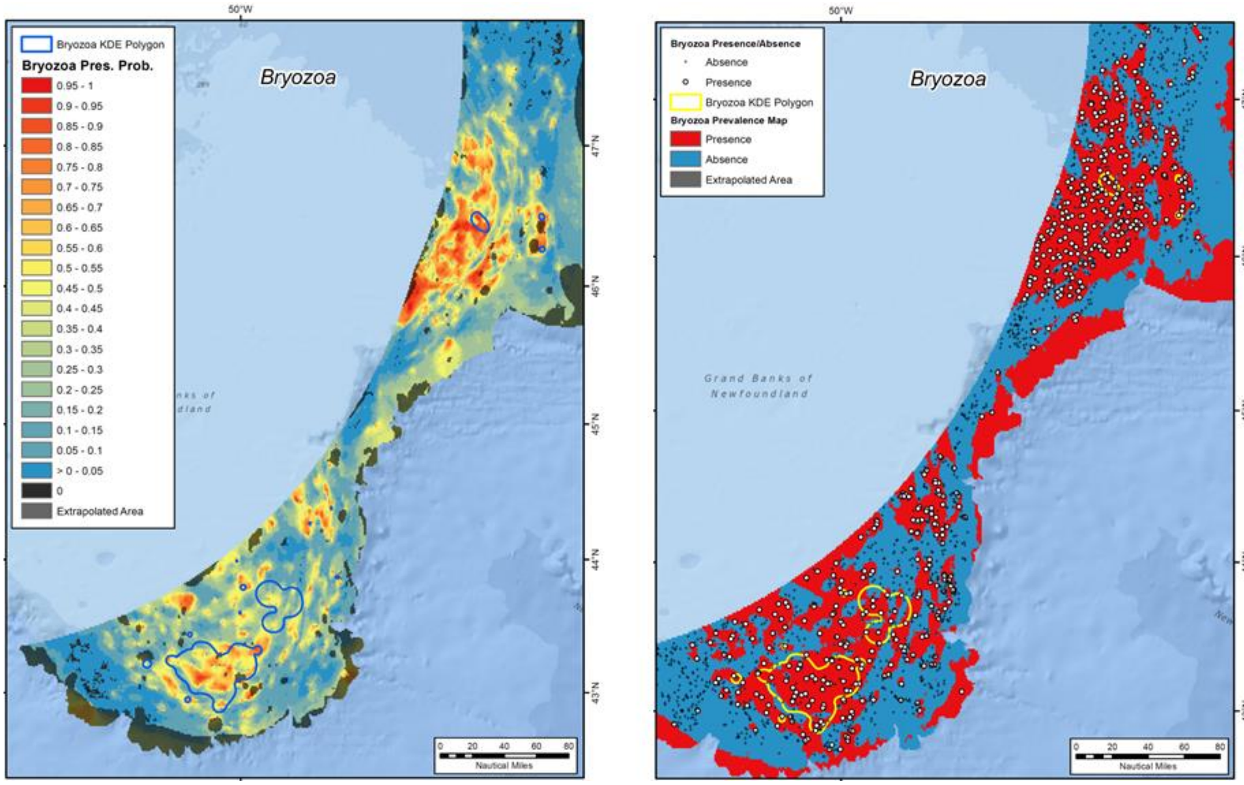

Fig. 1.3.20. KDE polygons denoting significant concentrations of Bryozoa overlain on the predicted presence probability (left) and binary presence-absence maps (right) of Bryozoa based on the random forest model of Bryozoa presence-absence from Canadian and Spanish multispecies trawl survey data from 2006 to 2017. The binary presence-absence map was created by reclassifying the predicted presence probability values into presence (suitable habitat) and absence (unsuitable habitat) of Bryozoa using species prevalence (i.e. the proportion of presences in the dataset).

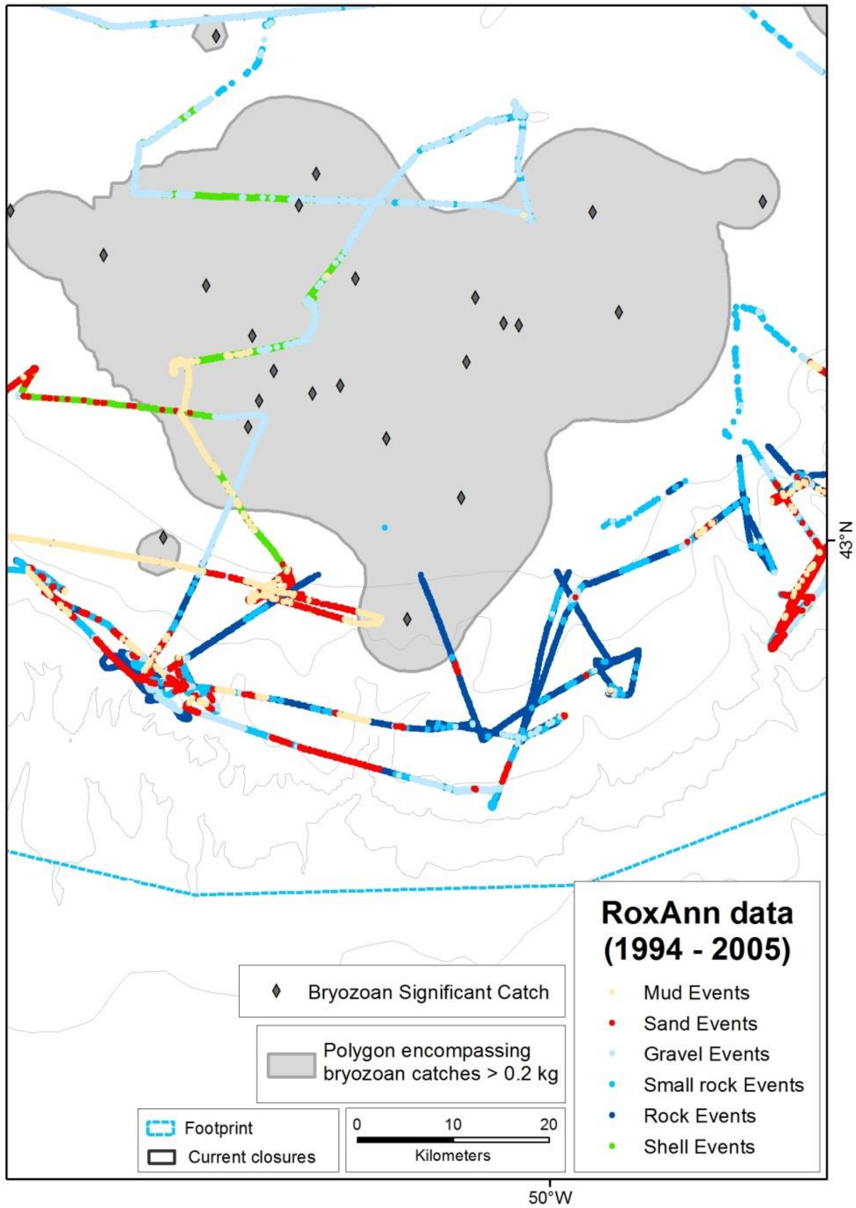

Fig. 1.3.21. Seabed classification from RoxAnn track lines collected between 1994 and 2005 on the Tail of Grand Bank in relation to a KDE Bryozoa polygon. Tow sets containing significant concentrations of bryozoans are plotted.

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NAFO. 2015. Report of the 8th Meeting of the NAFO Scientific Council Working Group on Ecosystem Science and Assessment (WG-ESA). NAFO Scientific Council Summary Document 15/19, Serial No. N6549, 176 pp.

ToR 1.4. Discussion on workplan and timetable for reassessment of VME fishery closures including seamount closures for 2020 assessment.

In order to progress the integration of new data and analysis pertaining to the status and extent of VME fishery closures to be reviewed by 2020 there is a need to identify and schedule tasks. The following set of tasks have been identified and agreed by the WG-ESA to progress over the next two meetings in preparation for the review.

- Update KDE analysis from 2014 – to include all additional VME indicator species data from trawl surveys, up-to and including the 2019 survey.
- Update on SDM (habitat) modelling incorporating sea pen SDMs from ATLAS R&D project.
- Inclusion of additional seabed physical data (*where available) in SDM models from Roxanne (sea bed sediment discrimination) for sponge and coral VMEs.
- Consideration of the connectivity of VMEs through links between propagule/larval transportation and VME distribution/location, as investigated by Kenchington *et al* , in prep.
- It was noted that the Corner Rise and New England Seamounts were originally discussed together; however, only revisions to the New England Seamounts have been progressed to date. To ensure consistency in approach other seamount closures,in particular the Corner Rise seamount should be progressed in preparation for the VME fishery closure review in 2020.
- Investigate the utility of including abundance and diversity information for different VME types in addition to the biomass data for the dominat VME taxa. Information on diversity will be useful when considering traits and functions associated with VME.
- To further our understanding of the functional importance of VMEs contact Myriam La Charité for advice on assessing the links between habitat diversity and biodiversity (epifauna); and Marta (infauna). Also to contact Marrion Boulard (Evan/Peter) to seek advice expert input aconcerning fishVME relationships (especially for seapens)
- Research needs
    - Initiate improved understanding of spatial dynamics of VMEs in response to climate change and/or impacts of fishing to better support the need for a possible adaptive management strategy in relation to closed areas and the need for periodic review of SAI
    - Investigate how to integrate information from trawl surveys with camera survey work, particularly given a plan to mitigate the loss/reduction of trawl surveys within closed areas.

THEME 2: STATUS, FUNCTIONING AND DYNAMICS OF NAFO MARINE ECOSYSTEMS.

ToR 2. Update on recent and relevant research related to status, functioning and dynamics of ecosystems in the NAFO area.

i) Update on the Research Activities Related to Ecosystem Function of Sponges by the EU-funded Horizon 2020 SponGES Project.

SponGES (Deep-Sea Sponge Grounds Ecosystems of the North Atlantic: an integrated approach towards their preservation and sustainable exploitation; http://www.deepseasponges.org/) is an EU-funded Horizon 2020 project initiated in March 2016 that is focused on research and innovation in the deep-water sponge grounds of the north Atlantic. Coordinated by Professor Hans Tore Rapp from the University of Bergen, the SponGES consortium consists of 19 partners from the EU, Canada, and the US that are dedicated to developing "an integrated ecosystem-based approach to preserve and sustainably use deep-sea sponge ecosystems of the North Atlantic". SponGES is organized into eight scientific work packages, the first four of which are aimed at strengthening the knowledge of deep-sea sponge ecosystems (WP1-4), innovation (WP5), and prediction (WP6-7), and the development of tools for conservation and sustainable exploitation (WP8) of these habitats. To address these objectives, a number of case study areas in the North Atlantic have been identified (Fig. 2.1), under which scientific research will be conducted. These case study areas represent the various temperate and boreal sponge ground ecosystems found in the North Atlantic, including ostur grounds (CS1, CS3) and glass sponge grounds (CS6, CS7). The Flemish Cap (CS1) was recognized by SponGES for its dense astrophorid grounds located along its slopes and on the Sackville Spur. The NAFO sponge closures here offer an ideal location to collect information on the impacts of trawling and recovery.

The emerging view is that deep-sea sponges play a major role in biogeochemical cycling and in the marine food web. SponGES Work Package 4 (WP4) on Ecosystem Function, Services and Goods, aims to increase our knowledge on 1) the impact of sponge grounds on benthic-pelagic coupling of major biogeochemical cycles of ocean nutrients silicon, nitrogen, and carbon, 2) on the marine food web, and 3) on deep-sea ecosystem metabolism (i.e., productivity and respiration). *In situ* and *ex situ* experimentation will be conducted on the dominant species of the different sponge grounds, including *Geodia* and other astrophorid species that are found in the NAFO Regulatory Area. Such quantitative information would be useful in models currently being developed by WG-ESA members to evaluate the impact of significant adverse impacts of fishing to ecosystem function of VME in the NAFO Regulatory Area. Experimental outputs associated with SponGES WP4 are due during months 36 and 40 of the project, or February and June 2019. However, quantitative measures may be available earlier (L. Beazley pers. comm. with SponGES PI) and could be disseminated to WG-ESA members prior to 2019.

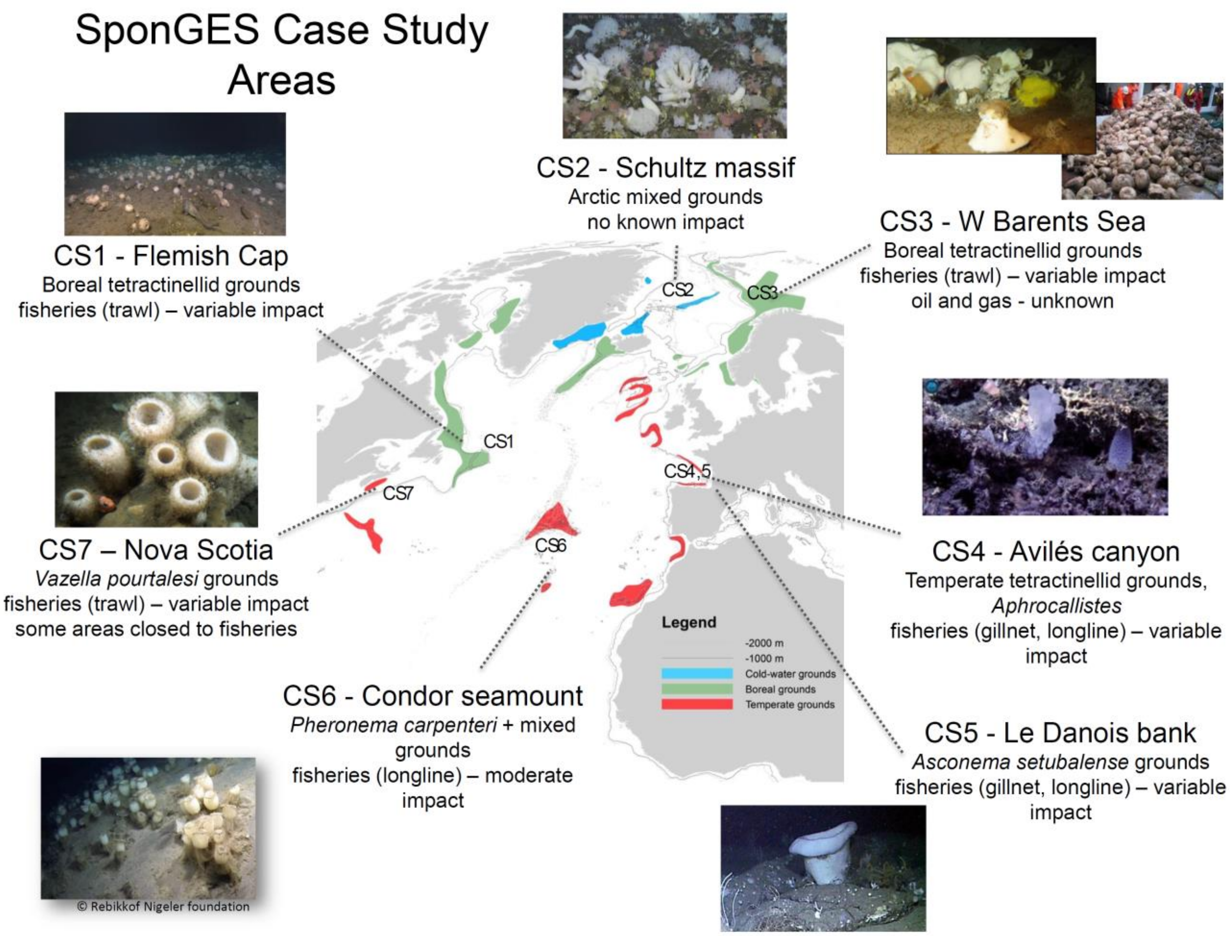

Fig. 2.1. Sponge grounds in the North Atlantic that are case study areas under the SponGES project.

ToR 2.1 NEREIDA: Initial Analysis of Sea Pen VME Resilience in the NAFO Regulatory Area.

i) Introduction

Following preliminary assessment of significant adverse impacts on coral and sponge VME in the NAFO footprint (NAFO, 2016), sea pen appeared to be more resilient than either the sponge (*Ostur*) or large gorgonian VME. Specifically, sea pen biomass is found in areas subject to fishing activity at levels proportionately greater than either sponge or large gorgonian VME. This observation raised the possibility that sea pen VME may recover (either partially or fully) following the cessation of fishing activities on a time scale commensurate with implementing dynamic fishery closures to sustain both sea pen VME biomass and fishing opportunities within sea pen VME. At the NAFO annual meeting in 2016 it was agreed to establish a temporary fishery closure to protect sea pen in the eastern part of the Flemish Cap, to be enforced in 2017, with the closure to be reviewed in 2018.

Accordingly, this study aims to provide essential scientific evidence to facilitate the identification of appropriate fisheries management options required to sustain sea pen VME in the NAFO footprint beyond 2018.

This study builds upon and develops the analysis previously undertaken to assess SAI on VME as part of the NAFO review of bottom fisheries in 2016 (NAFO, 2016). The study uses the same sources of biomass and VMS data (NAFO, 2016), but up-dated for the period 2006 to 2016 for sea pen survey trawl biomass, and 2008 – 2015 for fishing vessel VMS data.

The study report comprises three main sections which correspond to the projects principal objectives, namely: **i.**to determine swept area calculations through quantification of the actual direct area of impact derived from VMS data, **ii.** estimate the resilience of VME indicator species (specifically sea pen) to fishing impacts using the information on swept area impacts and VME biomass, specifically to estimate the time it takes for sea pen VME biomass to recover to a certain level post fishing impact, and iii. assess the functional significance of VME through a preliminary review of the literature and an analysis of the spatial/temporal dynamics of fisheries occurring near VME.

ii) Determining swept area impacts

Gear Dimensions

To estimate the potential seabed surface area of impact it is first necessary to understand the size and design of the bottom fishing gears and how they are deployed and operated in NAFO fisheries. There are essentially two types of bottom fishing gear employed for fin-fisheries in the NAFO footprint which have been assessed in this study, namely; i. redfish and cod fishery gears, and ii. Greenland halibut fishery gears. Estimates of gear dimensions was made following consultation with observers on EU fishing vessels working in the NAFO Regulatory Area, and this information is summarised in Table 2.1.1 below:

Table 2.1.1. Gear dimensions for redfish/cod and Greenland halibut fisheries used in the present study

Redfish and Cod fisheries	Gear Dimensions
Net horizontal opening	59 metres
Net vertical opening	5 metres
Door opening (between otter boards)	140 metres

Greenland halibut fishery	Gear Dimensions
Net horizontal opening	63 metres
Net vertical opening	6 metres
Door opening (between otter boards)	165 metres

In both cases the gears consist of a combination of fishing lines, nets, and otter boards such that the fishing warps from the vessel are attached to otter boards which in turn are attached to bridles which divide the headline (top of the net) from the fishing line (bottom of the net). The point at which the fishing line is designed to have close contact with the seabed is known as the footrope and typically it has several devices attached to it (such as rockhoppers, rubber wheel bobbins and discs) which are designed to prevent it from fouling the seabed. The horizontal net opening is generally measured from the point at which the bridles start, whereas the horizontal opening between the otter boards is associated with a significant unnetted part of the gear that is not designed to have close contact with the seabed. So, in practice, the full extent of fishing line and warps do not have continuous or close contact with the seabed. However, observations made by Canadian researchers, investigating impacts of similar otter trawl gear types in Canadian waters (pers. com. Corinna Favaro) revealed that unnetted parts of the fishing lines and warps have the potential to impact benthic organisms that stand erect off the seabed, such as the sea pens commonly encountered off the Flemish Cap *Halipteris* sp. (sea whip)(Fig. 2.1.1).

For this study, the worst case average swept area impact was estimated to be 150 metres based upon the gear dimensions employed by the EU fishing fleets.

Fig. 2.1.1 The sea pen *Halipteris finmarchica* (sea whip) approx. 50 cm – 100 cm in length commonly found around the northern flanks the Flemish Cap.

Simulating the Cumulative Unit Area of Fishing Impact

The rate of accumulation of swept area from repeated passes of a bottom trawl though an area of seabed was simulated using a slightly aggregating random placement of lines across a set area. The lines were buffered to the width of the expected ground impact of fishing gear used in the study area, and the increase in area covered was calculated for each added pass of the trawl. For the purpose of the simulation, width of ground impact from the fishing gear has been fixed at 150m as previously stated. However, the sensitivity of the impact and recovery calculations performed in this study to changes in the swept area dimensions has not been undertaken.

The analysis was done using a 1 km x 1 km polygon. An initial random starting point was created on the edge of the square. Fishing vessels in the study area follow bathymetric contours, making passes through a 1 km square most likely to follow a constant orientation. Therefore, to account for the typical towing behaviour, lines were constrained into passing the square with some variability in orientation introduced through randomly selecting the endpoint for each line from a sample of 1000 values drawn from a normal distribution, with a standard deviation of 50 m, centred around the starting point (excluding points falling outside the square edge – Fig. .1.2). Similarly, the next starting point was in turn randomly selected from a sample of 1000 values from a normal distribution with a standard deviation of 500 m (again excluding points that fell outside the square edge). The use of the normal distribution for new lines, instead of a fully random approach accounts for the tendency of fishermen to repeat successful tows. It is unlikely, however, that repeats would be accurate to within less than 500 m. Fig. 2.1.2 illustrates the process of adding lines and calculating areas

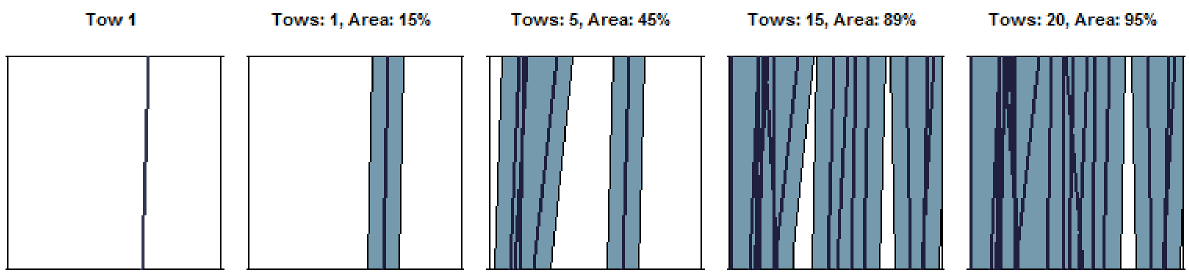

Fig. 2.1.2. Illustration of the simulation of the accumulation of area of ground impact through repeated random tows of 150 metre swath width in 1 km^2.

Ten iterations of simulated tow-lines were produced to capture the variability in the spatial distribution and intensity of trawling impact. For each iteration, a series of tow-lines were produced to ensure full coverage of the square. Each line was buffered to 150 m to create a tow-line and added to the existing swept area, recording the number and cumulative length of tow-lines as well as the cumulative area of tow-line impact, until the entire square was fully covered. The buffered lines (tow-lines) were also overlaid to estimate the percentage of the square with various number of accumulating passes (Fig. 2.1.3).

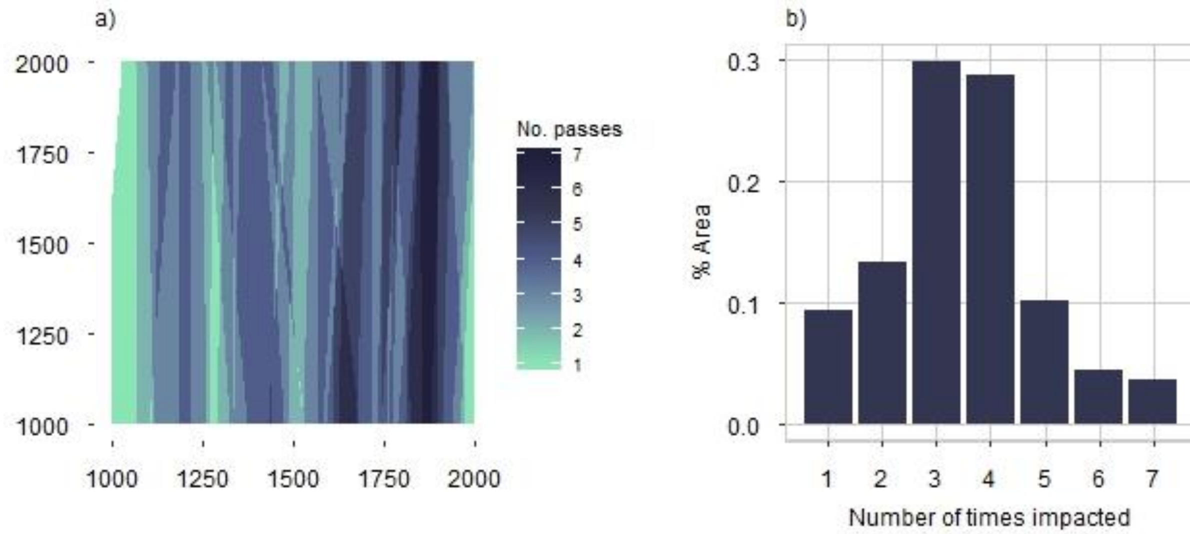

Fig. 2.1.3. Number of cumulative passes associated with random tows impacting the entire area of seabed: a) spatial distribution and intensity of impact, b) average percent of area impacted for a given number of passes (average of 10 iterations).

The analysis shows that on average about 60% of the any given area, subject to 100% trawling impact, will be repeatedly fished between 3 and 4 times. The time-interval over which the impact pattern described above occurs will depend on the amount of fishing effort (e.g. the speed of the vessel) and the dimensions of the gear (e.g. 150 m). The cumulative area of impact for each tow was plotted against the cumulative length of the of random tows (Fig. 2.1.4) which shows that it takes an increasing number tows to impact the last remaining area of seabed in any given area (e.g. it takes on average just under 4 km of trawling to impact 50% of the area, where as it takes over 31 km of trawling to impact 100% of the area). A Generalized Additive Model (GAM) was fitted to the data to find the best fit for a smooth curve between the cumulative length of tows and the cumulative percent of area covered. The best model was chosen based on visual fit on plotted points and the most even distribution of residuals. The final model was fitted on log-transformed cumulative line length using a Gaussian family and a logit link function, with 4.8 degrees of freedom. Deviance explained by the model was 93.1%.

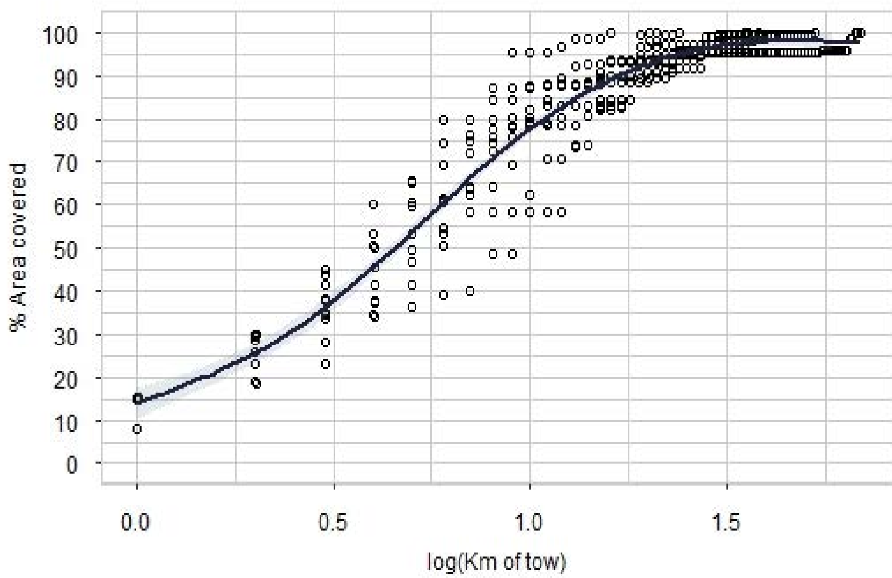

Fig. 2.1.4 Cumulative % area covered by successive simulated tows in a 1 km^2 box plotted against the log(10) of cumulative line length in kilometers. The line shows a GAM fitted with 4.8 degrees of freedom.

iii) Resilience of Sea Pen VME

Testing Assumption of Sea Pen Biomass Equilibrium

An equilibrium in overall sea pen biomass implies that the relationship between loss of biomass caused by fishing (and other sources of loss) remains in balance over time with the recovery of biomass in unfished areas. However, two factors are important in determining whether such an equilibrium state exits or not, namely; **i.** the extent of sea pen VME habitat and the proportion of that habitat subject to fishing activity at any one time and **ii.** how the fished area changes over time. For example, if fishing effort in sea pen habitat remains relatively stable over time, but the distribution of that effort shifts from one year to the next, then areas once fished may shows signs of recovery whilst previously unfished areas now fished would be expected to experience a decline in sea pen biomass. Therefore, as stated, an equilibrium is achieved if the overall loss of biomass (caused by fishing) is equal to the overall gain in biomass (by recolonization and growth) in sea pen habitat. To test if biomass is in equilibrium, the biomass and VMS data were first divided into two equal parts (of 4 years duration each), e.g., 2009 – 2012 and 2013 – 2016, and the cumulative biomass curves against fishing pressure for these two periods was then compared. If the cumulative biomass curves for these two periods are the same, then it is indicative of an equilibrium state.

Sea pen biomass layer

As part of the NAFO review of VME (coral and sponge) fishery closures undertaken in 2014, the spatial extent of VME was determined using species kernel density analysis (Kenchington *et al.* 2014). The analysis conducted for the review utilised VME indicator biomass data from Canadian and European trawl surveys sampled between 2003 and 2013 which resulted in a sea pen VME polygon (Fig. 2.1.5)

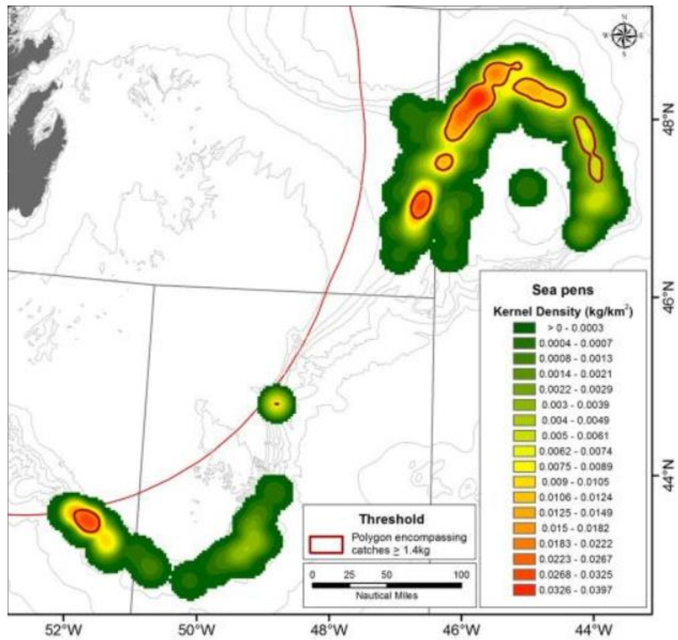

Fig. 2.1.5. The modelled distribution of sea pen showing the VME polygon (red outline) using a threshold biomass of 1.4kg from survey data (2003 – 2013), from Kenchington et al., (2014).

This KDA approach was re-applied to data incorporating the latest biomass trawl survey sample records, 2006 to 2016 (following the same methods given in Kenchington et al., 2014) (Fig. 2.1.6). The up-dated sea pen VME polygon forms a continuous 'horse-shoe' area around the North of the Flemish Cap which is consistent with habitat suitability model predictions (WG-ESA, 2013; Cefas, 2015) shown in Fig. 2.1.7.

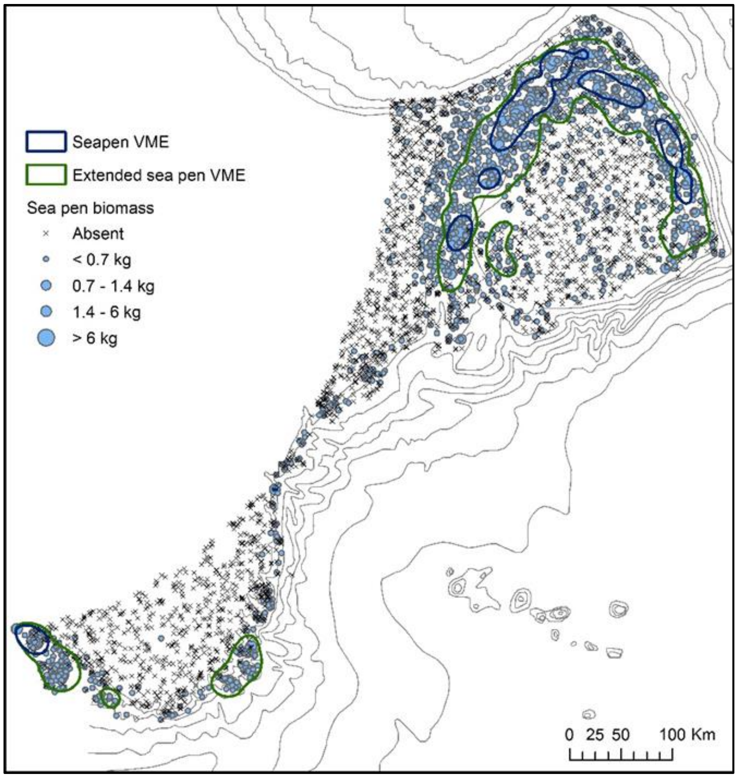

Fig. 2.1.6. Sea pen biomass in 1 km long scientific trawls collected between 2006-2016, with the core sea pen VME area identified using kernel density analysis with threshold values by Kenchington *et al.* (2014) and extended sea pen study area based on a simple kernel density analysis of updated dataset, encompassing all tows above the threshold identified in Kenchington *et al*. (2014). Bathymetric contours are shown at 500 m depth intervals.

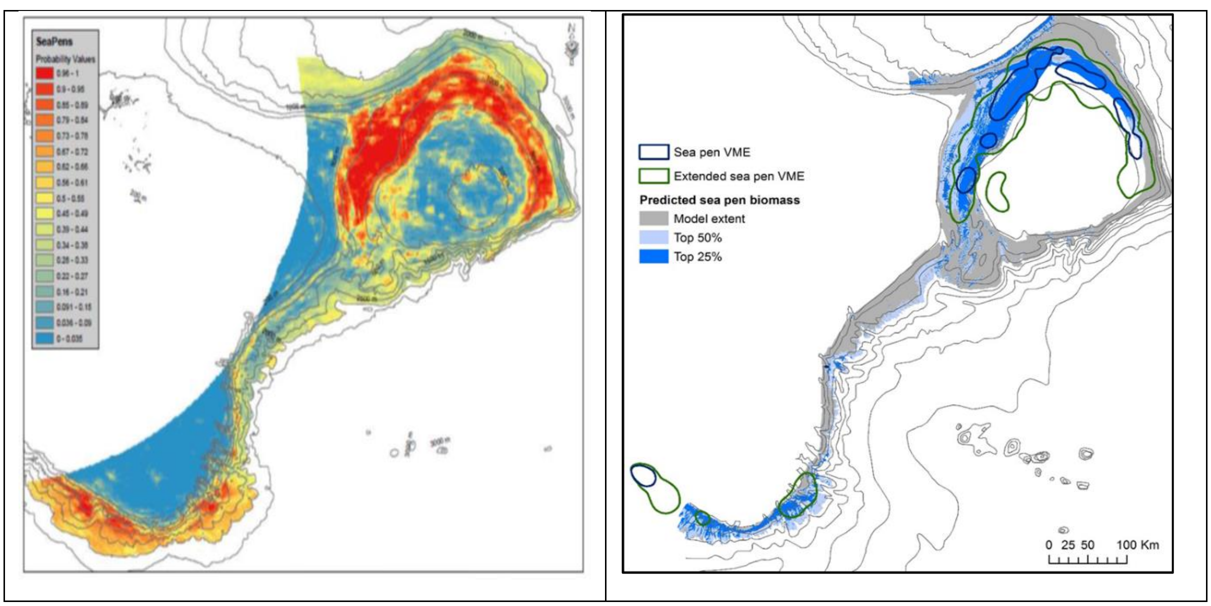

Fig. 2.1.7. Left panel shows the predicted extent of suitable sea pen VME habitat using sea pen presence/absence data (1.4 kg.km^{-2}), following methods described in WG-ESA (2013). Right panel shows the predicted extent of suitable sea pen VME habitat using all sea pen biomass data excluding areas subject to high levels of fishing activity, but restricted to depths between 400 and 2000 m, following methods reported by Cefas (2015).

The subsequent analysis and results (below) describing cumulative sea pen biomass against fishing pressure and the testing of biomass equilibrium was therefore performed on two biomass/VMS data sets corresponding to two different spatial extents, namely; **i.** data covering the original 2014 VME polygon area, and **ii.** data covering the revised sea pen VME polygon area which encompasses the original 2014 area.

Fishing Effort (VMS) data layer

Raw VMS data was supplied by NAFO for the period 2008 to 2015. From this a histogram of vessel speed was plotted (Fig. 2.1.8) and a filter then applied to the data to select only the VMS records most likely to be associated with fishing effort (e.g. between 1 and 5 knots).

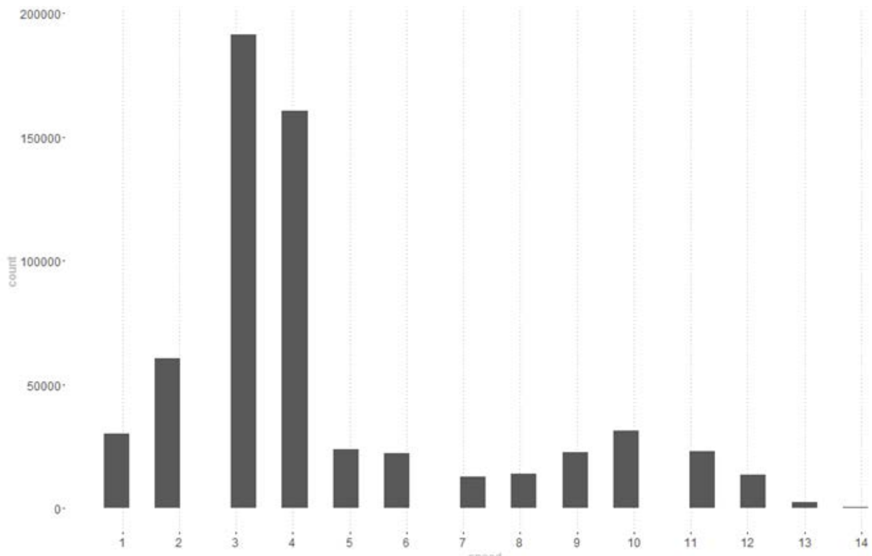

Fig. 2.1.8. Speed frequency distribution histogram for NAFO VMS data 2008 – 2015.

Fishing intensity, as hours of fishing per square kilometre per year (hrs.km^{-2}.yr^{-1}) was calculated in a 211m cell size grid individually for each year 2008 – 2015 for which VMS data is available. Fishing effort corresponding to each scientific trawl was extracted individually for each year in the time series. The point locations for trawls are coordinates of the start of a kilometre-long tow, with direction of tow unknown. Consequently, effort was calculated as the mean of cells falling inside a 1 km buffer of the trawl start point. To account for the cumulative nature of fishing effort, the effort corresponding to each scientific trawl was averaged across years preceding the trawl. This way effort occurring after a scientific trawl had been collected does not interfere with the result. It must be noted, however, that effort recorded for the earlier years in the data set does not allow for the effects of the shifting nature of effort from year to year, with fewer years of effort included. It is also not possible to account for any shifts in effort that have happened in the preceding decades, before the beginning of the VMS time series.

A map showing cumulative fishing effort and how this has changed over time between 2008 and 2015 is shown in Fig. 2.1.9.

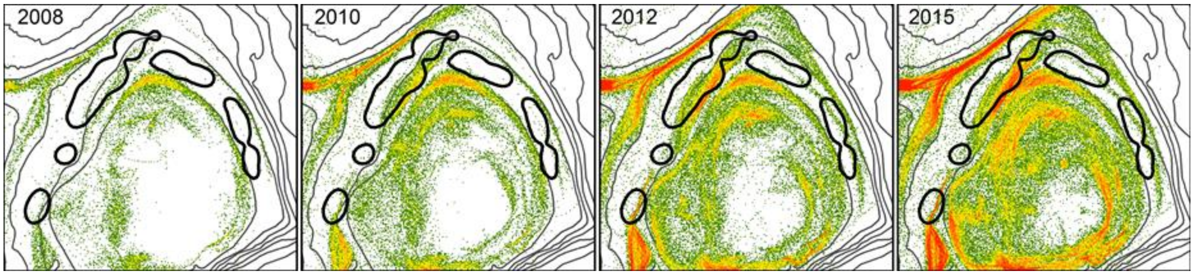

Fig. 2.1.9. Accumulation of fishing effort from 2008 to 2015 around the Flemish Cap.

Calculating cumulative sea pen biomass fishing pressure response curves

Original 2014 VME polygon area

Cumulative biomass (expressed as a percentage and absolute biomass) against fishing pressure was analysed for the original sea pen VME polygon area, for the two periods, to generate two separate biomass response curves, e.g. 2009 – 2012 and 2013 – 2016 (Fig. 2.1.10). The biomass and VMS data are offset by 1 year such that the 2009 biomass data was analysed against 2008 VMS data, the 2010 biomass data was analysed against the average of 2008 and 2009 VMS data, and so on. It should be noted that the number of samples between the two time-periods are substantially different, e.g. between 2009 – 2012 there are 45 samples, whereas between 2013 – 2016 there are 70 samples. Therefore, to generate plots of cumulative 'absolute' biomass for comparison between the two time-periods it was first necessary to randomly re-sample the samples associated with the 2013 – 2016 period to ensure that the number of samples between the two periods were the same. The re-sampling was done several times before fitting a GAM to all the re-sampled data (Fig. 2.1.10– right panel). There is considerable variability in the re-sampled plots which reduces the significance of the apparent difference in the curves.

The fitted curves for cumulative percent (%) biomass show in part a small, but significant, difference (based upon two standard errors), suggesting that an equilibrium state in sea pen biomass is not apparent at levels between 75 % and 95 % of the cumulative biomass. Indeed, the difference observed, suggests that the high VME biomass areas are being depleted over time. Furthermore, this assertion is supported by an examination of the spatial pattern of cumulative fishing effort between 2008 and 2015 (Fig. 2.1.11), which appears to show a recent spatial shift in effort (from 2010 onwards) towards deeper water to the Northwest of the Flemish Cap where higher biomass of sea pen is known to occur. By contrast, relatively low effort is observed in recent years to the east of the Flemish Cap over the same period.

Up-dated (most recent) VME polygon area

Cumulative biomass (expressed as a percentage and absolute biomass) against fishing pressure was analysed for the up-dated (extended) sea pen VME polygon area, for the two periods (e.g. 2009 – 2012 and 2013 – 2016), to generate two separate biomass response curves, (Fig. 2.1.11). It should be noted that the number of samples between the two time-periods are substantially different, e.g. between 2009 – 2012 there are 187 samples, whereas between 2013 – 2016 there are 309 samples. Therefore, to generate plots of cumulative 'absolute' biomass for comparison between the two time-periods it was first necessary to randomly re-sample the samples associated with the 2013 – 2016 period to ensure that the number of samples between the two periods were the same. The re-sampling was done several times before fitting a GAM to all the re-sampled data (Fig. 2.1.11– right panel). The response curves for cumulative % biomass show no significant difference indicating that an equilibrium state in sea pen biomass is likely apparent when assessed at the scale of the extended sea pen VME polygon. However, the absolute cumulative biomass response curves for the two periods do show a significant difference, with the more recent years exhibiting a greater total cumulative sample biomass compared to the earlier years. An explanation for this observed difference is not fully understood, but more cumulative sea pen biomass in recent years is clearly a more favourable outcome than having less biomass. This observation requires further investigation to ascertain the nature of this resonse in particular if it is an artefact of the statitstical approach adopted or an artefact of sample design not sufficiently well representing either the cumulative pattern of fishing effort or distribution of sea pen biomass at the scale of the larger VME polygon (e.g. there may be a larger number of samples associated with low fishing effort when using the extended polygon when compared to the smaller 2014 VME polygon), this apparent difference was not investigated further in the present study.

In conclusion, it appears reasonable to assume (especially for the extended VME polygon area) that sea pen biomass is at or close to an equilibrium state based upon the assessed fishing activity over the last 8 years. Therefore, it should be possible to estimate the recovery time to achieve a given level of biomass using a combination of the known fishing pressure as swept area impact over a given time and the associated biomass of sea pen sustained at the corresponding level of fishing pressure.

