WORKING GROUP ON ECOSYSTEM EFFECTS OF FISHING ACTIVITIES (WGECO)

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i Executive summary

The 2021 WGECO meeting was held entirely by remote meetings due to COVID-19 travel restrictions. Participation was strong, however, the remote setting limited the amount of work which could be completed. An initial plan to take up five Tors was made, but considering member availability and interest, only Tors A and C were addressed this year. WGECO decided to keep all of the Tors for 2022, and will consider developing additional Tors from Tor C (Horizon scanning). Much of this will depend on the current state of COVID-19 and member availability in 2022.

WGECO revisited work to examine the ecological consequences of stock rebuilding, with an emphasis on benthivorous fish (Tor A). Two case studies with data from the Northeast U.S. and Iceland compared the footprints of fishing effort and fish predation pressure on benthos. An index of spatial overlap was examined and minor (U.S.) or zero (Iceland) significant overlap was observed with bottom trawling effort and predation pressure. In contrast, dredging effort from the Northeast U.S. showed significant overlap with predation pressure for 11 of the 12 benthic prey taxa examined. Without an active or recent benthos monitoring program for the Northeast U.S. continental shelf, conclusions regarding competition between these two overlapping benthic pressures remain unknown.

WGECO carried out a "Horizon gazing" exercise to identify key emerging or expected issues, that would be appropriate for WGECO to address at future meetings. Nine topics were considered, listed below:

- Defining criteria for including results from ecosystem modelling etc. in advice
- Fish productivity measured by production ratio (R/SSB)
- Metrics for Ecosystem Overfishing
- Industrial zonation of fishing – the potential for identifying the key areas for fishing and to ring fence these
- B_{MSY} – the use and meaning of MSY based metrics on both sides of the Atlantic
- The elephant in the room, selectivity estimation in stock assessment
- Linking benthic knowledge to fisheries advice
- Shared-Socioeconomic-Pathways
- Fisheries and blue carbon sequestration

Potential ToRs were developed for the first four. The remaining issues were seen as important but not yet ripe for detailed examination. WGECO will keep a watching brief on these and propose additional work as appropriate.

ii Expert group information

Expert group name	Working group on the ecosystem effects of fishing activities (WGECO)
Expert group cycle	Annual
Year cycle started	2021
Reporting year in cycle	1/1
Chairs	Tobias van Kooten, Netherlands
	Brian Smith, USA
Meeting venue(s) and dates	13 April – 24 June 2021, Virtual meetings (17 participants)

1 Tor a: Investigate the ecological consequences of stock rebuilding, with particular emphasis on benthivorous fish and invertebrates. 1) Make first-order estimates of predation pressure on benthos; 2) Examine evidence of food limitation and density-dependent growth; 3) Compare the footprints of trawling to the footprints of predation pressure on benthos.

1.1 General Remarks

This is the third year of this term of reference for WGECO with a planned completion in 2022. The work in 2021 focused on comparing the footprints of bottom fishing effort and fish predation pressure on benthos for waters of the Northeast US and around Iceland. With similar methods, spatial overlap of fishing effort (trawling and dredging) and predation (biomass consumed) was examined for these waters.

1.2 A comparison of trawling and dredging footprints to predation pressure on benthos of the Northeast U.S. continental shelf.

1.2.1 Introduction

Fishing effort and fish diet data from NOAA Fisheries, Northeast Fisheries Science Center (NEFSC) were examined for two bottom fishing gear types: otter/beam trawls and dredges, and 14 benthivorous fishes (Table 1) of the northeast U.S. The number of trips from vessel trip reports (VTR) and the amount of benthic prey eaten were the primary data examined. From these data, fishing effort as annual mean trip frequency and community-level consumption (annual mean biomass of benthos eaten) were calculated for the northeast U.S. continental shelf.

Fishing effort and benthos consumption were estimated by 10 min squared grid cells and averaged across years. With estimates of fishing effort and benthos consumption per cell, Williamson's spatial overlap index (Williamson 1993) was calculated to determine the degree of overlap between fishing effort and predation pressure on the benthos.

Table 1. Fourteen fish predators.

Common name	Species
American plaice	*Hippoglossoides platessoides*
Black sea bass	*Centropristis striata*
Cod	*Gadus morhua*
Haddock	*Melanogrammus aeglefinus*
Little skate	*Leucoraja erinacea*
Longhorn sculpin	*Myoxocephalus octodecemspinosus*
Ocean pout	*Zoarces americanus*
Red hake	*Urophycis chuss*
Smooth dogfish	*Mustelus canis*
Thorny skate	*Amblyraja radiata*
Winter flounder	*Pseudopleuronectes americanus*
Winter skate	*Leucoraja ocellata*
Witch flounder	*Glyptocephalus cynoglossus*
Yellowtail flounder	*Limanda ferruginea*

1.2.2 Methods

Fishing effort

Effort from vessel trip report (VTR) data was quantified as the annual mean number of trips for two gear types: trawling and dredging from 1996-2019 for the northeast U.S. continental shelf. Dredging targeted clams, scallops, mussels, and other miscellaneous benthos. Trawling included unpaired, paired, and beam trawls targeting fish, shrimp, scallops, and other miscellaneous benthos. Annual mean number of trips per gear (trawl or dredge) were estimated for each 10 min squared grid cell across the shelf with a minimum annual average of one fishing trip.

Fish diet

Fourteen fish benthivores (Table 1) were included for estimating benthos consumption. These predators accounted for approximately 82% of all benthic invertebrate prey encountered in fish stomach samples of the northeast U.S. continental shelf from 1996-2019. Their diet data were aggregated spatially by 10 min squared grid cell.

Consumption estimates were calculated on a seasonal basis (two six-month periods) for each predator and 10 min squared grid cell, and summed as annual mean estimates. Although diet data collections for these predators started quantitatively in 1973 (mainly Order Gadiformes) and extends to the present (through 2019), not all benthivores were sampled during the full extent of this sampling program. Stomach sampling for the non-Gadiformes considered here began in 1977 and extends through 2019. For more details on the food habits sampling protocols and approaches, see Link and Almeida (2000) and Smith and Link (2010). This sampling program was part of the NEFSC bottom trawl survey program which samples primarily in spring (March-

May) and fall (September-November), but does include some winter (February) and summer (July-August) data. Further details of the survey program can be found in Azarovitz (1981), NEFC (1988), Reid *et al*. (1999), and Politis *et al*. (2014).

Diet data

Mean amounts of benthos eaten ($D_{i,c,t}$; as observed from diet sampling) for each predator (*i*), 10 min squared grid cell (*c*), and season (*t*, fall or spring) were weighted by the number of fish at length per tow and the total number of fish per tow as part of a two-stage cluster design (See Link and Almeida 2000; Latour *et al*. 2007). These means included empty stomachs, and units for these estimates are in grams (g).

Numbers of Stomachs

A minimum sample size equal to 20 stomachs for each predator per 10 min squared grid cell and season was used based on trophic diversity curves (e.g. Koen Alonso *et al*., 2002; Belleggia *et al*., 2008). With this approach, consumption of benthos was estimated for each predator species, 10 min squared grid cell, and season.

Prey

Twelve benthic invertebrate prey were considered for the estimation of benthos consumption (Table 2). The prey represented the dominant benthic invertebrate prey that were not highly mobile and regularly identified in the stomachs of the predators in Table 1. Highly mobile prey were excluded due to the potential reduction of footprint accuracy. Other benthos represented those taxa not specified including various crabs, gastropods, non-polychaete worms, benthic shrimps, and benthic structures such as animal tubes.

Table 2. Twelve prey taxa.

Taxonomic name	Common name
Anthozoa	Sea anemones, corals
Asteroidea	Sea stars
Bivalvia	Bivalves
Caprellidae	Caprellids
Echinoidea	Sea urchins, sand dollars
Gammaridea	Gammarids
Holothuroidea	Sea cucumbers
Isopoda	Isopods
Ophiuroidea	Brittle stars
Other benthos	Other benthos
Paguridae	Hermit crabs
Polychaeta	Polychaetes

Consumption Rates

To estimate per capita consumption for each predator species, we used the gastric evacuation rate method of Eggers (1977) and Elliot and Persson (1978).