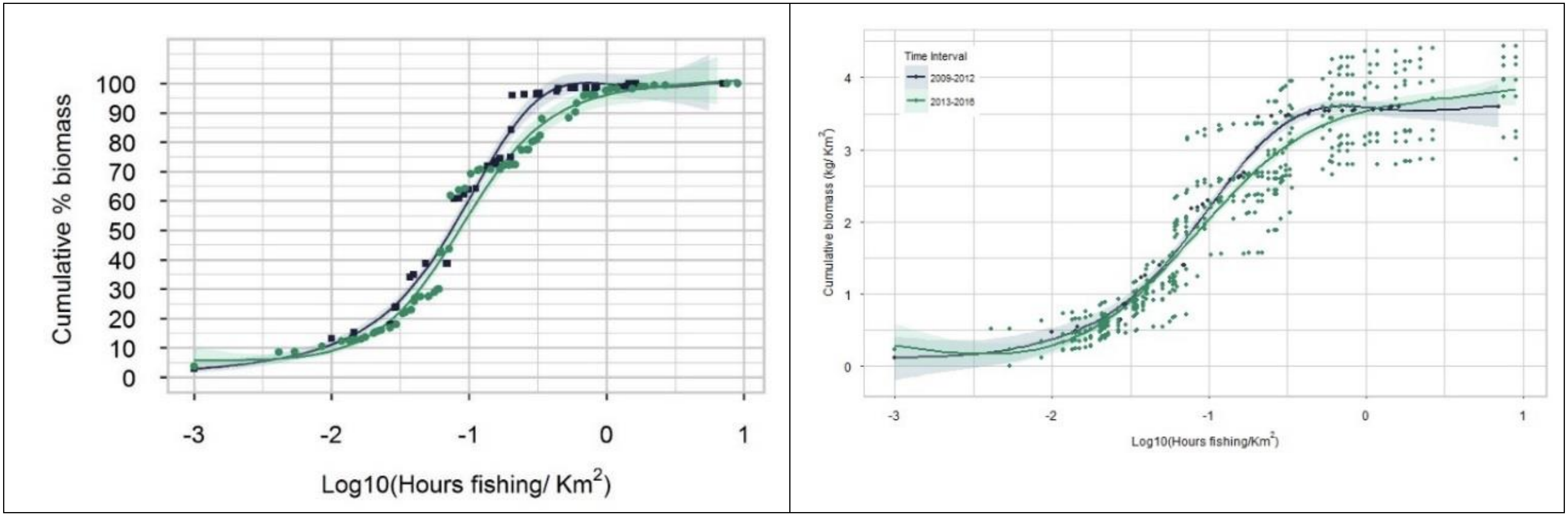

Fig. 2.1.10. Left panel. Cumulative % biomass for the 2014 sea pen VME over the gradient of increasing fishing intensity for the two periods 2009-2012 (blue) and 2013-2016 (green) in the 2014 sea pen VME polygon area. Right panel. Cumulative absolute biomass for the same set of data

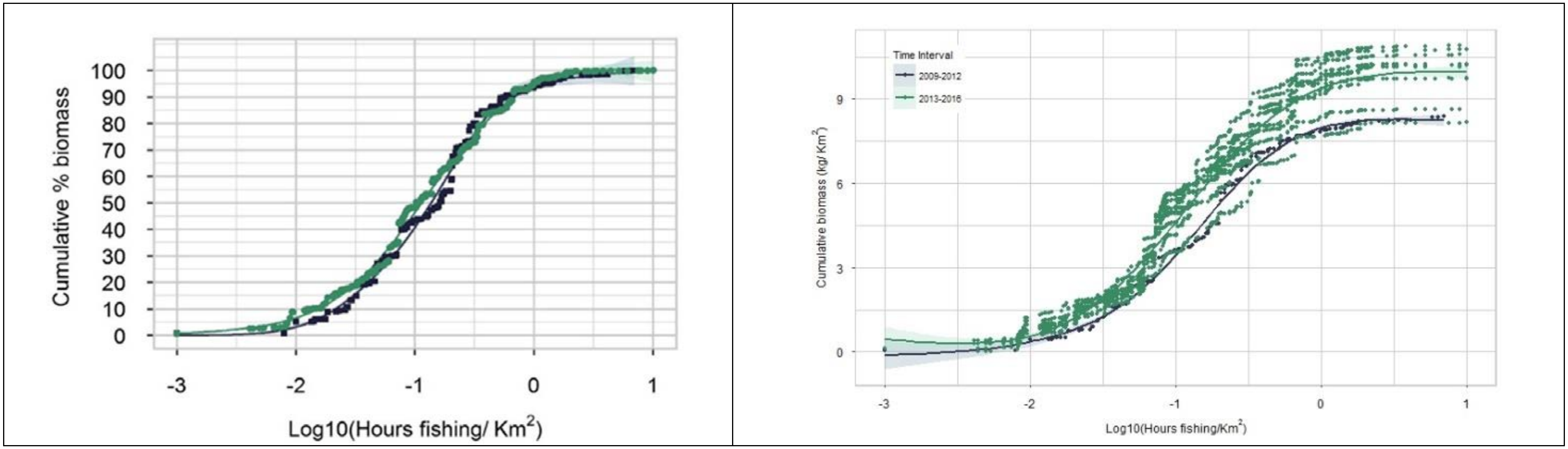

Fig. 2.1.11. Left panel. Cumulative % biomass for the extended sea pen VME area over the gradient of increasing fishing intensity for the two periods 2009-2012 (blue) and 2013-2016 (green) in the 2016 sea pen VME polygon area. Right panel. Cumulative absolute biomass for the same set of data

iv) Estimating the Recovery Time of Sea Pen Biomass

The analysis presented in Section 0 provides an estimate of the amount of sea pen biomass sustained at a given level of fishing effort (or swept area impact pressure) assuming an equilibrium state exists. The fishing effort, expressed as hrs.km^{-2}.yr^{-1}, was converted to total distance travelled and swept area using the previously defined gear dimensions at an estimated fishing speed of four knots. The total swept area was then equated to the total length of tow required to cover 99% of a 1 km x 1 km square, as estimated in Section 0. The relationship, therefore, between fishing effort and the time it takes to impact 99% of seabed (and hence sea pen biomass) can be determined, and this is shown in Fig. 2.1.12. By knowing how much time (t) it takes to impact 99% of the seabed area (or sea pen biomass) for a given level of fishing effort, and the proportion of seabed area impacted once (f_1), twice(f_2) etc., (see Fig. 2.1.13), it is then possible to estimate the recovery time to sustain a given level of sea pen biomass by applying the following equation:

Eq.1 $$\frac{\frac{tf_1}{2}+\frac{tf_2}{3}\ldots\frac{tf_n}{n+1}}{f_1+f_2+f_3\ldots f_n} = Ave.\,t_{recovery}$$

Where t is the time to impact 99% of the seabed area, f is the area of seabed impacted associated with either once (f_1), twice (f_2) etc., whose upper limit is determined by the corresponding level of biomass to be sustained, e.g. *area = biomass*. This is because the biomass sustained is most likely to be associated with the area of seabed least impacted – as defined in Fig. 2.1.3.

For example, from Fig. 2.1.11, the fishing effort which corresponds to 50% of the sustained cumulative biomass is seen to be about 0.13 hrs.km^{-2}.yr^{-1}. The total time to impact 99% of the seabed at 0.13 hrs.km^{-2}.yr^{-1} is estimated, from Fig. 2.1.12, to be about 20 years. We know that 50% of the biomass is sustained at this level of fishing pressure so [f1 + f2 + fn] = 50 (Fig. 2.1.13).

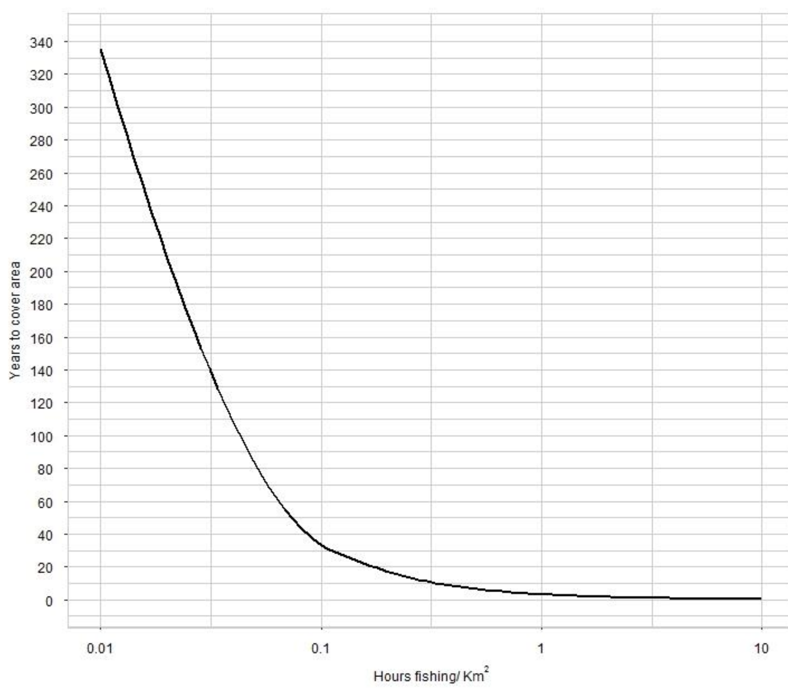

Fig. 2.1.12. Years taken to impact 99% of the sea floor at different levels of fishing effort.

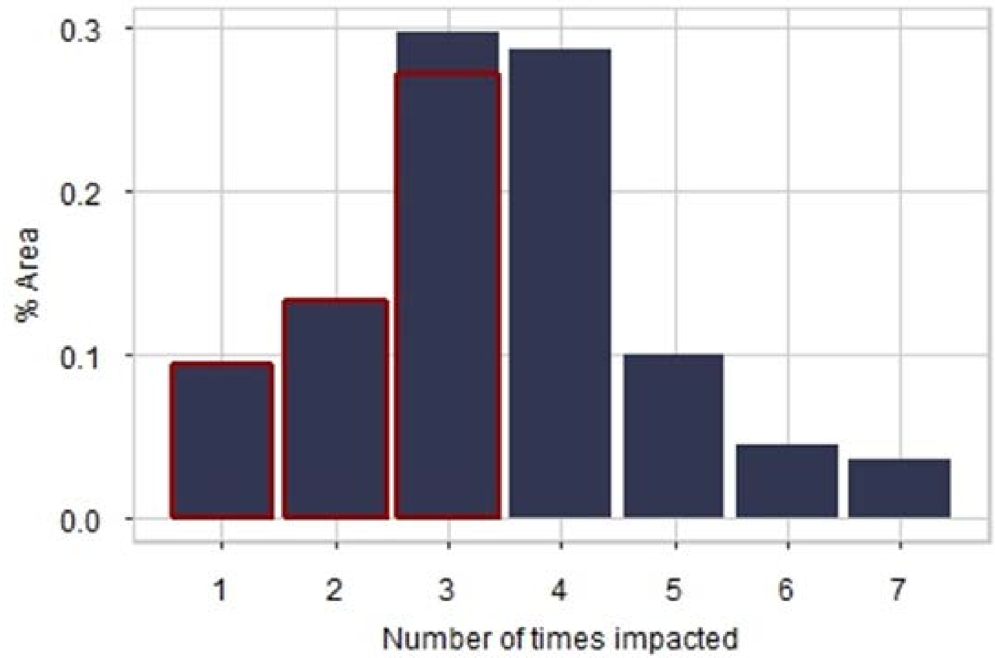

Fig. 2.1.13. Histogram showing the seabed area impacted a set number of times (over 20 years in the worked example) with the proportion amounting to 50% of total area highlighted in red.

So, from equation 1, the average recovery time in years to sustain 50% sea pen biomass is estimated to be:

$$\frac{\frac{20 \times 0.095}{2} + \frac{20 \times 0.13}{3} + \frac{20 \times 0.275}{4}}{0.095 + 0.13 + 0.275} = 6.4 \; years$$

Clearly there are many assumptions behind this calculation, most notably that the sea pen biomass is near or close to equilibrium. However, other factors will either tend to increase or decrease the recovery times. Some of the sources or error and their expected impact on recovery times are noted in (Table 2.1.2), along with an indication of which of these errors is likely to be more applicable in the present assessment. Section 4.1 indicates three sources of error applicable in the present study which tend to underestimate recovery times, whereas there are only two sources of error which tend to overestimate recovery times. Therefore, there is possibly a slight bias towards underestimating the recovery times in the present analysis, although the actual effect of each source of error is not known in the absence of more detailed analysis.

Table 2.1.2. Sources of error likely to impact estimates of recovery time either positively or negatively and what the tendency of the error is likely to be in the present assessment.

Potential sources of error in calculating recovery times	Impact on estimated recovery times	Likely error tendency in the present assessment
Swept area over estimated (direct and indirect loss of biomass)	↓	✓
Swept area under estimated (direct and indirect loss of biomass)	↑	-
Speed of vessel whilst trawling is over estimated	↓	✓
Speed of vessel whilst trawling is under estimated	↑	✓
Sea pen biomass is spatially clumped within suitable habitat	↑	-
Sea pen biomass is evenly distributed within suitable habitat	↓	✓
Trawl swept area is clumped	↑	✓
Trawl swept area is randomly distributed	↓	-

Nevertheless, the recovery time estimated above is in line with reported recovery times in the literature for selected species of sea pen which are commonly found in the NAFO Flemish Cap area. For example, Neves *et* *al*., (2015) conducted studies on the longevity of *Halipteris finmarchica* and reported that it is a "slow-growing, relatively long-lived organism whose recovery from damage can take over 20 years". The current study calculates that 50% of the sea pen biomass (as a composite of several commonly occurring species) can recover over a period of about 10 years. However, uncertainty remains as to the functional significance of sustaining sea pen biomass at 50% of its unimpacted state, and whether such a level of biomass would indeed represent an optimal level in terms of any functional attributes supporting commercially targeted fish stock biomass.

v) Functional Significance of Sea Pen VME

Spatial dynamics of the fisheries operating in sea pen VME

A sub-set of the VMS effort data, selected from the extended sea pen VME polygon area including the 2014 VME polygon area, was created. A high spatial resolution hexagonal regular grid was created (0.025 degrees) which captures better the effort at VME boundaries) compared to a square or rectangular regular grid (Birch *et al.,* 2007). To visualise how fishing activity has changed over-time in the VME the effort data is presented in 10^{th} percentile intervals (Fig. 2.1.14 & Fig. 2.1.15) and each hexagonal cell has a number which corresponds to the number of unique vessels fishing in that cell. For most years, the highest fishing effort is concentrated in the VME area at a depth <900 m. However, in 2012 it appears that some vessels are moving into deeper water areas, between 1,000 and 1,100 metres.

It is apparent that a significant decline in effort is observed to the east of the Flemish cap from 2009 onwards which coincides with a significant increase in effort located to the south west of the Flemish cap from 2010 – 2015, located in deeper water. The cause of this significant large scale spatial trend within the extended sea pen VME polygon is presently unknown. Some further interrogation of fisheries log-book (daily catch and haul by haul) data may help to explain this observed variation, especially if some fisheries were either opened or closed during this period. Nevertheless, it appears that the overall pattern of change observed in the spatial distribution of the fishery operating in the sea pen VME over the last 8 years (2008 – 2015) is of about the same duration as the time required to recover 50% of sea pen biomass (5 to 10 yrs). If this is the case, then the fishing effort observed in 2008 and 2009 to the east of the Flemish Cap may represent the tail-end of several years of higher fishing activity in this area, before the fishery moved onto new areas to the west and north of the Flemish cap. However, this assertion is speculation and requires further investigation before any direct and conclusive relationship between the broad scale spatial dynamics of the fishery and sea pen biomass can be made.

It should also be noted that the countries with greatest fleet presence in the extended sea pen VME are Portugal and Spain, with a yearly average of 1185 days and 823 days, respectively. The Spanish fleet operate with an average of 12 vessels per year, whilst Portugal typically operate with 10 vessels. Each vessel has on average 98 days fishing in the area.

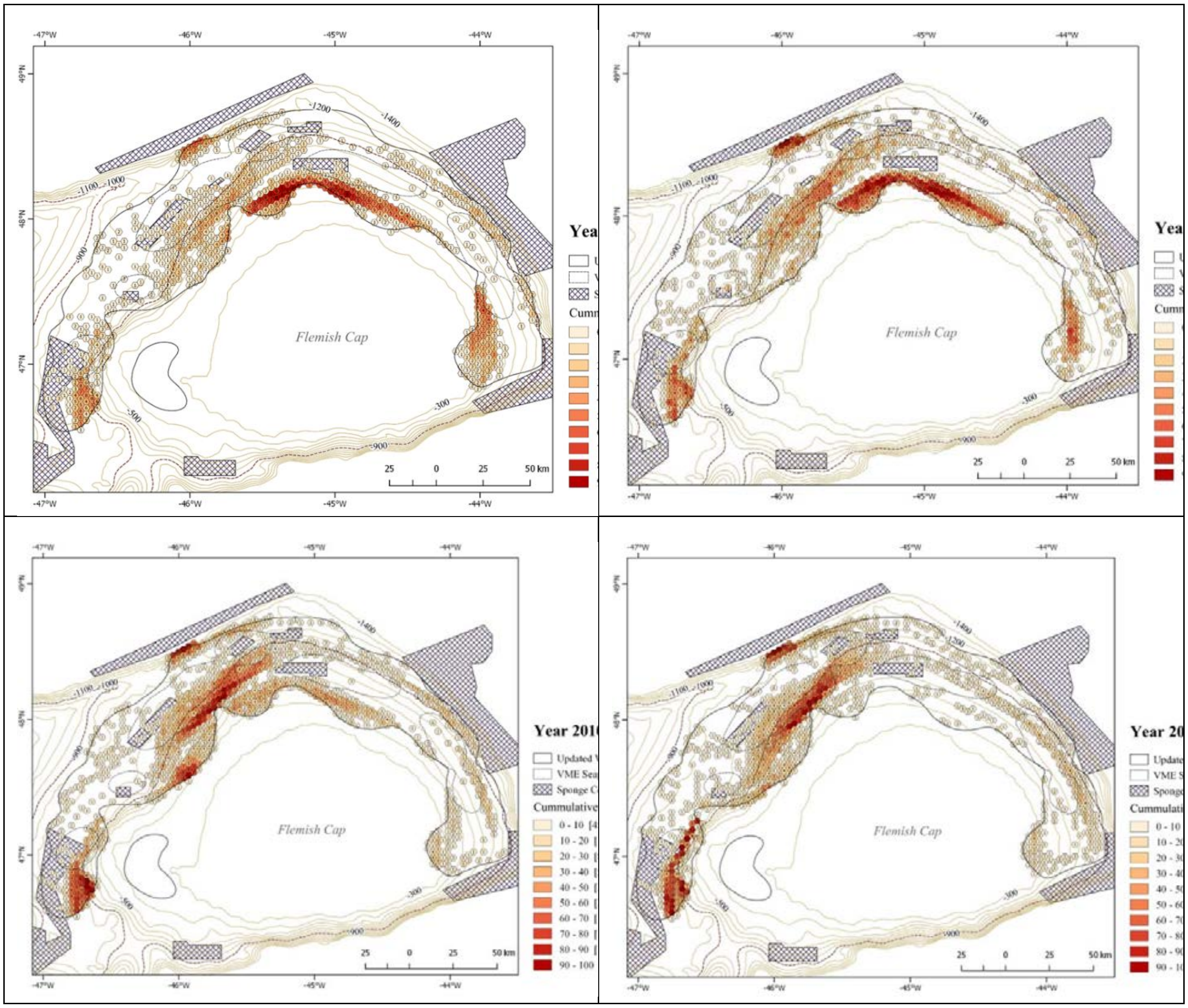

Fig. 2.1.14. Fishing effort as percentiles of effort with the top 10% of effort shown in dark red for 2008 – 2011.

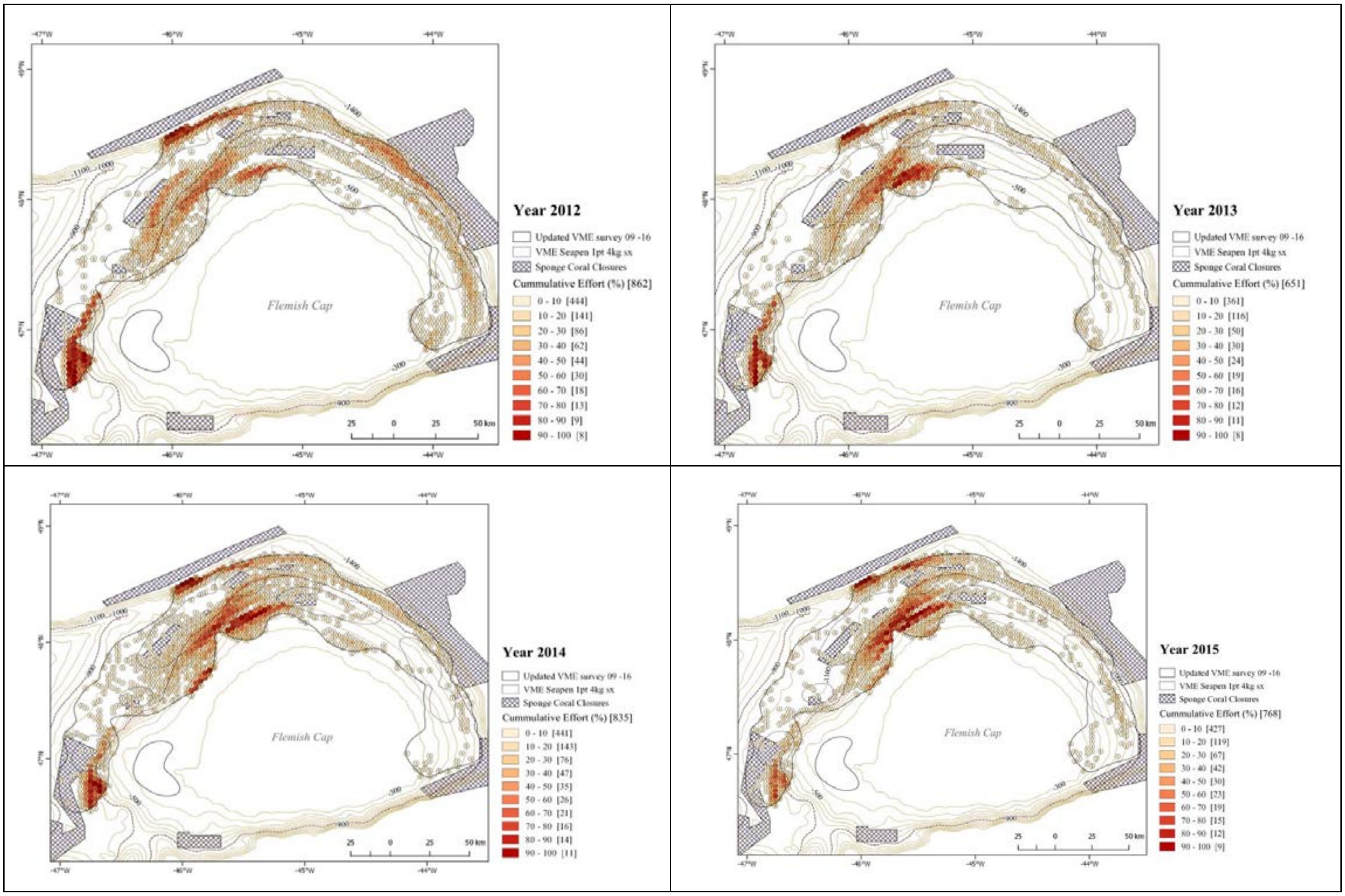

Fig. 2.1.15. Fishing effort as percentiles of effort with the top 10% of effort shown in dark red for 2012 – 2015.

Functional Role of Sea Pen VME

It is now widely appreciated (e.g. Elliot and Quintino, 2007) that observing changes in structural attributes of benthic assemblages provides only a limited capacity to understand ecosystem function which is at the heart of more recent EU policy drivers, such as the reform of the Common Fisheries Policy (CFP) and the Marine Strategy Framework Directive (MSFD). Recent studies show that, following both natural and anthropogenic stressors, functional impacts and functional recovery trajectories are not always matched by their structural counterparts (Cooper et al., 2008; Grilo et al., 2011; Bolam, 2012; Wan Hussin et al., 2012). Marine benthic habitats and their communities provide a wide range of goods (e.g. fish stock biomass, minerals, energy) and services (e.g. nutrient and carbon recycling, life support, atmospheric regulation) and changes in biological indicators, based on structural attributes, may not necessarily result in significant changes in the overall functioning of the ecosystem, or their associated provisions of goods and services. Consequently, the conservation of marine systems requires knowledge of not only the species present, but also of how the system works and the effects of multiple and potentially co-interacting threats (Bremner, 2008). To fully determine how an ecosystem is affected by anthropogenic pressures, emphasis has to be placed on its functioning (Elliott and Quintino, 2007; Duarte et al., 2013).

Sustaining a balance between marine resource exploitation and biodiversity so as to protect ecosystem functioning is the *raison d'être* of the ecosystem approach (CEC, 2008). It aims to safeguard function as well as biodiversity. Therefore, an ecosystem approach to fishing impacts means that benthic function needs to be understood before it can be managed. While directly measuring ecological function (e.g., food availability for higher trophic levels, nutrient flux with overlying water) remains time-consuming and methodologically and logistically difficult, the recent development of several numerical analytical approaches has allowed alterations to functioning to be estimated and functional recovery compared with that of structural recovery (Cooper et al., 2008; Barrio Froján et al., 2011; Wan Hussin et al., 2012). The relatively recent application of Biological Traits Analysis (BTA) has provided an enhanced understanding of the responses of the benthic functioning resulting from several anthropogenic pressures (e.g. Bremner et al., 2003; Tillin et al., 2006; Papageorgiou et al., 2009; Frid, 2011; Wan Hussin et al., 2012; Oug et al., 2012; Munari, 2013; Borja and Elliott, 2013; Bolam et al., 2014) and along environmental gradients (Dimitriadis et al., 2012; Van Son et al., 2013). Utilising assemblage information to determine what the organisms do within the ecosystem (i.e., their 'traits') as opposed to merely their taxonomic identity (i.e. what they are) offers great advances into our understanding of the functional capabilities of assemblages (Bremner, 2008). Currently, little is known about how these approaches can be useful in marine ecological assessments and management, although they have been successfully and widely applied in both freshwater and terrestrial ecosystems (Guilpart et al., 2012; Colas et al., 2014). Functional diversity, i.e., the diversity and range of functional traits possessed by the biota of an ecosystem (Wright et al., 2006), is likely to be the component of an ecosystem most relevant to the functioning of ecosystems (Hooper et al., 2004). Nonetheless, there is neither an accepted suitable method for the measurement of functional diversity, nor adequate information regarding the actual traits to be used for its derivation (Petchey and Gaston, 2006).

Most research on the functional role performed by corals in benthic ecosystems has been conducted in tropical regions (Glynn, 2012), however in recent years, there has been more research in cold-temperate regions (Buhl-Mortensen *et al.* 2010) following the increase in deep water marine resource development in these areas.

A review of the evidence of the functional role that sea pens (*Pennatulacea*) highlights the potential importance of; bioturbation and baffling of sediment flows, providing a food source for higher trophic levels, creating unique habitats, acting as nurseries for fish and invertebrates and refugia for predator avoidance. Sea pens occur in "fields or patches" in areas of soft sediment on the sea floor. Unlike many benthic invertebrates, sea pen morphology is rather simple with a single stem called 'rachis' populated with feeding polyps and a bulbous base called 'peduncle' which anchors the colony (Williams, 1995). However, what they lack in individual size and structure they more than make-up for by typically occurring in large densities over wide areas of suitable seabed habitat in the form of massive sea pen "fields" (Kenchington et al., 2010; Kenchington et al., 2011; Baker et al., 2012)

There are few observations of sea pens providing suitable hard substrate for attachment by other organisms, with the exception of the Northwest Atlantic, *Halipteris finmarchia*, which has been observed with commensal sea anemones *Stephanauge nexilis* firmly attached to the rachis (cf. Miner, 1950; Wareham and Edinger, 2007), which may increase food availability located higher in the water column.

Many invertebrates (e.g. crustaceans, nudibranch) have been observed feeding on sea pens as a primary food source (Birkeland, 1974; Moore & Rainbow, 1984; Krieger and Wing, 2002). Brodeur also observed hundreds of *Sebastes alutus* inside dense aggregations of *Halipteris willemoes* in the Bering Sea (Brodeur, 2001), suggesting sea pens provide an important habitat as a source of food for red fish. Furthermore, Baillon *et al.,* (2012) has also shown that sea pens can act as important nurseries for two at least two species of *Sebastes* sp. on the Grand Banks of Newfoundland, where the larvae were observed lodged between the polyp leaf and the main rachis with yolk sac still visible.

In conclusion, there is growing evidence that sea pen fields most likely provide an important functional role in relation to commercial fish species, most notably *Sebastes* sp. The most important functions being the indirect provision of food and substrate for *Sebastes* sp. spawning.

Concluding remarks

- The evidence presented in this study suggests that the level of sea pen VME biomass are near to an equilibrium state when evaluated in an extended VME area as determined by an up-dated VME KDA and sea pen habitat suitability models, e.g. the loss of biomass caused by fishing (including losses due to natural mortality) and the increase in sea pen biomass caused by recolonization and growth are in balance at this extended scale.
- The estimated time for sea pen biomass to recover to 50% of its pre-fished state is calculated to be between 5 and 10 years. This Fig. is in general agreement with reported findings for the recovery times of similar sea pen species after impact by bottom fishing activity.
- Deep-sea sea pens may be more resilient than other VME indicator species, but in the present study sea pen recovery times are likely to be near to 10 years for 50% of the pre-impact biomass, which when combined with their known longevity (in excess of 20 years) and their habitat forming attributes, indicates that sea pens are indeed particularly sensitive VME species.
- Fishing activity in the extended sea pen VME area has significantly changed spatially between 2008 and 2015, e.g. from 2010 onwards there is more fishing activity observed to the north and west of the Flemish cap which also extends into deeper water. In 2008 and 2009 there was more fishing activity to the east of the Flemish Cap compared to the most recent period.
- An up-dated KDA performed on sea pen sample data, including more recent biomass data (from 2015 and 2016 surveys), using similar methods (Including the same threshold value of 1.4 kg) to those used in 2014, reveal an extended sea pen VME polygon which forms a continuous VME in a horseshoe shape around the North of the Flemish Cap which is consistent with the maps of suitable sea pen habitat distribution, previously described.
- Sources of error in the present analysis have been identified and recommendations are made to evaluate the sensitivity of the present analysis against these errors and to investigate their reduction through acquiring better data.

Forward look

To improve the certainty of the findings (or otherwise) of present study there are a number of tasks which could be undertaken: e.g.

- To better understand which of the identified sources of error in determining the recovery potential of sea pens post fishing impact, we recommend that sensitivity analysis be performed on the effects of each error in estimating the recovery times. The outcome of this analysis will enable future resources to be targeted to reduce the source of error which the recovery estimate is most sensitive to.
- To undertake an analysis of VMS data integrated with daily catch, and haul by haul, records from 2015. High resolution data will be used to understand how the VMS effort data currently used in the current assessment of bottom fisheries relates to the actual area of seabed impact and therefore will provide a more accurate estimate of the cumulative VME biomass/VMS effort cut-off values used to determine VME sensitivity and resilience.
- To determine which characteristics of habitats are important for fish in the NAFO Regulatory Area. This will effectively identify and map specific habitats which are important for commercial bottom fishing activities (rather than VME indicator species biomass) and assess what proportion of the

fisheries habitat is fished at any one time. This will help to address the need for evaluating the functional criteria of Significant Adverse Impacts of fishing on VMEs and it may also provide an indicator for fisheries sustainability based upon habitat characteristics that will complement existing stock (TAC) based criteria.

- To develop fishery specific VME risk and impact assessments using existing data sets to investigate the spatial and temporal overlap between specific fisheries and VMEs in the NRA, which will help to quantify the functional importance of VME in providing essential fish habitat for commercial stocks.

vi) Towards modelling fishing impacts on Vulnerable Marine Ecosystems (VMEs)

Work was presented detailing ongoing efforts to develop a model to simulate the life history of corals and sponges to study the impacts of commercial fishing on selected VME indicator taxa. Basic questions this model aims to explore include how long it could take for VMEs to recover from specific patterns of perturbations from fishing operations, and how interconnected different VME habitat units may be. In order to address these types of questions, a spatially-explicit agent-based model is being constructed. This modelling approach is based on defining virtual entities (agents) that evolve in space and time following simple decision rules. In this specific case, the agents are collectives of corals/sponges. The model simulates key life history stages (e.g. egg, free swimming larvae, settled juvenile colony, adult colony) , and the simple rules being enacted correspond to the biological/ecological process that regulate the transitions between stages (e.g. larval mortality, settlement, sessile mortality, aging, reproduction) as well as movement in space during the larval stage (Fig.. 2.1.16).

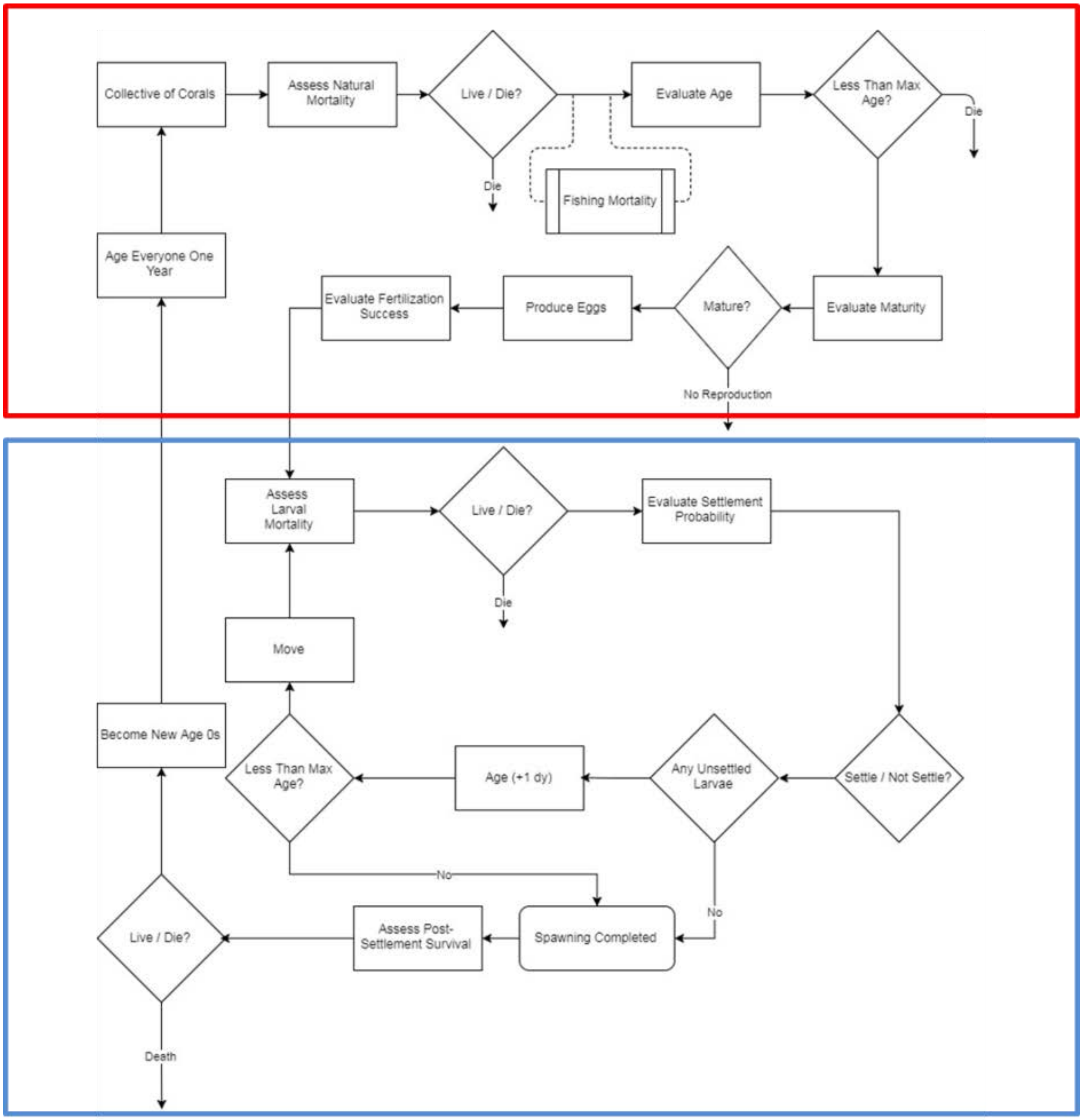

Fig. 2.1.16. Flowchart showing the structure of the agent-based model of coral/sponge life history currently under development. Sessile life history stages/processes are shown in the red box, and larval (mobile) in the blue box.

Life history processes have been implemented as stochastic events driven by probability distributions. These distributions have been defined based on the specific nature of the process being simulated and parameterized using published literature as well as consultations with species experts. In this initial phase of development, the model is being parameterized to represent the life history of the sea pen *Halipteris finmarchica* due to the availability of information. At the present time, spatial dispersion of larvae is driven by an average bottom current layer, settlement probability is based on velocity and slope, while post settlement mortality is based on a presence probability layer derived from a Species Distribution Model (SDM) (Kenchington et al. 2016). Although significant work needs to be done before this model is ready for wider implementation, the current working version is already capable of generating spatially sensible distributions of sea pens (Fig. 2.1.17).

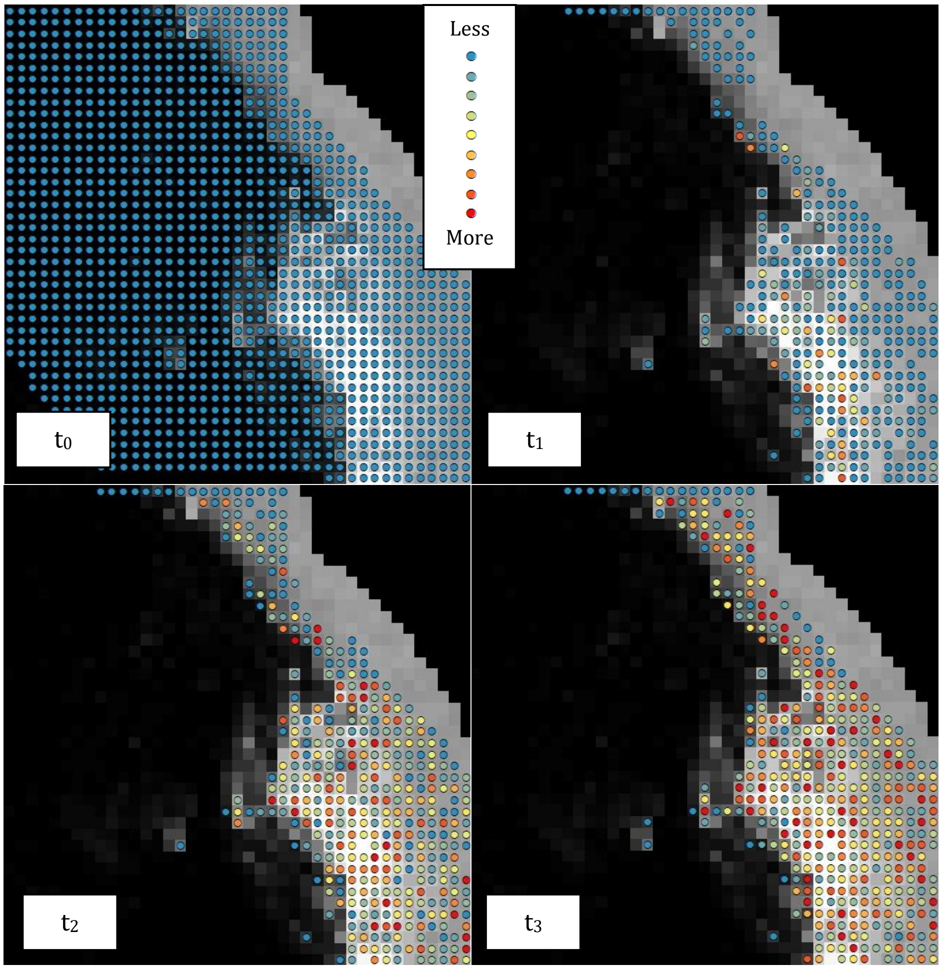

Fig. 2.1.17. Four time steps of the current working version of the ABM coral/sponge model overlaid on presence probability layer from Kenchington et.al. 2016 . At time t_0 all cells are seeded with low abundances of sea pens; as the model evolves over time (t_1, t_2, and t_3), sea pens in those locations with low suitability are lost, while abundances build up in those areas where suitability is higher.

Once the model is fully developed and validated to the extent possible (e.g. through a series of sensitivity analyses), fishing mortality will be added to assess the capability of the modeled VME to recover from these perturbations. Spatial patterns in fishing effort, as well as frequency of fishing derived from the VMS information will be used to create realistic fishing impacts scenarios.

Future work will also involve the development of models for major VME taxa, and the analysis of any common features emerging from the entire suite of models. Beyond the evaluation of direct fishing removals, and as results on VME ecosystem functions start to become available (e.g. from the SponGES project, see ToR 2), this model architecture can also be used as a platform to extend the assessment of impacts to VME ecological functionality.

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ToR 2.2. Assessment of NAFO bottom fisheries:

Maintain efforts to assess all of the six FAO criteria (Article 18 of the FAO International Guidelines for the Management of Deep Sea Fisheries in the High Seas) including the three FAO functional SAI criteria which could not be evaluated in the current assessment (recovery potential, ecosystem function alteration, and impact relative to habitat use duration of VME indicator species).

i) Biological Traits Analysis

To evaluate the functional significance of VMEs in relation to the impacts of bottom trawling, WG-ESA considers the application of biological traits analysis to be most appropriate. While directly measuring ecological function (e.g., secondary production, oxygen flux) remains time-consuming and can be methodologically and logistically difficult (Crisp, 1984; Tagliapietra et al., 1999), the recent development of a number of numerical approaches has allowed scientists to better estimate seabed functioning (Thrush et al., 2014; Bolam et al., 2016). The application of Biological Traits Analysis (BTA) to marine benthic data, for example, has provided an enhanced understanding of the changes in benthic functioning along environmental gradients (Dimitriadis et al., 2012;van Son et al., 2013). Utilising assemblage information to determine what the organisms do within the ecosystem (i.e. their 'traits') as opposed to merely determining their taxonomic identity (i.e. what they are) potentially offers great advances into our understanding of the functioning of benthic assemblages (Snelgrove, 1997; Bremner, 2008; Webb et al., 2009).

By quantifying how taxa interact with their environment, a number of important processes (e.g. bioturbation) can be associated with their regulatory, habitat or production functions (see Table 2.2.1), and these, rather than the species assemblages, can be used to define functional benthic assemblages.

To support the assessment of SAI and the selection and definition of functional criteria to be used in the reassessment of NAFO bottom fisheries, it is first necessary to develop a table of species traits through a review of the literature and the application of expert judgement. WG-ESA has, accordingly, developed a work-plan to progress the functional analysis over the next 2 years, namely:

1. Select appropriate sample data sets (trawl survey samples) from VMEs in the NAFO footprint. The selection of samples should consider both the level of taxonomic discrimination, as well as the spatial coverage of the VMEs between surveys (Fig. 2.2.1).
2. From these samples, select the species which account for the top 95% of biomass across all VME types to determine their associated biological traits (which traits remains to be determined). The biological traits of interest are those which are likely to be good indicators of bottom trawling impact, e.g. maximum size, maximum longevity, morphology, living habit etc. For each of the traits a number of trait modalities are defined. Each species is then 'fuzzy' scored against each of these trait modalities

such that the sum of assigned modality scores per trait adds up to one. This process is known as fuzzy coding the species traits.

3. The original species/trawl sample matrix is then combined with the defined species/traits matrix to generate a new matrix of sample/traits as in Fig. 2.2.1.
4. Multivariate analysis of the trait/sample matrix will enable the mapping of VMEs according to their functional differences and allow the dominant functions to be identified and quantified.
5. The analysis conducted under step 4 can also be used to help parameterise the VME functional models being developed (see Section 2.1)
6. Both steps 4 and 5 will provide the scientific basis for the selection of the functional criteria and their weighting to be used for future assessment of SAI.

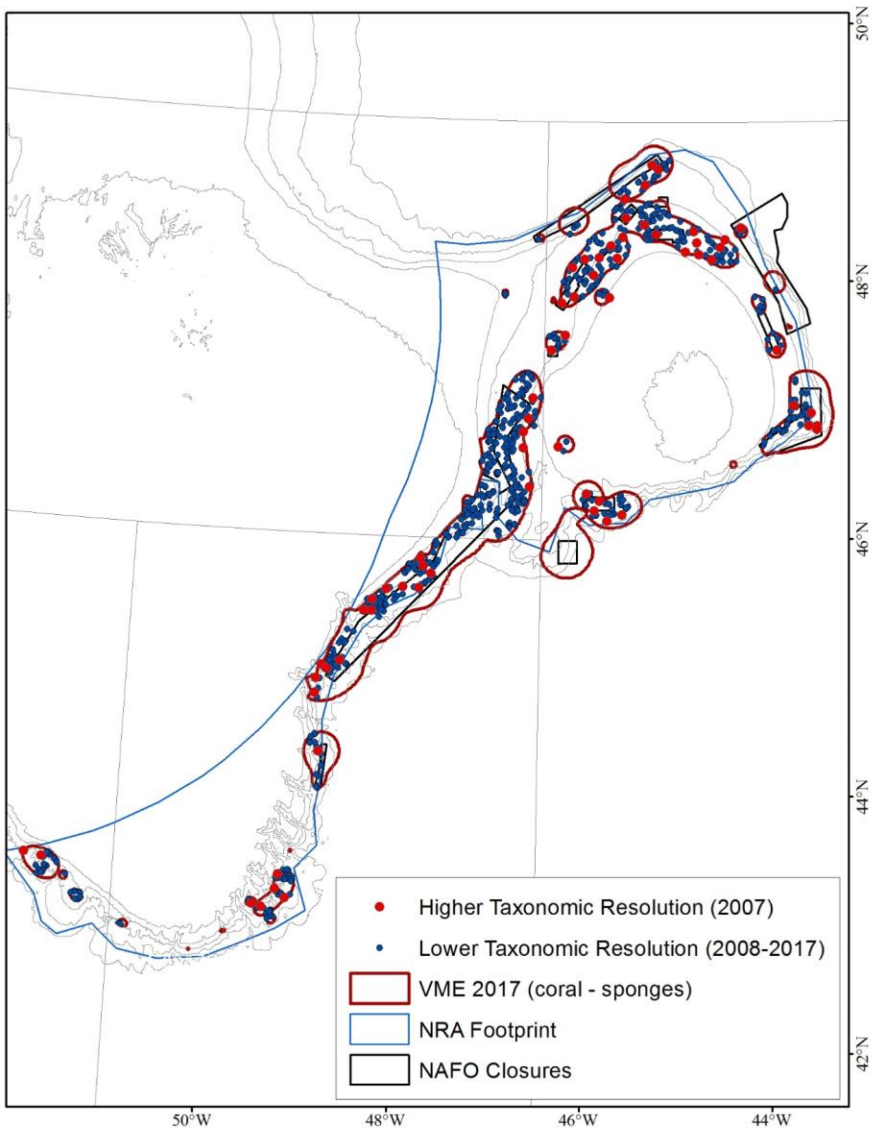


Fig. 2.2.1. Survey trawl samples which coincide with VME in the NAFO footprint. The 2007 surveys have been identified at a higher level of taxonomic discrimination than surveys between 2008 and 2016.

Table 2.2.1. The relationship between benthic organism biological traits, processes, functions and the goods and services they provide

Biological Traits

Traits → Processes → Functions → Good & Services

Traits	**Processes**	**Functions**	**Goods and services**
		Regulation functions	
Sessile infauna – conveyor belt deposit feeder	Bioturbation	Nutrient fluxes. Carbon storage.	Maintenance of primary production. Climate regulation.
Sessile epifauna – filter feeder	Benthic-pelagic coupling	Nutrient and carbon fluxes	Water purification.
		Habitat functions	
Sessile epifauna ‘reef’ building suspension feeder	Production of biogenic structures	Nursery & refuge function for other species	Recruitment and survival of commercially important species Presence of high biodiversity areas
		Production functions	
Soft body epifauna etc.	Prey for higher trophic predators	Secondary production of invertebrates and fish	Fish catches

Species abundance matrix

	Stn 1	Stn 2	Stn 3
Species a	22	1	2
Species b	4	88	50
Species c	0	13	134

Taxon by trait matrix

	Trait 1			Trait 2		Trait 3		
	Cat1	Cat2	Cat3	Cat1	Cat2	Cat1	Cat2	Cat3
Species a	0.5	0.5	0	0.75	0.25	0.25	0.25	0.5
Species b	0.33	0.33	0.33	1	0	0	0	1
Species c	1	0	0	0.33	0.66	0.66	0	0.33

Summed for all taxa

Station by trait matrix

		Stn 1	Stn 2	Stn 3
Trait 1	Cat1	12.3	42.5	151.5
	Cat2	12.3	29.5	17.5
	Cat3	1.3	29.0	16.5
Trait 2	Cat1	20.5	93.0	95.7
	Cat2	5.5	8.8	88.9
Trait 3	Cat1	5.5	8.8	88.9
	Cat2	5.5	0.25	0.5
	Cat3	15	92.8	95.2

Figure 3. Illustration of the derivation of a station-by-trait matrix from species abundance and taxon by trait matrices. Hypothetical example based on three species and three traits having either two or three trait categories.

Fig. 2.2.2. Illustration of the derivation of a station-by-trait matrix from species abundance and taxon by trait matrices.

ToR 2.3 Progress on expanded single species, multispecies and ecosystem production potential modelling

i) European Union SC05 project: Multispecies Fisheries Assessment for NAFO

The Specific Contract No. 5 "Multispecies Fisheries Assessment for NAFO" is financed by the EU DG-MARE under Framework Contract EASME/EMFF/2016/008 "Provisions of Scientific Advice for Fisheries Beyond EU Waters" started on the July 2017, and will have an overall duration of 21 months. The contract will be conducted by several partners (WMR, IEO, AZTI, CEFAS and MRAG).

The purpose of this specific study is to provide a comprehensive overview (from the economic and ecological perspective) of how multispecies assessments would fit into the scientific and decision-making processes within NAFO and to develop specific analyses and techniques on a case study, the Flemish Cap, that result in potential practical implementations for the multispecies approach. Finally, future steps and research activities to progress in the implementation of the multispecies assessment in the Flemish Cap, and extensively in the area NAFO will be identified.

The geographical scope of this study will be the Flemish Cap in the NAFO area 3M. The ecological scope will be focused mainly in the realm of the commercial species (cod, redfish and shrimp). However other abiotic (namely temperature) and biotic components of the ecosystem like different pelagic invertebrate taxa, non-commercial fish species will be also considered. From the institutional perspective, this study will be developed in tight connection and in agreement with the roadmap for the ecosystem approach to fisheries of NAFO (NAFO, 2010).

To this end the following tasks will be addressed during the development of the project (Table 2.3.1):

<u>Task 1:</u> A general overview of the different approaches and most cutting-edge techniques developed by the main fisheries research institutions and management agencies worldwide to bring the multispecies approach into practice. The different approaches will be assessed in relation to the roadmap for the Ecosystem Approach to Fisheries EAF of NAFO (WG-ESA, 2010). The study will also provide a thorough description of the ecological, fishery and scientific features that makes the Flemish Cap an ideal case study for the exploration of the multispecies approach to fisheries in the NAFO area.

<u>Task 2:</u> An updated version of the multispecies model GadCap (Flemish Cap cod, redfish and shrimp multispecies Gadget model, Pérez-Rodríguez et al (2016)) will be produced, by introducing new data sources and extending the time period covered. Some relevant technical elements, as well as a number of biological and ecological characteristics affecting the productivity and trade-offs between the stocks within the model will be improved.

<u>Task 3:</u> Explore the provision of scientific advice for a multispecies approach in the Flemish Cap from different fronts. As a first output from GadCap, natural mortality at age (residual+ predation, M1+M2) will be estimated and make available to be used as alternative values of natural mortality in single species models stock assessment model currently used in the Flemish Cap (e.g. the Bayesian-XSA 3M cod model). Second a first configuration of an MSE framework with GadCap as operating model will be develop (i.e. a multispecies MSE), where traditional single species and potential new multispecies reference points and HCRs could be assessed from the precautionary and MSY perspectives.

<u>Task 4:</u> A first analysis of the socio/economic implications of moving from single to multispecies assessment and management, and the available techniques and models needed to assess the trade-offs resulting of the decisions taken from a multispecies approach to management.

<u>Task 5:</u> Discussion and interaction between scientists and other stakeholders through the organization of a workshop to present the results of the study to main stakeholders and administrations in the EU. In parallel, the results of tasks 3 and 4 will be presented to the NAFO-WG-ESA and Scientific Council and the ways to integrate them within the Roadmap for the development of an ecosystem approach to fisheries management will be explored.

<u>Task 6:</u> The necessary future steps and research activities to progress in the implementation of the multispecies assessment in the Flemish Cap, and extensively in the area NAFO, will be compiled.

Table 2.3.1.- Workplan for main tasks of SC05 project.

	2017						2018												2019		
	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Tasks	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21
Task 0 - Project management	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Task 1 - Setting the context	■	■	■	■	■	■	■	■													
Task 2 - Update and improvement of GadCap multispecies model	■	■	■	■	■	■	■	■	■	■	■										
Task 3 - Application of multispecies model in stock assessment in the Flemish Cap									■	■	■	■	■	■	■	■	■	■	■		
Task 4 - Evaluation of economic implications of trade-offs															■	■	■	■	■		
Task 5 - Discussion and interaction between scientists and other stakeholders					■						■	■				■	■	■			
Task 6 - Future research directions and needs																		■	■		

Some of the approaches for the integration of the SC05 project into the roadmap for the EAF in NAFO were presented:

1.- The connection between tiers 2 and 3, i.e. the multispecies and single species tiers, is programmed to be developed by using the GadCap multispecies model in two essential aspects of scientific advice: the stock assessment and the determination of reference points and HCRs. In terms of stock assessment, the SC05 project is design to contribute through the estimates of predation mortality M2 and residual natural mortality M1. M2 and M1 values will be estimated using the GadCap multispecies model once it has been updated and improved in tasks 2 and 3 and will be tested during the benchmark of 3M cod in March-April 2018. A second contribution to the connection between tiers 1 and 2 will be by estimating alternative reference points and design of HCRs that meet the objectives of the NAFO precautionary approach, but from a multispecies approach.

2.- The connection between tiers 2 and 3 is an aspect that will be developed throughout the project. One of the potential connections will be the use of estimated potential fishery production for the demersal stocks as a reference value to define general values around which limiting the productivity of the modelled stocks, or at least values to which compare the productivity estimated in GadCap.

After the presentation there were some comments, which were mostly in the line of supporting this type of work as some of the steps to follow in order to develop and integrate the EAF into the NAFO management framework. The importance of attending the scientific council in person in June 2018 was highlighted in order to present the results and favour the interaction and transmission of the analyses and results to the scientific council in a more effective manner. There was also some concern about the amount of work that will be needed to achieve the different objectives of the project. However, it was clarified that this project is not intended to provide definitive answers. Instead, as the project's objectives state, this project is intended to shed light on the way in which the multispecies approach fits within the NAFO EAF roadmap, using the Flemish Cap as a case study, and defining the future lines of work necessary to continue with the development of the multi-species approach in NAFO. Another important goal of the project is start the discussions with stakeholders and creating awareness of the meaning of the multispecies approach and the implications in the management approach that this will imply. Regarding this aspect, some WG-ESA members stressed that it would be very positive if interaction with stakeholders could be started at the beginning of the project, and continued at different stages of the project development, so that when the results are presented to them they feel part of the process. Although it was recognized as a positive and desirable appreciation, however, it was highlighted that it is important to keep in mind that this project is really only the beginning of a work that will need further development in the future. As such, the results of the work developed in tasks 3 and 4 will be presented to the stakeholders in task 5, not as a definitive result but as a first approximation for which their inputs in terms of socioeconomic and fisheries technical aspects will be very necessary in order to improve HCRs and multispecies management strategies in the future.

ii) Multivariate State-Space Models in Flemish Cap:

Multivariate autoregressive state space models:

Understanding spatial structure and identifying subpopulations are critical for estimating population growth rate and extinction risk, and managing fisheries. One approach is to construct data-based, mathematical models which capture changes in the structure and functioning of the ecosystem. We observe a process (collect data) and then look for relationships, causes and effects in order to predict the ecological structure and true population dynamics (the state process). For population viability analysis and other modeling, separating variance (or error) into observational and process components is essential for the unbiased prediction of population growth rates and trends and other factors like extinction risk. Ecologists have long recognized the necessity to separate observation to process error in ecological modeling. Multivariate Autoregressive State-Space Models (MARSS) (Holmes et al., 2014) describe the evolution of two time series running in parallel: one is the observational process and the other is the state process. These models facilitate identification of key players through which abiotic and biotic drivers affect population dynamics, can be used to combine data from different sources (e.g. different surveys), and investigate the spatial structure of populations. It is also able to use missing value in the time series.

MARSS models have been used extensively to understand the dynamics of freshwater plankton community (Ives, 1995; Ives et al., 1999; Ives et al., 2003), to analyse population structure (Ward et al., 2010), for trend analysis in data-poor situation (Tonnes et al., 2016) or to ask questions about the spatial structure of populations and for population vitality analysis (Tolimieri et al., 2017).

Case of study: the Flemish Cap:

Three different population of redfish are found in the Flemish Cap.: *Sebastes fasciatus*, *S. mentella* and *S. norvegicus*. *S. mentella* and *S. fasciatus* are managed together as a single species stock. On the other hand, there are three main communities in the Flemish Cap: a shallow (< 250 m) , a mid (251-600 m) and a deep (> 600 m) (Nogueira et al., 2017). *S.norvegicus* is primarly found in the shallow, while *S.mentella* and *S.norvegicus* are found in the mid. Here we examine the population structure of three species of redfish in Flemish Cap through time and space, and how predation, competition, fishing or environmental changes affect their dynamics.

Data source:

We used the estimates abundance from the EU bottom survey in the Flemish Cap, from 1993 to 2015 (Vázquez et al., 2013). Until 2003, the survey was conducted on board the RV *Cornide de Saavedra* to depths up to 730 m. In 2003, the RV *Vizconde de Eza* replaced the former vessel.

To examine how prey, predator, environment and effect of fishing affects the population size, we included 15 different combination of the following covariates:

(1) North Atlantic Oscillation (NAO).

(2) *Gadus morhua* (Atlantic cod) abundance estimate as predator and competitor, and *Pandalus borealis* (Northern Shrimp) as prey.

(3) Commercial catches of redfish from commercial fishing vessels in NAFO Division 3M as effect of fishing (Avila de Melo, 2015).

Model specification:

We fit MARSS models in the following form:

$$\mathbf{x}_t = \mathbf{x}_{t-1} + \mathbf{u} + C_t + \mathbf{w}_t, \text{ where } \mathbf{w}_t \sim \text{MVN}(0, \mathbf{Q}). \quad \text{(1a)}$$
$$\mathbf{y}_t = \mathbf{Z}\mathbf{x}_t + \mathbf{a} + \mathbf{v}_t, \text{ where } \mathbf{v}_t \sim \text{MVN}(0, \mathbf{R}). \quad \text{(1b)}$$

The equation 1a is the process equation where x_t is the true state of the population, it is what we want to estimate, u is the population growth rate for each trajectory, C_t allows to include the covariates. Q is the process variance-covariance matrix. The models allow to specify different hypothesis about Q, here we assumed correlated process errors in all models, and different variances for each trajectory.

The equation 1b is the observation equation. Y_t is a column vector of the observations at year t. Z determines whether the model estimates a different trajectory for each species of redfish and in each assemblage. R is the variance-covariance matrix. A is an scaling factor, it allows to combine the two time series from different vessels.

We tested 7 different hypothesis about the structure of the three populations (Z):

(1) Same trend for three species in all the depth ranges: All same (1Z).

(2) Different trends for each species in each depth zone (shallow and intermediate): Spp x Depth (6Z).

(3) Different trend for each species: Spp (3Z)

(4) One overall trend for the three species within each depth zone: Depth (2Z).

(5) Same trend for Acadian redfish and deepwater redfish but different per golden redfish in all the depth range: [A.redfish & d.redfish] x g.redfish (2Z)

(6) Same trend for golden redfish and Acadian redfish but different for deepwater redfish: [A.redfish & g.redfish] x d.redfish (2Z)

(7) Three different trajectories: [A.redfish shallow & g.redfish shallow] x d. redfish shallow x [A.redfish mid & g.redfish mid & d.redfish mid] (3Z).

For each state process we allowed the population growth rate, u

(1) To be the same for all the trajectories

(2) To be different for each trajectory.

We conducted two types of analysis for each model combination:

(1) Long-term analysis

(2) Two period analysis: we broke the time series into two time periods based on regulatory changes. First period from 1993 to 2007 and the second period from 2008 to 2015. We broke the time series in 2008, because spawning stock biomass SSB) of cod was above the limit reference point for the first time since the collapse.

We used AICc (Akiake's Information Criterion corrected for sample size) to select the most parsimonious model.

Results and discussion:

We evaluated a total of 428 different models with and without covariates. In both analyses, long-term and two-periods analysis, the best-supported model included separate trajectories (six process states) for each species and in each depth zone. However all populations had same population growth rate across species and depth zones. The best-fit model includes a positive correlation between catch and redfish abundance. while each subpopulation has a unique underlying trajectory and trend, the three populations change in the same way in year-to-year growth rate (Results for the long period analysis: Fig. 2.3.1, table 1).

One advantage of MARSS is that it can combine different time-series from different vessels and gear through the scaling parameter **a**. The choice to combine time series via the **a** parameter should be made with some care, however. For example, here, we forced the model to combine the time-series from the two vessels, which assumes that the two vessels differ primarily in the total biomass they fish but do not sample radically different size classes of fish.

MARSS provides an excellent tool to modeling spatial and temporal variation of population dynamics to quantify the effect of drivers and to combine different time-series from different vessel. While the best-fit model included six different state processes (trends in biomass), one per species and in each different depth, all six states were best modeled with one combined population growth rate (or one in each period for the two-period analysis). Thus biomass for each species in each depth varied somewhat independently as a result of being separate species and having different size distributions with depth. However, the unified population growth rate supports treating the three species as a ‘complex’ for management purposes. Nevertheless, further work could be done, i.e analysis with different cohorts and the inclusion of recruitment data. We also may investigate the way to do predictions.

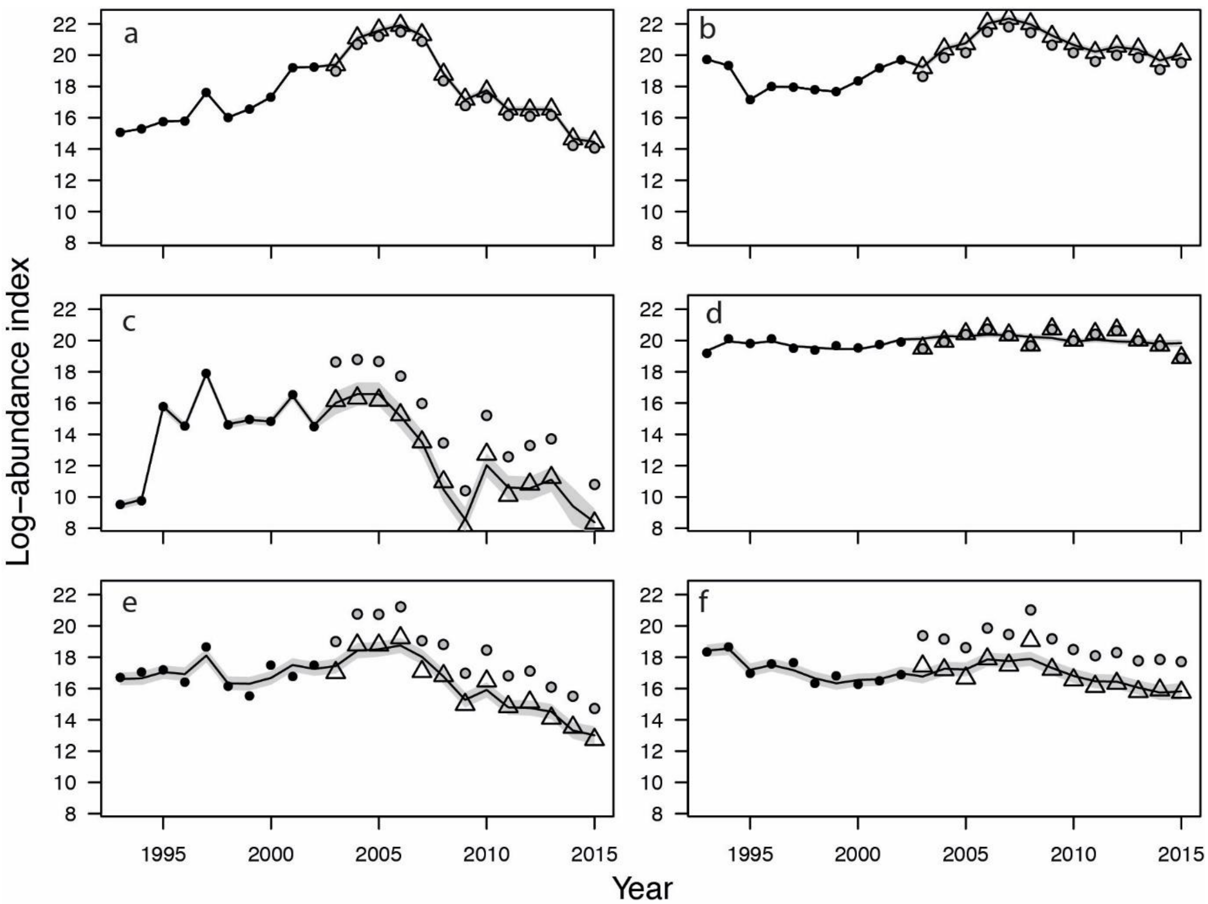


Fig. 2.3.1. Estimate trajectories (process states) for the three species of redfish in each depth (solid line), and the observational process for each vessel, R/V Cornide de Saavedra (solid circle) and, R/V Vizconde de Eza , original data (grey filled circle), corrected for the scaling effect **a** (triangle). a) *S. fasciatus* in the shallow zone b) *S. fasciatus* in the mid zone c) *S. mentella* in the shallow zone d) *S. mentella* in the mid zone e) *S. norvegicus* in the shallow zone f) *S. norvegicus* in the mid zone. Grey envelopes indicate 95% confidence intervals.

Table 2.3.2. Model results for the best model, Model 1. One u, 6 state processes. Covariate: catch (commercial catches of redfish). S.f. (*Sebastes fasciatus*), S.m. (*Sebastes mentella*), S.n. (*Sebastes norvegicus*). Zones: Shallow (129-250 m) and Mid (251-600 m). Vessel: R/V Cornide and R/V Vizconde.

Species	Zone	Observational variance (R)	Process varianc e (Q)	Growth rate (u)	Catc h	A cornide	A vizconde
S.f.	Shallow	0.000	1.220	0.058 +/- 0.0294	0.138	0	-0.407
S.m.	Shallow	0.022	4.560			0	2.472
S.n.	Shallow	0.213	0.672			0	1.982
S.f.	Mid	0.013	0.573			0	-0.554
S.m.	Mid	0.261	0.025			0	-0.035
S.n.	Mid	0.244	0.251			0	1.960

		Covariance (Q)
S.m. X S.f	Shallow	1.554
S.n. X S.f.	Shallow	0.807
S.n. X S.m.	Shallow	1.217
S.f. X S.f.	Shallow X Mid	0.305
S.m. X S.f.	Shallow X Mid	-0.655
S.n. X S.f.	Shallow X Mid	0.164
S.n. X S.m.	Shallow X Mid	-0.010
S.m. X S.f.	Mid XShallow	0.007
S.m. X S.m.	Mid XShallow	-0.180
S.n. X S.d.	Mid XShallow	-0.479
S.n. X S.f.	Mid XShallow	0.083
S.n. X S.n.	Mid XShallow	0.132
S.m. X S.f.	Mid	0.051
S.n. X S.f.	Mid	0.291
S.n. X S.m.	Mid	0.042

iii) Using Ecopath with Ecosim to support Ecosystem-based Fisheries Management

The Ecopath and Ecosim modelling framework (EwE) is composed of a mass balance model (Ecopath, Christensen and Walters 2004) from which temporal and spatial dynamic simulations can be developed (Walters et al. 1997, 1999, Christensen and Walters 2004). EwE is a quantitative, process- and species-based model, representing trophic flows in the ecosystem. It has been widely applied, being used to address ecological questions, evaluate ecosystem effects of fishing, explore management policy options, analyse the impact and placement of marine protected areas, model effect of environmental changes and it facilitates end-to-end model construction. It was primarily developed as a tool-box to help answer 'what if' questions about policy that could not be addressed with single-species assessment models (Pauly et al., 2000; Christensen and Walters, 2004, 2011). Here, the EwE is briefly outlined, some examples of its use for ecosystem-based fisheries management (EBFM) described and recent developments noted.

The Ecopath model provides a quantitative representation of the ecosystem, represented by functional groups that can be composed of species, groups of species with ecological similarities or ontogenetic fractions of a species. The key principle of Ecopath is mass balance: for each group represented in the model, the energy removed from that group, for example by predation or fishing, must be balanced by the energy consumed, i.e., consumption. Two linear equations represent the energy balance within a group and the energy balance among groups (see Christensen and Walters 2004 for further details). The key assumption of Ecopath is that the model is mass balanced.

Ecosim, the dynamic simulation model re-expresses the linear equations of Ecopath as difference and differential equations that dynamically respond to changes in fishing mortality and biomass, enabling dynamic simulations at the ecosystem level from the initial parameters of a baseline Ecopath model (Walters et al. 1997, 2000). Ecosim should be tuned to time series data, such as biomass, catch or mortality, using the goodness of fit measure, ideally fitting to data from multiple trophic levels. Details of the core principles and equations of EwE can be found in the EwE user guide available online (Christensen et al., 2008), and a recent publication on best practises is recommend reading (Heymans et al. 2016). Ecospace is a spatially explicit version of Ecosim that represents biomass dynamics over 2-D space (Walters et al. 1999, Christensen et al. 2014) but will not be discussed further here. The EwE software is downloadable online (www.ecopath.org).

EwE has been widely applied to for the purposes of EBFM and EBM. It is important to remember that EwE is a tool for strategic management, not tactical. It is also not a replacement for single species assessment, but rather puts single species in an ecosystem context and enables questions to be addressed that cannot be addressed within a single species framework, such tradeoffs across species, sectors or goals. Here, a few applications for EBFM are highlighted.

As noted, EwE fundamentally places species in their ecosystem context. Food webs, such as the one highlighted in Fig. 2.3.2, enable the trophic linkages of species of interest to be described and mortality rates estimated.

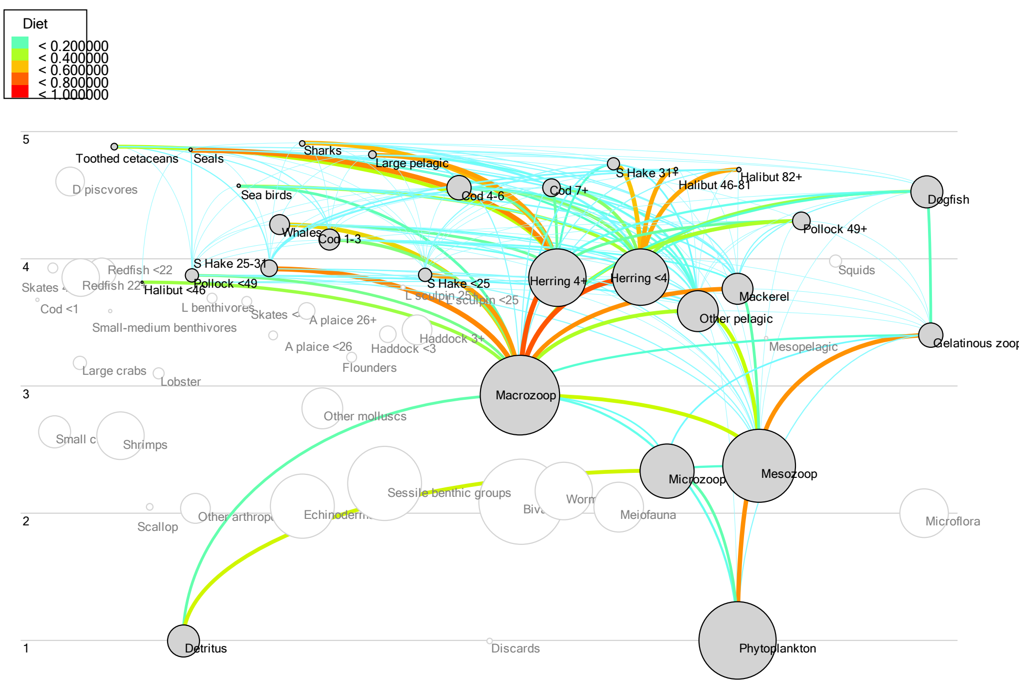


Fig. 2.3.2. Energy flow and biomass diagram for the western Scotian Shelf ecosystem. Nodes represent organisms within the ecosystem; the size of the node is proportional to the biomass it represents. Flows enter a node from the bottom and exit a node from the top and are scaled to flow proportion. The y-axis denotes the trophic level of the species.

EwE has been used in various jurisdictions to further understanding of the ecosystem effects of fishing and to provide ecosystem based advice for fisheries management, including Australia, USA and Europe. The North Sea EwE model (Mackinson 2013) is perhaps one of the most developed models, having been reviewed by the ICES WG Multispecies Assessment Methods. Recently, it has been used, together with 3 other models, was used in an STECF evaluation of proposed options for a multiannual plans for North Sea mixed demersal fisheries (STECF 2015). The model includes 68 biological groups and 12 fishing fleets with associated economic data on costs and prices. The main questions addressed was "What are the consequences of achieving, by 2016 and by 2020, fishing mortalities within the F_{MSY} ranges provided by ICES, with particular emphasis on the stocks of cod, haddock, whiting, saithe, sole, plaice and Nephrops?" Simulations highlighted the trade-offs among fleets and how indirect biological interactions affected the yield and value trade-offs among fleets. They also explored the use of an F_{MSY} ranges, and concluded that it gives scope to reconcile TACs for different species to come closer to being consistent with F_{MSY} and that fishing at the upper limit of the F_{MSY} range leads to increased risk to B_{lim}. This work was conducted using a new MSE plug-in developed by Cefas (Platts and Mackinson 2017). This plug-in is an important development as it enables the following types of error to be explored: 1) Model error (parameter uncertainty), (2) Observation error and (3) Implementation error, thus adding increased rigour to EwE.

EwE models have been used for policy exploration, including exploring the impact of forage fisheries by the Lenfest Forage Fish Task Force (Pikitch, E., et al. 2012). EwE models were a key tool used in their analysis to (1) quantify the value of forage fish both as an economic commodity and as ecological support for other species in the ecosystem and (ii) to simulate what happens to forage fish and their predators under a variety of fishing strategies. For the latter, they were able to quantify the impact of conventional versus precautionary management. Eddy et al. (2017) used a similar approach to assess the ecosystem effects of invertebrate fisheries.

Climate change is expected to cause profound changes in marine ecosystems that will vary in magnitude and effect among regions. Guénette et al. 2014 used an EwE for the western Scotian Shelf (Araújo and Bundy 2012) to explore the potential effects of climate change on the ecosystem using two scenarios of climatic changes. The model included the effects of temperature, pH, oxygen, decreased primary productivity and change in zooplankton size structure. These factors had differential, and sometimes opposing additive effects on the functional groups and species. The results also illustrate how the effects of climate change can be further enhanced or ameliorated by predator–prey interactions. At the individual species or functional group level, some effects were negligible, but at the ecosystem level, the combined predicted effect of climate change on the western Scotian Shelf led to a reduction in biomass of 19% to 29% with an associated decrease in catches of 20% and 22%. Dramatic declines in biomass due to climate drivers could be alleviated in part by a 50% decrease in exploitation rate.

Recently, EwE has been modularised, and the code made freely available so that uses can adapt the code and also develop packages (plugins) to add to the model (Steenbeek et al. 2016). This has made the EwE Framework into an extremely versatile tool to support EBFM.

In relation to the NAFO Road Map, EwE can be used to estimate single species, single species with species interactions MSYs and multispecies MSYs that can be used to address all three Tiers of the NAFO road map, with the latter providing an estimate of an overall catch cap or ceiling

There are multiple EwE models that have been developed for the NW Atlantic, including the northeast USA, the Scotian Shelf (east and west), the Gulf of St Lawrence (north and south) and Newfoundland-Labrador. New work has started on the EwE models for Newfoundland-Labrador as a result of the CoArc (A transatlantic innovation arena for sustainable development in the Arctic) project, which could contribute to the WG-ESA and the NAFO EBF roadmap.

iv) North Sea Ecosystem Modelling

“A multispecies modelling framework as used in the North Sea”.

Robert Thorpe gave a presentation on the multispecies and mixed fisheries model being developed and used in the North Sea. This included a description of the framework, and examples of the way in which it had been used so far.

The model is a length and species structured model of the fish community, and can be used to study multispecies interactions (where one stock eats or competes with another) and mixed fisheries effects (technical interactions, in which target and non-target stocks might be caught together in the same fishing gear). It can be used to analyse trade-offs, between fisheries yield and biological risk, and between different stocks and fleets.

Fisheries are often managed in accordance with “maximum sustainable yield” or MSY principles. This equates to taking the maximum yield from a stock or fishery that can be sustained in the long term. The concept makes intuitive sense, and in the case of a single stock, MSY can be readily calculated. However, for a multispecies system, “multispecies MSY” is not simply the sum of the individual species’ MSYs, and it practice it can be hard to determine. Here we use a pragmatic definition, considering the risk of stock depletion across the community alongside the overall reward (gross revenue = total landings x market price). Multispecies MSY is then the solution corresponding with maximum return for an acceptable level of risk, and any solution which yields close to the maximum with acceptable risk is consistent with multispecies pretty good yield (PGY).

An application of this approach to the North Sea was presented. The long-term risk and reward outcomes for each year's fishing patterns between 1970 and 2015 were estimated, and are presented in Fig. 2.3.3.

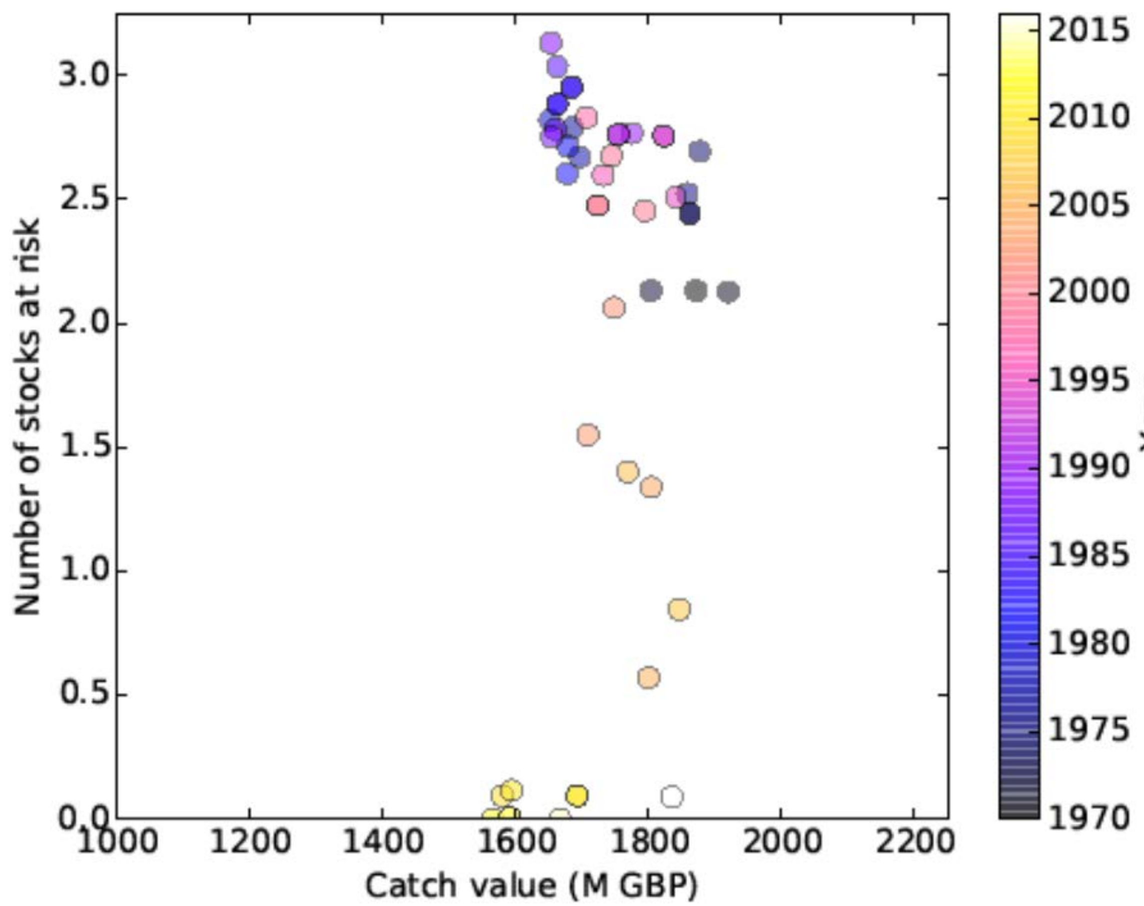


Fig. 2.3.3. Long-term mean gross revenue versus the number of stocks at risk of depletion to less than 10% of unfished biomass, given sustained fishing at estimated levels for the years 1970-2015.

The analysis shows that at the start of the period, yields were high, but so was the level of risk. Then between 1970 and 1980, risk levels increased whilst the associated yield went down, a pattern strongly suggestive of systematic over-fishing. The situation stabilised from the mid-1980s onwards. Then from the early 2000s there was a sharp decrease in the level of risk whilst yields decreased only modestly. This example shows the utility of a simple risk/reward framework for understanding outcomes in multispecies fisheries. When combined with a timeline of management policy interventions it may help policy-makers understand what interventions were most effective at improving management of the fishery.

Next the LeMans modelling framework was described. The model is structured by length and species and provides an ensemble estimate of the response of the fish community to different fishing strategies. It is an intermediate complexity model occupying the space between SMS (used to provide boundary conditions for single species assessments in the North Sea) that is very data-driven, and Ecopath (more strategic, energy flow) – see Fig. 2.3.4. The model has the form of a length-based stock assessment, but incorporates energy flow considerations (as per Ecopath).

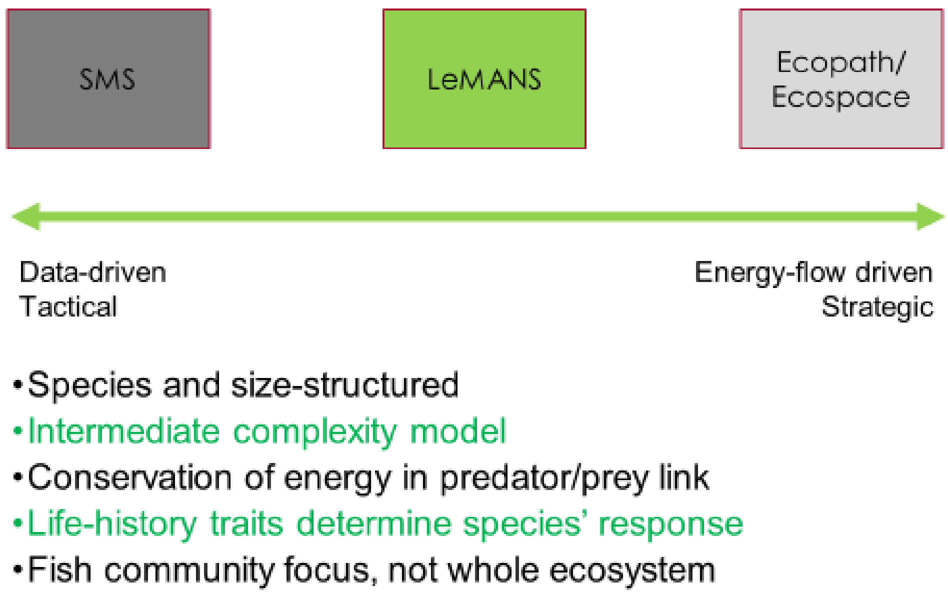


Fig. 2.3.4. Schematic of the LeMans ensemble model philosophy.

LeMans is based on Hall et al (2006), subsequently adapted for the North Sea (Rochet et al., 2011) and then further modified (Thorpe et al., 2015) to adopt an explicitly probabilistic approach. Mixed fisheries effects (Thorpe et al. 2016) and stochastic recruitment (Fig. 2.3.5 - Thorpe et al. 2017) have also been added.

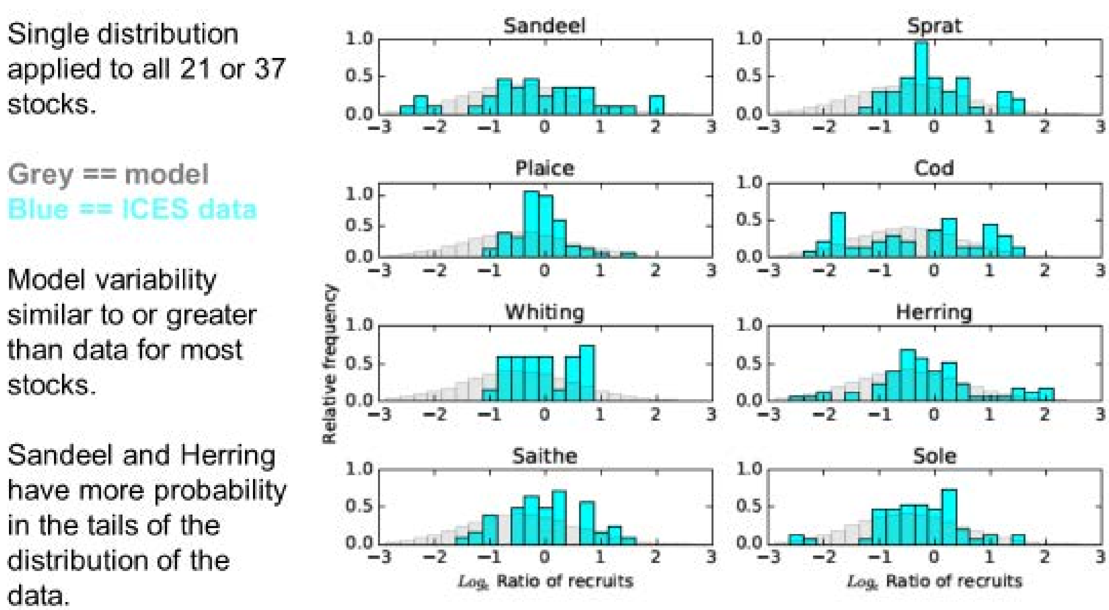


Fig. 2.3.5. Model-simulated recruitment variability (grey) and variability in the ICES stock-recruit database (blue) for eight assessed stocks.

A new version of the model is currently under development, with 37 stocks instead of 21, and considering the impact of grey seals (Fig. 2.3.6) and food-dependent growth.

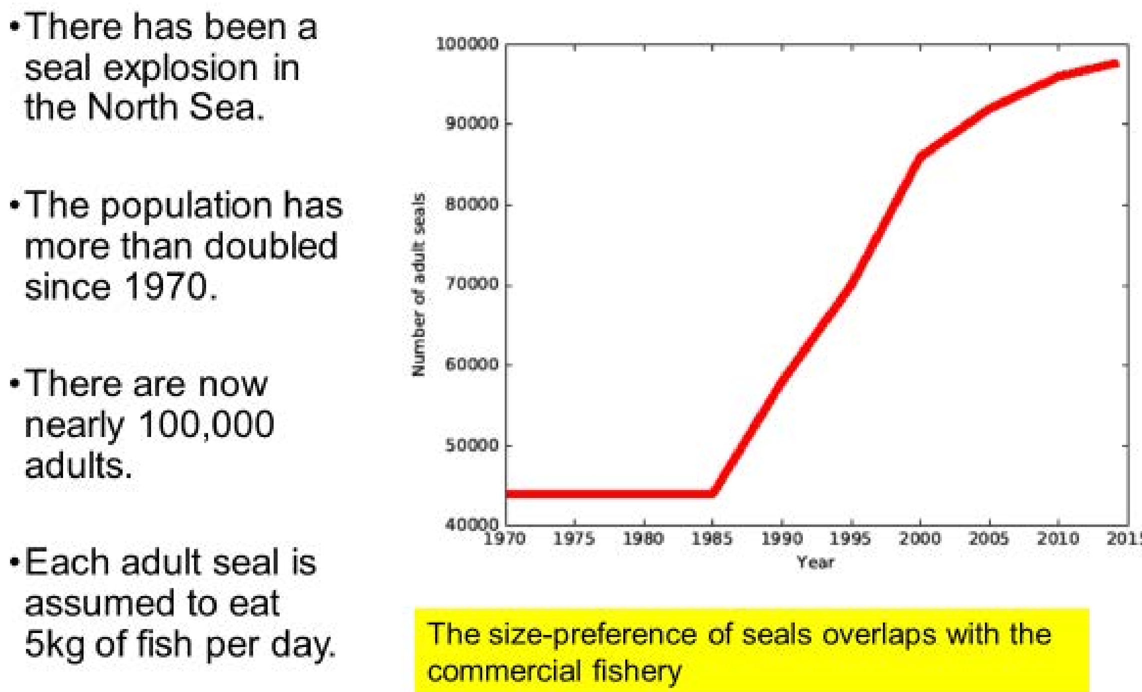


Fig. 2.3.6. Estimated adult population of grey seals in the North Sea since 1970.

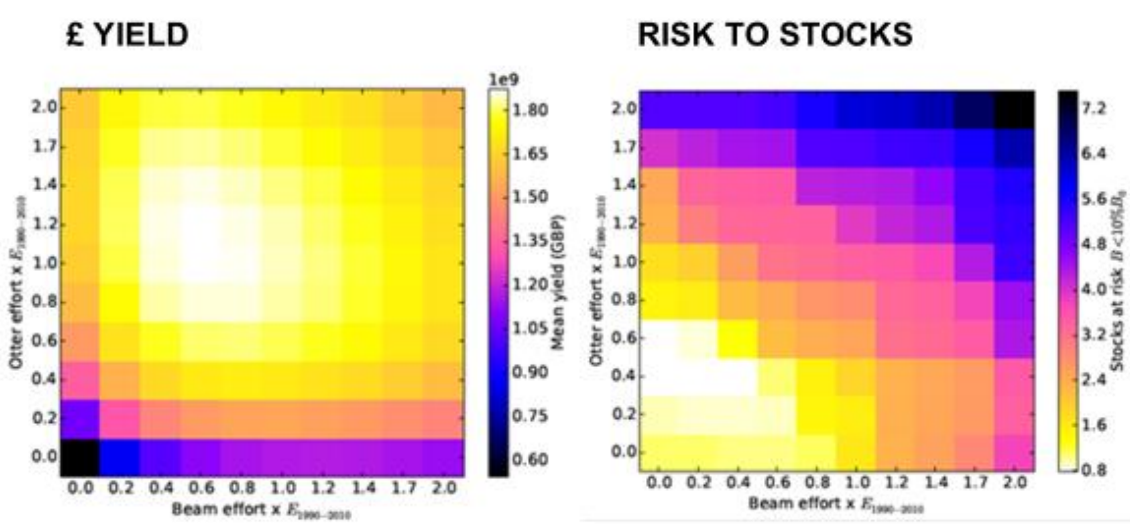
The performance of the new model has been evaluated by a hindcast simulation, in which it is tuned to assessments for the period 1990-2010 and then used to estimate outcomes for 2010-2015 which are compared with the subsequent assessments. In particular we ask whether the model framework performs better than persisting the results of the last assessment (2009) in terms of a) assessed stock biomasses, b) violation of the limit reference point, and c) predicting trends in the biomasses of 10 assessed stocks. It will need to have some skill in these terms if it is to be of use to decision-makers.