Using the evacuation rate model to calculate consumption requires two variables and two parameters. The daily per capita consumption rate of benthos, $C_{i,c,t}$, is calculated as:

$$C_{i,c,t} = 24 \cdot E_{i,c,t} \cdot D_{i,c,t} \quad ,$$

where 24 is the number of hours in a day. The evacuation rate $E_{i,c,t}$ is:

$$E_{i,c,t} = \alpha e^{\beta T_{i,c,t}} \quad ,$$

and is formulated such that estimates of mean benthos eaten ($D_{i,c,t}$) and ambient temperature ($T_{i,c,t}$) as stratified mean bottom temperature associated with the presence of each predator from the NEFSC bottom trawl surveys (Taylor and Bascuñán 2000; Taylor *et al*. 2005) are required. The parameters α (0.002 for elasmobranchs; 0.004 for teleosts) and β (0.115) were set as specified and chosen from the literature (Durbin *et al*. 1983; Tsou and Collie 2001a, 2001b; Temming and Herrmann 2003).

Fish Predator Abundance Estimation

Benthos consumption was scaled to the fish community level by including predator population abundance. Abundance from survey indices estimated as swept area abundance were available for each predator, year, and geographic region (Figure 1) as sampled each fall by the NEFSC bottom trawl survey. Catchability (q) was assumed to equal 1.0 which is standard for several of these species with index-based stock assessments (see https://www.fisheries.noaa.gov/new-england-mid-atlantic/population-assessments/fishery-stock-assessments-new-england-and-mid-atlantic). Mean annual predator abundance for each 10 min squared grid cell was derived from annual proportions of numbers of individuals caught per the annual total number caught in each geographic region by the NEFSC fall bottom trawl survey.

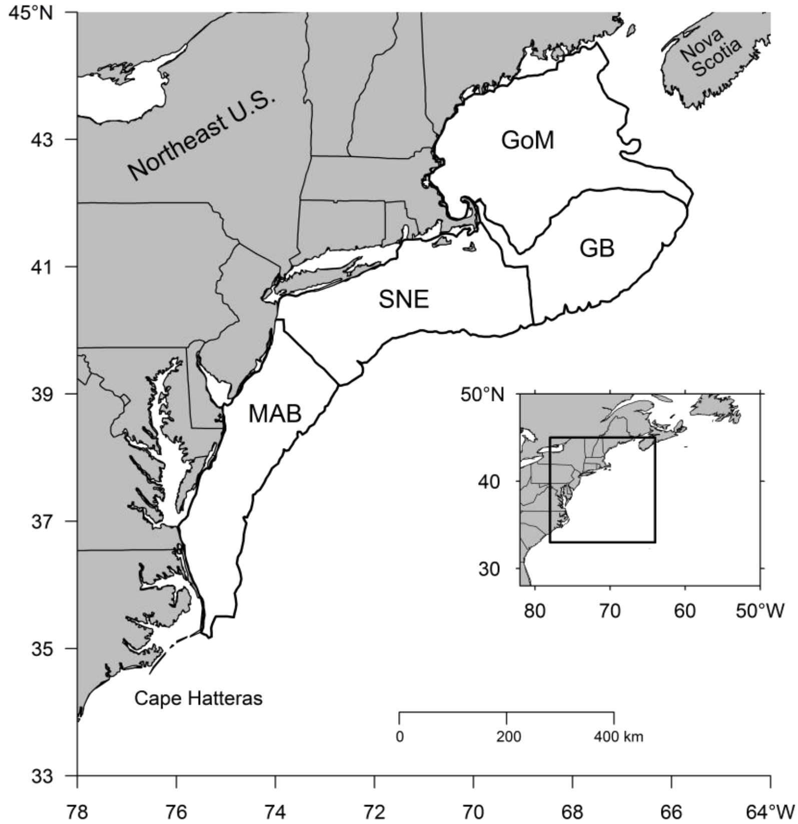

Figure 1. Map of geographic regions of the northeast U.S. continental shelf. GoM: Gulf of Maine, GB: Georges Bank, SNE: Southern New England, MAB: Mid-Atlantic Bight. Nova Scotia, Canada and Cape Hatteras, North Carolina labelled for reference.

Scaling Consumption

Following the estimation of consumption rates for each predator, 10 min squared grid cell, and season (t), estimates were scaled up to half-year estimates ($C'_{i,c,t}$) by multiplying the number of days in each half year (182.5):

$$C'_{i,c,t} = C_{i,c,t} \cdot 182.5 \quad .$$

These were then summed to provide an annual estimate by 10 min squared grid cell, $C'_{i,c}$:

$$C'_{i,c} = C_{i,c,fall} + C_{i,c,spring} \quad .$$

and were then scaled by the mean annual population abundance per 10 min squared grid cell to estimate a total annual amount of benthos removed by predator per 10 min squared grid cell, $C_{i,c}$:

$$C_{i,c} = C'_{i,c} \cdot N_{i,c} \quad .$$

The total consumption of benthos across predators is presented as annual tonnes 10 min squared grid cell^{-1}.

Spatial overlap

A comparison of fishing effort and benthos predation pressure footprints was made with Williamson's overlap index (O_{ij}; Williamson 1993; Link and Garrison 2002; Skaret *et al*. 2015) as:

$$O_{ij} = \frac{\sum_c (N_{ic} \cdot N_{jc}) \cdot m}{\sum_c N_{ic} \cdot \sum_c N_{jc}}$$

Where c denotes a specific grid cell, m is the total number of grid cells, and N_i and N_j are the annual mean number of fishing trips (i) and annual mean consumption of benthic prey (j). Index values greater/less than 1 indicate more/less overlap than expected, and values close to 1 indicate what would be expected with uniform distributions of fishing effort and benthos consumption.

Values were log transformed to normalize the data. To test for significant overlap, we applied a randomization approach similar to Link and Garrison (2002) and Skaret *et al*. (2015) where the observed overlap index for each fishing gear type (trawl or dredge) and each prey (12 taxa; 24 combinations) was identified within a simulated distribution of overlap values. For the simulated data, we randomly sampled with replacement the effort and consumption data. Random sampling was repeated 459 times (total number of overlapping grid cells) for each significance test and calculated an overlap index from the resulting data. A distribution of 10^5 overlap values was generated, and if the original index value was outside of the 2.5 or 97.5 quantiles of the simulated distribution, overlap was determined to be significantly different from the expectation of no relationship.

1.2.3 Results and Conclusions

Benthivorous fish diet sampling for the northeast U.S. continental shelf was extensive from 1996-2019 with numbers of stomachs collected per 10 min squared grid cell ranging from 20 to more than 1000 (Figure 2). Grid cells with only 20 stomachs represented data from only one predator (minimum number per predator allowed).

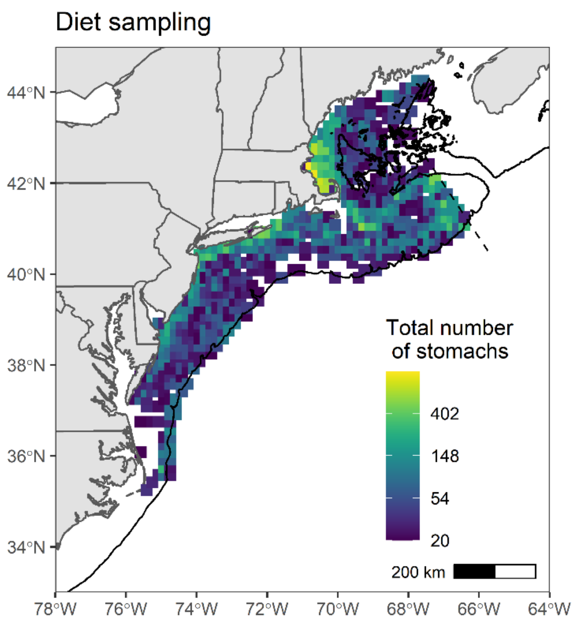

Figure 2. Total number of stomachs sampled by 10 min squared grid cells from 1996-2019 for the predators in Table 1. The dashed line indicates the U.S./Canada boundary. Bathymetry shown is 200 m. Data were log-transformed to normalize colour distribution.