The model is first spun up from unfished and run with F=0 for 50 years, allowing one to discard solutions which fail to preserve all stocks in the absence of fishing. It is then forced with Fs from assessments from 1970 onwards, and is tuned to assessment outcomes between 1990 and 2010. Finally for the 2010 period onwards, a forecast is made based on Fs as in the subsequent assessments. The performance of this forecast is summarised in Table 2.3.3.

Table 2.3.3. Performance of the model hindcast as compared with persisting the last (2009) assessment. Stocks in green are where the model gets the trend right, blue stocks are where the model hindcast trend is wrong.

	MODEL	PERSISTENCE
•BIOMASS	PEN = 126 7 stocks better	PEN =163 3 stocks better
•LIMIT POINT VIOLATION	2 false alarms, 2 events missed	2 false alarms, 2 events missed
•TRENDS	NOP, SOL, PLE, HAD, COD, POK, WHG, SAN, SPR, HER	NO INFORMATION

After establishing that the model framework does provide useful skill in the North Sea on the 1-5 year time horizon, a few applications were presented. One possible use concerns the evaluation of trade-offs between risk and reward, and between one fleet and another (Fig. 2.3.7).



Trade off between risk and yield cannot be avoided

Fig. 2.3.7. Trade-offs in the beam and otter trawl fisheries for a) gross revenue, and b) risk of stock depletion to less than 10% of unfished biomass. White areas are high reward or low risk, dark areas low reward or high risk.

The analysis can be used to determine the relative efforts of beam and otter fleets that provide the best compromise between gross revenue achieved and the risk of stock depletion. An analysis of the ICES concept of pretty good yield ranges in a multispecies and mixed fishery was also presented. Risk/reward outcomes were evaluated for different management targets going up the PGY ranges from the bottom to the top in steps of 5%, taking into account fleet management and model parameter uncertainties. Estimates for profit levels and employment (here described as jobs, but in practice hours of employment) are shown in Fig. 2.28.

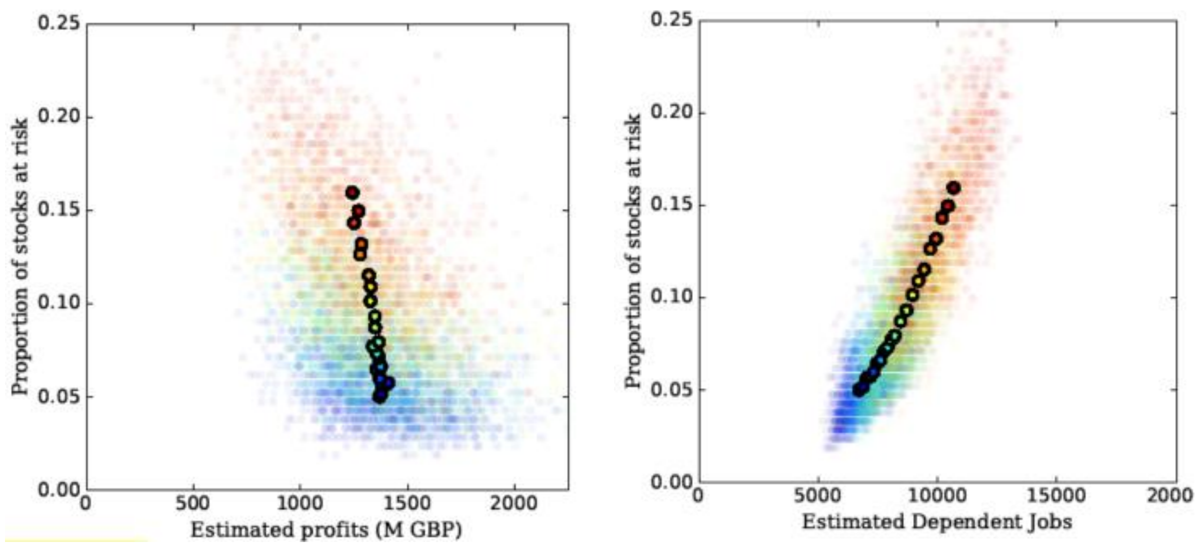


Fig. 2.3.8. Risk reward outcomes for managing the fishery to different parts of the F-PGY ranges for a) profits, and b) employment. The colours reflect the management target within the ranges – blue for bottom of the ranges, green for middle, and red for the top of the ranges. The solid circles represent outcomes for a given management target averaged across the fleet patterns. Other points of the same colour represent the spread of fleet outcomes subject to a particular management target.

The best outcomes in Fig. 2.3.8 are those in the bottom right, where risk is low and reward high. The analysis shows that in terms of profits, targeting the bottom of the ranges is best, with low risk and high returns. The picture is different for employment though, where both employment and risk increase with effort. Thus there is a trade-off to be made between the levels of employment and biological risk – it's not possible to maximise both. There is no clearly best level of fleet effort – the optimum strategy depends upon the relative value that society places upon revenue, profits, employment, and biological risk (Fig. 2.3.9).

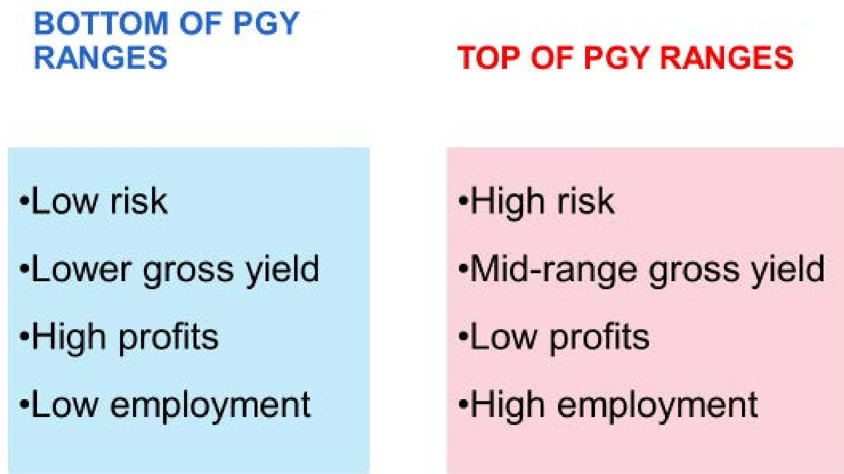


Fig. 2.3.9. Schematic showing societal outcomes of fishing at the top and bottom of the F-PGY ranges.

In summary, we have developed a 37-stock model with 5 fleets, seals, and food-dependent growth, which builds upon the earlier 21-stock model described in Thorpe et al. (2015,2016,2017). We have validated the model using a hindcast of the period 2010-2015, and show that it outperforms persistence of the last available assessment for this time period. We can use this model to look at trade-offs between stocks and fleets, to perform management strategy evaluation, and to assess risk/reward outcomes.

This framework has the advantage of being based upon generic principles (size-structuring, energy conservation, and life history characteristics) and so is capable of being adapted for use anywhere where these assumptions are valid. Arguably that is true of the NAFO region as a whole, and so the approach could be used to model the fish communities for which NAFO has management responsibility.

Setting up the model requires the following sources of data/information.

a) A list of the key fish species for explicit representation within the model.
b) Life history parameters for each species (growth parameters, maximum length, length at maturity, relationship between length and weight).
c) Diet matrix (which stock can eat which).
d) Fishery selectivity as a function of length for each stock, and/or information about fleet structure and selectivity.
e) Time series of fishing mortality (or effort) for each stock.
f) Catches and/or survey abundances through time for each stock.
g) Some estimate of community state at a particular time (e.g. for model initialisation).
h) Time series of seal or other top predator abundance, energy requirements and size selectivity.

The model framework is subject to top down (fisheries and predation) and bottom up (via the size, length structure and typical lifetime of the background energy/primary productivity), and so can be used to investigate the interaction of fisheries with environmental drivers. Within this framework, changes in the environment would be manifested as variations in the background density of food resource with length. For example a shift from the copepods *Calanus* to *Pseudocalanus* could be modelled as a downward shift in the energy spectrum to shorter lengths.

v) An Ecosystem-Based Management Procedure for Multispecies Fisheries on Georges Bank

Georges Bank is widely recognized as a highly productive marine ecosystem. It has supported generations of fishing communities on the northeast seaboard since the early 18th century when offshore fisheries first developed in the United States. The Georges Bank ecosystem was subject to a massive impact with the arrival of distant water fleets in 1961, resulting in the decimation of a number of fish stocks in a pattern of sequential depletion (Fogarty and Murawski 1998). The history of groundfish management on Georges Bank since then has involved seemingly intractable problems related to the pervasive technical and biological interactions in this system. In the following, we describe elements of an Operational Management Procedure (OPM) for multispecies fisheries designed to address these challenges. We argue for a system approach centered on the concept of functional group management. For our purposes these functional groups comprise species that are caught together and share similar life history characteristics and trophic positions. They lie at the intersection of fishery-related and ecological interactions.

OPMs are designed to establish a setting in which (potentially) simple management rules are identified and rigorously tested to address objectives for management developed in a transparent process with stakeholder involvement. At the request of the New England Fisheries Management Council (NEFMC), options for Ecosystem-Based Fisheries Management (EBFM) are being explored by its EBFM Plan Development Team, including the work described below.

The main elements of the multispecies OPM under consideration involve (1) the establishment of a dynamic ceiling or cap for total fishery removals from the Georges Bank ecosystem conditioned on changing productivity states of the system (2) specification of catch allocations to defined Fishery Functional Groups (FFGs). The sum of these catch allocations by FFG cannot exceed the system ceiling, and (3) identification of floors or thresholds below which individual species cannot be driven without invoking remedial action. We establish a multispecies harvest control rule (described below) based on these elements This Floors and Ceilings approach is now being tested by simulation to assess its performance using a size-structured multispecies multi-fleet model Hydra (Gaichas et al. 2016). A flow diagram of the principal elements of the model is provided in Fig. 2.3.10.

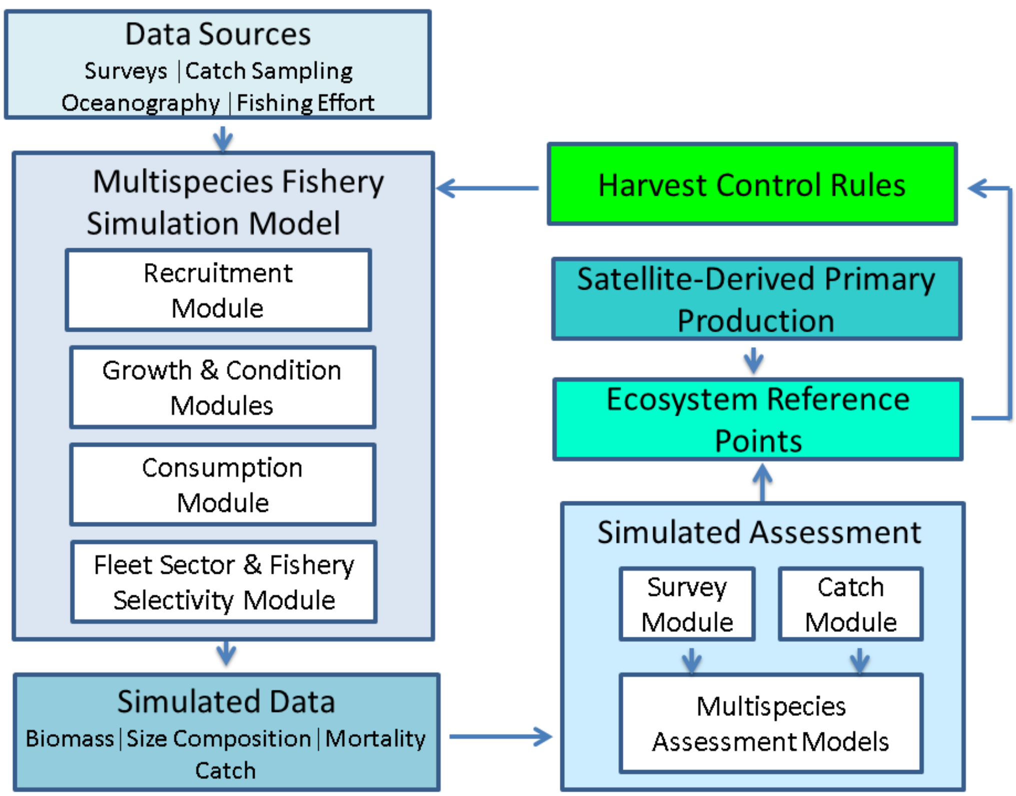


Fig. 2.3.10. Components of the simulation model used to test management procedures in Hydra

Hydra focuses on a 10 species subset of the Georges Bank fish community: Atlantic cod (Gadus morhua), haddock (Melanogrammus aeglefinus), silver hake (Merluccius bilinearis), winter flounder (Pseudopleuronectes americanus), yellowtail flounder (Limanda ferruginea), monkfish (Lophius americanus), spiny dogfish (Squalus acanthias), winter skate (Leucoraja ocellata), Atlantic herring (Clupea harengus), and Atlantic mackerel (Scomber scombrus). These species account for 86% of the landings of fish species for which NEFMC has complete or partial control during the period 1977-2014. This fraction increased to 90% during 2000-2014.

The harvest control rules examined here determine overfishing at the FFG level but overfished status at the species complex or individual species levels (Fig. 2.3.11) to ensure adequate protection for species comprising each FFG.. We explored 6 principal scenarios with four levels of exploitation nested within each (Table 2.3.4) to define Performance metrics

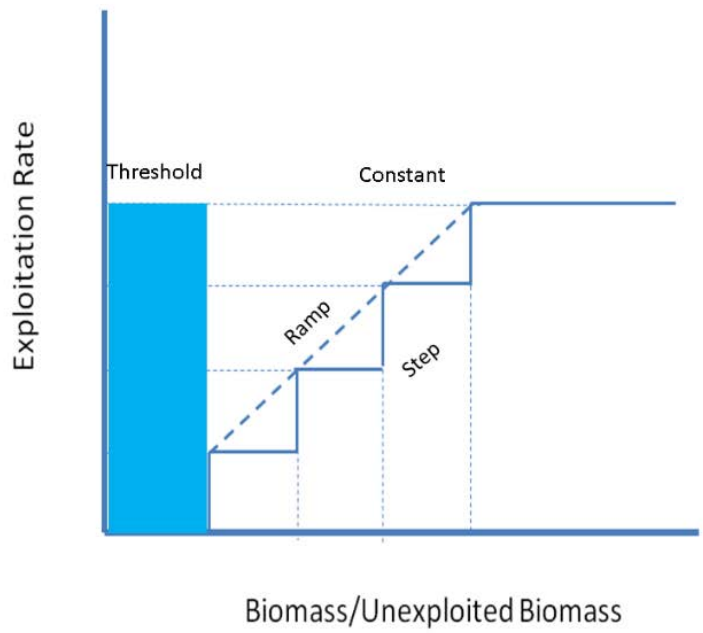


Fig. 2.3.11. Structure of the ecosystem-based harvest control rules tested. Overfishing is determined at the species complex level. Overfished status is determined at the species complex or individual species levels (see details in Table 2.3.4).

Table 2.3.4. Scenarios Tested in simulation studies of the EBMP

Scenario 1	Threshold exploitation (no ramp down) at Ex=0.15, 0.2, 0.25, 0.3 and Floor=0.2 of unfished biomass applied at the species complex level
Scenario 2	Threshold exploitation (no ramp down) at Ex= 0.15, 0.2, 0.25, 0.3 and Floor=0.2 of unfished biomass applied at the individual species level
Scenario 3	Threshold exploitation (no ramp down) at Ex= 0.15, 0.2, 0.25, 0.3 and Floor=0.2 of unfished biomass for each species except winter skate and dogfish (Floor=0.3 of unfished biomass) applied at the individual species level
Scenario 4	Ramp-down exploitation using 'steps' at Ex=0.15, 0.2, 0.25, 0.3 and Starting at B/Bo = 0.4 applied at the species complex level
Scenario 5	Ramp-down exploitation using 'steps' at Ex=0.15, 0.2, 0.25, 0.3 and Starting at B/Bo = 0.4 applied at the individual species level
Scenario 6	Ramp-down exploitation using 'steps' at Ex=0.15, 0.2, 0.25, 0.3 and Starting at B/Bo = 0.5 applied at the individual species level for winter skate and dogfish

To evaluate fishery performance, we examine Catch, Biomass, and the fraction of simulation runs in which the species and/or functional group constraint (floors) was exceeded. We used the median result of the 500 member ensemble to compare different control rules and their variants but show the full range of results characterizing uncertainty with a focus on the interquartile range. In the simulations, we also output the associated revenues, the size composition of the catch and the population for each species. Additional metrics including measures of biodiversity are also part of the output. Some key outcomes of the simulation studies conducted to date are shown in Fig. 2.3.12.

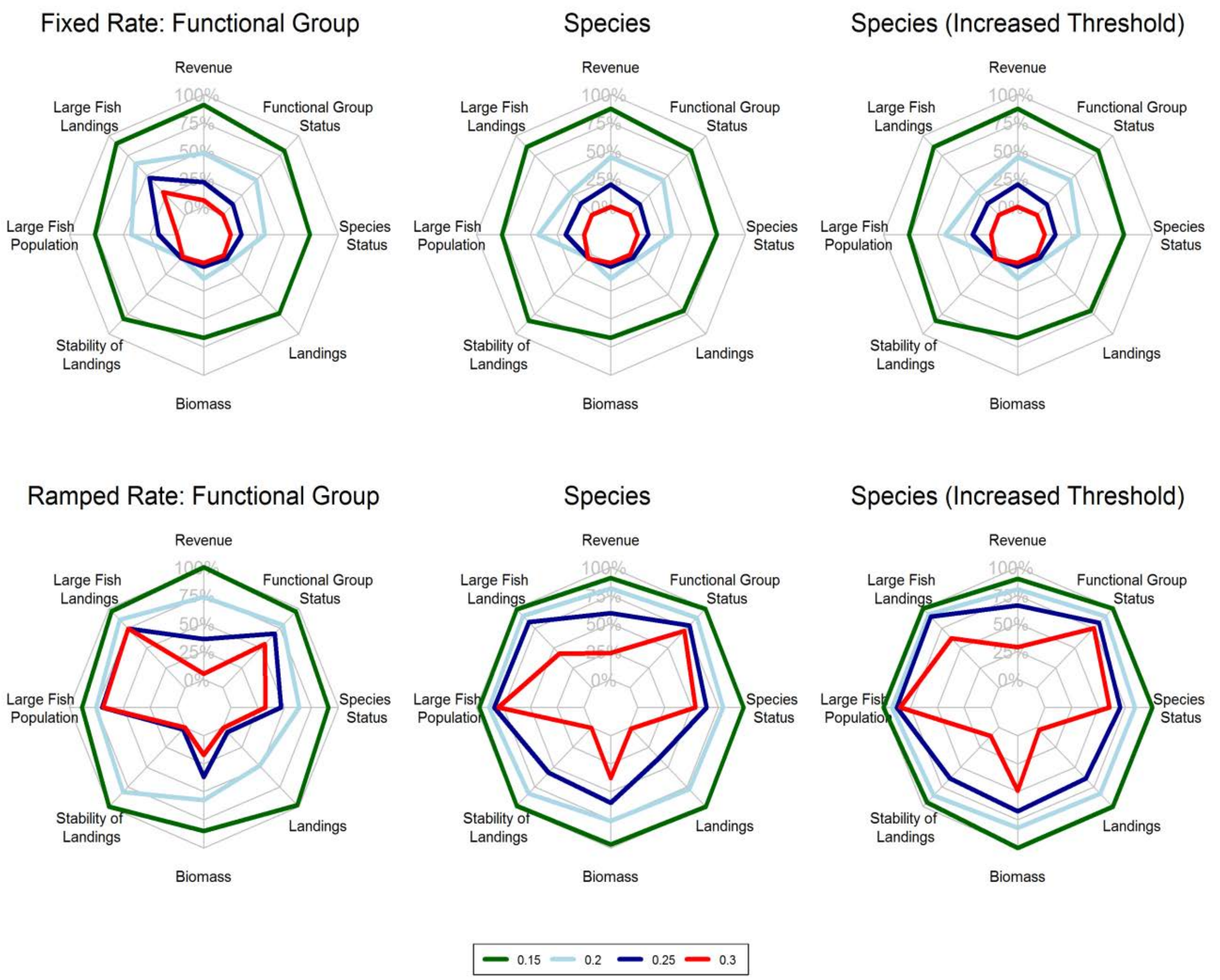


Fig. 2.3.12. Radar plots showing the relative performance of the six principal scenarios examined (see Table 1) for eight performance metrics. Each subplot shows results for levels of exploitation ranging from 0.15-0.3. Highest performance is indicated for metrics at the outer rim of the octagon.

The results indicate that:

Performance of fixed exploitation rate strategy was significantly worse for all metrics than ramp-down strategies at all exploitation levels

At exploitation rates as low as 0.15, performance of ramp-down strategies at the functional group and individual species levels, and the enhanced protection strategy for vulnerable species are very similar for all metrics.

At higher exploitation rates, the species-level and enhanced protection level strategy increasingly out-perform protections placed at the functional group level.

At highest exploitation rate examined (0.30), the enhanced protection strategy for vulnerable species pays the highest dividends.

Collectively, these simulation results suggest that defining overfishing at the species complex level and affording a biomass floor at the species level can sharply reduce the incidence of overfished status determinations.

vi) Exploring the dynamics of key components of the Newfoundland and Labrador marine community using empirical dynamic modelling

Introduction

The concept that multispecies assemblages and ecosystems can be described and studied using general dynamical systems theory has been fundamental to the development of modern ecology and food web theory (Yodzis 1989). Under this perspective, time series of species assemblages can be seen as describing the trajectory of a system along an attractor in a multidimensional space where each species defines a coordinate axis. The vector of species observations at a given moment in time represents a state of that multidimensional dynamic system.

Empirical dynamic modelling (EDM) is an equation-free approach that allows reconstructing that multidimensional attractor using lagged coordinates embedding of empirical time series data (Sugihara and May 1990, Deyle and Sugihara 2011). Current developments of this technique allow using multiple time series to better map the underlying attractor for short term forecasting (Ye et al. 2015), as well as to explore causality between pair of variables using convergent cross-mapping (CCM) (Sugihara et al. 2012). In this last instance, causality is inferred from the ability of predicting the observations of one variable from a reconstructed attractor based on a second variable. It is expected that the time series of the response variable would contain information on its driver, and hence, the attractor reconstructed from it would have a greater ability of mapping its driver, than the other way around.

Here these techniques were used to analyse the relationships between key components of the Newfoundland and Labrador (NL) marine ecosystem, as well as their linkages with large scale environmental signals. CCM was used to study the linkages between species, fisheries catches, and environmental conditions to identify potential driver-response relationships, and EDM to explore the dynamics of the Northern cod (2J3KL) stock taking into account the effects of species interactions and environmental conditions.

Data and analyses

The data considered in these analyses included environmental indices, fisheries catches and stock biomass indices.

The two environmental indices used here were the Atlantic Multidecadal Oscillation (AMO), and the Composite Environmental Index (CEI). Both indices are indicative of large scale environmental conditions, with the AMO representing the entire North Atlantic basin, while the CEI integrates more than 30 environmental and oceanographic variables from the Northwest Atlantic. Four time series were derived from these indices by considering the annual anomalies and the cumulated anomalies over time (Fig. 2.3.13). The cumulative anomalies were intended to better capture the concept of “environmental regime”, where “regime” refers to a multi-year period with sustained and relatively similar environmental conditions. The idea behind these regimes is that environmentally driven ecological changes require time to work themselves out, and hence, the environmental conditions need to be relatively stable for a period of time in order to drive ecological change in a specific direction.

The species considered in this analysis included Atlantic cod, capelin, and northern shrimp in the Newfoundland Shelf and northern Grand Bank (NAFO Divs 2J3KL).

Fisheries catches were represented by the nominal catch statistics reported to NAFO, and compiled in the STATLAN21A database. The time series of catch data covers the 1960-2015 period (Fig. 2.3.14).

The stock biomass time series correspond to the DFO Research Vessel (RV) Fall multispecies surveys for NAFO Divs 2J3KL, and the DFO RV Spring Acoustic surveys for capelin for NAFO Div. 3L (Fig. 2.3.15).

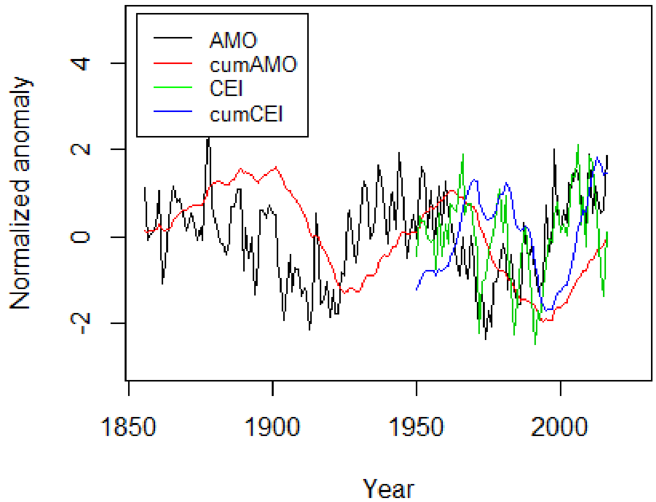


Fig. 2.3.13. Indices describing the overall environmental conditions in the Northwest Atlantic. AMO: Atlantic Multidecadal Oscillation, CEI: Composite Environmental Index; these indices are represented as normalized anomalies. cumAMO and cumCEI correspond to the cumulated normalized anomalies of AMO and CEI.

DFO RV multispecies survey uses a bottom trawl as sampling gear and changed it in 1994-1995, replacing the Engels (large mesh size, groundfish net) for a Campelen (small mesh size, shrimp net). This change improved sampling of small body-sized animals like shrimp and capelin. For this reason, time series from this survey for capelin and shrimp were only considered for the Campelen period (1995-2016). The cod time series covered the period 1981-2016, and a conversion factor was used to scale the Engels data into Campelen equivalents.

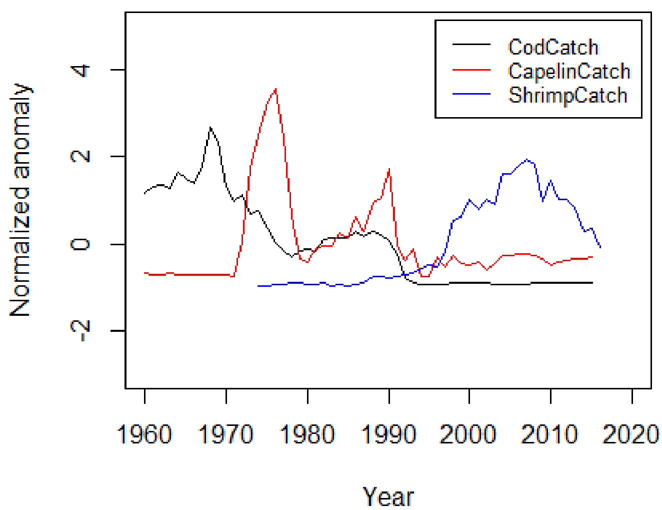


Fig. 2.3.14. Nominal catches for Atlantic cod, capelin and shrimp in NAFO Divs 2J3KL from NAFO STATLAN21A database.

DFO RV Spring Acoustic survey for capelin is focused on the historical core distribution area for the stock (3L), and it considered a good indicator of the status of the stock for the entire 2J3KL region. Even though the time series for this survey has several gaps over time, it spans over the 1982-2015 period. A comparison between the acoustic and bottom trawl surveys between 1995-2015 shows a weak, but significant positive correlation between surveys (Spearman Rank Correlation = 0.44, p-value<0.05) indicating that both surveys capture a similar overall trends over time, but they differ in their interannual signal.

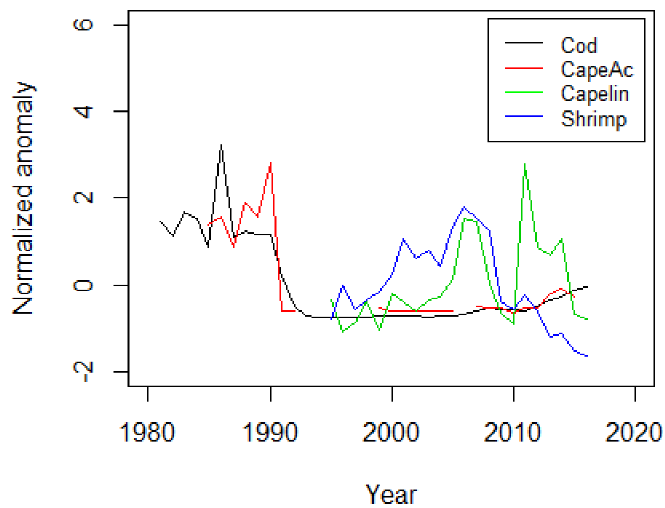


Fig. 2.3.15. Normalized anomalies of the RV biomass estimates for Atlantic cod, capelin and shrimp from DFO RV multispecies surveys in NAFO Divs 2J3KL, and of capelin from DFO RV Spring acoustic surveys in NAFO Div. 3L (CapeAc).

CCM plots were generated to explore the driver-response relationships between environmental conditions and stocks, between catches and stocks, and among stocks. The analyses involving capelin, given that different time span involved in the acoustic (1982-2015) and trawl (1995-2016) series, allow exploring linkages in the long term and the most recent period. Analyses involving shrimp are only focused on the most recent period. For those analyses involving catches and stocks, the catch series were lagged one year to represent the expected effect of fishing on stock level.

Different EDMs focused on Atlantic cod were developed by considering only the cod time series, pairwise combinations of cod and a single environmental or species interaction component, and a multivariate case were multiple components were considered. In the context of EDMs, these exercises need to be compared and interpreted as how much better the underlying multidimensional attractor can be reconstructed by considering information from multiple time series. In these cod-focused models, prey biomasses and cod catches were lagged one year to represent their expected impact on cod status. Model comparisons were based on the correlation coefficient between predicted and observed cod values for models predicting the same target period (1995-2015).

Results

CCM analyses indicated that environmental conditions emerged as drivers of cod, shrimp and capelin stocks (Fig. 2.3.16), with cumulated anomalies performing better than simple anomalies series (Fig. 2.3.17).

CCMs between stocks and their catches also indicated that catches were important drivers of cod and capelin in the long term (1980-2015 period), but recent catches of capelin, although still a likely driver, seemed to have a much weaker link with the stock trajectory (Fig.2.3.18). In the case of shrimp stock emerges as a likely driver of the catches. This suggests that fishery catches have had no direct effects on the stock trajectory in recent years (Fig. 2.3.18).

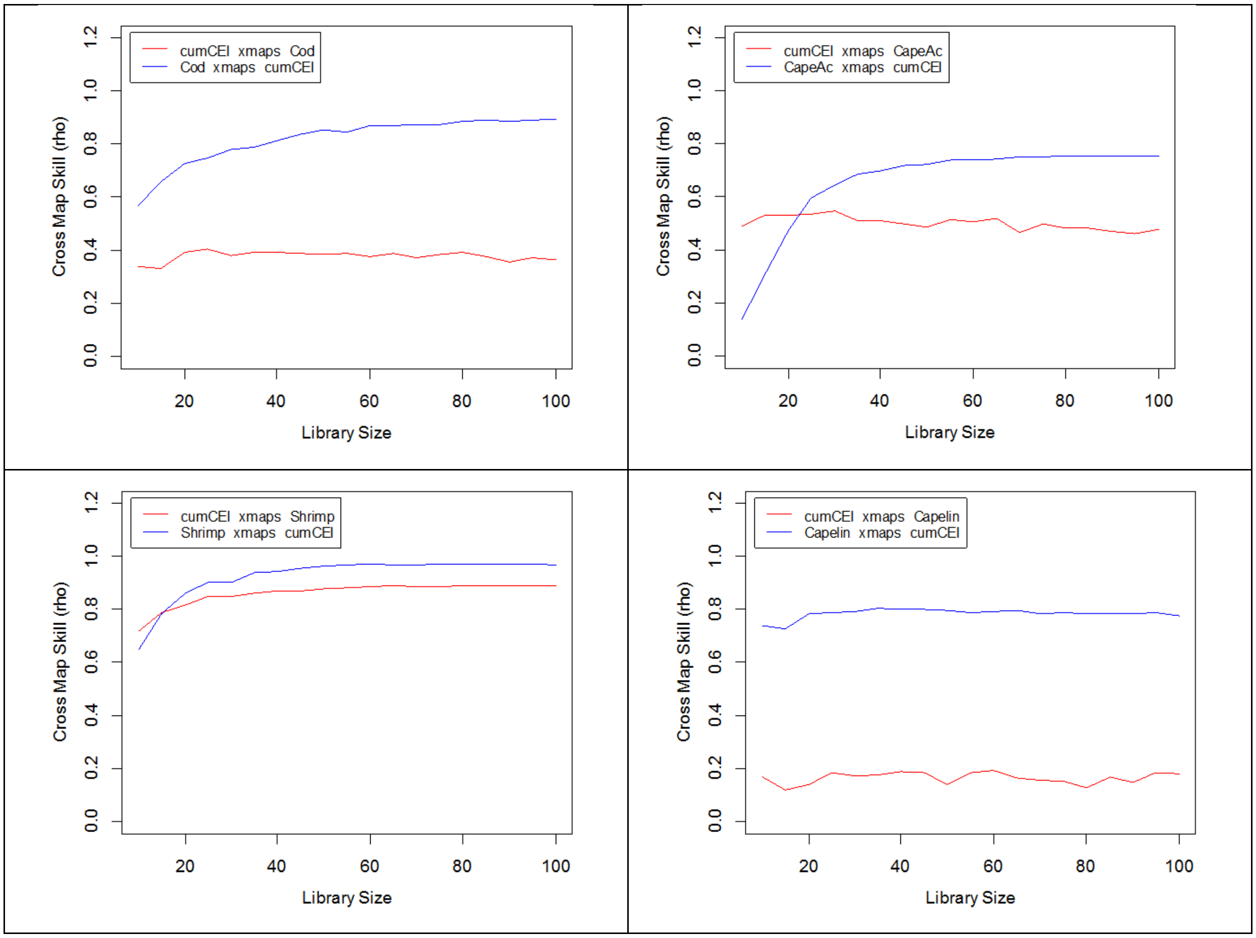


Fig. 2.3.16. CCM plots between the cumulative CEI (cumCEI) and stock biomass indices. In all cases the curve of predictions of cumCEI based on the reconstructed attractor from the stock time series has a higher cross mapping skill (correlation), than the reciprocal curve. This indicates that the stock time series contains more information on the environmental conditions than the reverse, suggesting that the environment is the likely driver of the stock time series. The high cross mapping skill of the cumCEI on shrimp suggest a very tight linkage between environmental conditions and stock responses. Analyses based on AMO show similar results.

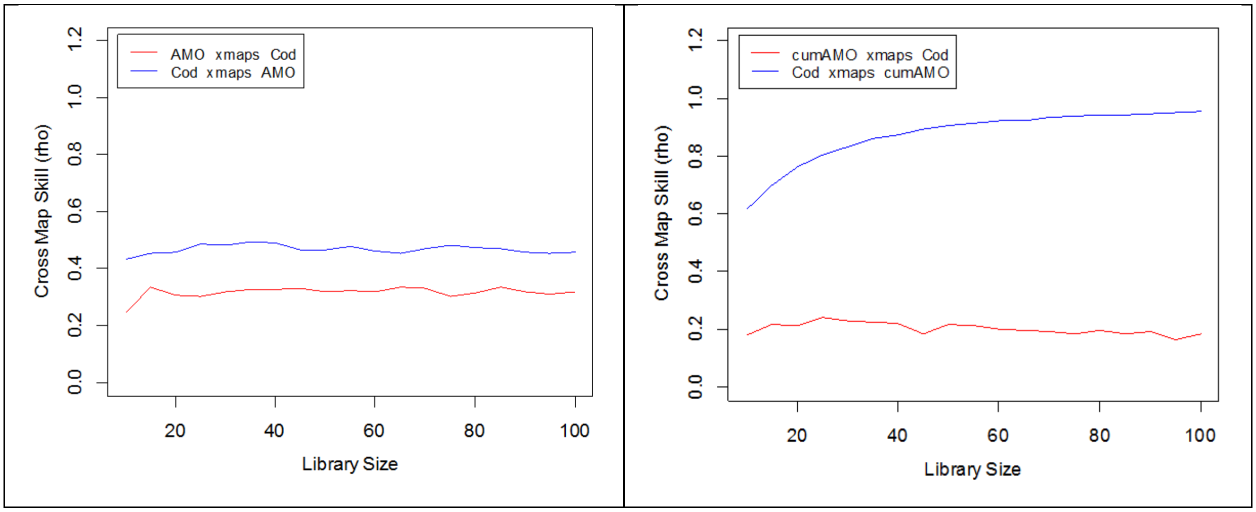


Fig. 2.3.17. Comparison of CCM plots of AMO and cumAMO with cod. In both cases the environmental signal emerge as a driver of the stock, but the cross mapping skill of the cumulative variable is much higher.

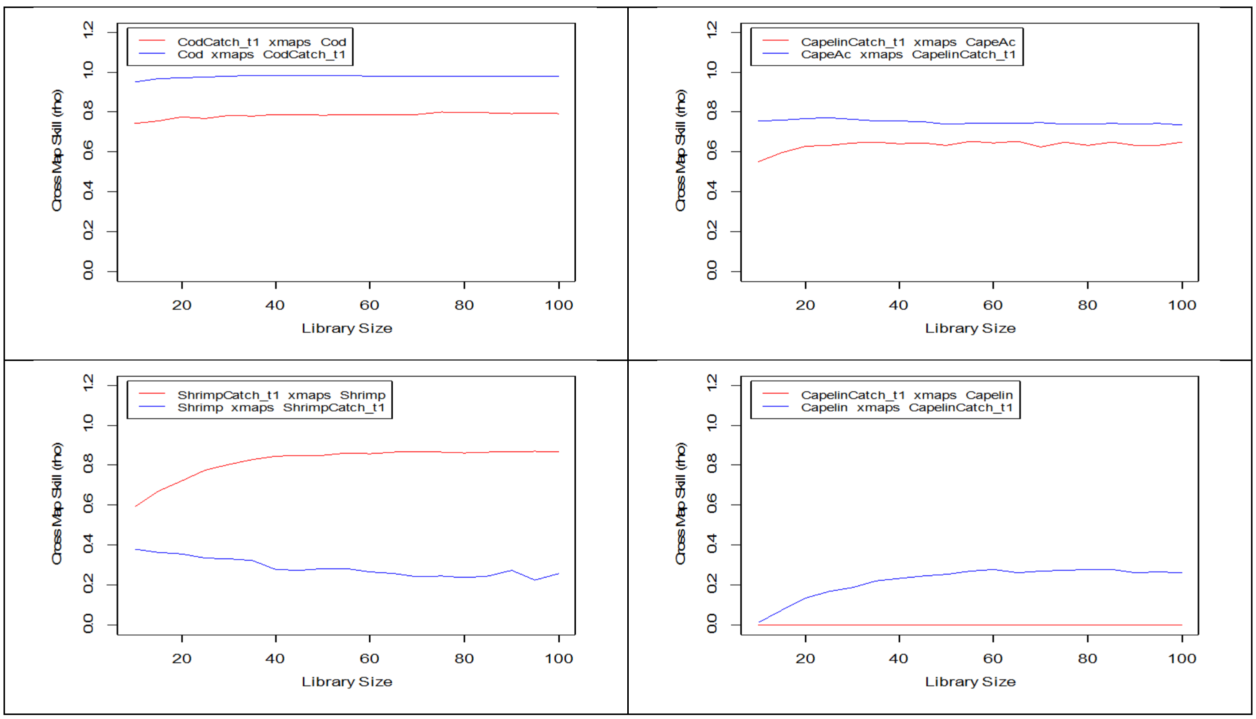


Fig. 2.3.18. CCM plots between the stock biomass indices and their catches lagged one year. In most cases the curve of predictions of catches based on the reconstructed attractor from the stock time series has a higher cross mapping skill (correlation), than the reciprocal curve, indicating that catches are the likely drivers of the stock time series. The CCM plots shrimp and capelin suggest that fisheries catches have had weak or no direct effect on these stocks in recent years.

Analyses of species interactions indicate that prey availability is the driver of the cod stock, suggesting bottom-up regulatory mechanisms (Fig. 2.3.19). Capelin emerges as a strong long term driver of cod, but the link between these species in recent years is extremely weak. Shrimp is the prey that emerges as an important driver in recent years. Although capelin and shrimp do not prey on each other, shrimp appear to have some driving effect on capelin, indicating some possible indirect effect between these key forage species.

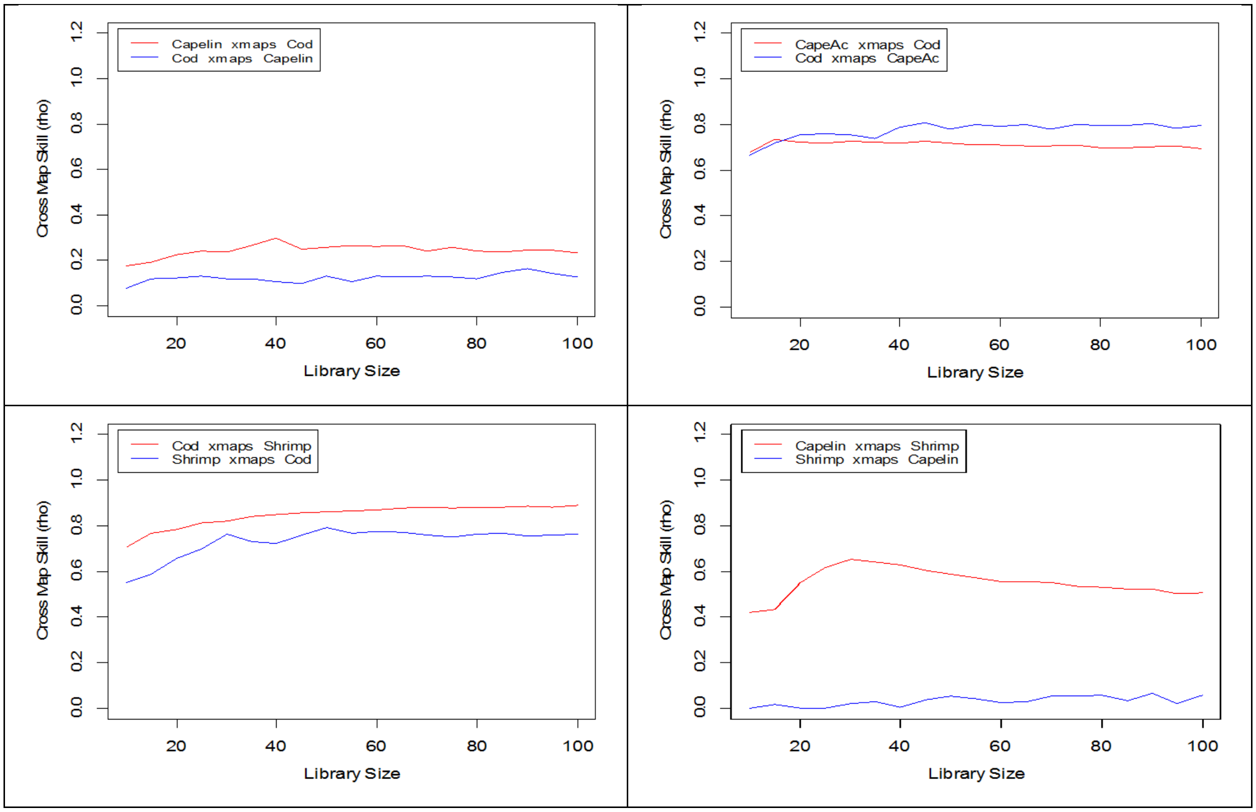


Fig. 2.3.19. CCM plots between the cod, capelin, and shrimp stocks. The Capelin and Shrimp series only cover the 1995-2015 period, and hence, only allow representing interactions in recent years. The Cod and CapeAc series include pre and post collapse years and provide a long term perspective on the interaction between cod and capelin.

On the basis of these results, the trajectory and forecasting of Northern cod was explored using EDMs with multiple structures (Table X.1).

Table 2.3.5. Variables considered in the EDMs developed for Northern Cod

Model	Variables included in the model
s	Cod (t), Cod (t-1), Cod (t-2)
m1	Cod (t), Cod (t-1), cumCEI
m2	Cod (t), Cod (t-1), CapeAc (t-1)
m3	Cod (t), Cod (t-1), Shrimp (t-1)
m4	Cod (t), Cod (t-1), CodCatch (t-1)
m5	Cod (t), Cod (t-1), Capelin (t-1)
m6	Cod (t), Cod (t-1), CodCatch (t-1), CapeAc (t-1), Capelin (t-1), Shrimp (t-1)

Although the model including environmental effects, catches, and multiple prey performed the best (Table X.2), all models produced sensible fits to the cod time series data (Fig. 2.3.20).

These models were used to forecast cod in 2016-2017. Most models reasonably forecast the observed 2016 value, and all models predicted that the cod stock will remain stable or decline in 2017 (Fig. 2.3.21). This forecast is very different from expectations based on the current Northern cod assessment, which predicted an increasing stock in 2016-2018 with less than 5% probability of a decline (DFO 2016). Although the models developed here are only exploratory, and they are not intended as a replacement of the current stock assessment model, the 2017 RV Fall survey estimate for this cod stock will provide an interesting test for the potential forecast performance of EDMs in comparison with an established single species stock assessment model.

Table 2.3.6 Summary statistics for the Northern cod EDMs explored in this study. The prediction range considered here was 1996-2015.