Similar to diet sampling, fishing effort as measured by the mean number of trips per year per 10 min squared grid cell was widespread across the continental shelf from 1996-2019 (Figure 3). For trawl and dredge gears, we observed a minimum mean of one trip per year and a maximum mean of 149 (dredge) and 274 (trawl) trips per year per grid cell. Dredging effort was highest in the coastal southern part of the Gulf of Maine, parts of Georges Bank, eastern Southern New England, coastal Southern New England, and northern/central Mid-Atlantic Bight (Figure 3A). Somewhat in contrast, trawling was more widespread in the Gulf of Maine (probably due to greater gear accessibility), but was also concentrated in the coastal southern part of the Gulf of Maine, northern edge of Georges Bank, coastal Southern New England, and sporadic across the Mid-Atlantic Bight (Figure 3B). Aside from gear accessibility, targeted fisheries also played a role in determining the spatial footprints of dredging and trawling and their differences. To no surprise, dredging primarily targeted benthic invertebrates—scallops, clams, and mussels, whereas trawling primarily targeted fish and shrimp, and to a lesser degree benthic invertebrates such as scallops.

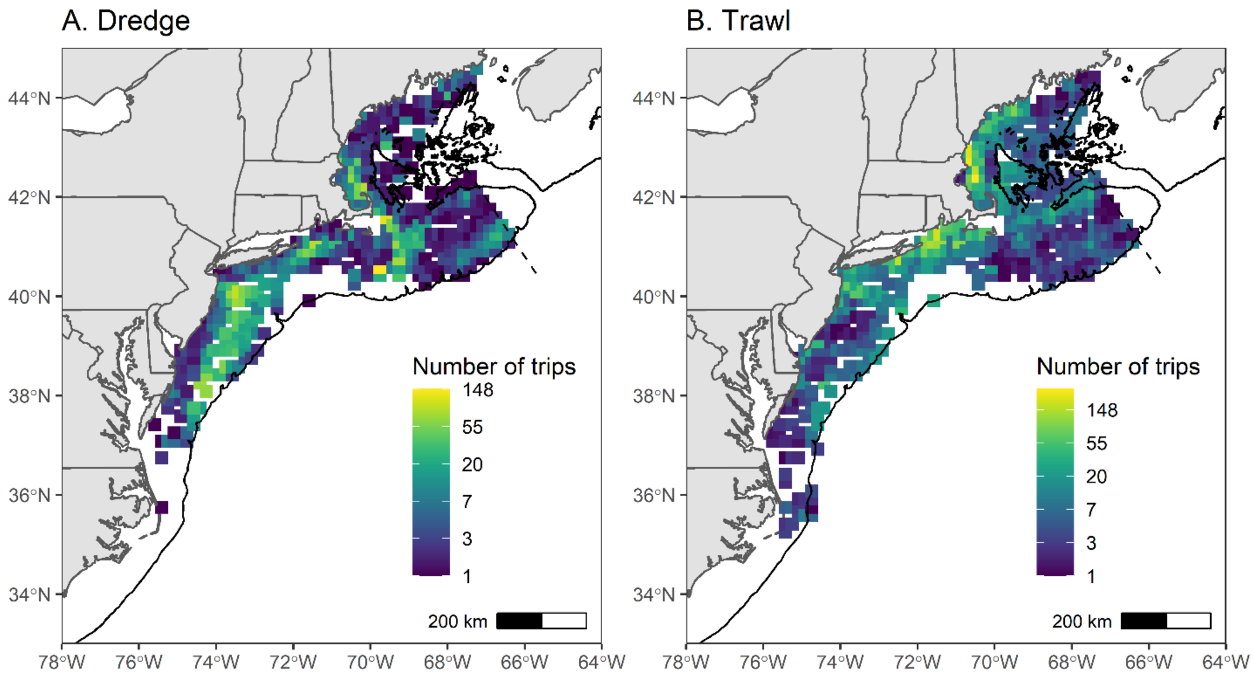

Figure 3. Fishing effort as mean number of trips per year for dredge (A) and trawl (B) gears by 10 min squared grid cells. The dashed line indicates the U.S./Canada boundary. Bathymetry shown is 200 m. Data were log-transformed to normalize colour distribution.

Mean annual consumption of the 12 benthic taxa varied greatly ranging from less than 1 KG per 10 min squared grid cell to approximately 950 tonnes (Polychaeta) and 1,976 tonnes (Other benthos) per grid cell (Figure 4). Benthos consumption occurred throughout the continental shelf, but for most prey taxa, their presence in the diet was isolated given their distributions, preferred habitat, and their taxonomic classification (e.g. Bivalvia vs Caprellidae; Figure 4C, D). Prey that were most widespread across the continental shelf included Bivalvia, Gammaridea, Isopoda, Other benthos, and Polychaeta (Figure 4C, F, H, J, L). One isolated "hot spot" of consumption for all prey included the coastal area of southern Gulf of Maine (coastal Massachusetts; Figure 4). Additionally, Anthozoa was consumed on parts of Georges Bank, and coastal Southern New England and Mid-Atlantic Bight (Figure 4A); Caprellidae and Echinoidea were observed across the majority of Georges Bank and some of Southern New England (Figure 4D, E); Ophiuroidea was heavily consumed in the Gulf of Maine and parts of Georges Bank (Figure 4I); and Paguridae was mostly eaten on Georges Bank and the Mid-Atlantic Bight (Figure 4K).

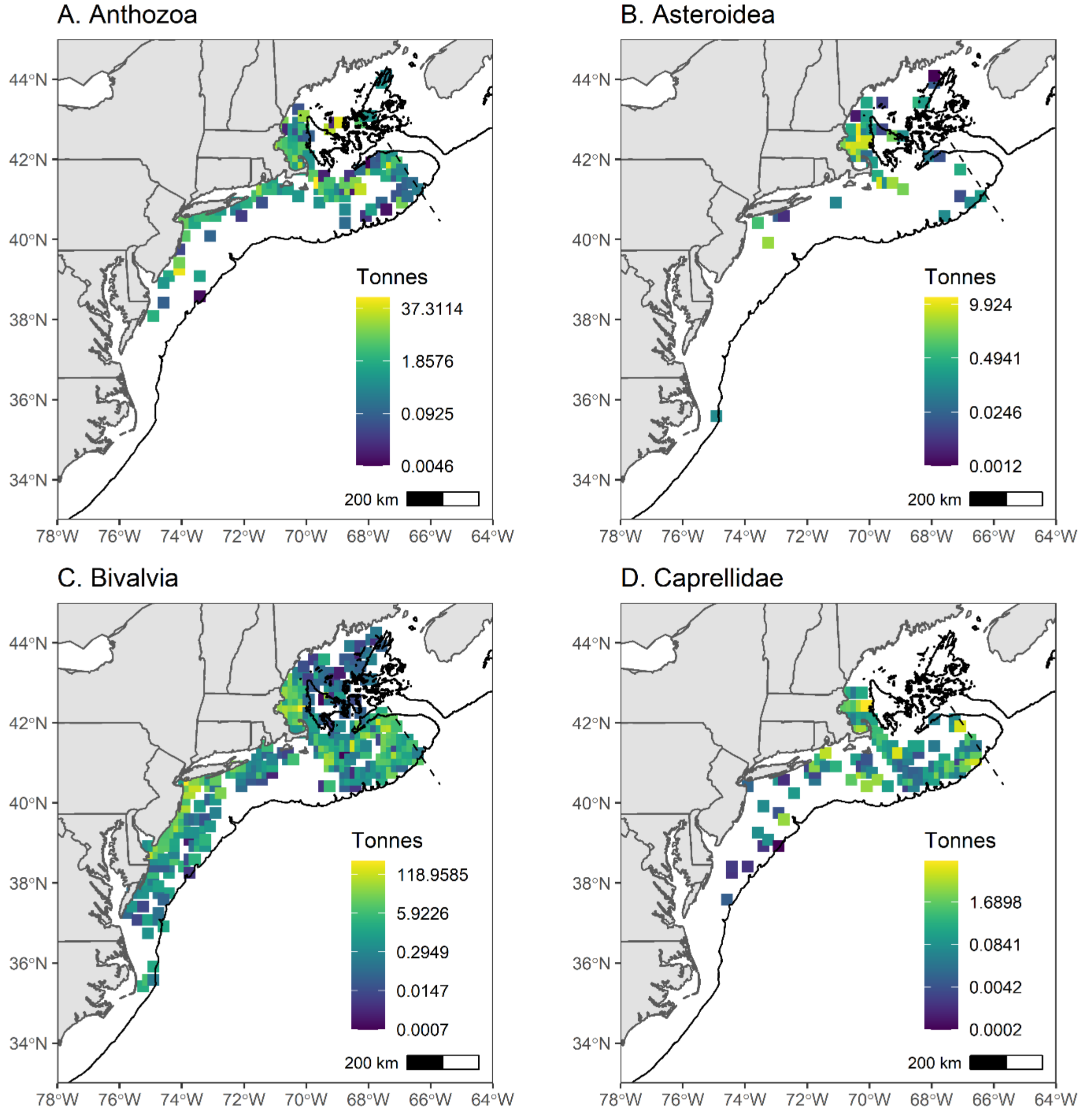

Figure 4. Annual mean consumption (tonnes of prey removed) for Anthozoa (A), Asteroidea (B), Bivalvia (C), and Caprellidae (D) by 10 min squared grid cell. The dashed line indicates the U.S./Canada boundary. Bathymetry shown is 200 m. Data were log-transformed to normalize colour distribution.

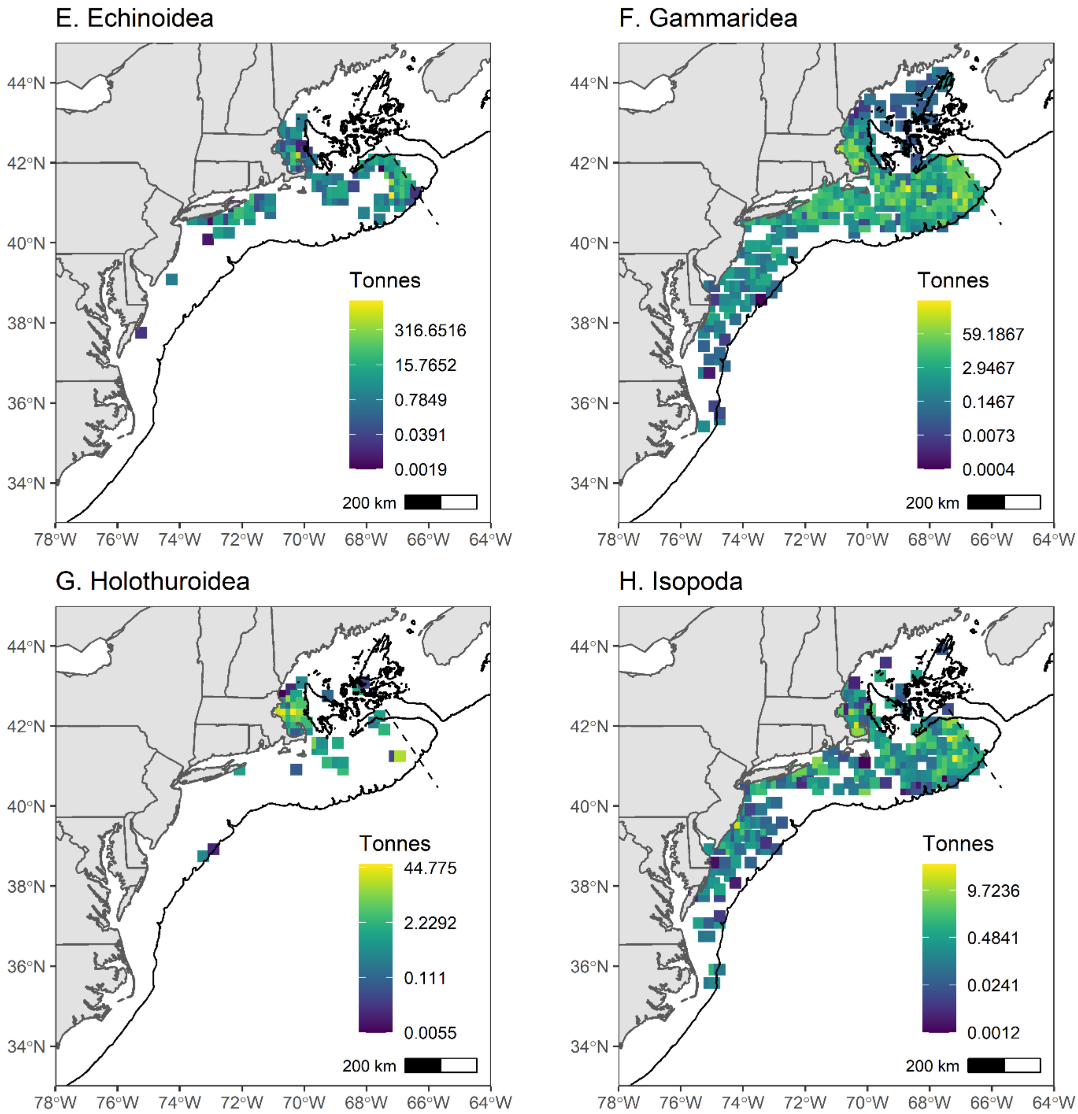

Figure 4 (continued). Annual mean consumption (tonnes of prey removed) for Echinoidea (E), Gammaridea (F), Holothuroidea (G), and Isopoda (H) by 10 min squared grid cell. The dashed line indicates the U.S./Canada boundary. Bathymetry shown is 200 m. Data were log-transformed to normalize colour distribution.

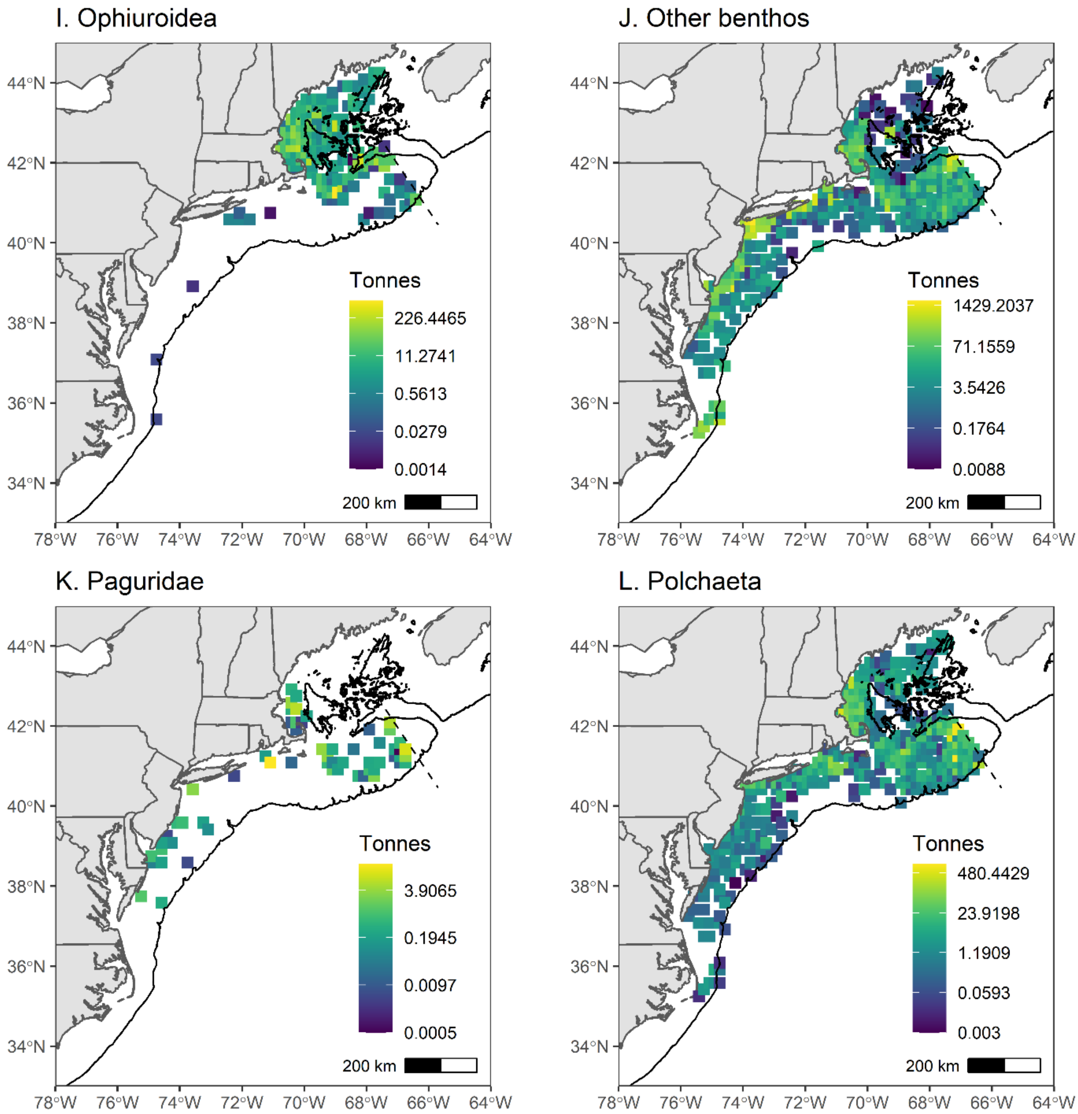

Figure 4 (continued). Annual mean consumption (tonnes of prey removed) for Ophiuroidea (I), other benthos (J), Paguridae (K), and Polychaeta (L) by 10 min squared grid cell. The dashed line indicates the U.S./Canada boundary. Bathymetry shown is 200 m. Data were log-transformed to normalize colour distribution.