Description	Model	Number of predictions	Correlation (rho)	Mean Absolute Error (MAE)	p-value
Cod	s	19	0.868	0.065	5.90E-08
Cod+Env	m1	19	0.916	0.037	2.02E-10
Cod+CapeAc	m2	15	0.880	0.076	9.59E-07
Cod+Shrimp	m3	19	0.730	0.097	1.03E-04
Cod+Catch	m4	19	0.903	0.056	1.36E-09
Cod+Capelin	m5	19	0.910	0.056	5.00E-10
Multispecies	m6	19	0.938	0.037	3.12E-12

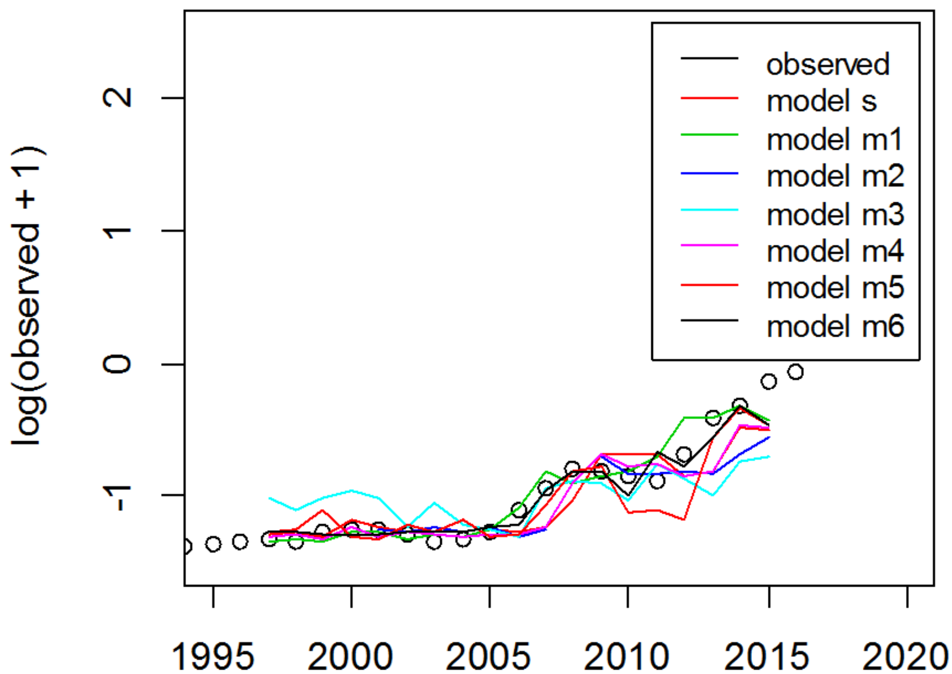


Fig. 2.3.20. EDM model fits to the observed Northern cod time series (circles) for 1996-2015.

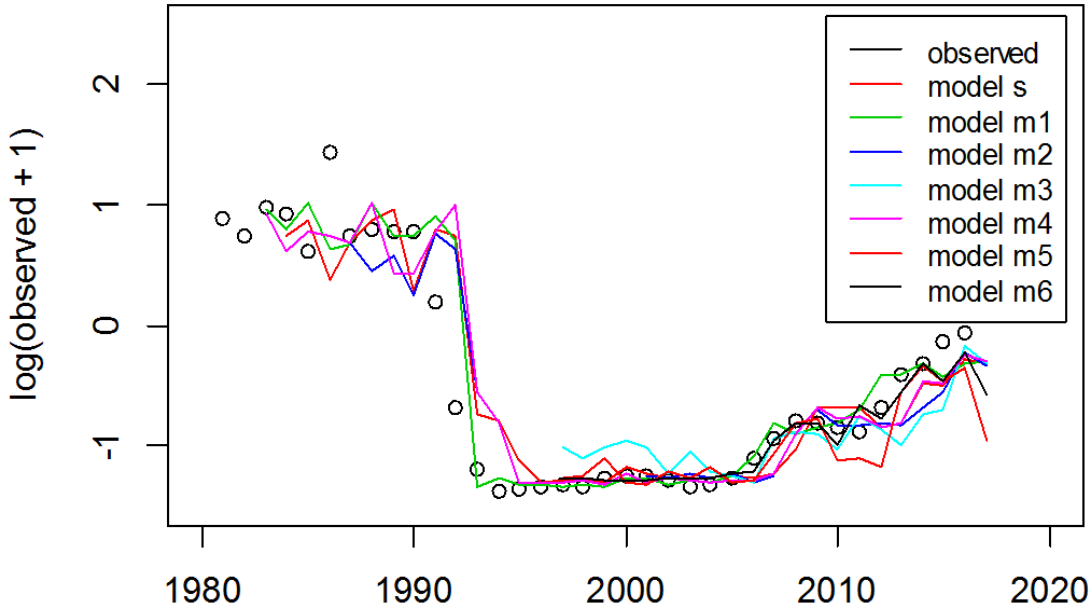


Fig. 2.3.21. Northern cod EDM fits and forecasts for the period 1983-2017.

Overall, the results obtained here, despite their current exploratory nature, can be seen from two complementary perspectives. On the methodological side, they highlight the potential for integration and short term forecasting of EDMs, which could be used to provide a useful companion and complementary forecasting piece to more standard assessment techniques. On the ecological side, these analyses further reinforce current views on the processes that regulate the NL ecosystems. These EDM-based explorations support the ideas that both fishing and environmental conditions had an important role in the collapse of the Northern cod stock in the 1990s as part of a broader collapse of the groundfish community (ToR 3.2 in this report), and that bottom-up processes (both environmental conditions and prey availability) are important regulatory forces of the cod stock, with capelin representing an historically important driver, while shrimp emerges as a significant driver in the post-collapse period. Finally, these results also suggest that the rebuilding trend experienced by Northern cod since the mid-late 2000s could be withering. This is also consistent with other ecosystem-level signals which indicate that NL ecosystems are likely experiencing bottom-up driven low productivity conditions (ToR 3.2 in this report).

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ToR 2.4. Review of oceanographic and ecosystem status conditions in the NRA

i) Oceanographic conditions on the Northwest Atlantic Shelves off Canada

This report essentially draws from the discussions that occurred at STACFEN in June of 2017 and the documents produced by the contributors to that meeting.

The information reviewed in this section is derived from the Atlantic Zone Monitoring Program (AZMP) which collects data on the physical, chemical and biological oceanographic properties on continental shelves and slopes off Newfoundland, Nova Scotia and in the Gulf of St. Lawrence (DFO 2017; Colbourne et al. 2017; Hebert and Pettipas 2017; Maillet et al. 2017). Data presented below are gathered from 14 oceanographic sections that are sampled seasonally, and five nearshore sites that are sampled once or twice a month. We report on the amount of nutrients available for phytoplankton, the overall abundance of phytoplankton and important features of the spring bloom, and the abundance of zooplankton species that are key prey for upper trophic level animals based on the data available from 1999 to the present. To simplify the presentation of information in this section, environmental conditions are usually expressed as anomalies, *i.e.*, deviations from their long-term means, calculated using a reference period of 1980-2010 for physical oceanographic variables and 1999-2010 for biogeochemical parameters. Furthermore, because measurements of nutrients, phytoplankton and zooplankton are expressed using different units, each anomaly time series is normalized by dividing by the standard deviation (SD) of the data from the reference period. This allows a more direct comparison of the various series and ensures that the inherent local or regional level of variability (the signal detected by our program) is considered similar for all parts of the Atlantic. A composite index for each variable is calculated by summing the anomalies across all sources of information.

Physical conditions

The focus of this summary is based on state and trend in temperature within the region. Sea surface temperatures were close to normal on the Newfoundland Shelf whereas they were 1-3 SD above normal in different parts of the Scotian Shelf and Georges Bank. The spatial differences in surface conditions may reflect differences in the general coherence between environmental drivers, principally winds, and the association with the Atlantic Multi-decadal Oscillation (AMO). The composite climate index on the Newfoundland Shelf is slightly above normal, after being below normal in 2014-2015 for the first time since 1996. Composite physical oceanographic indices across NAFO areas from Labrador to the eastern Gulf of Maine indicate that the region remains in a warm phase since the mid-1990s (Fig. 2.4.1). There appears to be increased inter-annual variability in sea surface temperatures in the recent warm period relative to the earlier cold period. There is greater variability in the southern parts of the region relative to northern areas and bottom water conditions demonstrate more persistence in state than surface waters.

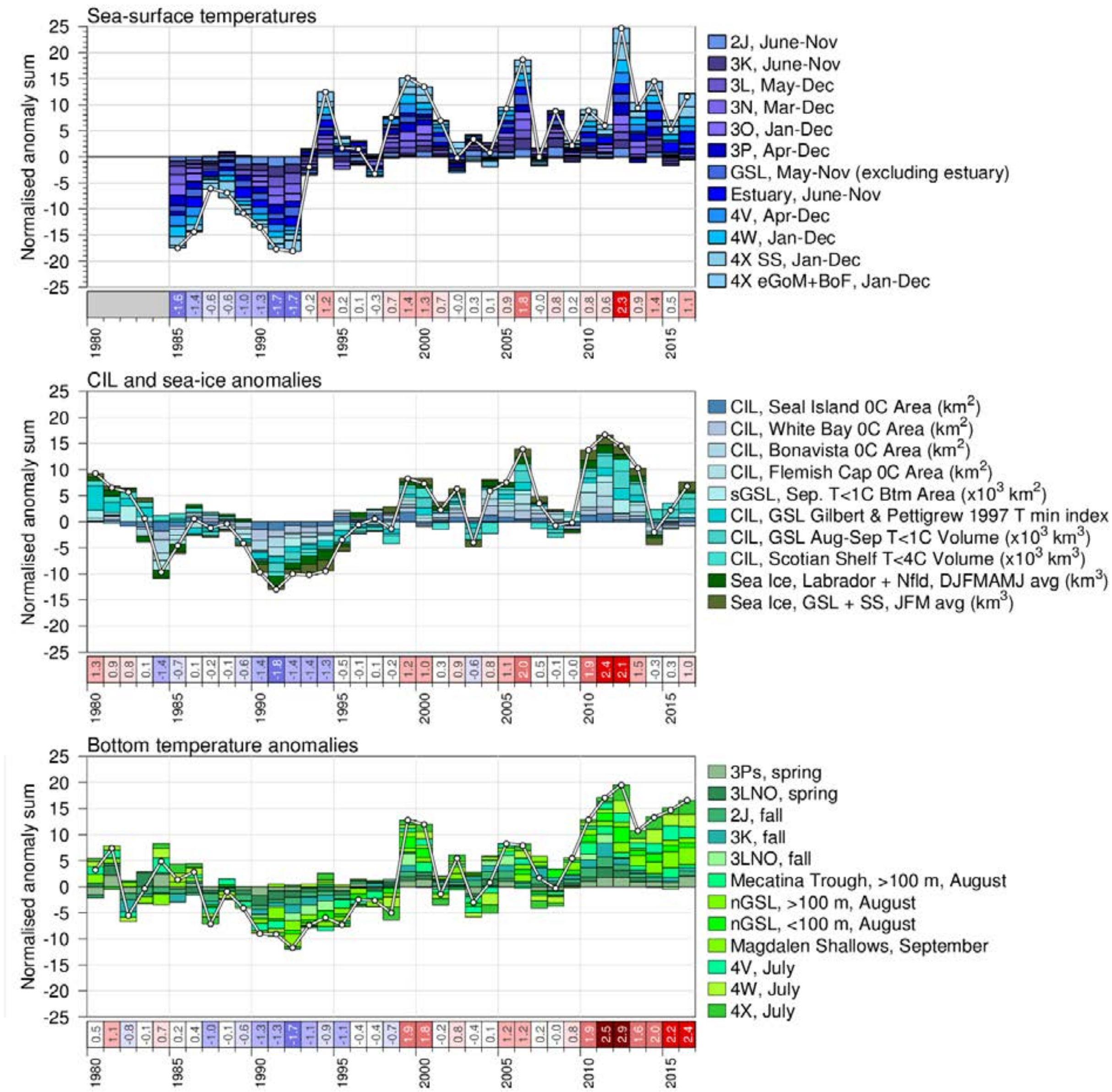

Fig. 2.4.1. Composite climate indices (white lines and dots) derived by summing various standardized anomalies from different parts of the environment (colored boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel sums sea-surface temperature anomalies, middle panel sums cold intermediate layer and sea-ice anomalies with areas and volumes in reversed scale (positive anomalies are warm conditions) and bottom panel sums bottom temperature anomalies.

Nutrients

The amount of nitrate contained in waters below the surface mixed layer at depths of 50-150 m (*i.e.*, the "deep water nitrate inventory") is generally not greatly influenced by the growth of phytoplankton and therefore provides a good indicator of the resources for phytoplankton growth that can be mixed into the water column during winter, or during summer and fall through upwelling. Nitrate inventories, and the relative abundances of other nutrients, are mostly dependent on the source waters that make up the deep water on continental shelves, and these can vary from year-to-year. Deep water inventories of nutrients are highly variable in the short term, but the patterns of variation in the Atlantic have been dominated by a general declining trend from 1999 to 2010, when a minimum was reached, followed by a general return to average conditions from 2010 to

2016 (Fig. 2.4.2). Changes in the amount of nutrients were not uniform in all parts of the Atlantic and they are highly variable in the short term, with frequent observations of conditions that are well below the long term average in different parts of the western Atlantic over the last five years. The greatest declines, which persisted until 2014-15, occurred on the Newfoundland Shelf. Conditions in the Gulf of St. Lawrence and Scotian Shelf had more moderate shifts in nutrient concentrations over time although the most recent states are near and below normal, respectively.

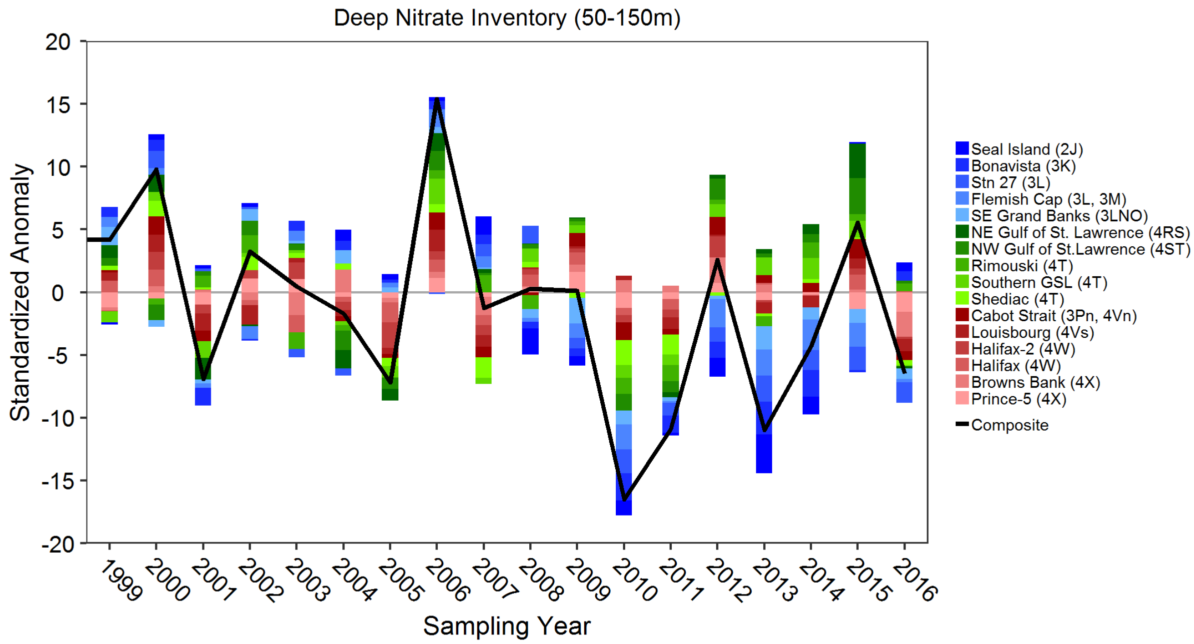

Fig. 2.4.2. Summary of nitrate (combined nitrate and nitrite which represents the principal limiting nutrient for phytoplankton growth) inventories in the lower (50-150m or bottom if shallower) water column from different oceanographic transects and fixed stations from the Atlantic Zone Monitoring Program from 1999 to 2016. The standardized anomalies are the differences between the annual average for a given year and the long-term mean (1999-2010) divided by the standard deviation for each oceanographic section. Each section is identified based on DFO (2017) along with the North Atlantic Fisheries Organization Subareas; the solid line represents the composite index which is the sum of the anomalies for each year. The contribution from each of the section is represented by colour and height of the vertical bar.

Phytoplankton

Chlorophyll inventories in the upper ocean (between 0-100 m), which represent phytoplankton biomass, demonstrated a high degree of year-to-year variability including exceptional values either above or below the long term average (Fig. 2.4.3). The general trend has seen a gradual decline in overall phytoplankton abundance in the Atlantic, with a general decline from 1999 to a minimum in 2011 followed by a gradual recovery to average conditions until 2015 after which most parts of the region had phytoplankton levels well below normal. Conditions were generally below average in 2016 in all regions. Patterns of variation in phytoplankton abundance are generally similar to what we reported for deep nutrient inventories, but they lag behind nutrient variability by about one year. Although the relationship is weak and explains only 23% of the variation in the data, the link between available nutrients and the standing stock of phytoplankton is noteworthy.

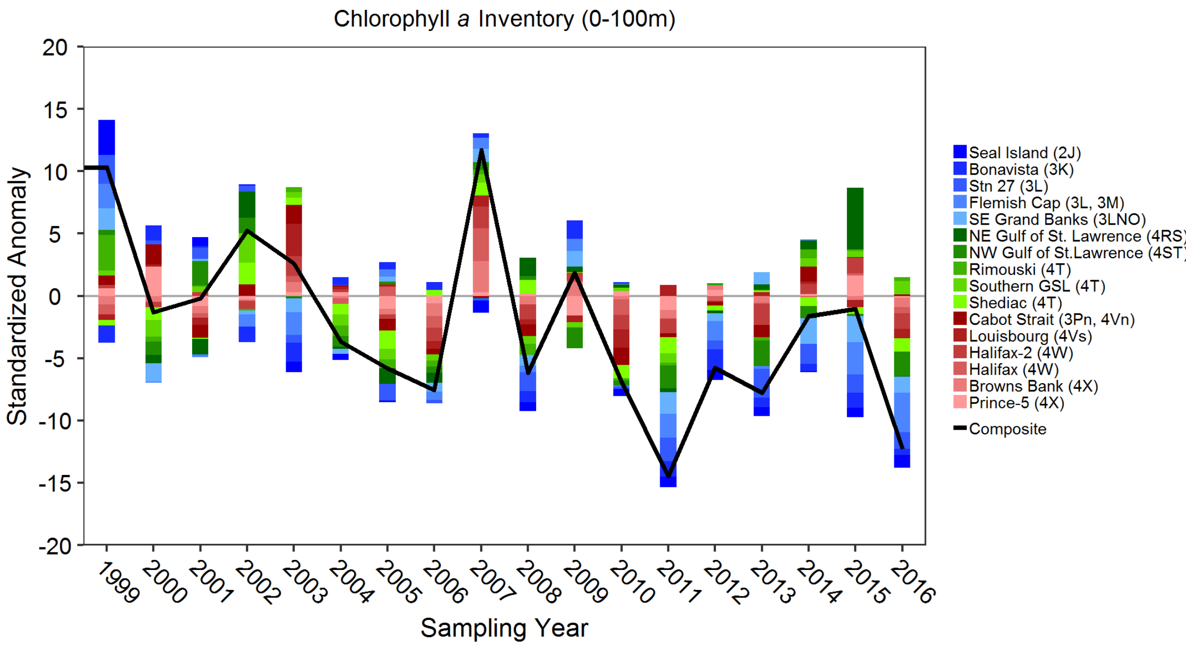

Fig. 2.4.3 Surface chlorophyll inventory. Summary of chlorophyll (a measure of phytoplankton biomass) inventories in the upper (0-100m or bottom if shallower) water column from different oceanographic transects and fixed stations from the Atlantic Zone Monitoring Program from 1999 to 2016. The standardized anomalies are the differences between the annual average for a given year and the long-term mean (1999-2010) divided by the standard deviation for each oceanographic section. Each section is identified based on DFO (2017) along with the North Atlantic Fisheries Organization Subareas; the solid line represents the composite index which is the sum of the anomalies for each year. The contribution from each of the section is represented by colour and height of the vertical bar.

There have been relatively consistent patterns of variation in the features of the spring phytoplankton bloom across the western north Atlantic region (Fig. 2.4.4). The amplitude of the spring bloom increased from 1999 to 2011, when it reached its highest peak, and then declined afterward to an average state by 2016. Spring bloom magnitude, which is not shown, varied in a similar pattern. The day of year at which the bloom reaches its maximum amplitude ("peak time") has been more variable from year to year than the bloom amplitude, shifting from year in which the bloom is generally either early or late relative to the norm over periods of 3 to 5 years. During the very warm 2010-2012period between, spring phytoplankton blooms were early, but the gradual cooling of ocean conditions since then appear to have resulted in a general delay in the onset of the bloom. Duration of the bloom varies greatly among the different parts of the western north Atlantic, but there was a general decline in the overall duration of the bloom from 1999 to 2011 after which average conditions returned to near normal. Many environmental features contribute to the initiation and seasonal progression of the spring bloom, notably the rate of warming, strength of winds, mixing and stability of the water column's density, ice cover extent and duration, as well as the nutritive content of deep water masses. Therefore the features of the bloom in any part of the Atlantic is impacted by the combined effects of broad scale longer term trends in the physical environment and by local or regional conditions that vary on shorter time scales. The variability of the spring bloom parameters (e.g. amplitude, magnitude, timing and duration) will likely have different consequences on other organisms in the Atlantic ecosystem, and these consequences are under investigation.

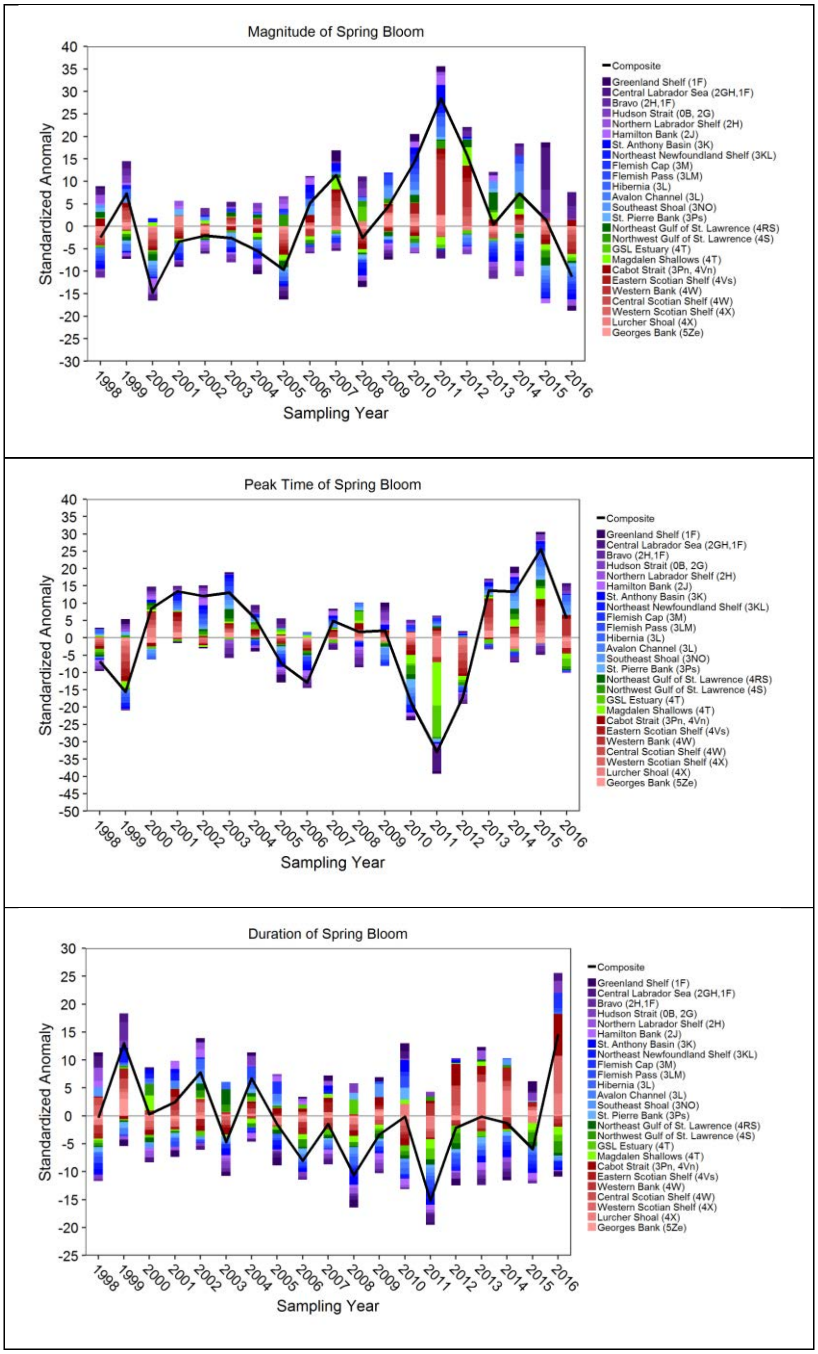

Fig. 2.4.4. Summary of annual ocean colour anomalies from satellite observations across different statistical sub-regions of the Atlantic Zone from 1999 to 2016. The top panel shows the amplitude of the bloom, the middle panel shows the anomalies in the peak time of the bloom, and the bottom panel shows the duration of the spring bloom. The standardized anomalies are the differences between the annual average for a given year and the long-term mean (1998-2010) divided by the standard deviation. The contribution from each of the sub-region is represented by colour and height of the vertical bar. The sub-regions are sorted from open sea to regional shelf regions.

Zooplankton

Zooplankton community structure is strongly influenced by depth, temperature and season, and the complexity of the community differs substantially among the three bioregions of the western north Atlantic. Despite its complexity and diversity in different parts of the region, we have concluded that four indices of abundance provide good indicators of the state of the zooplankton community. Zooplankton abundance indices demonstrate a high degree of large spatial scale coherence in their signal across different parts of the Atlantic zone. Two copepod taxa serve to represent different broad groups with similar life histories: *Calanus finmarchicus* is a large ubiquitous copepod that develops large energy reserves in later developmental stages and is therefore a rich source of food for pelagic fish and a dominant species in terms of biomass throughout much of the region; *Pseudocalanus* spp. are small copepods that are widespread throughout the Atlantic region and that have much smaller energy reserves relative to *C. finmarchicus* but their life history features are generally representative of those of smaller taxa in the copepod community. The other indices provide information on the total abundance of copepods and non-copepod taxa.

A zooplankton community shift has been observed in recent years, characterized by lower abundance of the large energy-rich copepod *Calanus finmarchicus*, higher abundances of small and warm water copepods, and higher abundance of non-copepods (Fig. 2.4.5). The strongest negative anomalies in *C. finmarchicus* occurred on the Scotian Shelf, closest to the southern edge of its range in the Gulf of Maine. In general terms, the abundance of *C. finmarchicus* has been in decline since 2009, as has the abundance of two similar arctic *Calanus* species. In contrast, the abundance of *Pseudocalanus* spp. has demonstrated a general pattern of increase during at least a decade, and despite a drop to very low abundance levels in 2012 has reached record abundance levels throughout much of the Atlantic zone. Total copepod abundances have also increased to higher than normal levels since 2014. Non-copepod zooplankton, which consist principally of the larval stages of benthic invertebrates, carnivorous groups that feed on other zooplankton, and small-particle feeders, were above average throughout the zone, with record high values observed in all three regions since 2014. The strongest positive anomalies in *Pseudocalanus* sp. and non-copepods occurred in the Gulf of St. Lawrence and the Newfoundland Shelf, and total copepod positive anomalies were strongest on the Newfoundland and Labrador shelves and in the Gulf of St. Lawrence. Overall, recent changes in zooplankton community structure indicate that important shifts in the flow of energy among lower trophic levels of the marine ecosystem in the Canada's Atlantic waters are taking place, but the consequences to higher trophic levels will require further investigation.

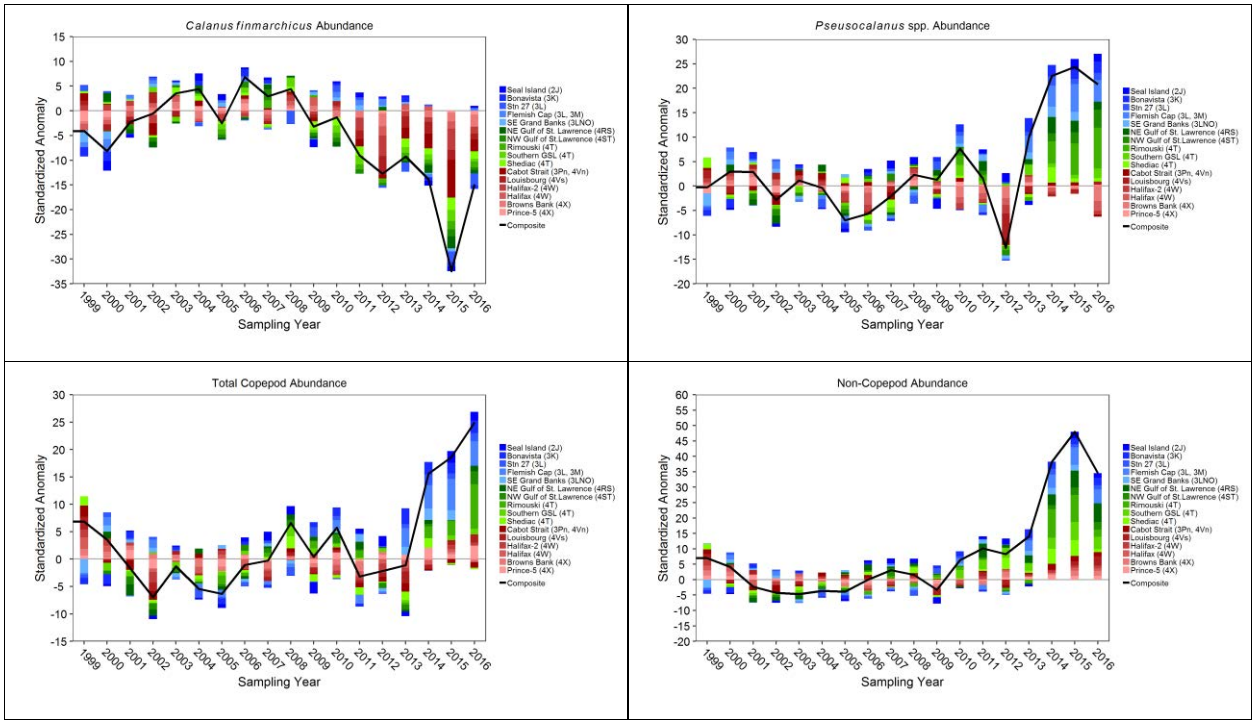

Fig. 2.4.5. Time series of dominant copepods *Calanus finmarchicus* (upper left panel), *Pseudocalanus* spp. (upper right panel), total copepod (lower left panel) and non-copepod (lower right panel) abundance anomalies from different oceanographic transects and fixed stations from the Atlantic Zone Monitoring Program during 1999-2016. The standardized anomalies are the differences from the long-term mean (1999-2010) divided by the standard deviation. The contribution from each section is represented by colour and height of the vertical bar. The solid black line is the cumulative (composite) anomaly across all sections in a given year.

Conclusion

The Northwest Atlantic is currently in a warm phase but there are spatial differences in the short term trends at the surface. There is a general zonal decline in nutrient inventories that appears to be mirrored in chlorophyll standing stock, with the strongest correspondence on the Grand Banks. Changes in the features of the spring phytoplankton bloom have trickle-down consequences to zooplankton productivity (not shown) but the dominant effect is associated with the timing of the spring bloom (and hence temperature cycles). Zooplankton community structure is shifting; large energy-rich copepods are in decline and small copepods and non-copepods demonstrated substantial increases in abundance.

Overall, there appear to have been important changes in general patterns of productivity of lower trophic levels in the last 5 years. General declines in nutrient and chlorophyll inventories may be indicative of lower ecosystem production potential than in the previous decade and the shift in zooplankton community structure from large lipid-rich copepods to smaller taxa may have consequences to the transfer efficiency from primary producers to upper trophic levels. Although there is an association of large–scale changes in nitrate inventories with changes in phytoplankton biomass across the zone, understanding variations in zooplankton abundance have been less clear and do not follow simple functional relationships.

ii) Update on the status and trends of the fish community in the Newfoundland and Labrador Bioregion

Introduction

The Newfoundland and Labrador (NL) bioregion has a long history of fishing, and in the early 1990s underwent important changes associated with overfishing and a regime shift.

The ecosystem structure of this large marine ecosystem can be described in terms of four Ecosystem Production Units (EPUs): the Labrador Shelf (2GH), the Newfoundland Shelf (2J3K), the Grand Bank (3LNO), and southern Newfoundland (3Ps). Although there is limited information on trends in the fish community in the most northerly EPU, regular Research Vessel (RV) surveys are conducted in the others. This analysis describes changes and trends in the fish community in these ecosystems (Fig.. 2.4.6) on the basis of DFO RV Fall and Spring multispecies surveys.

Trends were summarized by fish functional groups defined in terms of general fish size and feeding habits: small, medium, and large benthivores, piscivores, plank-piscivores, planktivores, and shellfish (only commercial species, recorded since 1995).

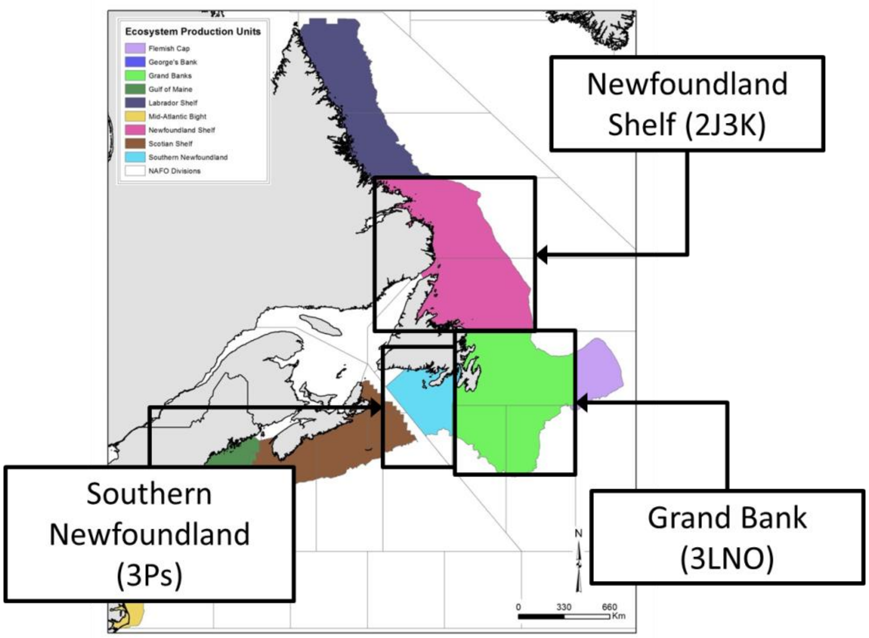

Fig. 2.4.6. Ecosystem Production Units (EPUs) in the Newfoundland and Labrador (NL) Bioregion considered in this summary: the Newfoundland Shelf (2J3K), the Grand Bank (3LNO), and southern Newfoundland (3Ps).

Newfoundland Shelf (2J3K)

In 2J3K, the collapse in the 1990s involved the entire fish community, and also involved a decline in fish size. After the collapse, the system was highly dominated by shellfish (Fig. 2.4.7). The changes observed have a coherent internal structure; increases in small fish and shellfish are associated with declines in forage and large fishes (Fig. 2.4.8). Consistent signals of rebuilding of the groundfish community appeared in the mid-late 2000s; this signal is also associated with an increase in fish size. In the 2010s the overall biomass remained relatively stable, but the dominance of groundfishes increased, and shellfish decreased. After 2014 overall biomass has shown some hints of a decline (Fig. 2.4.7), while several functional groups are showing consistent signals of declines in abundance (Fig. 2.4.9).

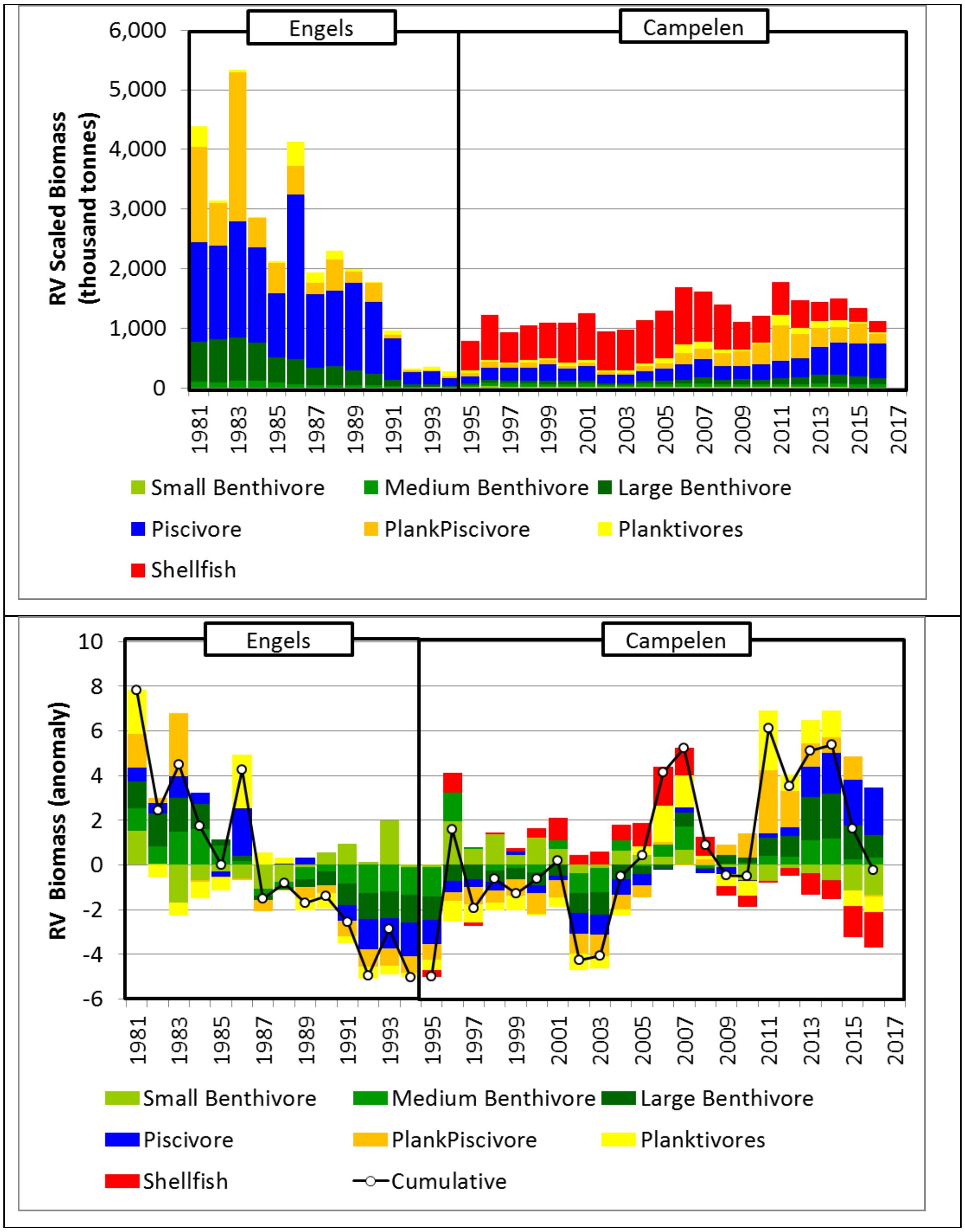

Fig. 2.4.7. RV Biomass by fish functional groups in the Newfoundland Shelf (NAFO Divs 2J3K) from DFO RV Fall multispecies survey. **Top**: Scaled RV biomass where the earlier part of the time series, when the survey used the Engels gear, has been corrected using coarse scaling factors by fish functional group. These scaling factors are only approximate. Data on commercial shellfish species only started to be consistently recorded during the Campelen period. **Bottom**: Cumulated normalized anomalies of RV Biomass by fish functional groups. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

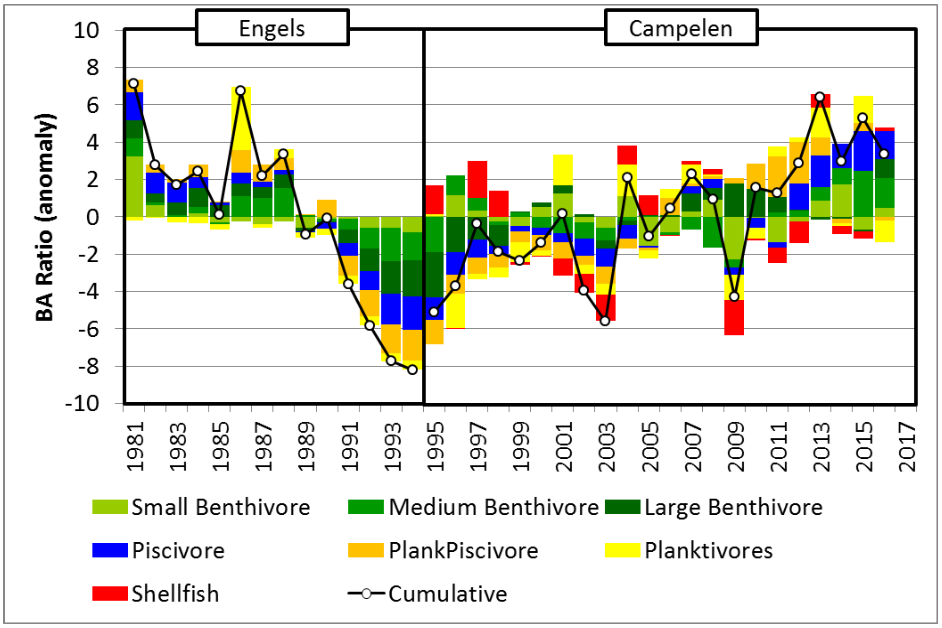

Fig. 2.4.8. Cumulated anomalies for the RV Biomass/Abundance (BA) Ratio by fish functional groups in the Newfoundland Shelf (NAFO Divs 2J3K) from DFO RV Fall multispecies survey. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

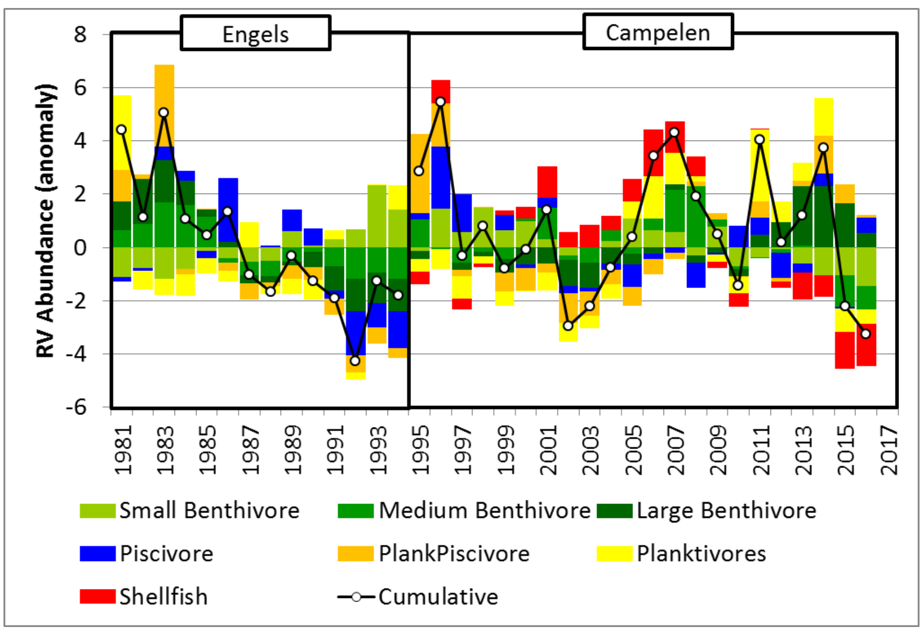

Fig. 2.4.9. Cumulated anomalies for the RV Abundance by fish functional groups in the Newfoundland Shelf (NAFO Divs 2J3K) from DFO RV Fall multispecies survey. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

Grand Bank (3LNO)

In 3LNO the collapse in the 1990s also involved the entire fish community, and a decline in fish size (Figs. 2.39 and 2.40), but it was not as severe are in the northern area. This EPU shows a higher dominance of benthivores, and it was never dominated by shellfish. The groundfish community started to show signals of rebuilding around the late 2000s, but piscivores did not regain their dominant role. Overall build-up of groundfishes was initially led by medium benthivores and later by plank-piscivores (Fig. 2.39). In the early 2010s the overall biomass remained relatively stable, but clear signals of decline have been observed in recent years, with total biomass in 2016-2017 showing a reduction of 30-40% from the early 2010s (Fig. 2.39).