The overlap of benthic predation and effort from dredging and trawling as measured by Williamson's index (Williamson 1993) was significantly greater than expected for the 12 prey taxa considered here (Table 3). Specifically, 11 of the 12 prey demonstrated statistically greater overlap with dredging effort, whereas 5 of the 12 prey had greater overlap with trawling effort. None of the prey had less than expected overlap. The top-5 prey with the greatest overlap with dredge effort were (descending order) Holothuroidea, Paguridae, Asteroidea, Echinoidea, and Caprellidae (Table 3). For trawl effort, Asteroidea had the greatest overlap. Interestingly, Ophiuroidea which was the one prey that did not significantly overlap with dredging effort, had significant overlap with trawling effort. This was due to Ophiuroidea's distribution being primarily in the Gulf of Maine where trawling was more widespread in comparison to dredging (Figures 3, 4I).

Table 3. Values of Williamson's overlap index and range of 0.025 and 0.975 quantiles from simulated data for each prey and gear type. Gray shading denotes significance for overlap indices outside of the quantile range. Significant values above 1.00 demonstrate greater than expected overlap.

Prey	Dredge	Trawl
Anthozoa	1.25 (0.85, 1.16)	1.07 (0.90, 1.11)
Asteroidea	1.52 (0.70, 1.33)	1.35 (0.80, 1.21)
Bivalvia	1.21 (0.91, 1.10)	1.14 (0.94, 1.06)
Caprellidae	1.42 (0.77, 1.25)	0.94 (0.85, 1.16)
Echinoidea	1.51 (0.82, 1.19)	1.06 (0.88, 1.12)
Gammaridea	1.35 (0.91, 1.09)	1.02 (0.94, 1.06)
Holothuroidea	1.64 (0.74, 1.28)	1.26 (0.83, 1.18)
Isopoda	1.21 (0.87, 1.13)	1.00 (0.92, 1.09)
Ophiuroidea	1.00 (0.88, 1.12)	1.20 (0.93, 1.08)
Other benthos	1.13 (0.94, 1.06)	1.02 (0.96, 1.04)
Paguridae	1.53 (0.72, 1.31)	1.08 (0.82, 1.20)
Polychaeta	1.15 (0.94, 1.06)	1.06 (0.96, 1.04)

The notable overlap of predation with dredging effort and less with trawling effort is not completely surprising. With similar targets, benthic predation and dredging are competing for similar resources—mostly sedentary benthic invertebrates. In terms of ecological consequences of fish stocks rebuilding, the demand for these particular benthic prey and other prey will increase; thus, overlap especially with dredging will become greater. It is also suspected that overlap with trawling effort could increase to higher levels as well, but may be less dramatic compared to dredging. Ultimately, the spatial hotspots of fishing effort and consumption of most prey taxa by fishes and their significant overlap suggest strong competition for the benthos and their bottom habitat may exist. Ongoing work to examine benthic production for these prey taxa and the proportion eaten similar to previous work for this continental shelf (ICES 2019) is of interest at the spatial scale presented here.

The disturbance of benthic habitats and subsequent impact from dredge and trawl fisheries is well known globally often resulting in a net loss of resources for sustainably managing ecosystems (e.g. Collie *et al*. 2000a; Jennings *et al*. 2001; Kaiser *et al*. 2006; Jørgensen *et al*. 2015). For the northeast U.S. continental shelf, the same outcome has been shown (Collie *et al*. 2000b; Hermsen *et al*. 2003; Collie *et al*. 2005) along with impacts to fish feeding (Smith *et al*. 2013). We document notable overlap, and with this, the potential for competition between dredging effort and predation within benthic habitat – a shared spatial resource. Continued protection of benthic habitat and increased monitoring are essential. Predation (quantified as tonnes of prey removed) can be a useful tool to gauge how important and available these benthic taxa are for fish communities. But, data for benthic prey availability is often limited as is true for this continental shelf with shelf-wide sampling of benthos occurring over 50 years ago; Theroux & Wigley 1998). With a planned rebuild of fish stocks, prioritizing adequate resources for all elements, including buffers for ecological demands will be essential, particularly as resources become limited or distributions of fishing effort and prey biogeography change due to climate or other environmental drivers (Spalding *et al*. 2014; Roberts *et al*. 2017).

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1.3 Overlap in the spatial distribution of bottom trawling effort and predation pressure by haddock (*Melanogrammus aeglefinus*) around Iceland

1.3.1 Introduction

Overlaps in the spatial distribution of bottom fishing effort and predation pressures by haddock (*Melanogrammus aeglefinus*) were calculated within grid cells of 15 min latitude and 30 min longitude using data from the Marine and Freshwater Research Institute (MFRI) for the period 2006-2020. The analytical approaches applied followed closely those carried out in the Northeast U.S. continental shelf case study (section 1.2).

1.3.2 Methods

Fishing effort

The bottom fishing effort (Vessel Monitoring System (VMS) and logbook data combined) was calculated as the mean annual tow duration and mean annual tow frequency for the period 2006-2020.

Haddock consumption and spatial overlaps

The haddock was chosen for this case study due to their high preference for benthic prey taxa (Jaworski and Ragnarsson 2006). Annual collection of diets of haddock (and including many other demersal fish species) was initiated in the Icelandic spring Groundfish Survey from 2006 onwards. From each haul, stomachs were generally obtained from the first five haddock captured, but for very large hauls, more stomachs were collected (but rarely beyond 10). Food items were identified on board the research vessel to the lowest taxonomic resolution possible. More information on the sampling approaches can be found in Anon. (2010) and Jaworski and Ragnarsson (2006).

For each grid cell, the calculation of means of each prey taxa per stomach was weighted by the number of haddock per tow larger than 19 cm with prey. Grid cells with more than 20 stomachs were selected for analysis. The 12 prey taxa that were found in more than 100 grid cells (out of the 235 sampled over the period 2006-2020), were selected for analysis. The consumption rates were calculated in the same manner as in the US study (see 1.2.2.).

For the study period, the consumption of benthic prey types by haddock per grid cell was scaled by its total stock size (numbers by age, see https://dt.hafogvatn.is/astand/2020/2_HAD_is.html), and by the estimates of the mean abundance of haddock per grid cell (15 min latitude and 30 min longitude). The total consumption of haddock on benthos was calculated in the same way as in the US study, except that these estimates were scaled with a window of 3 months (91.25 days; representing one season) and not 6 months (182.5 days; representing two seasons), as the spring Icelandic Groundfish Survey sampling takes place every year in March.

The overlap in the spatial distribution of the fishing pressure and the haddock predation pressure was calculated using the Williamson's overlap index, in the same manner as in the US study.

1.3.3 Results and conclusions

Over the period 2006-2020 (Figure 5), most of the gridcells were adequately sampled, with 42% of the grid cells with >100 haddock stomachs and 82% with >20 stomachs (but those with fewer stomachs than 20 were excluded from analysis).

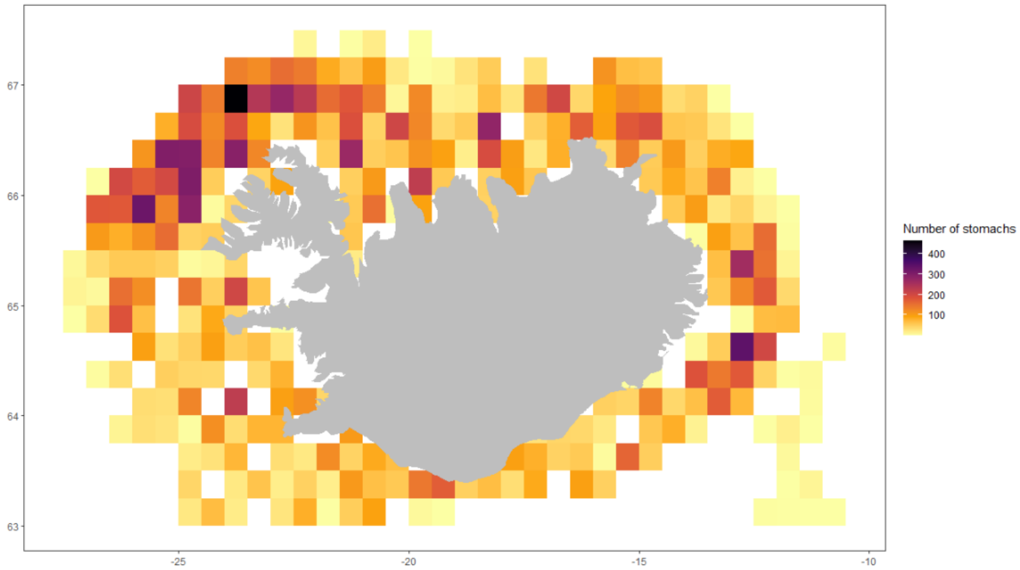

Figure 5. Total number of haddock stomachs (11832) sampled per 15 min latitude by 30 min longitude grid cells within Icelandic waters between 2006 and 2020.

To better visualise the patterns in spatial distribution of the bottom trawl effort, it is shown in Figure 6 at a spatial resolution of 0.025 min latitude x 0.05 min longitude, using 2020 as an example. The fishing effort with otter-trawl was largely confined to the shelf and the shelf break and was particularly intense off the NW and SE Iceland, with tow duration in some grid cells exceeding 30 hours. At the spatial resolution of the 15 min latitude by 30 min longitude grid cells, the most intensively grid cells were towed more than 400 times a year and with tow duration exceeding 1500 hours (Fig 7 a and b).

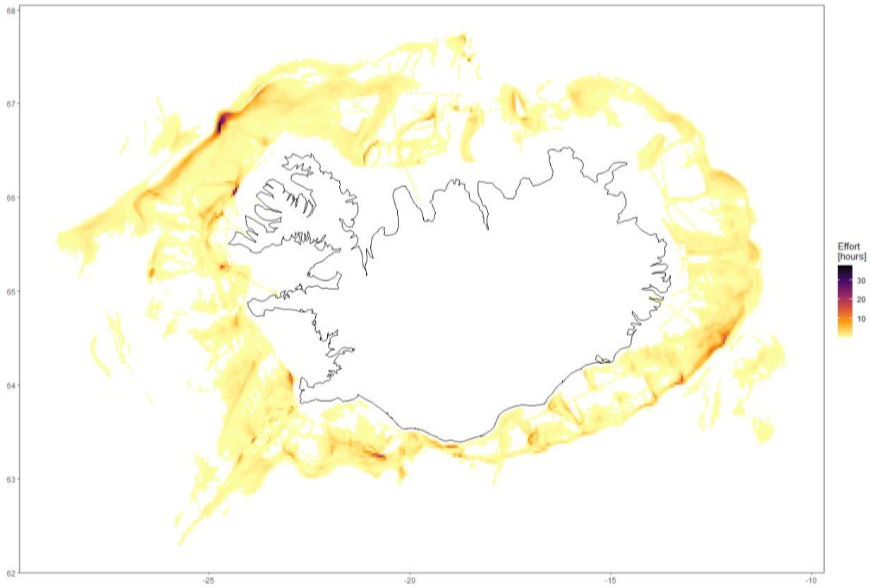

Figure 6. Bottom trawl fishing effort in 2020 portrayed as number of hours trawled per grid cell size of 0.025 latitude and 0.05 min longitude.

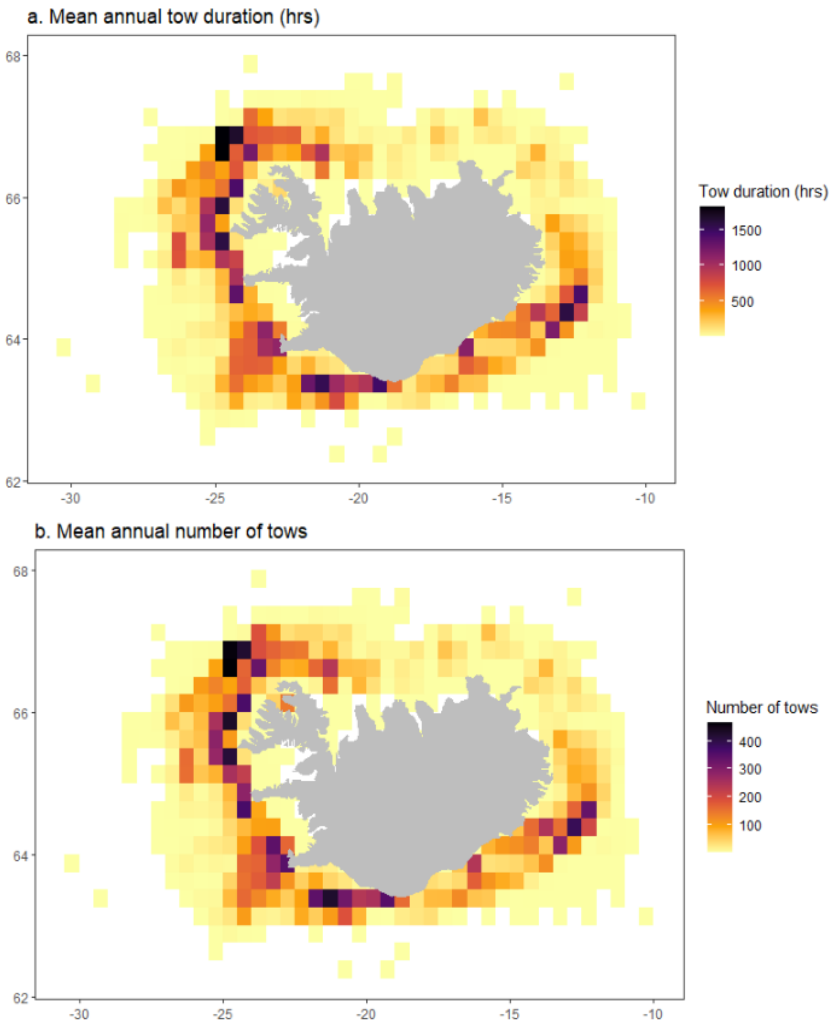

Figure 7. Fishing effort of otter-trawl as mean number of hours trawled a year and mean number of tows per year per 15 min latitude by 30 min longitude grid cells within Icelandic waters over the period 2006-2020.

The dominant benthic prey taxa that were consumed by haddock were echinoids, holothurians, ophiuroids, polychaetes and gastropods (Table 4). However, the consumption of benthic prey types by haddock could be highly variable among grid cells. As an example, while the consumption of echinoids was below 200 tonnes in most grid cells, the consumption exceeded 800 tonnes in a few cells. No clear spatial distribution patterns were seen in the consumption of most of the benthic prey types, such as polychaetes, ophiuroids, bivalves, echinoids, gammarids, gastropods (Figure 8 a-f) and hermit crabs (Figure 8 k), while the remaining prey taxa tended to be less commonly consumed off S and SE- Iceland. The consumption of *Pandalus borealis* was much less pronounced off SE and E Iceland compared to the remaining areas (Figure 8 g). Holothurians were mainly consumed in areas between NW and SE off Iceland (Figure 8 h) while unidentified benthos and unidentified crustaceans were mostly consumed off NW Iceland (Figure 8 i and l). There was more or less no consumption of *Hyas coarctatus* off S Iceland (Figure 8 k).