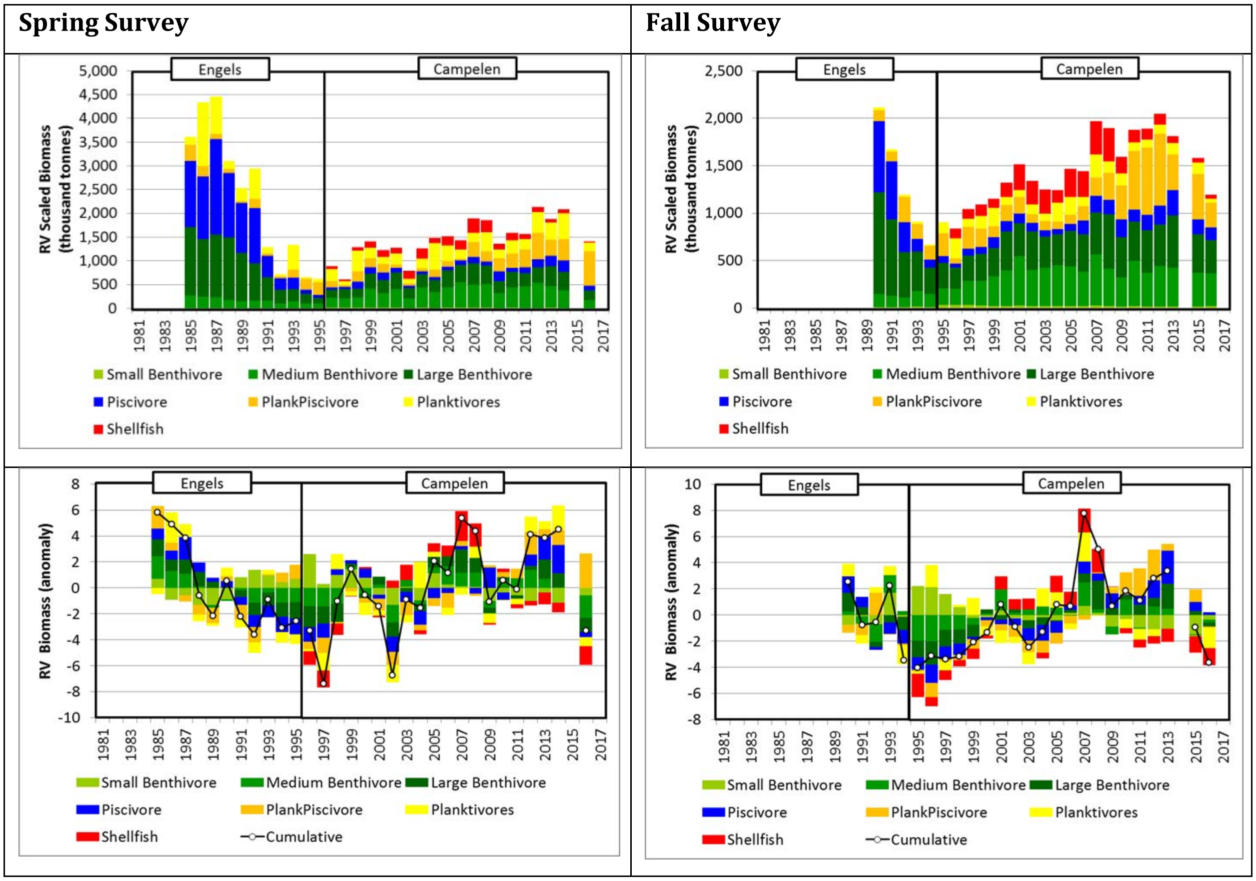

Fig. 2.4.10. RV Biomass by fish functional groups in the Grand Bank (NAFO Divs 3LNO) from DFO RV Spring and Fall multispecies surveys. **Top**: Scaled RV biomass where the earlier part of the time series, when the survey used the Engels gear, has been corrected using coarse scaling factors by fish functional group. These scaling factors are only approximate. Data on commercial shellfish species only started to be consistently recorded during the Campelen period. **Bottom**: Cumulated normalized anomalies of RV Biomass by fish functional groups. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

Although there was a upward trend in fish size in the late 1990s and early 2000s, fish sized has declined since, and has oscillated around the post-collapse average since the late 2000s, showing low values in the most recent years (Fig.. 2.4.11). The recent declines in total biomass and reduced fish sizes is also matched by reduced abundances, with most functional groups showing negative anomalies in 2015-2016 (Fig.. 2.4.12). Other change observed during this period is an increase in silver hake (warm water species) among piscivores (especially on the western portion of the Grand Bank, NAFO Div. 3O), and declines in key forage species (e.g. capelin).

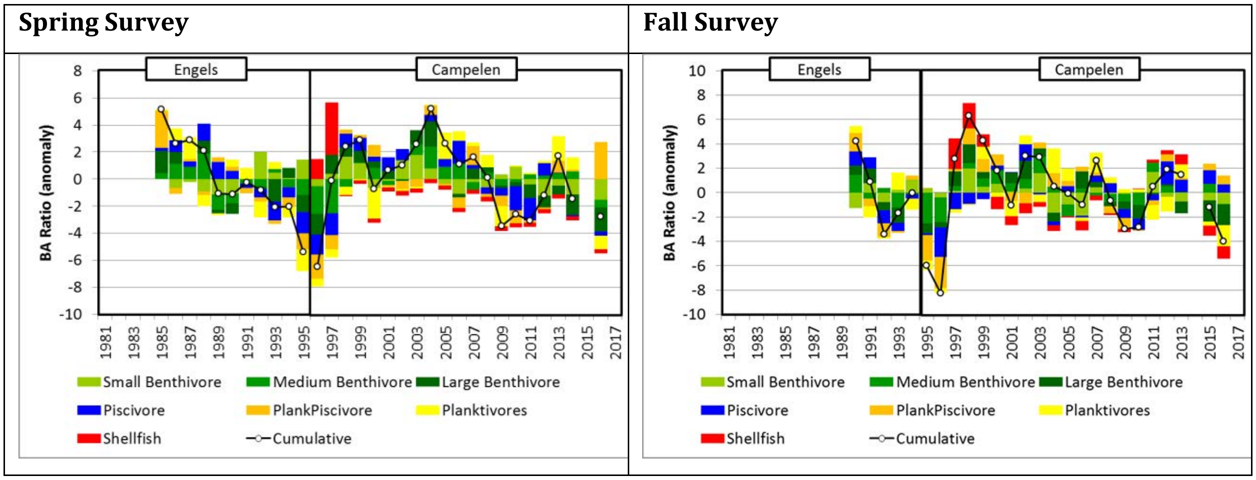

Fig. 2.4.11. Cumulated anomalies for the RV Biomass/Abundance (BA) Ratio by fish functional groups in the Grand Bank (NAFO Divs 3LNO) from DFO RV Spring and Fall multispecies surveys. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

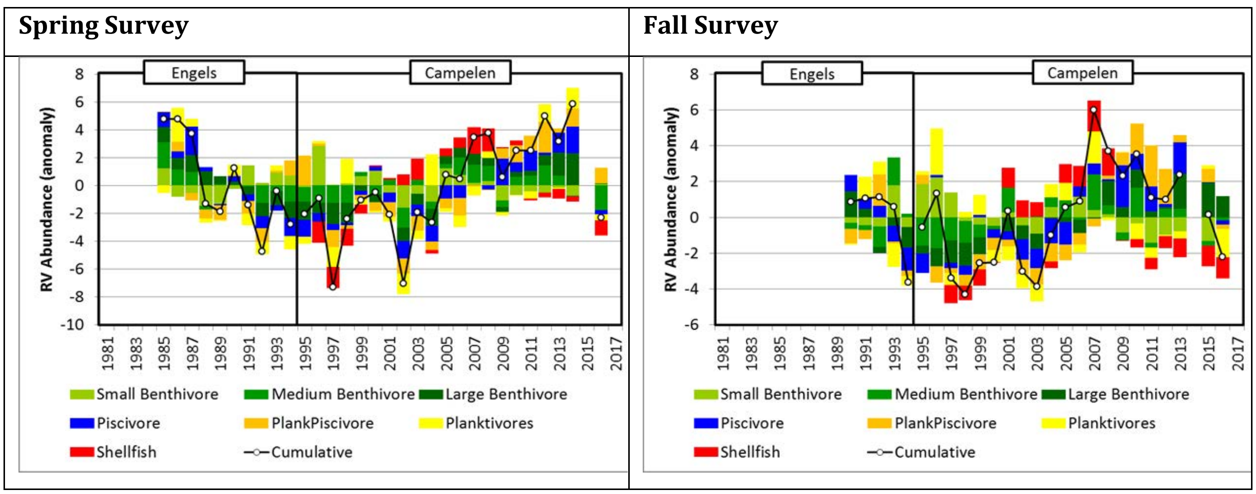

Fig. 2.4.12. Cumulated anomalies for the RV Abundance by fish functional groups in the Grand Bank (NAFO Divs 3LNO) from DFO RV Spring and Fall multispecies surveys. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

Southern Newfoundland (3Ps)

The decline in the 1990s also involved the entire fish community and included reductions in fish size (Fig.s 2.4.13 and 2.4.14). The overall decline seemed less severe than other ecosystem units in this bioregion. Since the mid-late 1990s, the overall biomass of the fish community has not increased significantly, but abundance did (Fig.. 2.4.15). However, both biomass and abundance after 2014 have shown reduced levels in comparison to immediately precedent years (Fig.s 2.4.13 and 2.415).

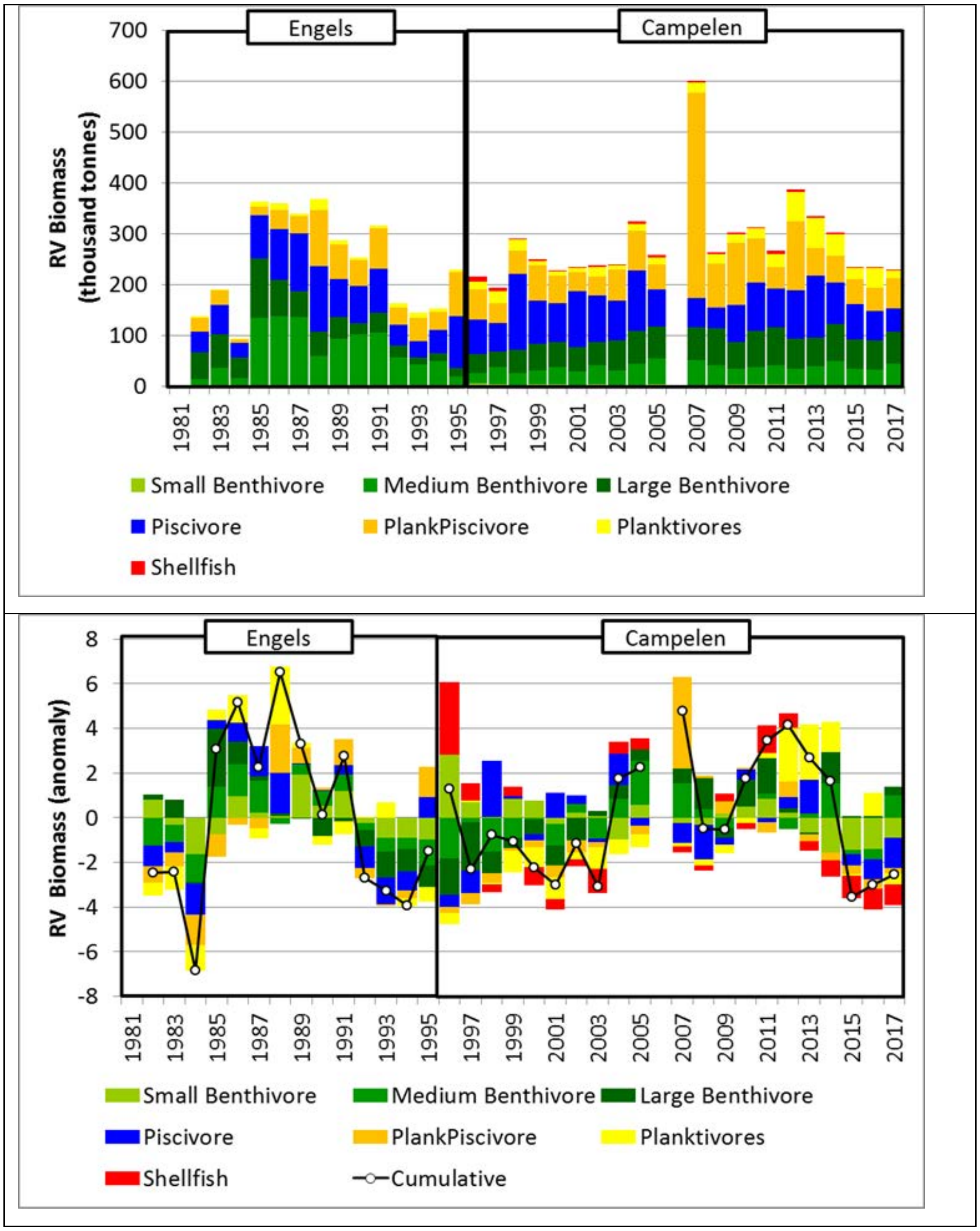

Fig. 2.4.13. RV Biomass by fish functional groups in Southern Newfoundland (NAFO Sub-Div. 3Ps) from DFO RV Spring multispecies survey. **Top**: RV biomass within indication of the periods where different gears were used in the survey (Engels and Campelen); magnitudes between gear periods are not directly comparable. Data on commercial shellfish species only started to be consistently recorded during the Campelen period. **Bottom**: Cumulated normalized anomalies of RV Biomass by fish functional groups. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

Average fish size did not improve in the post collapse period, but showed a further decline in the mid 2000s, and still remains at that lower level (Fig. 2.4.14).

Ongoing warming trends, together with the increasing dominance of warm water species (e.g. silver hake), and the reduced fish sizes across fish functional groups suggest that this ecosystem is undergoing structural changes, and potentially experiencing reduced productivity conditions.

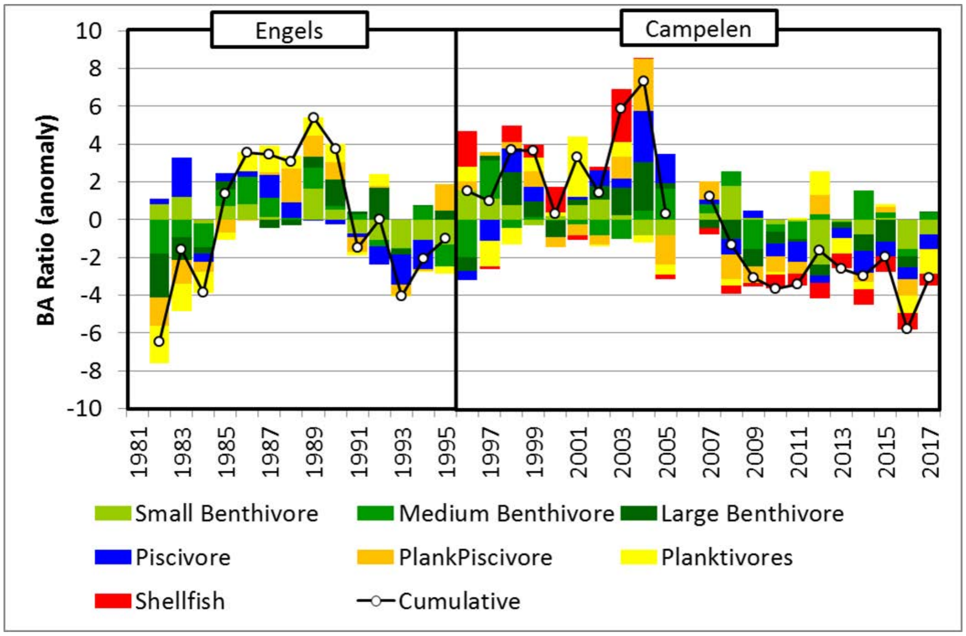

Fig. 2.4.14. Cumulated anomalies for the RV Biomass/Abundance (BA) Ratio by fish functional Southern Newfoundland (NAFO Sub-Div. 3Ps) from DFO RV Spring multispecies survey. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

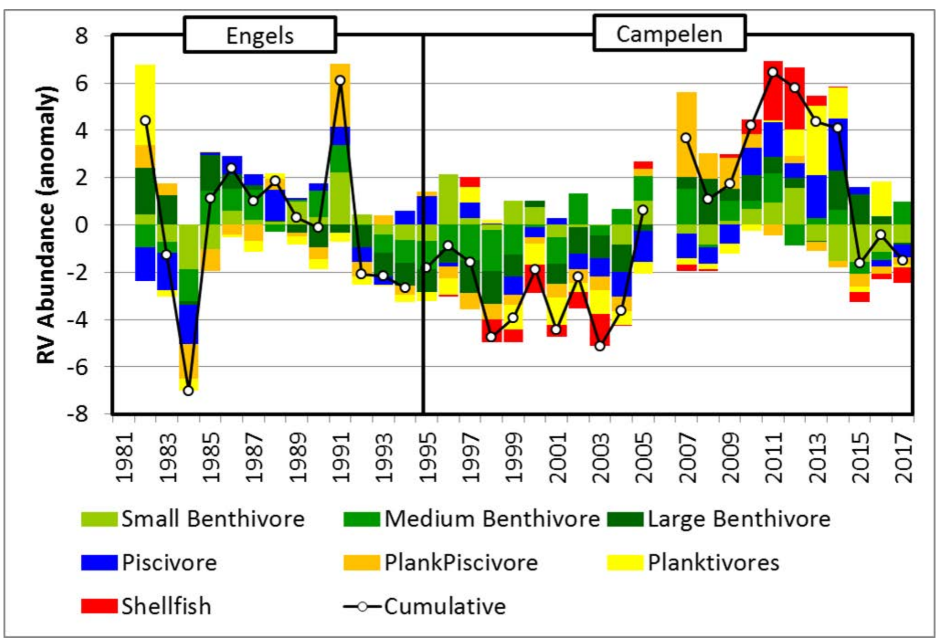

Fig. 2.4.15. Cumulated anomalies for the RV Abundance by fish functional groups Southern Newfoundland (NAFO Sub-Div. 3Ps) from DFO RV Spring multispecies survey. Normalization was done within each gear period (Engels and Campelen); magnitudes of the anomalies are not directly comparable.

Synoptic comparison across EPUs

Overall, the collapses in the 1990s involved entire fish communities, and included declines in fish size across all EPUs. The collapse was more severe are in the north, and less in the southern Newfoundland region. These collapses were accompanied by changes in community structure. Shellfish became a dominant functional group in 2J3K after the collapse, but although increased its dominance in other ecosystems, never reached the overwhelming dominance observed in the northern region (Fig.. 2.4.16).

The groundfish community started to show signals of rebuilding during the mid-late 2000s, but current levels are still well below pre-collapse level. The functional groups leading the groundfish rebuilding were not the same across ecosystems; piscivores are important drivers in the northern area, but they have a lesser role in southern ecosystems (Fig.. 2.4.16).

After initial build-ups, finfish biomass was relatively stable in 2010-2014, but recent surveys are indicating a downward trend. This is clearly evident on the Grand Bank (3LNO) EPU. Overall, it appears that the conditions that led to the start of a rebuilding have withered. This may be linked to the simultaneous reductions in capelin and shrimp availability, as well as other changes in ecosystem conditions (e.g. declines in zooplankton levels in recent years).

Silver hake, a warm water species, is increasing its dominance among piscivores. They have become a major component of this functional group in 3Ps, and are increasing in the Grand Bank. This may hint of the changes to be expected under warming conditions; the full extent of these kinds of impacts on these ecosystems remains largely unknown.

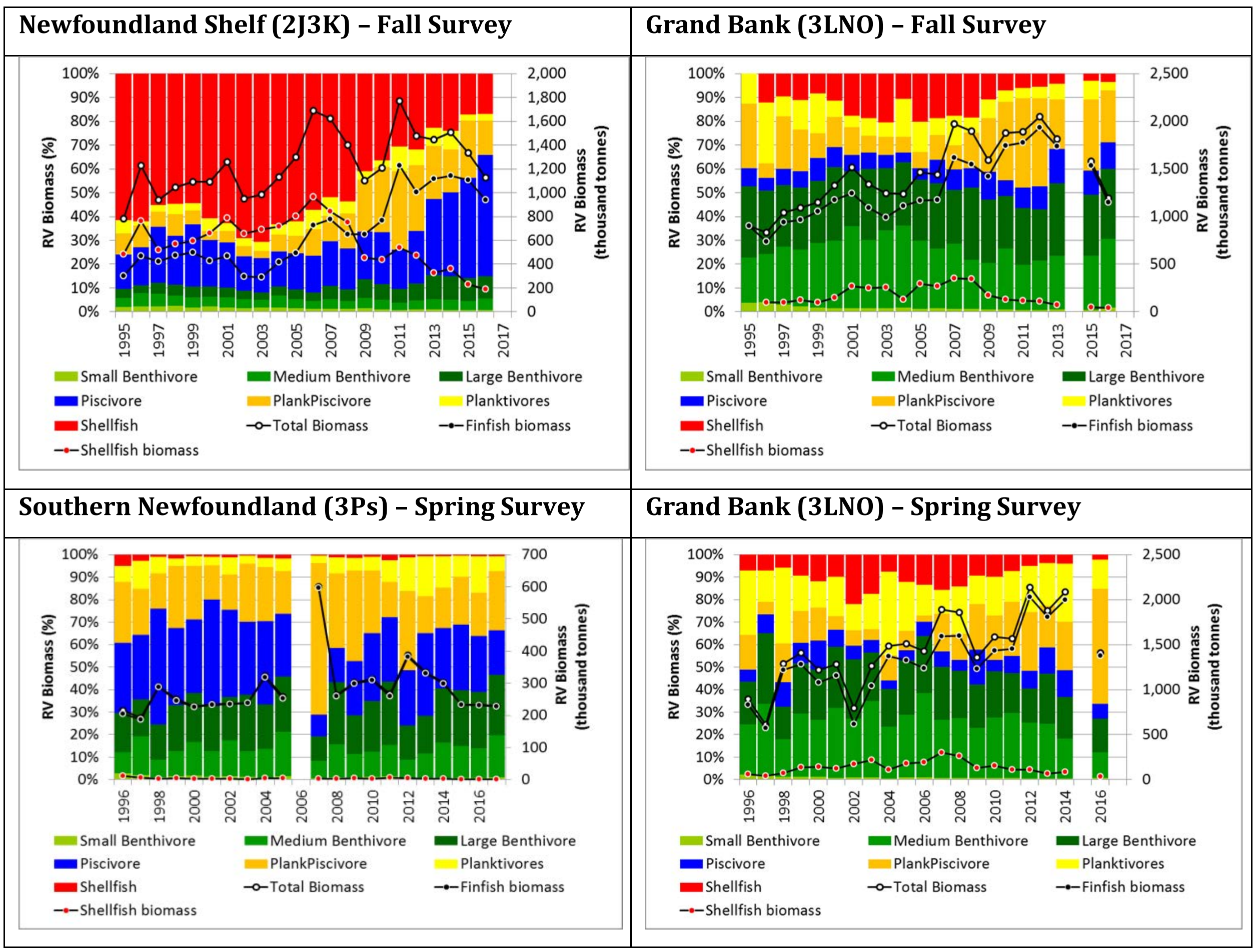

Fig. 2.4.16. Synoptic comparison of the structure and trends in the fish communities during 1995-2017 among three NL Bioregion EPUs: the Newfoundland Shelf (2J3K), the Grand Bank (3LNO) and Southern Newfoundland (3Ps).

iii) Identifying optimal sets of ecosystem indicators:

A comparative study of data analysis methods and regional results

Scientific advice for ecosystem based fisheries management requires information on the marine ecosystem, which can be provided by data-based indicators of the fish community as well as environmental and fishing pressures. Significant effort has focused on selecting the most useful biological indicators, but there has been less assessment of pressures. A brief overview of an on-going research project with the goal of identifying which sets of pressure indicators can best model changes in the fish communities of the Grand Bank and Georges Bank is provided here.

The Grand Bank (NAFO division 3LNO) experienced significant changes over the past several decades, including a collapse of fish biomass and subsequent restructuring of the community. In the first phase of the project, a suite of 40 ecological indicators that reflect these changes was synthesized from various sources and published (Dempsey et al., 2017). Correlations showed that relationships among fish functional groups changed after the collapse, and that a subset of indicators sufficiently characterized each indicator category. Lagged correlations highlighted that changes in the pressures are often not immediately manifest in the fish community. Indicators were also organized into the driver-pressure-state-impact-response framework, which illustrated that indicator categorization is contextual and not straightforward (Dempsey et al., 2017).

In the second phase, multivariate multiple linear regression was used to select sets of pressure indicators (including delay lengths and types) that most directly influence the Grand Bank fish community (Dempsey et al., in press). All possible subsets of 9 fishing and environmental indicators (identified in Phase 1) were evaluated as predictors of the fish community structure (represented by the biomasses of 6 functional groups), for Before (1985 – 1995) and After (1996 – 2013) the collapse of biomass, and the Full time series. The analysis was repeated with different lengths (0 to 5 years) and types (moving average vs. lags) of time delays imposed on the predictors. Both fishing and environmental indicators were included in the best models for all types and length of time delays, reinforcing that there is no single type of pressure impacting the fish community. Results show notable differences in the most influential pressures Before and After the collapse, which reflects the changes in harvester behavior in response to the groundfish moratoria. Moving average predictors generally had higher explanatory power than lagged sets, implying that trends in pressures are important for predicting changes in the fish community.

In Phase 3, a similar analysis will be conducted using neural networks (NN) to evaluate how the above results change when the statistical model does not presume linear relationships. NNs are a type of machine learning that implicitly models non-linear relationships. Preliminary results show that explanatory power can be improved using NN, and that there is potential for using this method to forecasting trends in the fish community on medium-term time scales.

The final phase of the project will be a regional comparison to test the generality of the results and conclusions. Key analyses will be repeated for the Georges Bank, Gulf of Maine ecosystem, which has also experienced complex ecological changes over the past several decades. Results will be compared to those for Grand Bank (e.g. explanatory power and most frequent pressure), and used to gain insight on these regions and indicator sets (e.g. evidence for generic or ecosystem-specific sets).

iv) European Union SC02 project: Selecting ecosystem indicators for fisheries targeting Highly Migratory Species HMS.

The Specific Contract No. 2 under Framework Contract EASME/EMFF/2016/008 provisions of Scientific Advice for Fisheries Beyond EU Waters started on the 14th of December 2016, the day the contract was signed. As per Terms of Reference, the overall duration of the project is 18 months. The contract will be conducted by several partners (AZTI, AGROCAMPUS, CEFAS, IEO, IPMA, WMR, IRD, MRAG).

The purpose of this specific study is providing a list of ecosystem indicators (and guidance for associated reference points) to monitor impacts of fisheries targeting Highly Migratory Species (HMS), as well as a set of criteria and guidelines to choose ecological regions with meaningful ecological boundaries for HMS and its fisheries in order to facilitate the operationalization an EAFM in marine pelagic ecosystems. An integrative framework and an EAFM plan using two ecoregions as case studies within the International Commission for the Conservation of Atlantic Tunas (ICCAT) and Indian Ocean Tuna Commission (IOTC) convention areas. This EAFM plan will facilitate the linkage between ecosystem science and fisheries management and will include a selection of indicators and guidance to set reference points to monitor the impacts of fisheries targeting HMS on all ecological components of the ecosystem and will suggest potential management actions to be activated when necessary. Recommendations to better link ecosystem indicators and management to foster the implementation of an EAFM.

The main up-to-date results of the SC02 project were presented, setting the focus on task 1, 2 and 4 in relation to selection of ecosystem indicators, defining a guidance to set reference points and a framework to facilitate the transference of information from the selected ecosystem indicators to managers and stakeholders.

Selection of ecosystem indicators (tasks 1 and 2):

As a first step in the selection of indicators an extensive review of management organizations and projects dealing with the use of ecosystem indicators was addressed:

Areas:

- North Pacific Fishery Management Council (NPFMC)
- Conservation of Antarctic Marine Living Resources (CCAMLR)
- Northwest Atlantic Fisheries Organization (NAFO)

Projects:

- Indicators for the Seas: IndiSeas
- Marine Strategy Framework Directive (MSFD) – Indicators of Good Environmental Status (GES)
- DEVelopment Of innovative Tools for understanding marine biodiversity and assessing good Environmental Status - DEVOTES

From this review work a total number of 200 ecological indicators were pre-selected, as well as good practices and lessons learned in these areas/projects. However, after a first screening this initial list was reduced to 32 indicators, excluding others that were conventional single species indices or not ready for further consideration. The subset investigated: related to target species, bycatch and threatened species (marine mammals, seabirds, sharks and turtles), pelagic habitats (plankton indicators), and trophic relationships (seabirds and primary production). Next the set of criteria defined by (Queirós et al. 2016) were applied to this shortened list of indicators in order to score and decide a final list of indicators. These criteria were: scientific basis, ecosystem relevance, responsiveness to pressure, possibility to set targets, precautionary capacity/early warning, quality of sampling method, cost-effective, existing and ongoing monitoring programme.

Design of a guidance to set reference points (Task 4.1)

Although the number of indicators have increased remarkably in the last years there is a lack of clear methodologies to estimate reference points (indicator value that can represent a limit or a target management point). As part of the work developed in SC02 a guidance on how reference points can be set and used in association with the selected indicators has been designed.

Based on the literature review in the previous section, a rule-based decision tree has been developed in SC02 project (Fig. 2.4.17) that steps through the various options to set reference points for ecosystem indicators. Data availability and the knowledge of the process(es) being assessed are key to determine which methodology is applicable. The framework presented by (Samhouri et al. 2012) was taken as the basis to create a general decision tree that incorporates the methods proposed by (Rossberg et al. 2017), (Probst et al. 2013, Probst and Stelzenmüller 2015) and (Shephard et al. 2015). This guideline is designed with the intention to track a route that does not necessarily scale the different options in a better-to-worse situation, but should be considered as a framework to organize the different options available depending on the model reliability, data availability, quality of time series, etc.

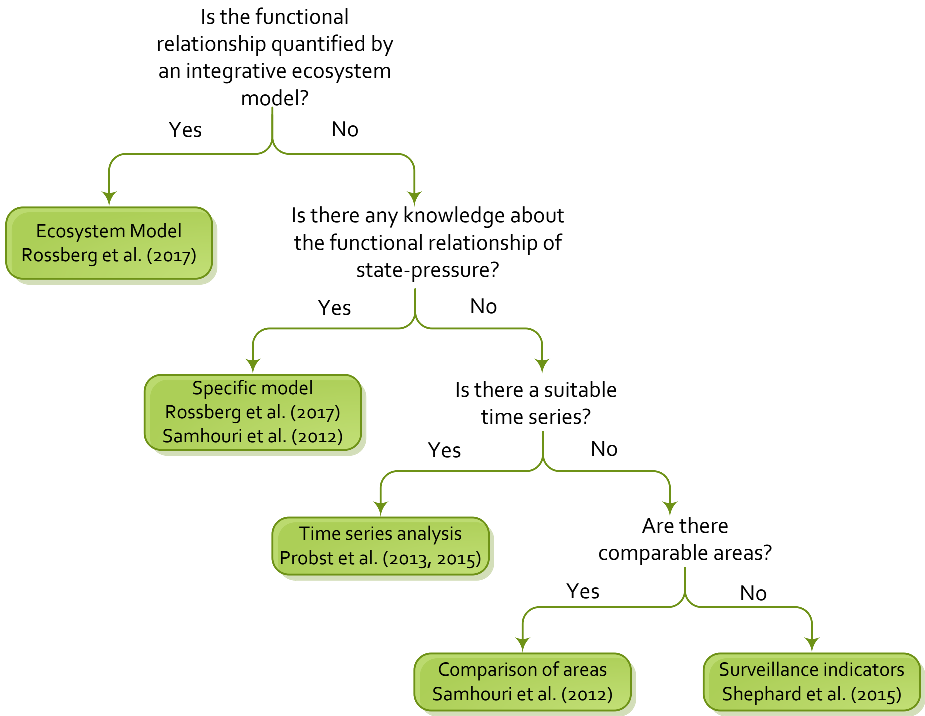

Fig. 2.4.17. Guidance to estimate reference points for ecosystem indicators

All three different approaches (functional relationship, time series and spatial comparison) are potentially equally useful to define reference points, and have to be critically evaluated before considering as the selected alternative for setting reference points. Having an ecosystem model does not necessarily mean that is should be used to estimate reference points for a given ecosystem indicator if there are doubts about the credibility of the output. Furthermore, having an ecosystem model (even if it is known to produce reliable results) does not preclude of using time series if they are available, and estimating reference points using the two methods. The same applies for the spatial comparison approach. Indeed, the best option would be to determine reference points from each of the possible methods and compare the findings.

Developing a framework to transfer information to the management procedure (Task 4.2)

After selecting the proper set of indicators and defining the guidance to set the reference points, one fundamental question within SC02 was exploring potential frameworks to transmit the information from ecosystem indicators and fisheries stock assessments so it can be better incorporated into the management decisions-making process.

As a first step, different areas and projects developed around the world were explored, compiling information from various reports:

- North Pacific Fishery Management Council NPFMC (NPFMC 2007a, b, 2014)
- Conservation of Antarctic Marine Living Resources CCAMLR
- Ocean Health Index Project OHI (Halpern et al. 2012)
- NEAT-DEVOTES (Berg et al. 2017, Borja et al. 2017)

The final framework selected as candidate was a multilayer approach, where each tier has a different degree of synthesized information and scope:

1. A synthesizing component to summarize the information of all or groups of indexes in a single or few numerical values, intended to be a first and easy approach to the ecosystem state:

a) Structuring and synthesis based on the method developed in the OHI, which integrates state, trend, pressure and resilience at the cost of a high complexity and potentially important assumptions. In addition there is a lack of a developed software to apply this index.
b) Structuring and synthesis based on NEAT, in which the synthesis is carried out only in terms of status, and the pressure is evaluated in the same way as the state indicators. The software NEAT would be used to perform the analysis.

2. An ecosystem report card in which the result of the integrated analysis in the previous tier is presented in an amenable and simple way, together with a selection of indicators for which the time series would be displayed and the values with respect to the reference values as well as the values trends in the last five years. The latter would be of special relevance in the case of using NEAT as a synthesizing tool.

3. An ecosystem assessment in which all the analysis developed for all the indicators and presented in the ecosystem report card is explained in detail. Analysis, results and discussions.

4. A Fisheries Ecosystem Plan FEP for each of the managed ecoregions as a way to formalize and strengthen the delivery of ecosystem information to the Scientific Council and to provide a transparent tool for evaluating emergent trade-offs between conflicting management objectives. The FEPs should include an ecosystem overview describing and integrating the existing research and information about the main physical, ecological and socio-economic components of the ecosystem and their interactions. It is also convenient including a conceptual model of the ecosystem and an ecosystem risk assessment which allows the identification of key ecosystem interactions that examined the ecological and economic impacts of the different commercial activities on the regions. These products provide general guidance to the Council on priority areas and issues for management attention and further research and analysis (NPFMC 2007a). The FEP also intends to be an educational tool and a resource for the Council and any other interested stakeholders which synthesizes the ecosystem context for fishery management decisions (NPFMC 2007b).

The presentation of the SC02 project and up to date results was very welcomed by WG-ESA, and it was considered to provide a good comprehensive perspective that would be very supportive in the discussions for the development of an Ecosystem Summary Sheet for the different Ecosystem Production Units EPU in the NAFO area. Some concern was expressed in relation to the applicability of the OHI to the NAFO area, as well as regarding the lack of coherence across the different elements of this framework in relation to the ecosystem indicators covered by the OHI, the NPFMC or the NEAT. It was then clarified that what it is important in this exercise is the framework itself, the goal is not the specific content or the exact ecosystem indicators utilized but the general framework. The final content in terms of ecosystem indicator and goals should be adapted to the area where this framework wants to be applied.

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THEME 3: PRACTICAL APPLICATION OF EAFM

ToR 3. Update on recent and relevant research related to the application of ecosystem knowledge for fisheries management in the NAFO area.

Tor 3.1. Development and application of the EAF Roadmap

NAFO's revised Convention highlights a commitment to the implementation of an Ecosystem Based Approach to Management (EAM). The process and guiding principles that NAFO is following to achieve this goal is summarized in the organization's "Roadmap for developing an Ecosystem Approach to Fisheries for NAFO" (Roadmap). The current representation of the Roadmap (Fig.. 3.1.1) provides an operational perspective of how the Ecosystem Approach to Fisheries (EAF) is being conceived in a work-flow process that suits NAFO structure and practices. This schematic incorporates the hierarchical approach to define exploitation rates, and integrates the impacts on benthic communities (e.g. Vulnerable Marine Ecosystems –VMEs-) associated with the different fisheries that take place within the ecosystem. The Roadmap is not a fixed plan; as its name indicates, it is a guiding set of ideas whose details evolve as it is developed and implemented.

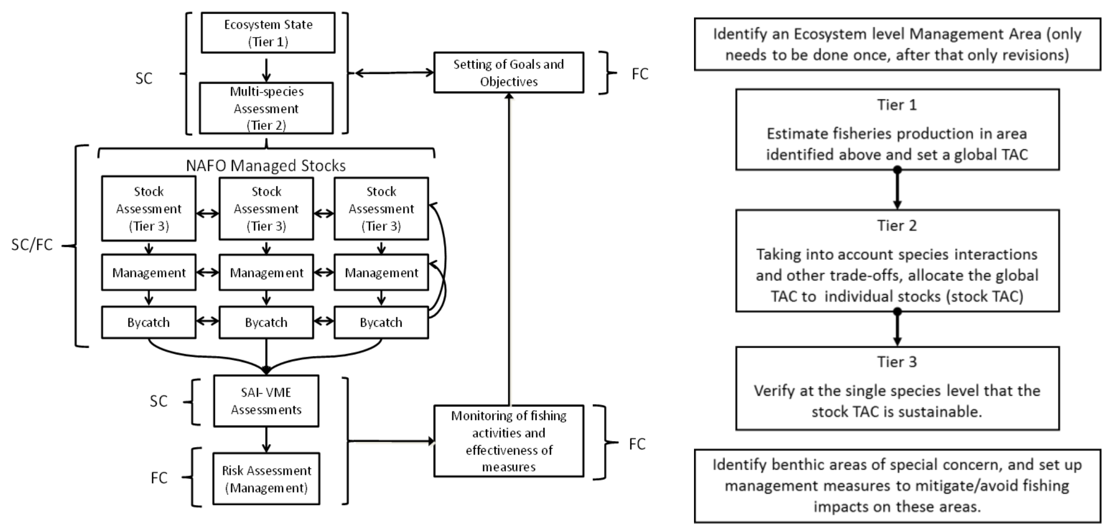


Fig. 3.1.1 Current working template of the NAFO "Roadmap" (left), with a synoptic overview of the key steps required for using it (right). SC: Scientific Council, FC: Fisheries Commission, SAI: Significant Adverse Impact, VME: Vulnerable Marine Ecosystem

To date, WG-ESA has made significant progress in several areas of the Roadmap. The identification and delineation of areas with significant concentrations of VMEs has been thoroughly documented and information is being continuously added to the knowledge base, procedures to improve the delineation process are being developed and refined, and a comprehensive assessment of the potential interaction between VME and fishing activities is being developed (see other parts of this report). In addition, WG-ESA has defined Ecosystem Production Units (EPUs) within NAFO Regulatory Area (NRA), demonstrated the robustness of the delineation of ecosystem elements to changes in information content ecoregions (EPUs) within broad biogeographic setting which are essentially consistent with the separation of major fish stocks despite some overlap and exchange among EPUs for some stocks.

There has also been considerable progress on development of tiered modelling approaches to investigate ecosystem production potential (EPP – Tier 1) and multispecies interaction (Tier 2). EPP models provide a good representation of energy flow through key functional ecosystem components and the research conducted to date provides a comprehensive assessment of reliance of predictions on food web complexity/structure. Section 3.1.1 highlights how EPP estimates of Total Catch Ceilings (TCC) should represent an essential foundational element that delimits overall production potential of higher trophic levels among all EPUs given that currently there have been no alternate approaches have been put forth to set ecosystem level reference points. The WG-ESA **recommends** that *NAFO set operational objectives to guide the implementation of an EAM*.

Section 3.1.1 aims to provide limits of certainty of TCCs under alternate exploitation scenarios, develop operational guidelines for application of TCCs to decision-making, and how they should be linked to reports developed in the Ecosystem Status Sheets.

There has also been considerable progress in development of environmental and multispecies (EMS) models in the past activities of WG-ESA (References to GADCAP; GoM/GB multi-model inferences; drivers of production on NL shelf stocks). However, there has yet to be a case study in which the output from an EMS model has been applied in the provision of advice for a specific stock or stocks. Following discussion of the various modelling approaches (sections 2.3…) that could serve to information NAFO, the WG identified two paths by which to move the application of EMS modelling forward. First, WG-ESA **recommends** *application of the model by Perez-Rodriguez et al. (2017) that describes cod-redfish-shrimp-fishery interactions for the Flemish Cap EPU (3M) (GADCAP) o inform the single species stock assessments when any of the 3M stocks are next assessed.* The model, and ongoing developments and improvements, will be presented and discussed as part of the benchmark review of the 3M cod assessments, but it is essential that the insights that can be derived from that model be part of assessment procedures for 3M during the June 2018 meeting of SC. Furthermore, a comparison of the inferences from GADCAP should be contrasted with those that can be derived from the simpler Lotka-Voltera model (REF) developed for cod-redfish-shrimp in 3M. Second, discussions centered on presentations of alternative modelling approaches available to NAFO identified the need to complete the development of two multispecies/ecosystem models for the Grand Bank EPU (3LNO). The outcome of ongoing modelling based on Ecopath with Ecosim (EwE), as part of the CoArc project (A transatlantic innovation arena for sustainable development in the Arctic) (A. Bundy and J. Tam, with others) should be reviewed by WG-ESA in November of 2018. In addition, a minimum realistic multispecies model (M. Koen-Alonso) should be implemented for the EPU and reported on at the same meeting. These two relatively simple modelling frameworks should serve to inform our understanding of the influence of changes in of finfish and invertebrate community structure on regional productivity and exploitation potential and provide a basis to identify research needed to further evaluate the importance of multispecies interactions on the provision of advice in single species stock assessments.

The case studies of EMS modelling application to EPUs 3M and 3LNO will the consequences of ecosystem-level considerations on single species advice. In order to make progress on either of these case studies, however, two important sources of reliable data have to be provided to the investigators involved in the research. First, a reliable source of catch data, consistent with those considered appropriate for the annual stock assessments must be made available from SC because concerns have been expressed about the reliability of data derived from STATLAN 21B. Furthermore, the data from the EU surveys in 3M will need to be made available for the model intercomparison.

Therefore**,** WG-ESA **recommends** that *the catch and survey data series used by SC for stock assessments should be made available to WG-ESA for use in multi-species modeling.*

i) 3.1.1. Updated Guidelines for Total Catch Ceilings (TCC) in NAFO Ecosystem Production Units (EPUs)

In 2017 the new NAFO convention came into force, and with it, the formal commitment by NAFO to apply an ecosystem approach to fisheries management in the Northwest Atlantic that includes safeguarding the marine environment, conserving its marine biodiversity, minimizing the risk of long term or irreversible adverse effects of fishing activities, and taking account of the relationship between all components of the ecosystem.

In terms of setting sustainable exploitation levels, the Roadmap follows a 3-tier, hierarchical sequence that allows considering the sustainability of the exploitation at the ecosystem, multispecies assemblage, and single stock level (Fig. 3.1.2). Tier 1 defines fishery production potential at the ecosystem level, taking into account environmental conditions and ecosystem state. This allows a first order consideration for the potential influence of large scale climate/ecological forcing on fishery production, as well as explicitly considering the basic limitation imposed by primary production on ecosystem productivity.

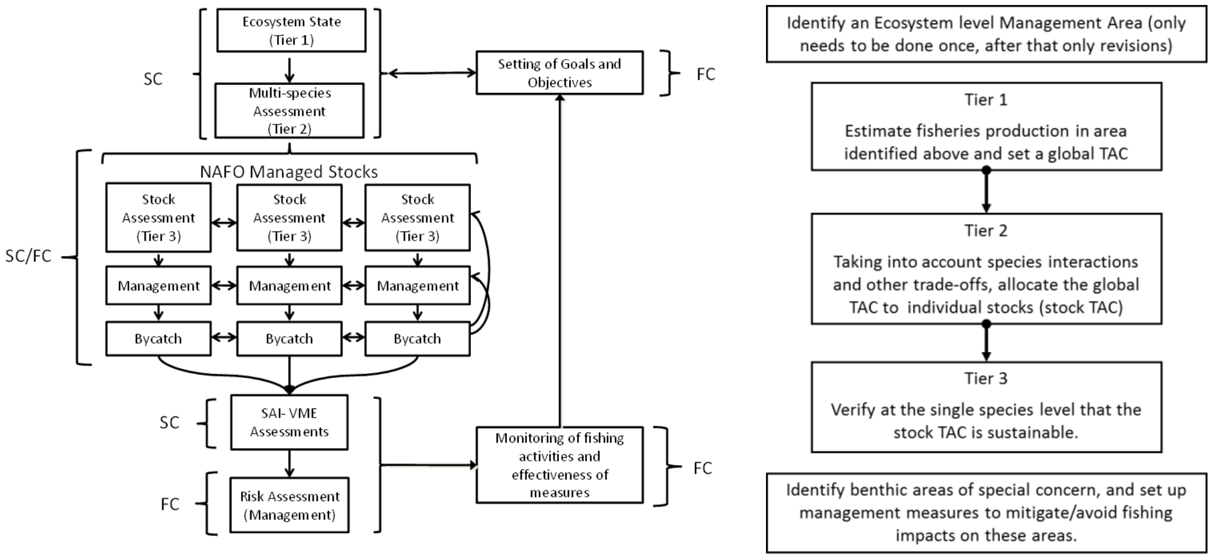


Fig. 3.1.2. Current working template of the NAFO "Roadmap" (left), with a synoptic overview of the key steps required for using it (right). SC: Scientific Council, FC: Fisheries Commission, SAI: Significant Adverse Impact, VME: Vulnerable Marine Ecosystem

Towards implementing Tier 1, WG-ESA and SC have been developing Ecosystem Production Potential (EPP) models for the three Ecosystem Production Units (EPUs targeted for pilot Roadmap implementation. These EPUs are the Flemish Cap (3M), The Grand Bank (3LNO), and the Newfoundland Shelf (2J3K) (Fig. 3.1.3). These EPP models have been used to derive Total Catch Ceilings (TCCs) for these ecosystem units.