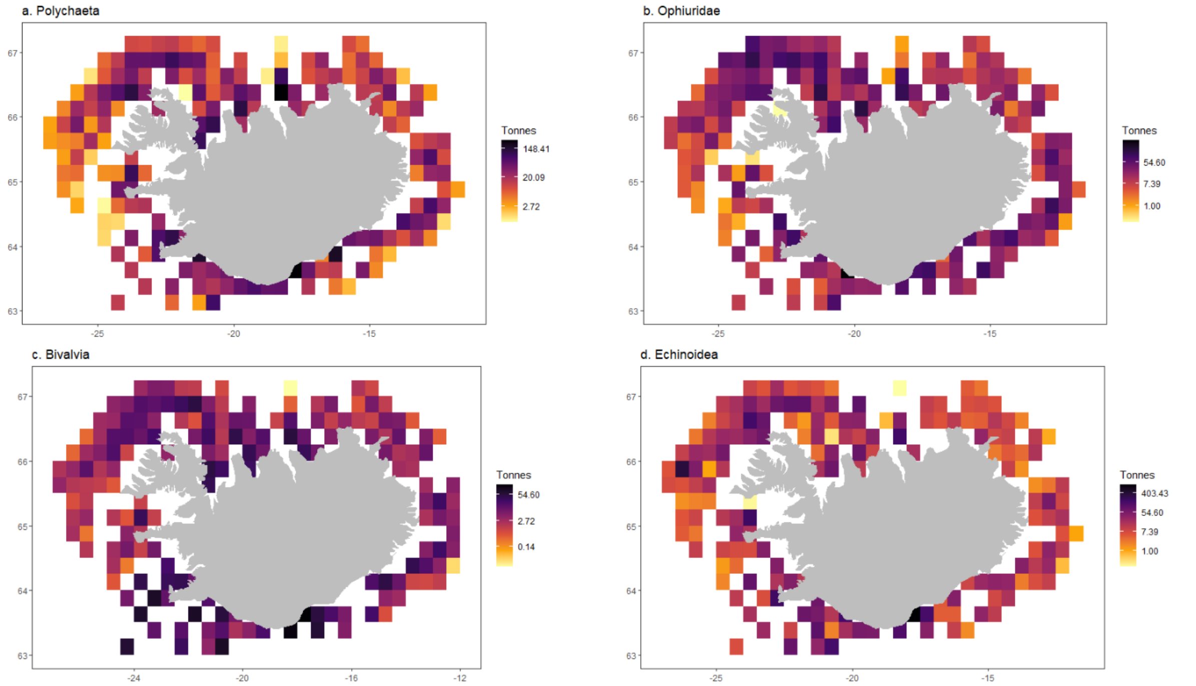

Figure 8. Annual mean consumption (tonnes of prey removed) by haddock of a) Polychaeta, b) Ophiuridae, c) Bivalvia and d) Echinoidea. Data were log-transformed to improve visualisation.

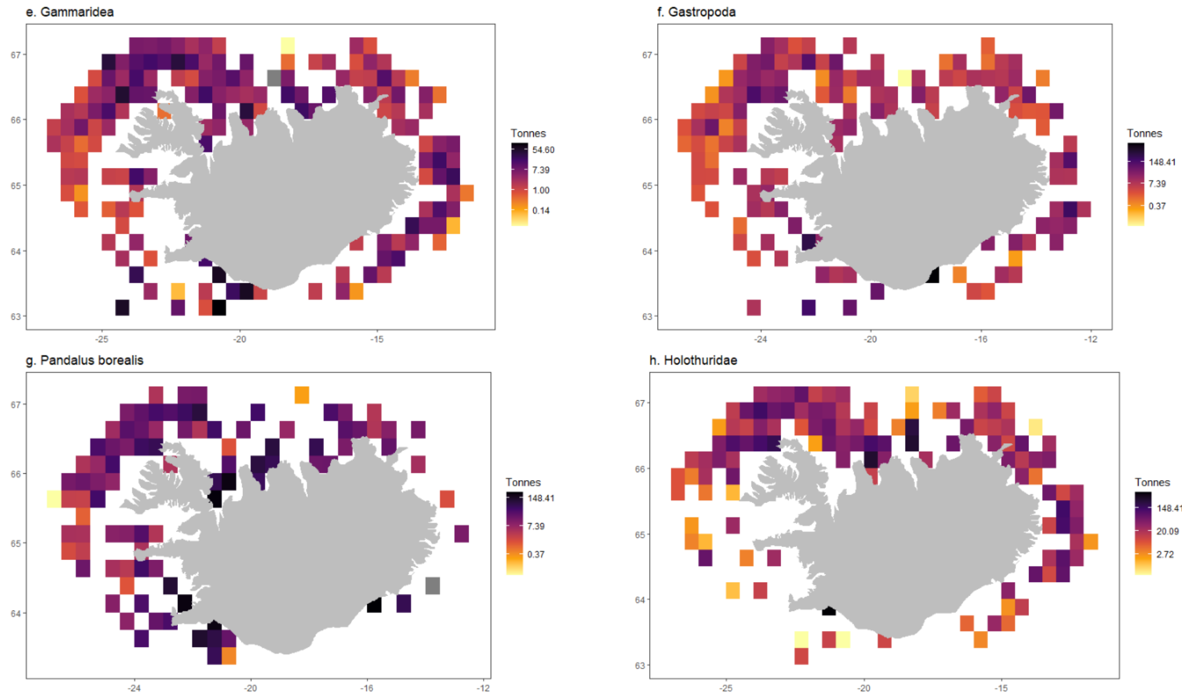

Figure 8 (continued). Annual mean consumption (tonnes of prey removed) by haddock of e) Gammaridea, f) Gastropoda, g) *Pandalus borealis* and h) Holothuridae. Data were log-transformed to improve visualisation.

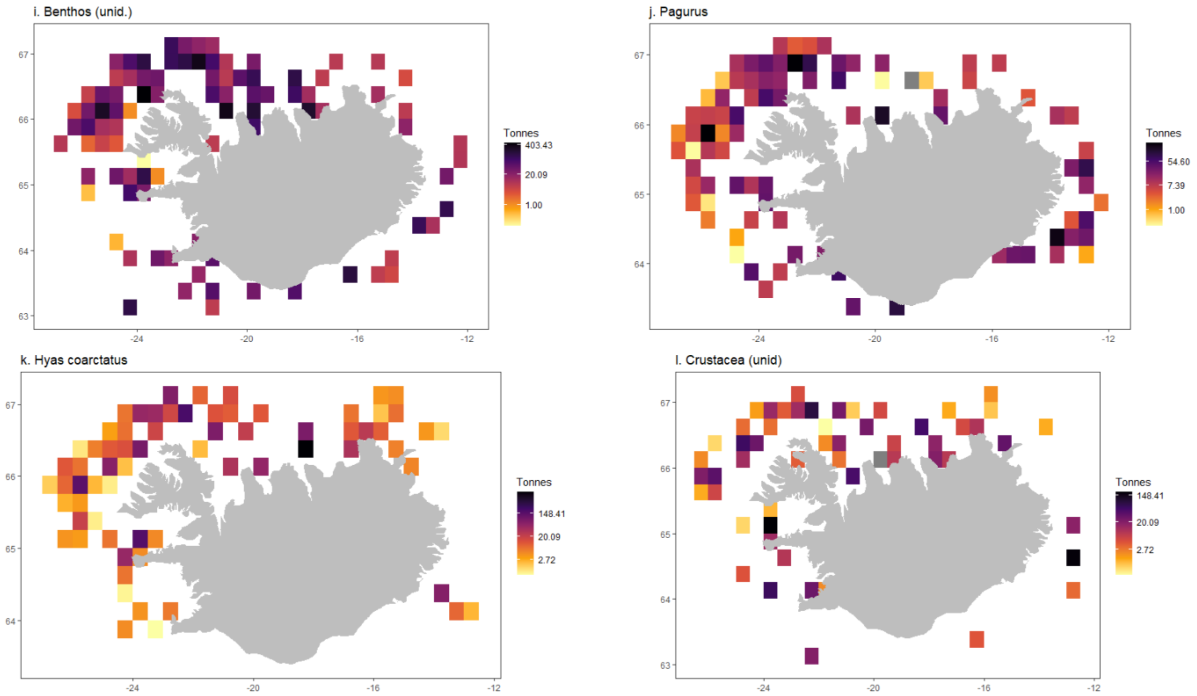

Figure 8 (continued). Annual mean consumption (tonnes of prey removed) by haddock of i) benthos (unidentified), j) Paguridae, k) *Hyas coarctatus* and l) Crustacea (unidentified). Data were log-transformed to improve visualisation.

When tested with the Williamson's index, none of the 12 benthic prey taxa investigated exhibited significant overlap of benthic predation and bottom trawl effort. This finding suggests that the spatial distribution of these prey taxa was uniform relative to that of the fishing effort. In contrast, albeit somewhat similar, only 5 out of the 12 prey types investigated in the US study had greater overlap with bottom trawling effort than from the random expectation (see Table 3). In the US study, dredging effort showed the highest overlap with the consumption of benthic taxa and this gear type was not considered here as it is confined to a few coastal water locations. It is also possible that the differences in the methodology used in these two studies (i.e., 14 predators analysed versus 1 and about 4.5 times difference in the grid cells used) may have played a role. Future work includes repeating the Icelandic case study with benthic diet data from more fish predators and carry out the analysis on 10 min squared grid cells.