The process for deriving the TCCs is schematically depicted in Fig. 3.1.4. Following this process, the TCCs and associated median values for each one of the three targeted EPUs were calculated (Table X.1). These values were updated from the ones presented in 2016 on two accounts. The areas of the EPUs were updated to fully match current delineations, and the penalty factors used for the Newfoundland Shelf (2J3K) and the Grand Bank (3LNO) were updated given the declines observed in total biomass in these EPUs. Following with the practice started in 2016, TCC values are given by individual fishable nodes in the EPP model and the "Standard Demersal Components" (SDC) aggregate which combines benthivore and piscivore nodes and includes all traditional groundfish and shellfish commercial species in these EPUs.

In order to compare nominal catches with TCC values, it is necessary to recognize that production for individual target species is associated to different EPP nodes due to diet changes linked to different life history stages. Analyses done by WG-ESA in 2016 for the Flemish Cap EPU indicated that assigning 100% of Greenland halibut to the piscivore node seemed reasonable, but fractionation for cod and redfish was required. Although work on these aspects is ongoing, an initial fractionation for cod and redfish for EPUs in the NL bioregion was implemented in 2017. Overall, fractionation factors have been derived from information on diet composition (2J3K, 3LNO and 3M), and the size distribution of commercial catches (3M only) (Table 3.1.2).

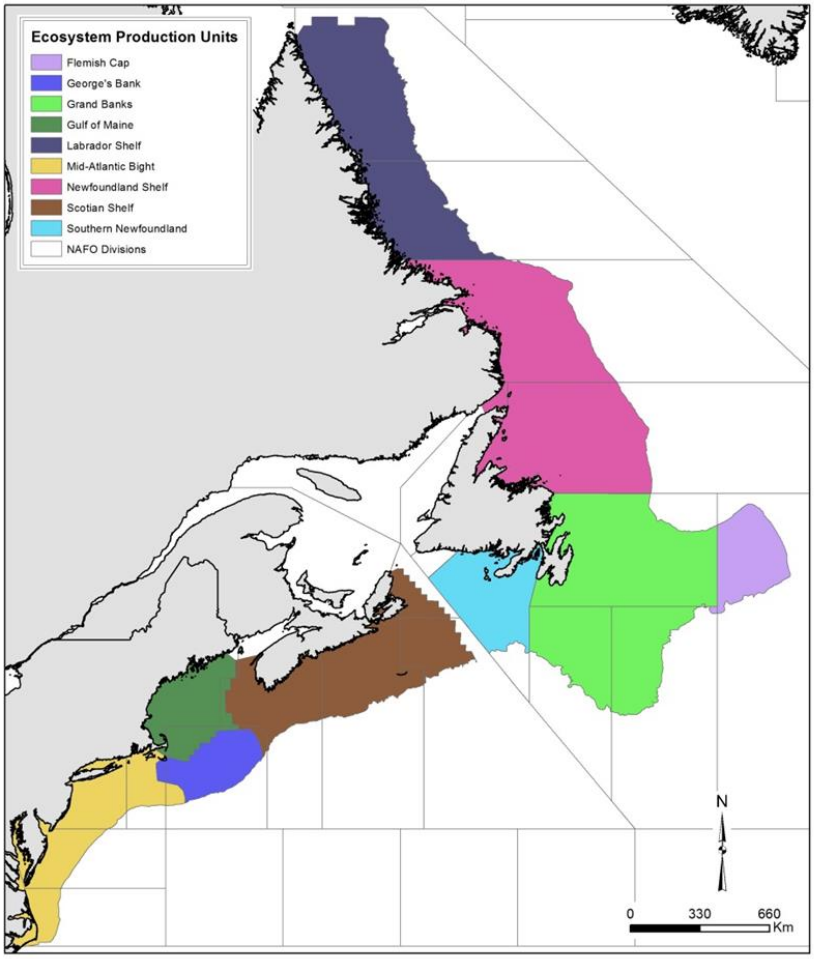


Fig. 3.1.3. Ecosystem Production Units (EPUs) identified across the shelf ecosystems in the NAFO Convention Area. These EPUs have been proposed as candidate Ecosystem-level Management Areas, and pilot exercises on the Roadmap implementation are been conducted by SC on the Flemish Cap (3M), the Grand Bank (3LNO), and the Newfoundland Shelf (2J3K) EPUs.

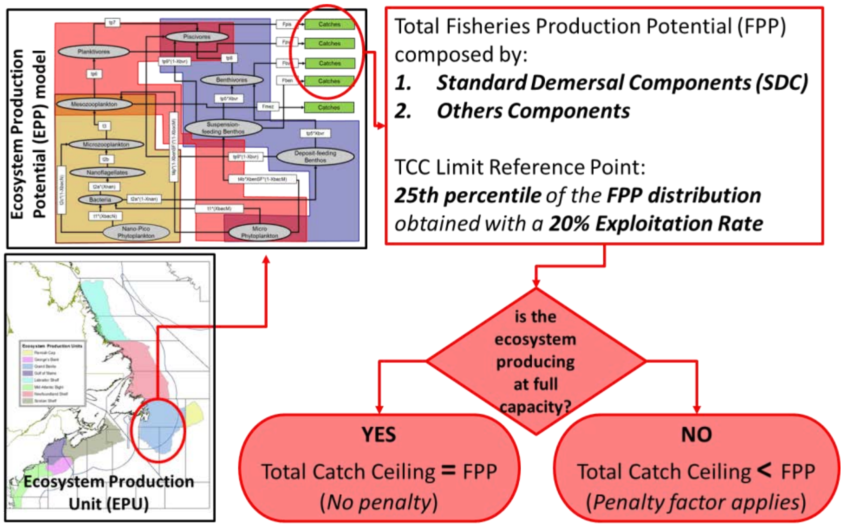


Fig. 3.1.4. Schematic depiction of the process to derive TCC limit reference points (LRP) from the FPP estimated using the EPP model, including the discrimination between SDC and Other FPP.

Table 3.1.1. Updated guidelines for Total Catch Ceilings (TCC) for the Flemish Cap (3M), Grand Bank (3LNO), and Newfoundland Shelf (2J3K) Ecosystem Production Units (EPUs) based on the estimated distributions of the Fisheries Production Potential (FPP) for these areas, and the application of penalty factors when required. TCCs are provided for each fishable model node (piscivores, benthivores, planktivores, and suspension feeding (SF) benthos), and the Standard Demersal Components (SDC) aggregate which is the summation of piscivores and benthivores nodes , and includes traditional groundfish stocks as well as shellfish species (e.g. Atlantic cod, Greenland halibut, American Plaice, Redfish, Yellowtail flounder, Witch flounder, Northern Shrimp, snow crab).

	Total Catch Ceiling (TCC) (25th percentile of FPP distribution) in thousand tonnes per year			Median (50th percentile of FPP distribution) in thousand tonnes per year		
	NL Shelf (2J3K)	Grand Bank (3LNO)	Flemish Cap (3M)	NL Shelf (2J3K)	Grand Bank (3LNO)	Flemish Cap (3M)
Area (thousand km^2)	254.319	311.646	58.412			
Penalty factor	0.6	0.7	0.0	0.6	0.7	0.0
EPP Node or Aggregate						
Piscivores	16.62	19.73	11.72	23.27	27.19	16.26
Benthivores	48.36	57.68	33.71	81.00	95.81	56.95
Planktivores	63.09	74.87	44.94	90.26	105.22	62.67
SF Benthos	8.43	9.06	5.39	15.41	15.99	9.65
SDC	64.99	77.41	45.43	104.27	123.00	73.21

Table 3.1.2. Fractionation used to split cod and redfish nominal catches to the Piscivore EPP node (Piscivore fraction of the nominal catch). The complementary fraction of the catches was assigned to the planktivore EPP node.

Species	NL Shelf (2J3K)	Grand Bank (3LNO)	Flemish Cap (3M)
Cod	90%	90%	85%
Redfish	70%	70%	60%

The comparison of nominal catches against TCC levels (Fig. 3.1.5) indicates that fisheries in the Flemish Cap continue to be highly concentrated on piscivores (cod and redfish), and have been consistently above the TCC level since 2010. From this perspective, this EPU can be considered to be experiencing ecosystem overfishing.

Both EPUs in the NL bioregion are considered to be experiencing low productivity conditions in recent years, which prompted a further reduction of their TCC levels. These ecosystems were already considered to be under stress, and their previous TCC values included a penalty factor of 50%. Given the declines in total biomass observed since the mid 2010s, these penalty factor, which are based on the ratio between current total biomass and the median levels observed prior the collapse in the late 1980s and early 1990s, were re-evaluated. The result from these analyses indicated an increase in the penalty factors from 50% to 60% and 70% for the Newfoundland Shelf (2J3K) and the Grand Bank (3LNO).

The Newfoundland Shelf has fisheries targeting piscivores and benthivores nodes, but catches are more concentrated on bethivores (shrimp and snow crab), which have been above the estimated TCC levels for many years. Even though most recent catch levels have drop below the TCC, it is likely that this ecosystem many have also experienced ecosystem overfishing.

The Grand Bank has fisheries more evenly distributed between piscivores and benthivores, which have been below the estimated TCCs over the last 10 years. However, the reduced productivity of this EPU, in combination with the increasing trend in piscivore catches, indicates that this EPU could be pushing this ecosystem into overfishing.

It is also worth highlighting that this EPU is the only one with significant catches of suspension feeding benthos among the three EPUs analyzed here. These catches are mostly composed by surf clam, and seem to follow a boom-bust pattern (Fig. 3.1.6). Catches have been virtually nil since the late 2000s, but suddenly spiked in 2016 to the levels observed during the 2002-2006 period. Given the reduction in TCC levels after 2014, the 2016 catches are well above the estimated TCC. However, the estimation of TCC for SF Benthos includes an assumption that only 10% of the production of this group is composed by species of commercial value, so ephemeral overshooting of the TCC for this group may be less critical than for other fishable nodes (e.g. piscivores, and benthivores).

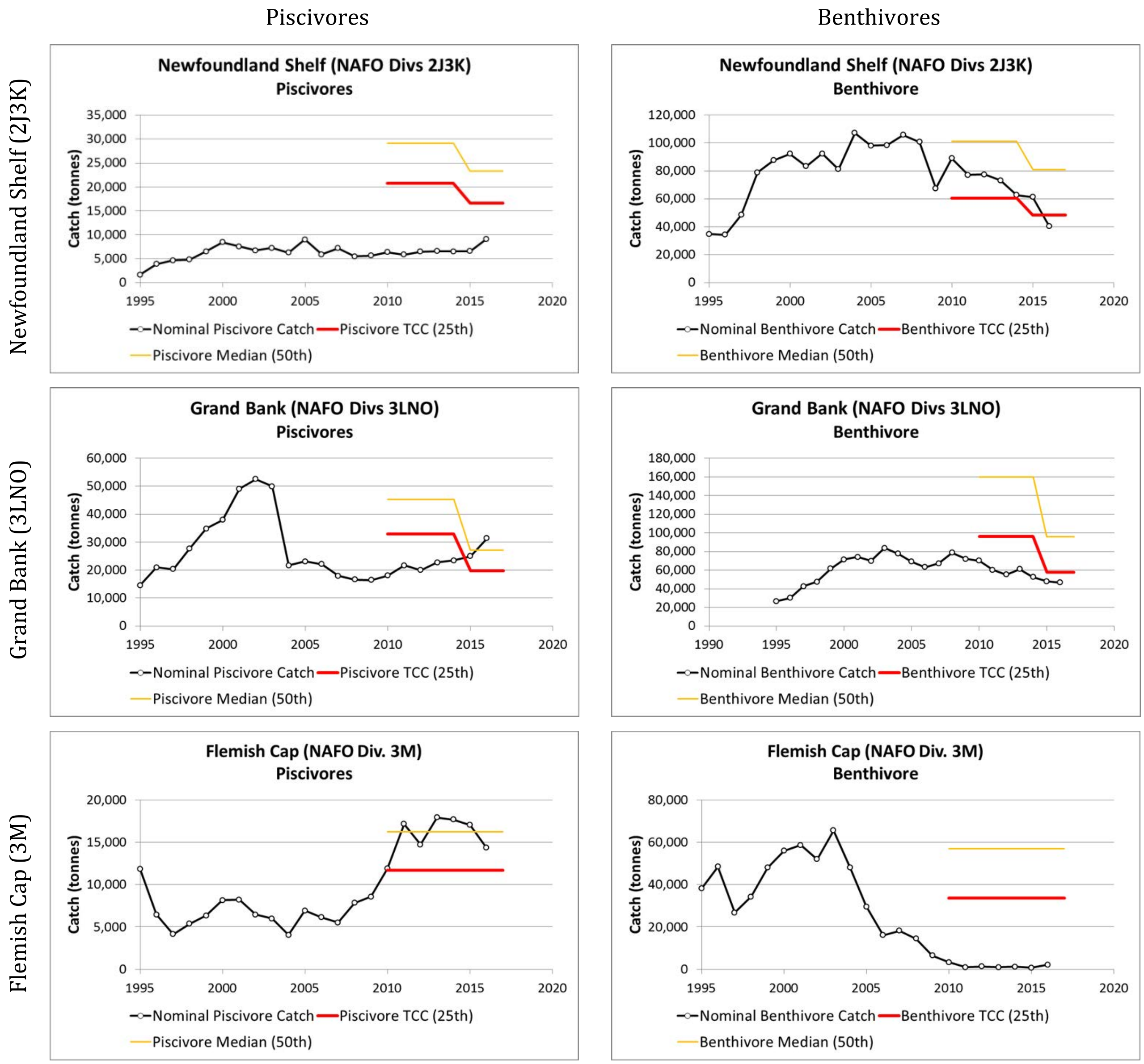


Fig. 3.1.5. Comparisons between nominal catches and the updated TCC levels for Piscivores and Benthivores in the Newfoundland Shelf (2J3K), Grand Bank (3LNO), and Flemish Cap (3M) EPUs. The reductions in TCCs after 2014 for the EPUs in the NL bioregion are linked to the declines in total biomass observed in these EPUs, and which under the assumption of a relatively constant ecosystem-level P/B ratio, is an indicator of reduced ecosystem productivity.

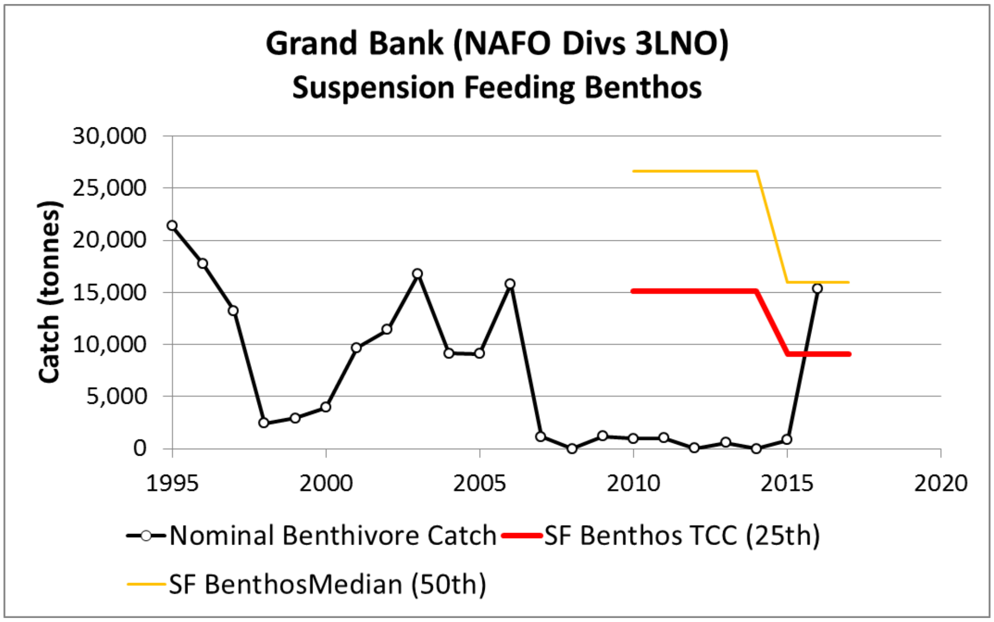


Fig. 3.1.6. Comparison between nominal catches and the updated TCC levels for Suspension Feeding (SF) Benthos in the Grand Bank (3LNO) EPU. The reductions in TCCs after 2014 is linked to the decline in total biomass observed in this EPU, and which under the assumption of a relatively constant ecosystem-level P/B ratio, is an indicator of reduced ecosystem productivity.

ToR 3.2 Develop draft summary sheets at ecosystem level [SC Request #2 Continued development of ecosystem summary sheets (ESS)]

Design of ecosystem summaries is based on NAFO's revised convention objective which aims "to ensure the long term conservation and sustainable use of the fishery resources in the Convention Area and, in so doing, to safeguard the marine ecosystems in which these resources are found". In part, this will be achieved through NAFO's commitment to apply an ecosystem approach to fisheries management that includes safeguarding the marine environment, conserving marine biodiversity, minimizing the risk of long term or irreversible adverse effects of fishing activities, and taking account of the relationship between key components of the ecosystem. Summaries are to consist of two element groups: one based on measures of state (e.g. oceanographic, production, ecological features) and species interactions within each of the major Ecosystem Production Units that have been the focus of WG-ESA activities (i.e. Flemish Cap, Grand Bank, and Newfoundland Shelf); the second based on the relationship of the state variables relative to management framework and objectives.

The design aims to mirror the basic objectives that underlie the structure of the stock summary sheets but in a manner that recognizes how environmental conditions and ecosystem structure affect NAFO's ability to report on the objectives of the Convention. Ecosystem summary assessments should be carried at medium-term intervals (3-5 years).

Development of the ESS highlighted gaps in knowledge of the changes in the status of VMEs and the levels and importance of bycatches of regulated and unregulated taxa. Work is required before those sections of the report can be populated to reflect the knowledge available to NAFO. The WG **therefore recommends**:

[1] That the trawl survey time series from Canadian and EU surveys be used to provide an index of the abundance (and other indices of state) of the major VME groups (seapens, sponges, gorgonians, others) within the VME polygons (i.e. areas of high likelihood of occurrence) and the frequency of occurrence outside;

[2] That the Secretariat provides information on annual levels by-catch levels based on analysis of log-book data and provide a summary of the types and extent of regulatory measures that are intended to mitigate impact or extent of bycatch;

[3] That the WG or Scientific Council undertake research to assess potential significance of bycatch on productivity of stocks and unregulated species and assess whether there are technical interactions among fisheries

The WG will also explore the potential to access trawl data collected in NAFO areas by the predecessor of the Russian Federation that may serve to provide information on the state of VMEs prior to the current trawl survey time series.

A first exploration of the production of an ESS will be undertaken for presentation the 2018 meeting of Scientific Council based on the design that follows. The exploration will be based on information for the Grand Bank EPU (3LNO).

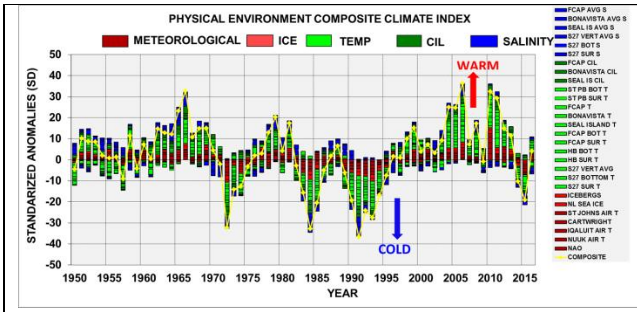
ECOSYSTEM SUMMARY SHEET

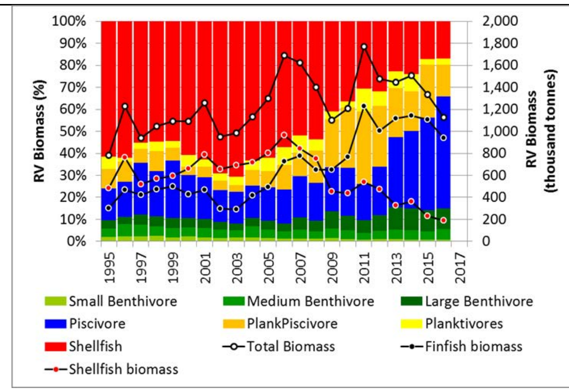
Recommendation to SC / Commission – target strategic considerations of changes in ecosystem indicators (including environment) and their possible consequences to single species assessments; provide SC/Commission a chance to adapt to changes taking place in state/trends and impact on medium term objectives

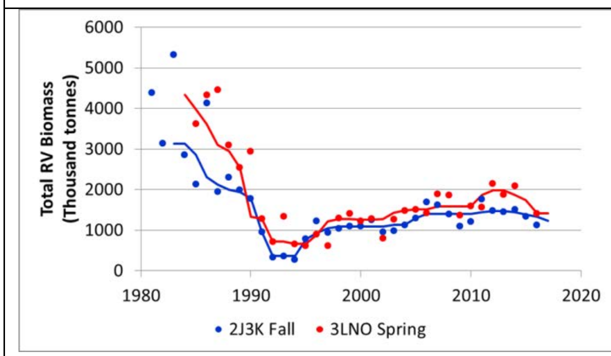
Convention Objective			Status	Comment
a	Ecosystem Trends and Status *(Long term sustainability of fisheries resources)*			**Summary of multiple trends/state – direction and relation with reference period**
	1	Environment (Composite Index of physical conditions) – from STACFEN	Arrow indicator trend; state green, yellow, red	Two metrics - Trends (5 year) and most recent state (relative to defined reference period)
	2	Primary Productivity (Standing stock of phytoplankton and indicators of magnitude and timing of spring bloom) – from STACFEN		Same
	3	Secondary Productivity (Abundance and biomass (and maybe size fractions) of key zooplankton taxa consistent with STACFEN presentations)		Same
	4	Fish productivity (total fish biomass)		Same
	5	Community composition – similarity in composition of functional groups relative to reference period (1980s) when the ecosystem was considered "healthy" or "productive"?		Same
b	Is ecosystem productivity at or above sustainable level?			**Summary of multiple trends/ state – direction and relation with reference period**
	1	Current Fisheries Production Potential (*Analogous to penalty factor in Ecosystem Production Potential models*; current total biomass as a fraction of reference period when system was production) **(Is this too close to a4?)**		State and trends of fraction relative to "healthy" or productive ecosystem period
	2	Status of key forage components (based on data on capelin, sandlance, arctic cod, shrimp or other key forage components) – represented as anomalies from trawl survey data		Trends (5 year) and state relative to reference period
	3	Signals of food web disruption (reflects both changes in prey composition and amount of food key piscivorous species – cod to be initial keystone species)		Patterns of change (3-5 year trend) and most recent state in composition of

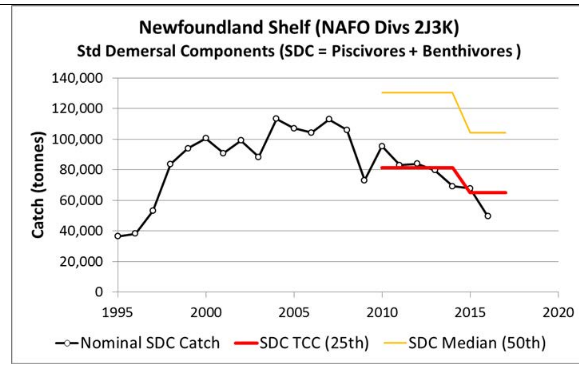
				ecosystem critical elements (prey) and total amount of prey in stomachs
	4			
c	State of biological diversity			**Summary of multiple indicators**
	1	Status of VMEs		**Will need new metrics to quantify state and change in recent period**
	2	Status of depleted species		Proportion of depleted species (those below 20% of some period of maximum biomass for each species) based on trends and status from time series of trawl survey indices of as many species from trawl surveys as possible (including unregulated taxa)
	3			
d	Apply Precautionary Approach			**Metrics of level management actions**
	1	Ecosystem productivity and total catches	Focus on most recent state	Total catches , including disaggregated functional groups, relative to EPU TCC prediction; should take into consideration of changes in ecosystem productivity of LTL
	2	Consideration of multispecies and/or environmental interactions on stock dynamics	Good; uncertain; bad; unknown	Proportion of assessed stocks in which species or environmental relationships are being considered

	3	Production potential of single species	Good; uncertain; bad	Proportion of assessed stocks with LRPs
e	Minimize harmful impacts of fishing on ecosystems			
	1	Level of protection of VMEs	Good; uncertain; bad	State and trend in estimated overlap between fishing activity and VME polygons – link to SAI?
	2	Level of protection of commercially exploited species (and others?)		Proportion of stocks above LRP
	3			
f	Assess significance of incidental mortality in fishing operations			
	1	By-catch level across fisheries		[1] Information on by-catch levels from secretariat analysis of log-books [2] Need research to assess potential significance of bycatch on productivity of stocks and unregulated species [3] Establish whether there are technical interactions among fisheries [4] Need information on regulatory measures used to mitigate impact or extent of bycatch
	2	By-catch of depleted species		[1] Research about potential interaction of fishery activities for target species with non-target taxa at low biomass levels
	3			


PHYSICAL ENVIRONMENT COMPOSITE CLIMATE INDEX
METEOROLOGICAL
ICE
TEMP
CIL
SALINITY
WARM
COLD
STANDARIZED ANOMALIES (SD)
YEAR


RV Biomass (%)
RV Biomass (thousand tonnes)
Small Benthivore
Medium Benthivore
Large Benthivore
Piscivore
PlankPiscivore
Planktivores
Shellfish
Total Biomass
Finfish biomass
Shellfish biomass


Total RV Biomass (Thousand tonnes)
2J3K Fall
3LNO Spring


Newfoundland Shelf (NAFO Divs 2J3K)
Std Demersal Components (SDC = Piscivores + Benthivores)
Catch (tonnes)
Nominal SDC Catch
SDC TCC (25th)
SDC Median (50th)

ToR 3.3 Consideration of stock recruitment patterns through the application of EAFM

i) Background

During the 2017 NAFO Annual Meeting, the commissions's Feedback questions to SC regarding its scientific advice (SC-WP 17/42) included the request:

The draft report of the June Scientific Council meeting identifies a low recruitment as one of the main drivers behind a declining abundance in some stocks. Could the Scientific Council further elaborate on what could be the reasons for such low recruitment in recent years in so many stocks and also in different NAFO divisions? This seems to be particularly the case for Cod in Division 3M, Witch Flounder in in Division 3NO and redfish in Division 3M.

In its response, the Scientific Council presented some preliminary analysis of data on historic recruitment patters and commited to continue this work in 2017 and beyond through the work of WG-ESA and STACFEN.

ii) Evaluation of stock recruitment patterns through the application of EAFM

In September, Scientific Council carried out a preliminary analysis of data on historic recruitment patterns in NAFO assessed stocks. Preliminary results seem to suggest that reduced recruitment has been occurring in recent years across many stocks including the three mentioned in the request. Recruitment patterns may reflect stock-specific response to local conditions (e.g. environment, predator, indirect fishery impacts) or broader regional changes in the oceanographic regimes. A better understanding of the contribution of different factors may emerge from the continued development of an ecosystem-based approach in the NRA but lengthy time series are generally required to detect coincidence in recruitment patterns among stocks.

The analyses were based on data from nine stocks and extracted from the most recent assessments for: 3M Cod; 3M Redfish; 3M American plaice; 3NO Cod; 3LNO American plaice; 3NO Witch flounder; 3LNO Yellowtail flounder; 3NO White hake; and 3LNOP Thorny skate. The nature of the data varied greatly among stocks with some indices of spawning stock biomass (SSB) and recruitment (R) derived from model-based assessments while others represent data from aggregated survey-based estimates of abundance for specific length classes that are considered the best available indices for these two variables. There may therefore be some degree of over smoothing or autocorrelation introduced time series used in the analyses reported below. In collating the data there were instances where SSB or R were reported using several indices – each of these series was standardized to mean of 1 and averaged across available indices. Age at recruitment varied among stocks and indices but the estimate of recruitment in a given year was lagged back to the year of spawning based on the information contained in the assessment documents or expert advice.

The first analysis investigated trends in recruitment qualitatively using the cumulated sum of recruitment for the period 2001 to the most recent index of recruitment – an inflexion in the cumulated recruitment during the most recent period (3+ years) would be considered indicative of a decline in recruitment. The second analysis focussed on patterns of variation in indices of recruits-per-spawner (RS = LN [R/SSB]) in an attempt investigate changes in reproductive potential among stocks. Each time series was standardized to zero mean and unit standard deviation based on the 1997-2010 period when data from all nine stocks was available. Three elements contributed to this analysis. First, the contrast in the distribution of RS for 2002-2008 (7 years) with that from 2009-2015 (2-7 years because of differences in the age at recruitment among stocks) for each stock was evaluated based on box-whisker plots. Second, the linear trends during each of these periods were contrasted for each stock to evaluate whether the general patterns of variations had changed in more recent times relative to the early part of the century. Finally, a dynamics factor analysis (DFA) of common trends among stocks based on relationship with different combinations of 5 environmental variables 1996-2015: climate composite index for the Newfoundland shelf and Grand Bank (Colbourne et al. 2017); composite indices of the abundance of *Calanus finmarchicus* and *Pseudocalanus* spp from the oceanographic sections (Maillet et al. 2017) that cross areas 2J3KLMNO; and composite indices for the magnitude and timing of the spring phytoplankton bloom measured from 8-day composites of surface chlorophyll concentrations for statistical areas in areas 2J3JKLMNO.

Cumulative recruitment indices demonstrate evidence of an inflexion in recent years in 4 of the nine stocks (3M redfish, 3M cod, 3LNO American Plaice and 3NO Cod) but the patterns of recruitment for the other stocks are equivocal (Fig. 3.3.1).

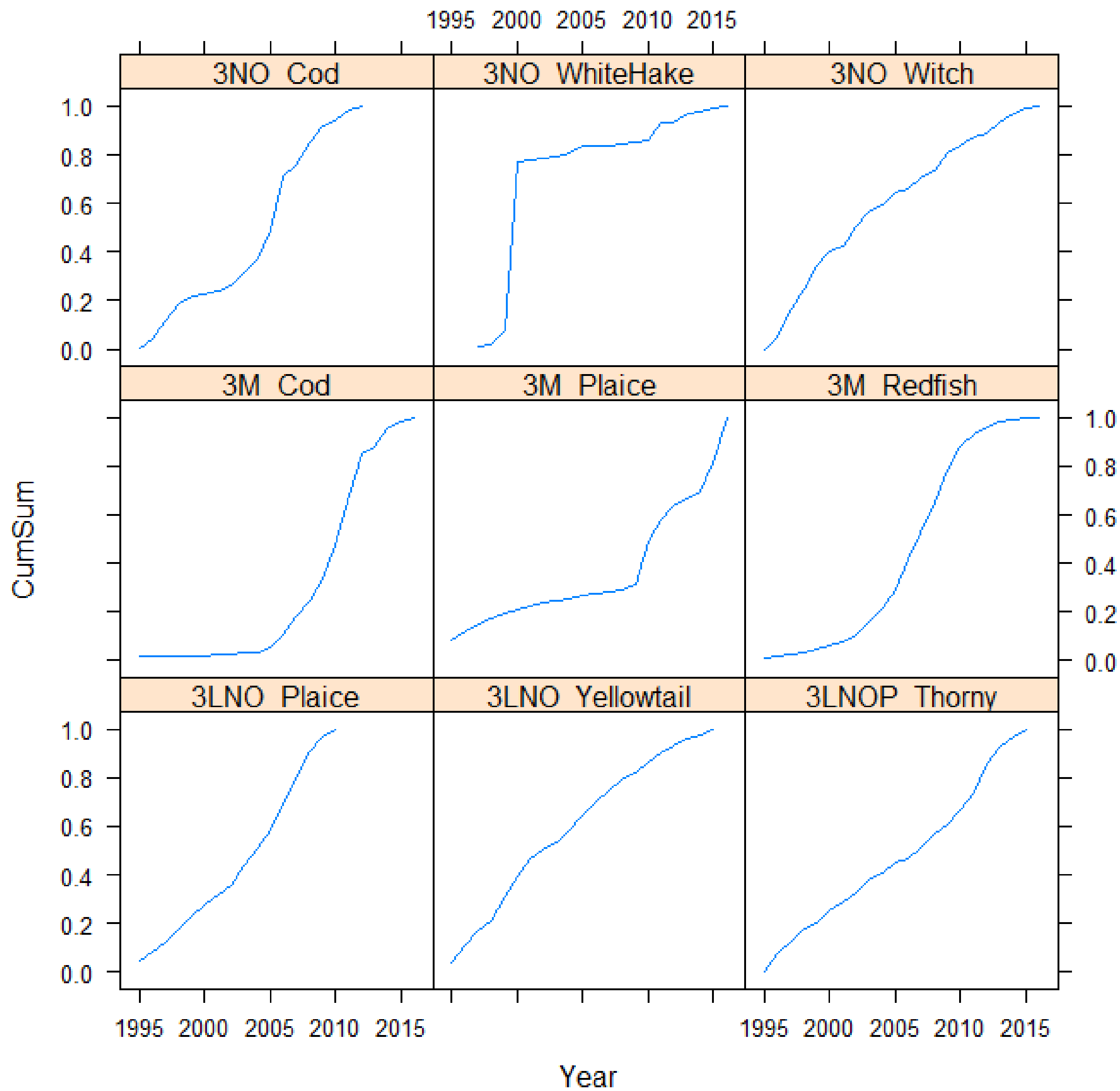


Fig. 3.3.1. Scaled cumulative recruitment data from 1995 to the most recent assessment for nine stocks in the NAFO Regulatory Area.

The distribution of standardized indices of RS revealed that reproductive productivity was comparable or lower in 2009-2015 relative to 2002-2008 in seven of the nine stocks, with 3NO white hake and 3LNOP thorny skate demonstrating higher levels of productivity in the most recent 5-7 years (Fig. 3.3.2). Trends demonstrated a stronger contrast in reproductive productivity with all stocks demonstrating a negative trend in the most recent period relative to the earlier period during which five of the nine stocks had demonstrated an increase in reproductive productivity (Fig. 3.3.2).

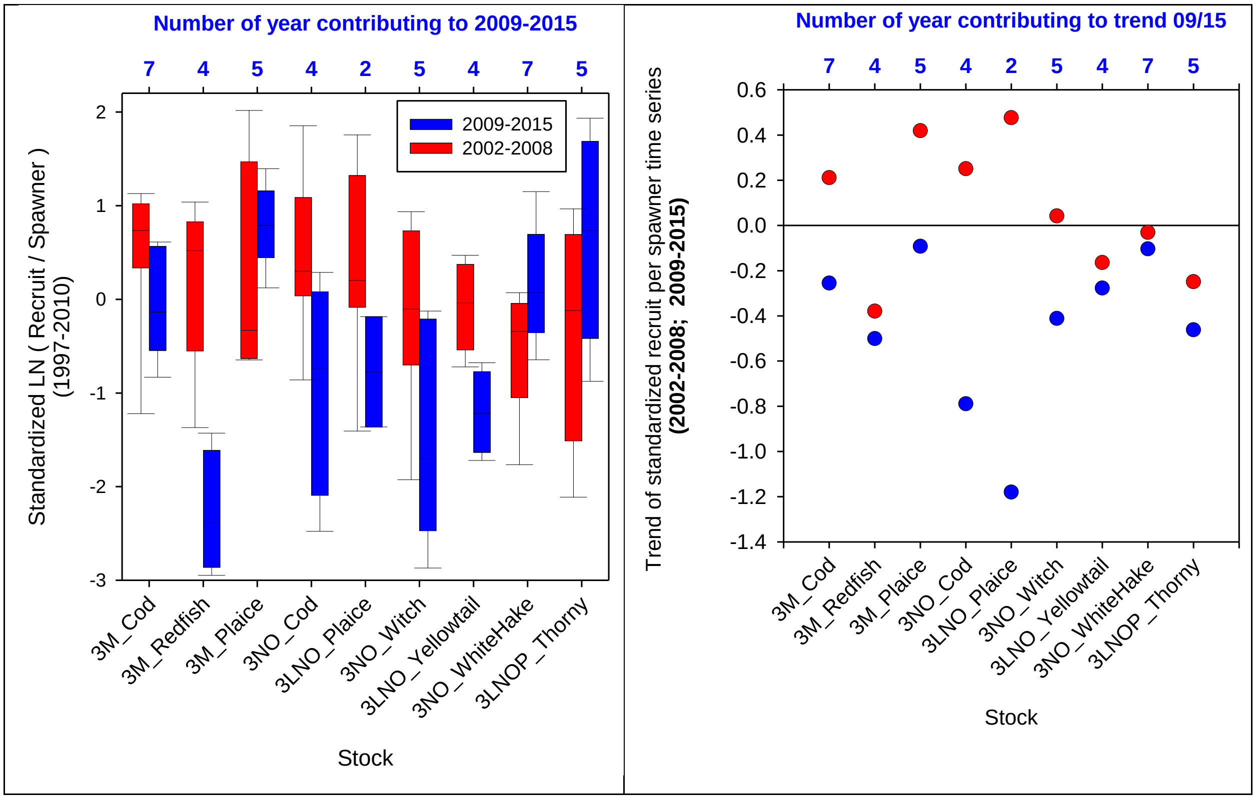


Fig. 3.3.2. Box-whisker plot of the standardized indices of recruit-per-spawner for the nine stocks in the NAFO Regulatory Area during the periods 2002-2008 (red) and 2009-2015 (blue) (left panel). Slope (trend) in recruit-per-spawner versus year of spawning for the nine stocks in the NAFO Regulatory Area during the periods 2002-2008 (red) and 2009-2015 (blue) (right panel). Note that the upper x-axis reports the number of years of available data for each stock during the period 2009-2015.

Dynamic factor analysis revealed that two trends were sufficient to identify the major trends in the nine time series (Fig. 3.3.3). The most important trend showed an increase from 1996 to the mid-2000s, consistent with the period that saw evidence of some recovery in the demersal finfish populations in areas 2J3KLNO, followed by a comparable decline in RS that leveled off around 2011 but with high levels of uncertainty around the most recent data. The second trend was characterized by a consistent decline in RS among stocks starting in 2001-2002 and continuing until 2013. The canonical correlations with the first and second trends reveal commonalities and differences among stocks (Fig. 3.3.3). Cod and plaice stocks demonstrate positive associations with Trend 1 whereas the opposite is true for white hake, thorny skate, 3NO witch flounder and 3LNO yellowtail. Redfish in division 3M along with 3NO witch flounder and 3LNO yellowtail demonstrate a strong positive association with Trend 2 while 3LNO American plaice is negatively associated with that trend.

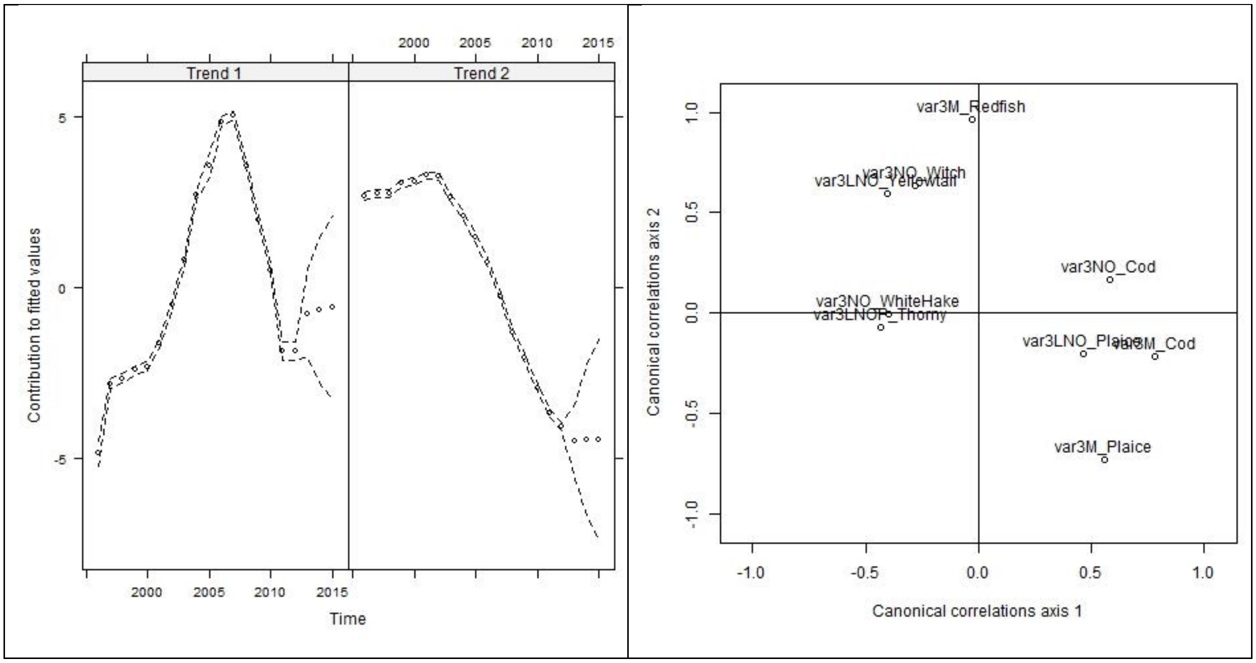


Fig. 3.3.3. Dominant trends among RS time series based on their relationship with the five indices of environmental state (left panel) and stock specific canonical correlations with the first (x-axis) and second (y-axis) trends (right panel).

In conclusion, recruit-per-spawner for 2009-2015 is generally lower than during 2002-2008 period, with the exceptions of White Hake and Thorny Skate. The rate of change in RS is always negative in 2009-2015 while trends in 2002-2008 are mixed. Dynamic factor analysis reveals that dominant trends in RS during recent period are all negative and associated with environmental conditions. Although the most recent 2-3 years may have not demonstrated strong changes in recruitment, the overall patterns of change in indices of reproductive success during 1996-2015 are in decline (Fig. 3.3.4). For all stocks considered in the analysis, the most recent measures of RS are below the maximum observed for any stock.

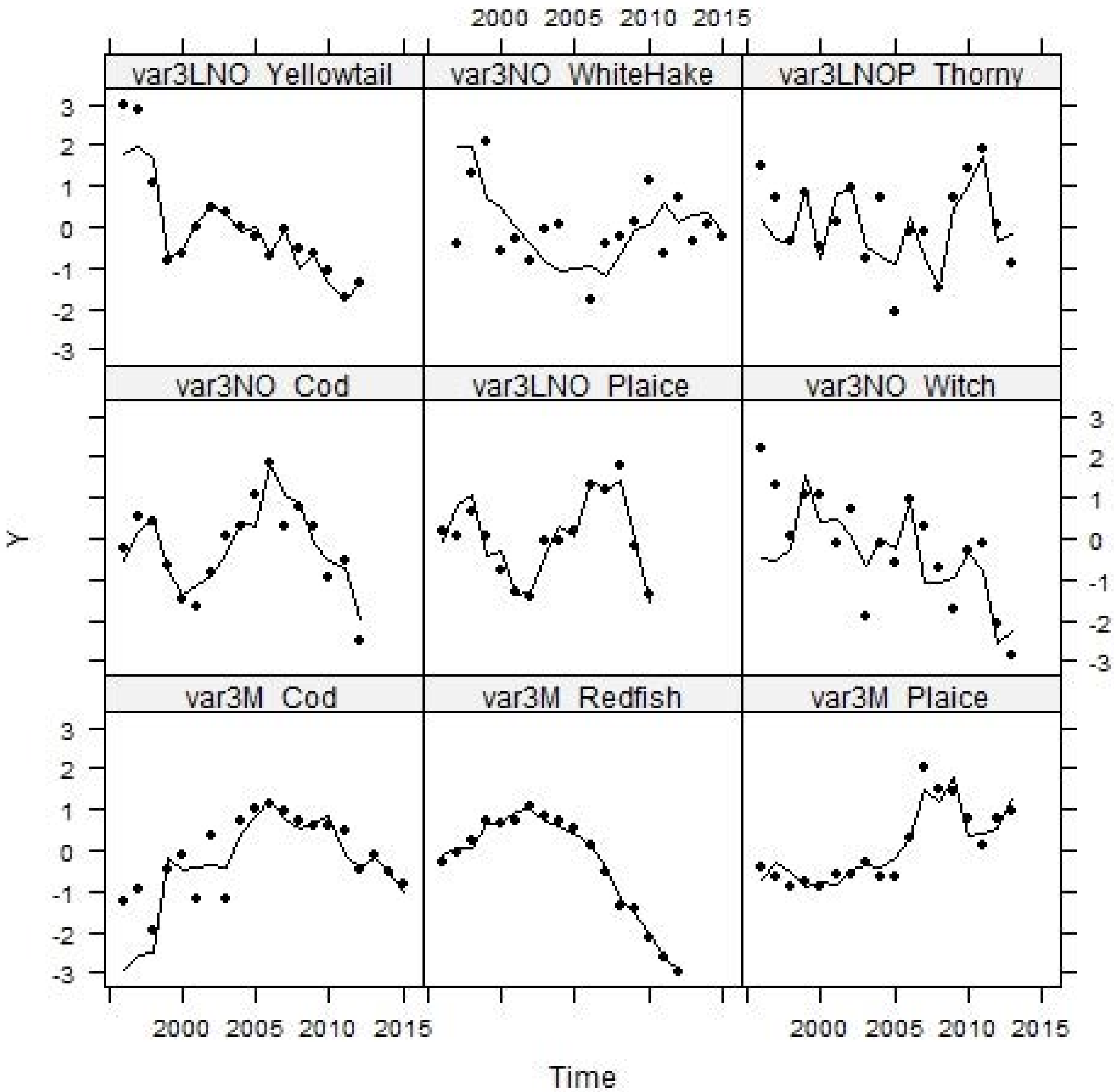


Fig. 3.3.4. ime series of standardized recruit-per-spawner for each of the nine stocks considered in the analyses along with the fitted estimate from the dynamic factor analysis based on 5 environmental variables.

References

Colbourne, E.B., Holden, J., Lewis, S., Senciall, D., Bailey, W., Snook, S., Higdon, J. 2017. Physical oceanographic environment on the Newfoundland and Labrador Shelf in NAFO subareas 2 and 3 in 2016. NAFO SCR Doc. 17/11, 31p.

Maillet, G., Pepin, P., Johnson, C., Plourde, S., Casault, B., Devred, E., Galbraith, P.S., Caverhill, C., Devine, L., Scarratt, M., Starr, M., Head, E., Spry, J., Porter, C., Cogswell, A., St-Pierre, J.F., St-Amand, L., Joly, P. Fraser, S., Doyle, G., Robar, A., Higdon, J., Maass, H. 2017. Biological oceanographic conditions in the northwest Atlantic in 2016. NAFO SCR Doc. 17/12, 24p.

ToR 3.4 evelopments to assess overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts.

FC 2017 request 6a. *Assess the overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts;*

Highlights:

1. Haul-by-haul logbook data was merged with the vessel monitoring system (VMS) data to map fishing effort from VMS positions that occurred within the reported fishing time interval.
2. The use of haul-by-haul logbook data permitted VMS pings to be extracted and mapped if they occurred within reported start and end times for fishing. This provided a more accurate measure of when vessels were trawling and allowed each haul to be assigned to a fishery.
3. The haul-by-haul effort maps were considered to be an improvement over past effort maps derived from a 1 – 5 nautical mile per hour speed filter because it reduced spurious effort points.
4. WG-ESA **recommends** to SC that additional information be recorded in the haul-by-haul data as follows (1) an appropriate measure of gear dimensions to facilitate future work on developing estimates of the area being swept by the trawl and (2) target species.

This section details the 2016 fishing footprint maps derived from vessel monitoring system (VMS) and haul-by-haul catch data.

Haul-by-haul catch data is logbook data collected during vessel fishing activities. Specifically, timestamps and geographic coordinates for gear deployment and retrieval are recorded, as well as the catch and discard weight for each species caught. This new data format, implemented in 2016, is an improvement over 2015 where data was recorded only for only the top three species by weight and did not include fishing timestamps.

Use of the haul-by-haul data permits VMS pings to be assigned as “fishing” or “non-fishing” based on whether or not they fall within fishing time intervals reported in the haul-by-haul data. That is, start and end of fishing timestamps from the logbooks are used to extract relevant VMS points which are then mapped in space to represent fishing effort. Because these VMS points are directly within the reported fishing times, they are considered to be associated with fishing activity. In previous years, a simple speed filter of 1 – 5 knots (rounded to the nearest integer) was used to filter VMS points and assign them as fishing activities, but it was challenging to decide which thresholds were appropriate across entire fleets. While applying a speed filter is a very common method for extracting VMS points associated with fishing, there will inevitably be some points that are misclassified at a rate that is difficult to quantify.

At this year’s WG-ESA meeting, fishing footprint layers were created for fisheries-specific and cumulative fishing effort using VMS data and new haul-by-haul catch data from the year 2016. To create fishery-specific effort maps, VMS points were assigned to a fishery based on the species with the highest retained catch weight in the logbook during the corresponding logbook fishing time interval. This definition of fishery is based solely on the main species in the catch and in some cases the main species may differ from the main species sought.

Filtered VMS points were assigned a “ping-time” interval to represent the duration of fishing. This value was calculated as the forward difference in time between VMS points. Typically, ping intervals were approximately one hour, so if the interval exceeded 2 hours, it was assigned to be 2 hours to avoid inflating effort within a cell. The last VMS point in a vessel’s series was assigned the mean ping-time interval for that vessel. The VMS points were aggregated over a 0.05 x 0.05 degree grid and the ping-time intervals were summed to represent the hours fished in each cell.

A second set of fishing effort layers were produced from the same data using the methods in NAFO (2015). VMS points were assigned to a fishery based on the main catch from the daily catch records, and VMS points were filtered if they reported a speed between 1 – 5 knots. Effort was represented by VMS ping time, i.e. the time intervals between consecutive fishing pings, which were summed and applied to a 0.05 x 0.05 degree grid.

The fishing effort layers, referred to as “logbook haul-time filter” for the haul-by-haul data and “simple speed filter” for the 1 – 5 knot speed data, were compared side by side and visually examined for congruence.

Overall, the areas represented by the logbook haul-time filter method and the simple speed filter method showed fishing activities in the same general areas with similar patterns of intensity. However, the footprint from the logbook haul-time method was considered an improvement because it tended to have fewer spurious points outside of the main footprint area (Fig. 3.4.1). With the new method, there were also fewer cells displaying fishing effort within the vulnerable marine ecosystem (VME) closures, and if we assume the closures are being respected, this would indicate that the simple speed method over represents fishing effort in some cells, particularly where effort appears to be low. In the logbook haul-time filtered maps there were still some points outside of the NAFO fishing footprint, in deep waters, likely due to VMS points associated with steaming. This probably occurred because of an incorrect start/end time, or delayed reporting of fishing “end time”.

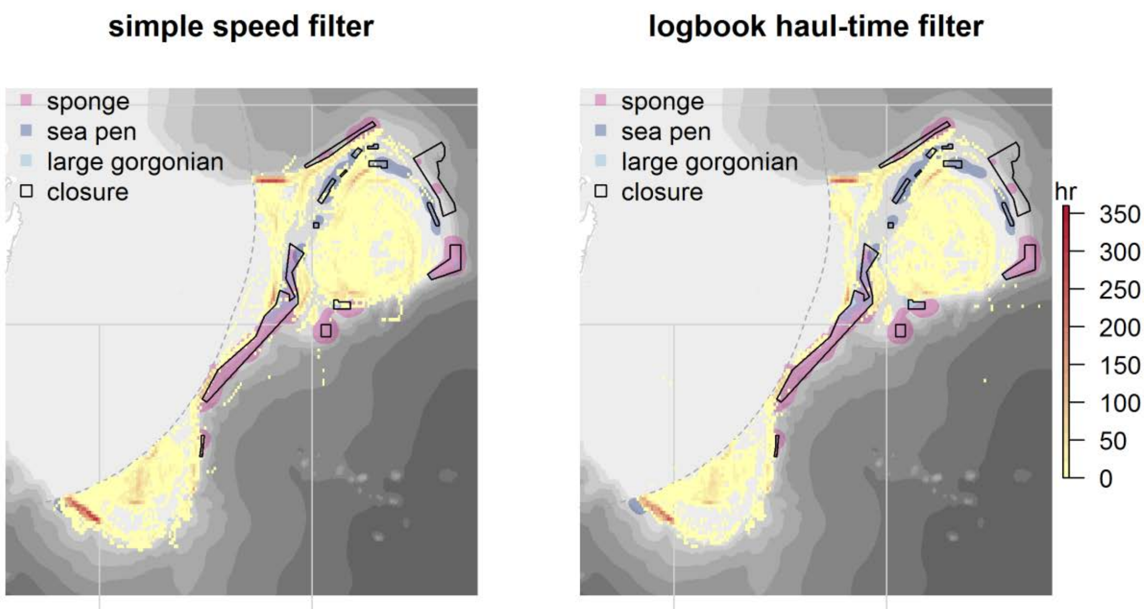


Fig. 3.4.1. Cumulative fishing effort maps (hours fished per cell) from 2016 VMS and logbook data produced by two different methods. Left: VMS data was filtered for speeds within 1-5 knots, right: VMS was filtered if it was within the reported fishing time interval in the logbook.

Key fishing effort layers and comparison Fig.s are shown below. Greenland halibut appeared to have fewer spurious cells (individual cells) as part of the fishing footprint when using the logbook haul-time filter (Fig. 3.4.2), such as on the top of the Flemish Cap. Also, cells on the tail of the Grand Banks (Division 3N) that were represented as part of the fishing footprint with the simple speed filter (left panel) were no longer represented in the layer with the logbook haul-time filter (right panel). This example also highlights how the use of haul-by-haul data to assign to a particular fishery can change in comparison with the daily catch records. In the right panel of Fig. 3.4.2 there is a string of cells on the east side of the Flemish Cap, slightly over top of the sea pen vulnerable marine ecosystem (VME) polygon. That string of points is not represented in the corresponding left panel, but it appears in the cod bottom otter trawl effort in the right panel (Fig. 3.4.3). Fig.s are shown for redfish bottom otter trawl in 3M (Fig. 3.4.4) and redfish bottom otter trawl in 3LNO (Fig. 3.4.5).

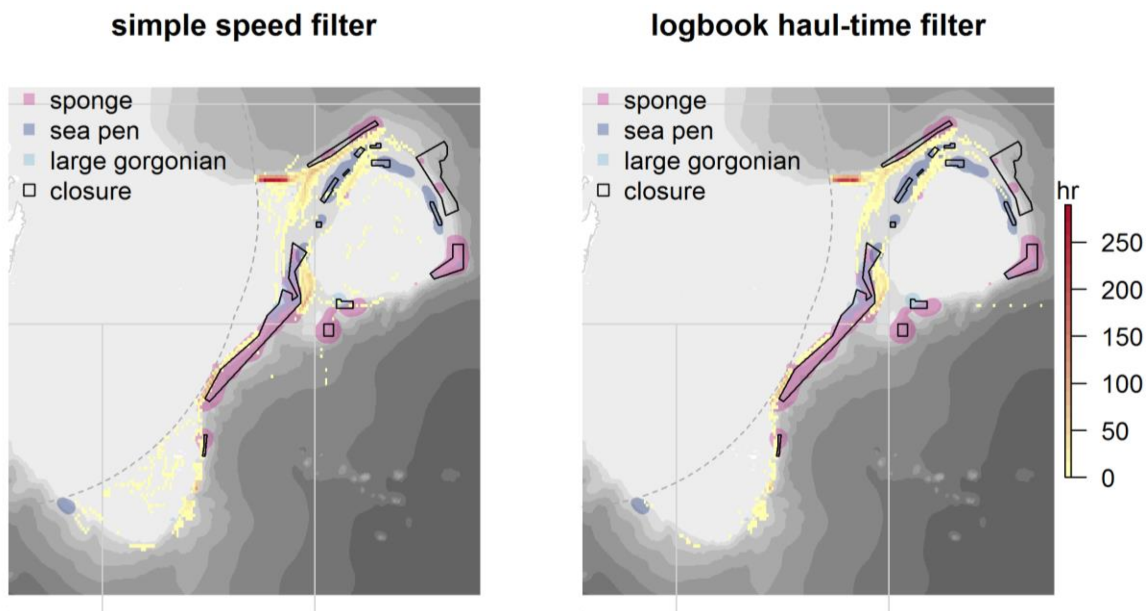


Fig. 3.4.2. Greenland halibut fishing effort maps (hours fished per cell) from 2016 VMS and logbook data produced by two different methods. Left: VMS data was filtered for speeds within 1-5 knots, right: VMS was filtered if it was within the reported fishing time interval in the logbook.

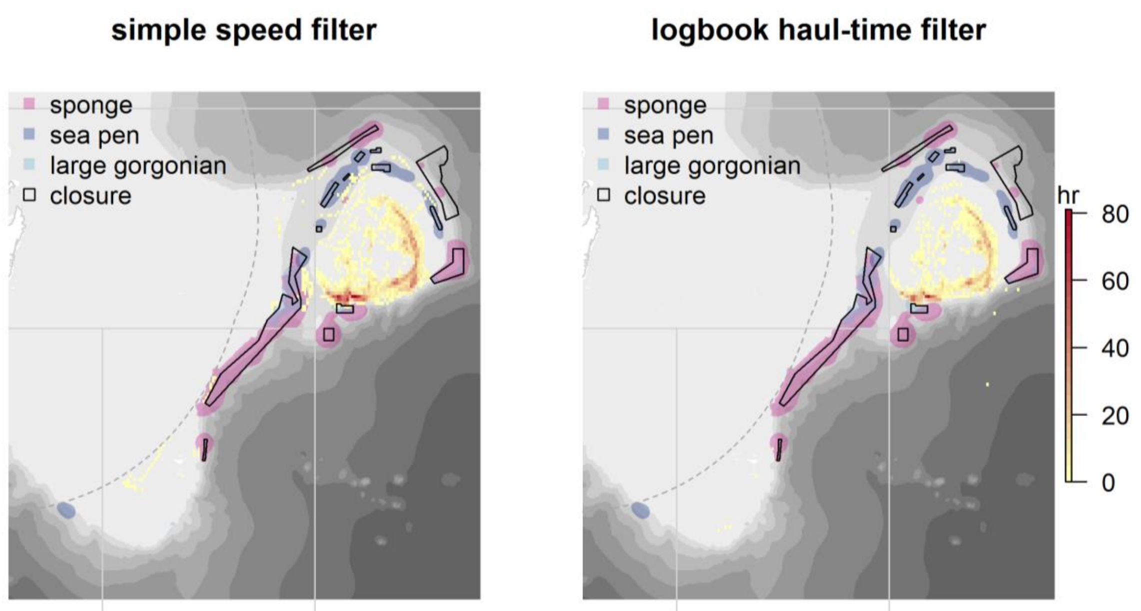


Fig. 3.4.3. Cod bottom otter trawl fishing effort maps (hours fished per cell) from 2016 VMS and logbook data produced by two different methods. Left: VMS data was filtered for speeds within 1-5 knots, right: VMS was filtered if it was within the reported fishing time interval in the logbook.

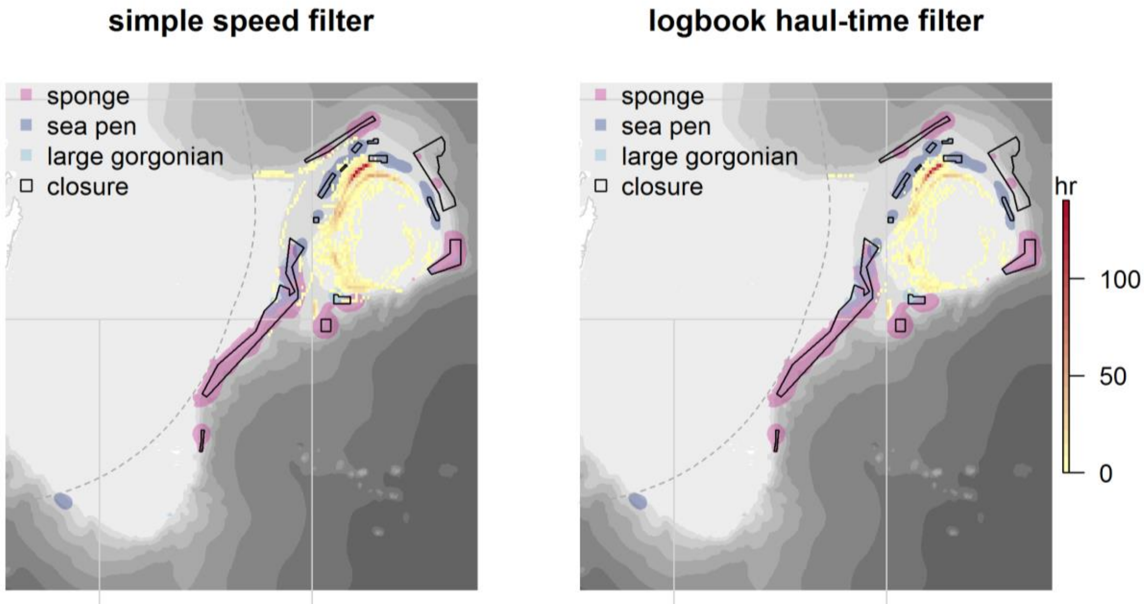


Fig. 3.4.4. Redfish 3M bottom trawl fishing effort maps (hours fished per cell) from 2016 VMS and logbook data produced by two different methods. Left: VMS data was filtered for speeds within 1-5 knots, right: VMS was filtered if it was within the reported fishing time interval in the logbook.

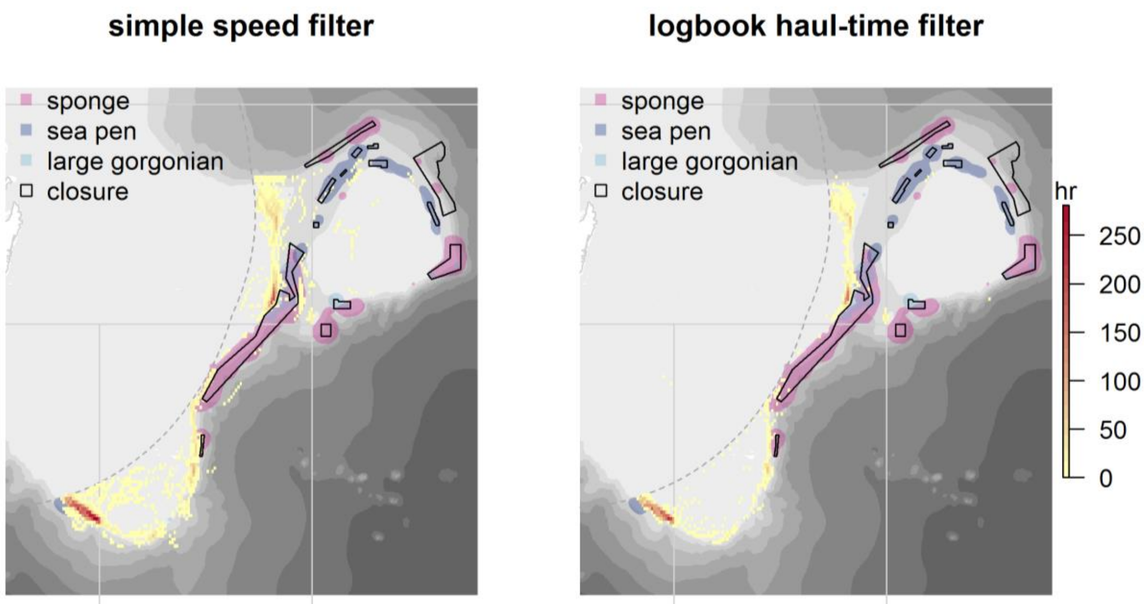


Fig. 3.4.5. Redfish 3LNO bottom trawl fishing effort maps (hours fished per cell) from 2016 VMS and logbook data produced by two different methods. Left: VMS data was filtered for speeds within 1-5 knots, right: VMS was filtered if it was within the reported fishing time interval in the logbook.

The ability to filter VMS points that are within reported fishing times allowed us to examine the speed frequency histograms as a means to evaluate the efficacy of the original assumption that speeds between 1-5 nautical miles represented fishing effort. Fishing speeds for all fisheries had mean = 3.3 knots and median = 3.4 knots. Histograms of speeds for the various fisheries generally occurred within 1 – 5 knots but also had slower speeds, and in some cases such as cod-longline and Atlantic halibut, there were some speeds > 5 knots (Fig. 3.4.6). This is not unexpected given the method of deployment for these fixed gears

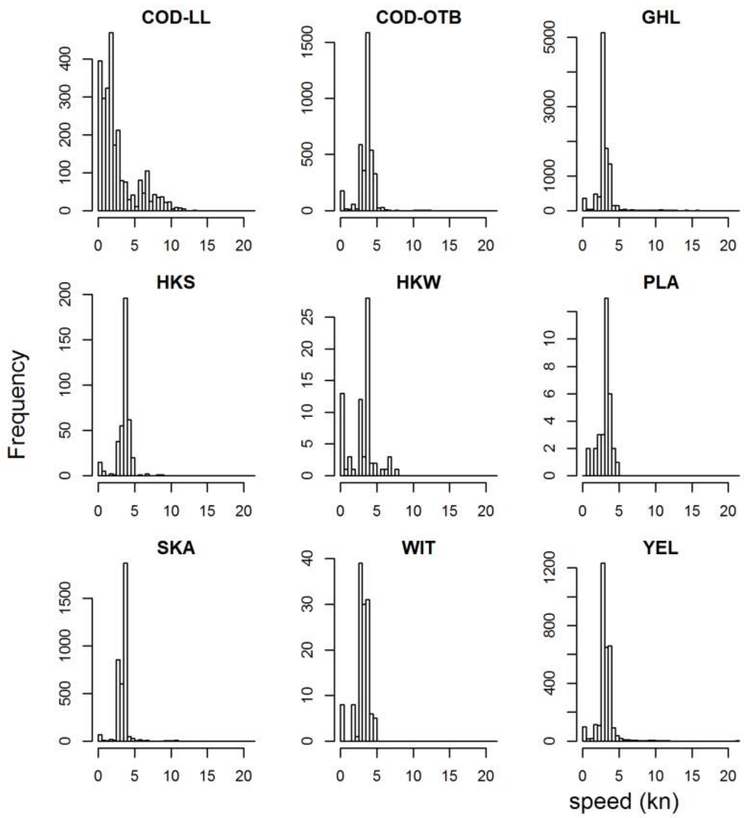


Fig. 3.4.6. Fishery-specific speed histograms from VMS points within haul-time intervals. COD-LL = cod longline, COD-OTB = cod bottom otter trawl, GHL = Greenland halibut, HAD = haddock, HAL = Atlantic halibut, HKS = silver hake, HKW = white hake, PLA = American plaice, RED = redfish, SKA = skates, WIT = witch, YEL = yellowtail flounder.

We conducted a simple overlay analysis to estimate the area of VME polygons that is overlapped by the 2016 cumulative fishing footprint and fisheries-specific footprints (Fig. 3.4.7). The fishing effort layers used were based on logbook haul-time filtering. Overall, we found that 20% of the total VME area had some degree of fishing in 2016, with fishing activities occurring in each of the three VME taxa polygons. Sea pen, large gorgonian, and sponge VMEs respectively had 21%, 22% and 19% of their area within the 2016 fishing footprint. The Greenland halibut fishery had the greatest areal overlap with the VME polygons, for each of the VME taxa. Redfish in 3M and 3LNO had the next largest overlap in the three VME types.

The fishing effort overlay analysis using the logbook haul-time filtering on 2016 data are in agreement with results of the previous WG-ESA meeting (NAFO 2016) where the overlay analysis was conducted on fishing for the 2012-2015 time period. Those results also showed that Greenland halibut bottom otter trawl fishery appeared to have the largest footprint in the various VME polygons, followed by redfish fisheries. When several years of fishing data are combined into one fishing footprint layer, the extent is larger than that of a single year; therefore the absolute percentage of VME overlapped was higher.

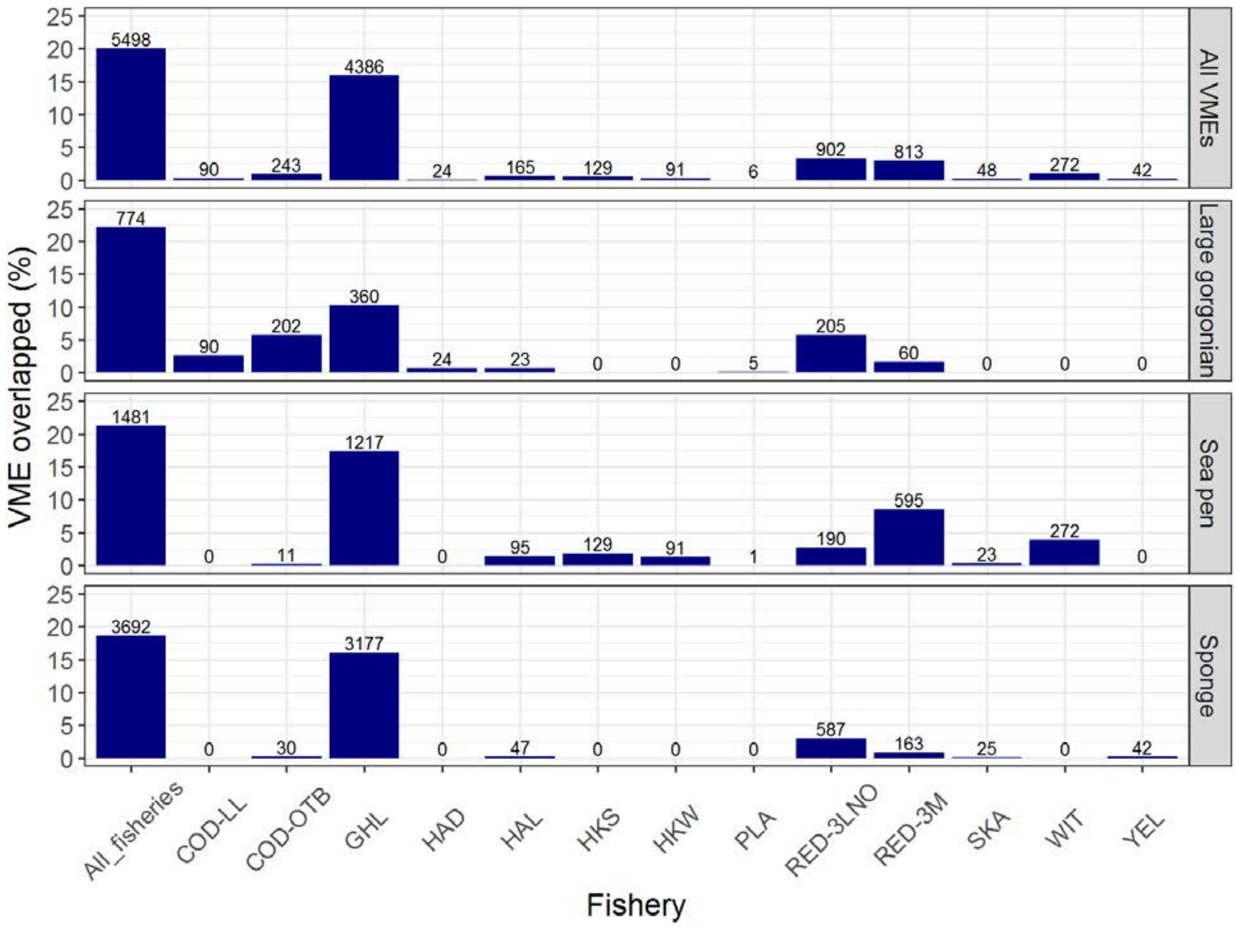


Fig. 3.4.7. The percent of VME polygon overlapped by cumulative fisheries (far-left bars) and fisheries-specific footprints using the haul-by-haul time filtering of 2016 VMS records. The top panel represents the area of all VMEs combined, and the bottom three panels represent the specific VME polygons by taxa. The number on top of each bar represents the absolute area of VME (km^2) that is overlapped by the fishing footprint. Note that the VME polygons are not the same as the VME closure areas. The fisheries abbreviations are given in the caption for Fig. 3.4.6.

Overall, the haul-time method appears to improve the fishing effort spatial layers in several ways. First, only points that are within reported fishing times are mapped, and provided that the reported start and end times are correct, this reduces the likelihood that non-fishing points are included in the effort. Second, using this new method reduces effort that is represented inside of VME closures. Third, there are fewer points that appeared to be spurious effort, i.e. individual cells with low levels of fishing, often in deep waters. Finally, the ability to assign fisheries on a haul-by-haul basis provides more detail and certainty to the fishing activity associated with each VMS ping. However, it is important to keep in mind that the resolution used is coarse with a 0.05 x 0.05 degree grid cell size and does not allow us to evaluate the fine-scale impacts that occur on the sea floor.

Going forward from the 2017 meeting, the WG agreed that they would like to see ongoing yearly mapping of the cumulative and fisheries-specific fishing effort. This will help understand if and how fishing effort is changing over the years. It was also suggested that the WG examine fishing speed ranges extracted for each vessel and for each species it caught as this information can be applied to past data, and used to verify accuracy of past work. Additionally, the WG discussed future work on mapping trawl tracks to further refine the fishing footprint. The current practice of aggregating points over grid cells can inflate estimates of fished area in locations where relative effort is low. However, mapping tracks requires information on gear dimensions to estimate the swept area. Therefore WG-ESA **recommends** that *additional information be recorded in the haul-*

by-haul data as follows: (1) appropriate measures of gear dimensions be recorded in the haul-by-haul data to facilitate future work on developing estimates of the area being swept by the trawl and (2) target species. This information would be critical to future efforts to map swept area, which would be the best representation of fishing effort that is possible.

References

NAFO. 2015. Report of the 8th Meeting of the NAFO Scientific Council (SC) Working Group on Ecosystem Science and Assessment (WG-ESA) [Formerly SC WGEAFM]. NAFO SCS Doc. 15/19, Serial No. N6549, 176 pp.

ToR 3.5. Up-date on plan to continue work on the risk assessment of scientific trawl surveys impact on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments.

FC 2017 request 3: *FC requests that Scientific Council continue its risk assessment of scientific trawl surveys impact on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments.*

There are presently 15 closed areas in the NAFO Regulatory area to protect Vulnerable Marine Ecosystems. Scientific surveys have been ongoing in these areas for several decades, the designs for which were constructed decades before the area closures were implemented. While recognizing the need to protect these areas from all trawling, Scientific Council was required to investigate how removing these areas from survey designs might impact index data used in stock assessments. To provide an update on the progress of this work, WG-ESA considered an overview of all analysis conducted on this subject by SC since initially raised by WGEAFFM during its 2015 meeting.

In 2016, WG-ESA (SCS Doc 16/21) conducted an analysis of the spatial overlap of significant catches of sea pens, large gorgonians and corals (as defined by their respective thresholds) in survey trawl catches. The significant catches were considered across three categories: i) NAFO closed areas, ii) areas inside the VME polygons but outside of NAFO closed areas, and, iii) areas outside of closures and outside of VME polygons. It was found that the vast majority of significant catches - and the highest rate of such catches - occur in the areas covered by current closures. This finding is expected as the VME polygons, and indeed the NAFO closed areas, were determined on the basis of these catches.

In both 2016 and 2017, SC reviewed analysis investigating the impact of excluding survey tows within the current closures from the EU Flemish Cap (Div. 3M) survey and also the Canadian (Divs. 3LNO) spring and autumn surveys (for species assessed by NAFO SC). In all cases, differences between survey index values computed using the complete time series and those computed using survey tows outside of closed areas were minimal with the exception of those for Roughhead Grenadier and Greenland Halibut. For those species, differences – although larger - were still relatively minor and the overall trends were similar.

An analysis of the length and age-disaggregated survey indices for these species was conducted for the Canadian survey data, and results were indistinguishable. Therefore it was concluded that the impact of excluding the closed areas from future Canadian surveys would enhance protection of VME elements while not compromising the ability to determine stock status of NAFO-managed resources.

The meeting was informed that it was likely that the length and age-disaggregated indices from the EU Flemish Cap survey would be available for consideration at the SC June 2018 meeting. A review of the EU-Spain survey data in Divs. 3LNO should also be expedited to allow SC to make a final recommendation to the Commission.

ToR 3.6. Up-date development in the use of non-destructive sampling techniques to monitor VMEs and options for integrating with existing survey trawl data.

Recommended Monitoring Tools

The requirement for non-invasive sampling of VME is in large part driven by the need to reduce the impact of trawl surveys on VME. However, at present the trawl survey provides the only annual systematic broad-scale monitoring of VME status. To migrate to non-invasive sampling some R&D will be needed to understand how trawl sample catches relate to other (non-invasive) sampling methods (see below).

Table 3.6.1 summary of available sampling tooks.

Attribute	**Data Required**	**Recommended Methods**	**Recommended Tools**	**Use WG-ESA**	**Comments**
Distribution (regional scale to > 1-3 km)	• Geo-referenced presence and absence, abundance and biomass as well as size distributions • Identification to species level if possible	Data from depth-stratified random stations as utilized in the RV multispecies surveys.	RV Trawl	Regional scale distributions, kernel density estimation (KDE), species distribution modelling (SDM)	Resolution scale appropriate to management actions
Distribution (small scale < 5 km)	• Geo-referenced presence and absence	Geo-referenced imagery at appropriate scale. (Beware of observation bias and false absence, and how this could alter the analysis. Also behaviour responses of species to disturbance by gear)	AUV, ROV, Drop Camera	Advice for bryozoan and ascidian significant concentrations on Tail of Grand Bank	Mismatch between KDE and in situ images due to fine scale distribution patterns within area.
Spatial Structure (Habitat Diversity/ Beta Diversity). Scales from metres to 10s of kilomtres	• Geo-referenced presence of benthic habitats • Identification of an/isotropic orientation of habitats	Geo-referenced imagery at appropriate resolution and spatial extent. Consider isotropic effects especially for benthic filter feeders.	AUV, ROV, Drop Camera, Towed Camera		Limited use of this data to date. Potential to link scales: assemblages-habitats-regional distributions.

Spatial Structure within Habitats e.g. Patch size, Aggregations, Community composition, Species associations, and Spillover effect	• Geo-referenced presence and absence of epibenthic mega and macrofaunal species • Baseline spatial structure	Geo-referenced imagery at appropriate resolution and spatial extent. Limitations: species identification from imagery is limited without corresponding samples. Many invertebrates cannot be identified from their dorsal surfaces or require dissection (e.g., sponges). Individual sizes can be difficult to estimate precisely. Previous fishing history is required to place data in context of disturbance.	ROV, Drop Camera Benthic samplers	Evidence for increased biodiversity associated with sponge grounds on Sackville Spur (Area 6) and Flemish Pass (Area 2)	Limited other uses of this data to date. Potential to link scales: assemblages-habitats-regional distributions
Abundance within Habitats	• Geo-referenced presence • Baseline damage • Size • Physical condition	Geo-referenced imagery	ROV, Drop Camera		Monitoring effectiveness of closed areas
Biomass within Habitats	• Weight of physical specimens	Targeted specimen collections (to convert image collected abundance and size data to biomass); collections need to be across environmental gradients and distribution to extend results beyond sampling locations	ROV, videograb		Monitoring effectiveness of closed areas
Size Distribution within Habitats recruitment, mortality, and population growth	• Geo-referenced presence • Size	Geo-referenced imagery and *in situ* measurements	ROV, Drop Camera		Monitoring effectiveness of closed areas

There are many texts written on methods for sampling the benthos (e.g., Eleftheriou and McIntyre, 2008) and benthic ecologists have proposed sampling plans for specific regions and applications (e.g., Circumpolar Biodiversity Monitoring Program of the Arctic Council). The intent here is not to review that literature, but rather to place the sampling tools in current and emerging use in the NRA into context with the use or potential use of data derived from them. Table 3.6.1 summarizes this perspective. Thus far data from AUVs have not been used in NAFO decision-making, however we have included them in our overview because a growing number of these devices are being deployed in Atlantic Canada and they serve as a prime tool to sample beta diversity, that is bridging the gap between the regional and local scales. This is a knowledge gap, along with patch sizes, that has not been as yet incorporated into our advice.

Way forward

Assuming that the analysis of the impact of removing survey sets on stock assessment metrics using the EU survey data reveals an insignificant affect(see Section 3.5), comparable to the Canadian data, then the impact of survey trawls on VME inside closed areas can effectively be eliminated. NAFO currently has not devised appropriate monitoring plans for VMEs and the above text indicates that tools other than trawls are more appropriate at small spatial scales. WGESA will discuss the Way Forward at its next meeting by outlining a VME monitoring plan for each VME group (sponges, sea pens etc.).

Reference

Eleftheriou, A. and McIntyre, A. 2008. Methods for the Study of Marine Benthos. John Wiley & Sons, 440 pp.

ToR 3.7. Develop a workplan to consider clearer objective ranking processes and options for objective weighting criteria for the overall assessment of SAI and risk of SAI

In 2016, during the last assessment of bottom fishing activities, the criteria applied to assess significant adverse impacts were essentially equally weighted, which implies that each of the VMEs are of equal functional importance, e.g. a 10% impact of the Sea Pen VME was evaluated the same as a 10% impact of Sponge VME. To overcome this limitation it is necessary to better understand the functional characteristics of each of the VME types. Studies have now been initiated to fill some of the gaps gaps in our understanding of the functional properties of VME, namely an analysis of VME biological traits (described under ToR 2.2), modelling of bottom fishing impacts on VME functions (described under ToR 2.1) and studies reviewing and assessing the recovery potential of VMEs (also described under ToR 2.1). The work described under ToRs 2.1 and 2.2 will be progressed over the next three meetings of WG-ESA supported by research grants awarded by the EU and Canadian Government to be completed ahead of the next reassessment of bottom fisheries expected in 2021. The results will then be used to weight the SAI criteria in line with the observed quanitified differences in the finctional charcteritics of the VMEs.

THEME 4: SPECIFIC REQUESTS

No additional requests wwere received from the Scientific Counciland hence there were no matters to report under this ToR.

AOB.

Date and place of next meeting

The next meeting will be held from 13 to 22 November 2018, location to be decided.

ANNEX 1: WG-ESA 2017 MEETING AGENDA TERMS OF REFERENCE AND SPECIFIC TOPICS TO ADDRESS

Theme 1: Spatial considerations

ToR 1. Update on identification and mapping of sensitive species and habitats (VMEs) in the NAFO area.

1. Update on VME indicator species data and VME indicator species distribution (Mar, Ellen)
2. Discussion on up-dating Kernel Density Analysis and SDM's for VME indicator species especially for sea pens (Ellen, Cam)
3. Continue to work on non-sponge and coral VMEs (for example bryozoan and sea squirts) to prepare for the next reassessment of bottom fisheries. (Ellen + Others).
4. Discussion on workplan and timetable for reassessment of VME fishery closures including seamount closures for 2020 assessment. (Ellen, Andy + Others)

Theme 2: Status, functioning and dynamics of NAFO marine ecosystems.

ToR 2. Update on recent and relevant research related to status, functioning and dynamics of ecosystems in the NAFO area.

1. Progress of analysis undertaken by EU NEREIDA research – Sea pen resilience. (Andy)
2. Maintain efforts to assess all six FAO criteria (Article 18 of the FAO International Guidelines for the Management of Deep Sea Fisheries in the High Seas) including the three FAO functional SAI criteria which could not be evaluated in the current assessment (recovery potential, ecosystem function alteration, and impact relative to habitat use duration of VME indicator species). (Vonda, Anna, Sarah)
3. Progress on expanded single species, multispecies and ecosystem production potential modelling (Robert, Alfonso, Pierre, Mariano)
4. Review of oceanographic and ecosystem status conditions in the NRA (Pierre, Mariano, Diana)

Theme 3: Practical application of ecosystem knowledge to fisheries management

ToR 3. Update on recent and relevant research related to the application of ecosystem knowledge for fisheries management in the NAFO area.

1. Development and application of the EAF Roadmap (Pierre, Mariano)
2. Develop draft summary sheets at ecosystem level (Pierre, Mariano).
3. Consideration of stock recruitment patterns through the application of EAFM (Pierre, Mariano) – SC Request
4. Developments to assess overlap of NAFO fisheries with VME to evaluate fishery specific impacts in addition to the cumulative impacts (Corinna, Neil, Don)
5. Up-date on plan to continue work on the risk assessment of scientific trawl surveys impact on VME in closed areas, and the effect of excluding surveys from these areas on stock assessments. (All)
6. Up-date development in the use of non-destructive sampling techniques to monitor VMEs and options for integrating with existing survey trawl data. (All)
7. Develop a workplan to consider clearer objective ranking processes and options for objective weighting criteria for the overall assessment of SAI and risk of SAI (All)

AOB.

1. Date and place of next meeting

ANNEX 2: SUMMARY OF RECOMMENDATIONS

- WG-ESA **recommends** *Scientific Council examine the current format and inclusion of species in the List of VME Indicator Species in Annex 1.E of the NCEM and determine whether:*
  - *a) The list should include only those VME Indicator Species likely to be encountered in trawl gear, or whether:*
  - *b) The list be revised to encompass a full list of VME Indicator Species in the NRA that could be encountered or recorded by use of non-destructive or alternative sampling gears such as camera/video surveys, as well as trawl gear.*
- WG-ESA **recommends** that *NAFO sets operational objectives to guide the implementation of an EAM*
- WG-ESA **recommends** *application of the model by Perez-Rodriguez et al. (2017) that describes cod-redfish-shrimp-fishery interactions for the Flemish Cap EPU (3M) (GADCAP) to inform the single species stock assessments when any of the 3M stocks are next assessed.*
- WG-ESA **recommends** that *the catch and survey data series used by SC for stock assessments should be made available to WG-ESA for use in multi-species modeling*
- Development of the ESS highlighted gaps in knowledge of the changes in the status of VMEs and the levels and importance of bycatches of regulated and unregulated taxa. Work is required before those sections of the report can be populated to reflect the knowledge available to NAFO. WG-ESA therefore **recommends:**
  - *a) That the trawl survey time series from Canadian and EU surveys be used to provide an index of the abundance (and other indices of state) of the major VME groups (seapens, sponges, gorgonians, others) within the VME polygons (i.e. areas of high likelihood of occurrence) and the frequency of occurrence outside;*
  - *b) That the Secretariat provides information on annual levels by-catch levels based on analysis of log-book data and provide a summary of the types and extent of regulatory measures that are intended to mitigate impact or extent of bycatch;*
  - *c) That the WG or Scientific Council undertake research to assess potential significance of bycatch on productivity of stocks and unregulated species and assess whether there are technical interactions among fisheries*
- WG-ESA **recommends** that *additional information be recorded in the haul-by-haul data as follows: (1) appropriate measures of gear dimensions be recorded in the haul-by-haul data to facilitate future work on developing estimates of the area being swept by the trawl and (2) target species.*

ANNEX 3: LIST OF PARTICIPANTS

Name	Affiliation	E-mail
	CHAIRS	
Andrew Kenny (WG-ESA Co-Chair)	CEFAS, Lowestoft Laboratory, Lowestoft, UK	andrew.kenny@cefas.co.uk
Pierre Pepin (WG-ESA Co-Chair)	Fisheries and Oceans Canada, St. John's, NL	pierre.pepin@dfo-mpo.gc.ca
Brian Healey (SC Chair)	Fisheries and Oceans Canada, St. John's, NL	brian.healey@dfo-mpo.gc.ca
	CANADA	
Robin Anderson	Fisheries and Oceans Canada, St. John's, NL	m.robin.anderson@dfo-mpo.gc.ca
Lindsay Beazley	Fisheries and Oceans Canada, Dartmouth, NS	lindsay.beazley@dfo-mpo.gc.ca
Alida Bundy	Fisheries and Oceans Canada, St. John's, NL	alida.bundy@dfo-mpo.gc.ca
Andrew Cuff	Fisheries and Oceans Canada, St. John's, NL	andrew.cuff@dfo-mpo.gc.ca
Corinna Favaro	Fisheries and Oceans Canada, St. John's, NL	corinna.favaro@dfo-mpo.gc.ca
Ellen Kenchington	Fisheries and Oceans Canada, Dartmouth, NS	ellen.kenchington@dfo-mpo.gc.ca
Mariano Koen-Alonso	Fisheries and Oceans Canada, St. John's, NL	mariano.koen-alonso@dfo-mpo.gc.ca
Camille Lirette	Fisheries and Oceans Canada, Dartmouth, NS	camille.lirette@dfo-mpo.gc.ca
Francisco Javier Murillo-Perez	Fisheries and Oceans Canada, Dartmouth, NS	javier.murillo-perez@dfo-mpo.gc.ca
Barbara Neves	Fisheries and Oceans Canada, St. John's, NL	barbara.neves@dfo-mpo.gc.ca
Neil Ollerhead	Fisheries and Oceans Canada, St. John's, NL	neil.ollerhead@dfo-mpo.gc.ca
Fred Phelan	Fisheries and Oceans Canada, St. John's, NL	fred.phelan@dfo-mpo.gc.ca
Don Power	Fisheries and Oceans Canada, St. John's, NL	don.power@dfo-mpo.gc.ca
Paul Regular (via WebEx)	Fisheries and Oceans Canada, St. John's, NL	paul.regular@dfo-mpo.gc.ca
Garry Stenson	Fisheries and Oceans Canada, St. John's, NL	garry.stenson@dfo-mpo.gc.ca
Vonda Wareham	Fisheries and Oceans Canada, St. John's, NL	vonda.wareham@dfo-mpo.gc.ca
	DALHOUSIE UNIVERSITY	
Danielle Dempsey	Dalhousie University, Halifax, NS, Canada	dempseydanielle@dal.ca
Sarah de Mendonça	Dalhousie University, Halifax, NS, Canada	sarah.de.mendonca@gmail.com
Anna Metaxas	Dalhousie University, Halifax, NS, Canada	metaxas@dal.ca

DENMARK (IN RESPECT OF FAROE ISLANDS AND GREENLAND)		
Adriana Nogueira	Greenland Institute of Natural Resources, Nuuk, Greenland	adno@natur.gl
ECOLOGY ACTION CENTRE		
Susanna Fuller	Ecology Action Centre, Halifax, NS, Canada	marine@ecologyaction.ca
EUROPEAN UNION		
Pablo Durán Muñoz	Instituto Español de Oceanografía, Vigo, Spain	pablo.duran@ ieo.es
Laura Robson (via WebEx)	JNCC, Peterborough, UK	laura.robson@jncc.gov.uk
Alfonso Pérez-Rodriguez	Institute of Marine Research, Bergen, Norway	alfonso.perez.rodriguez@imr.no
Mar Sacau	Instituto Español de Oceanografía, Vigo, Spain	mar.sacau@ ieo.es
Robert Thorpe	CEFAS, Lowestoft Laboratory, Lowestoft, UK	robert.thorpe@cefas.co.uk
FOOD AND AGRICULTURE ORGANIZATION (FAO)		
Hassan Moustahfid	Food and Agriculture Organization of the United Nations	hassan.moustahfid@fao.org
UNITED STATES OF AMERICA		
Geret DePiper	NOAA	geret.depiper@noaa.gov
Mike Fogarty (*via* videoconference)	Northeast Fisheries Science Center, Woods Hole, MA	michael.fogarty@noaa.gov
NAFO SECRETARIAT		
Tom Blasdale	NAFO Secretariat, Dartmouth, NS, Canada	tblasdale@nafo.int
Dayna Bell MacCallum	NAFO Secretariat, Dartmouth, NS, Canada	dbell@nafo.int