Table 4. Mean annual consumption by haddock and values of Williamson's overlap index and range of 0.025 and 0.975 quantiles from simulated data for haddock prey. A value < 1 and > 1 indicates less than and greater than expected overlap, respectively: value = 1 indicates uniform distribution and values that do not lie within the quantile ranges are considered significant.

			Overlap	
Taxonomic name	Common name	Mean annual consumption (tonnes)	Tow duration	Tow frequency
Bivalvia	Bivalves	2645	1.00003 (0.96, 1.03)	0.99 (0.96, 1.04)
Echinoidea	Sea urchins	6226	0.99 (0.96, 1.04)	1.00006 (0.97, 1.02)
Gammaridea	Amphipods	1244	0.99 (0.97, 1.03)	0.99 (0.95, 1.04)
Holothuroidea	Sea cucumbers	5467	1.00002(0.97, 1.04)	0.99 (0.96, 1.04)
Ophiuroidea	Brittle stars	5369	0.9999 (0.97, 1.03)	0.99 (0.97, 1.03)
Benthos (unid.)	Unidentified benthic taxa	5270	1.00001 (0.96, 1.04)	0.99 (0.95, 1.04)
Paguridae	Hermit crabs	2475	0.99 (0.95, 1.04)	1 (0.97, 1.03)
Polychaeta	Polychaetes	5364	1.000001 (0.97, 1.02)	1.000003 (0.97, 1.03)
Gastropoda	Snails	4572	1.00005 (0.96, 1.04)	1.00007 (0.96, 1.04)
Pandalus bore-alis	Northern shrimp	3641	1.00005 (0.96, 1.03)	1.0005 (0.96, 1.04)
Hyas coarctatus	Toad crab	2593	0.99 (0.96, 1.04)	0.99 (0.95, 1.05)
Crustacea (unid.)	Unidentified benthic taxa	1177	0.99 (0.95, 1.05)	1.00006 (0.94, 1.05)

1.3.4 References

Anon. 2010. Manuals for the Icelandic bottom-trawl surveys. Hafrannsóknir nr. 156.

Jaworski A, Ragnarsson SA. 2006. Feeding habits of demersal fish in Icelandic waters: a multivariate approach ICES Journal of Marine Science, 63: 1682–1694

2 Tor c: Conduct a "reality check" and horizon scanning survey within WGECO. The aim is to develop a consensus view of the major emerging issues in relation to fisheries and ecosystems, and on which WGECO could focus future work. WGECO members will provide a list of emerging issues (horizon scanning), that would benefit from scrutiny by WGECO. This list will be collated and used as material for a plenary discussion, and with the aim of producing a perspectives paper in the ICES JMS or Fish and Fisheries.

2.1 Defining criteria for including results from ecosystem modelling etc. in advice

In a number of cases (WKIrish and WKDEICE for example), groups have proposed approaches to use ecosystem understandings (modelled or empirical) in the delivery of advice. This could range from subtle alterations within the Fmsy ranges, (Bentley *et al* 2021) through to changes in reference points based on evidence of ecosystem changes (trends, cycles, or step changes). This would be most critical when trends in the ecosystem indicators (i.e. recurring, directional change) would challenge or invalidate assumptions in the stock assessment and contribute additional uncertainty and bias that would warrant adjusting the F, or making some other change.

In most, but not all, cases ecosystem based changes have been rejected for a variety of reasons including inter alia: increased variance in the assessment/advice; difficulty in changing reference points (cf. WKRPchange); lack of a quantified mechanism for any linkage; lack of a full MSE etc. As well as, arguably, some inertia in the system, and in the response of the managers when change is proposed. ICES is now in looking at this, in a general sense, in the ACOM-SCICOM EBM sub-group, and in a specific sense by the planned WKREF. WGECO decided not to propose this in the meantime as a new ToR, but to offer to review what comes out of the EBM sub-group, and WKREF. This may include WGECO examining what criteria should be required to consider an ecosystem understanding for inclusion in the advice process (e.g. ecosystem productivity changes, density dependent growth of benthic predators, Harvest Control rules and proposals in the WKIrish F_{eco} proposal). At present, there are no guidelines for the evaluation of such proposals, and there is an impression of something of a "moving target".

Bentley, J. W., M. G. Lundy, *et al*. (2021). Refining Fisheries Advice With Stock-Specific Ecosystem Information. Frontiers in Marine Science 8(346).

Suggested ToR:

> Review the work of WKRPchange, WKREF, the ACOM-SCICOM EBM sub-group and the NOAA Workshop on multispecies models in support of fisheries management and make recommendations for criteria for inclusion of multi-species and ecosystem models in the assessment and/or tactical advice provision

2.2 Fish productivity measured by production ratio (R/SSB)

One of the questions of major importance for tackling fish productivity regime shifts considering only one single stock is the lack of understanding of an indicator to measure the productivity of a stock. In many cases discussions at the ADGs/ACOM when looking at specific cases, it has been mentioned that instead of looking only for the Recruitment relationship with SSB, to derive FMSY another metric called the production ratio (Recruitment/SSB) could be used to indicate if the productivity changed in a consistent way. The regime shift concept has been discussed during the eighties in many conferences around the world, yet it needs to advance to include the production ratio as an indicator to be monitored along with the other metrics in the operational stock assessment in order to decide if in fact the productivity has changed in a given population. The abiotic variables that might explain the regime shift of a single population seem to be specific of each population and geographic area. Include possibly condition factor for fish in the adult stock as a valuable indicator.

Suggested ToR:

> Carry out a comprehensive literature search on the concept of the production ratio (Recruitment/SSB) as a valuable species specific indicator of productivity status. Evaluate the status of the indicator over time for a selection of stocks with analytical assessments and make recommendations for its use.

2.3 Metrics for Ecosystem Overfishing

There have been a number of Ecosystem Overfishing (EOF) indicators proposed in the literature. These include the Ryther, Fogarty and Friedland indices (Ryther 1969, Fogarty *et al*. 2016, Friedland 2012. Developed in Link & Watson (2019) where they say:

"These are based on the ecological principle of trophic transfer, with specific thresholds developed for each index to delineate whether EOF is actually occurring. The Ryther index is composed of total catch presented on a unit area basis for an ecosystem. The Fogarty index is the ratio of total catches to total primary productivity in an ecosystem. The Friedland index is the ratio of total catches to chlorophyll in an ecosystem. The proposed thresholds are based on facets of carrying capacity limits to production of communities of fish populations, limited by trophic transfer efficiencies (TEs)"

The link to fisheries economics was recently developed by Marshak & Link 2021). These approaches are also being used for advice in the USA. The key question mark against these approaches is that they depend on some reliable estimation of primary production, which can be a subject of debate. However, such data are available, and highly spatially and temporally resolved, e.g. the CMEMS NWS Multiyear biogeochemistry data product and the OSU Eppley VGPM Modis data product. WGECO proposes reviewing these approaches and giving a general guidance on whether, how, and where these methods would be valuable.

These metrics are all based on catch relative to primary production. WGECO should apply some critical thinking on the meaning of this index, when is it in a good or bad state, and what reference values might be appropriate. The consideration should include looking at using only large phytoplankton production as well as total NPP, not including e.g. picoplankton. WGECO Should also consider whether NPP status can also be also linked to e.g. recruitment success, for instance herring recruitment in relation to NPP. Include a literature review on this subject.

Fogarty, M. J., A. A. Rosenberg, *et al*. (2016). Fishery production potential of large marine ecosystems: A prototype analysis. Environmental Development. (Supplement 1): 211-219.

Friedland, K.D., *et al*., 2012. Pathways between primary production and fisheries yields of large marine ecosystems. PloS One 7 (1), e28945

Link, J. S. and R. A. Watson (2019). Global ecosystem overfishing: Clear delineation within real limits to production. Science Advances 5(6)

Marshak, A. R. and J. S. Link (2021). Primary production ultimately limits fisheries economic performance. Scientific Reports 11(1): 12154.

Ryther, J.H. (1969) Photosynthesis and fish production from the sea. Science 166, 72–76.

Suggested ToR:

Carry out a critical examination of metrics for Ecosystem Overfishing (EOF) in relation to primary productivity, and provide recommendations on the evaluation of the derived indicators. This should include the use of Net Primary Production but also restricting to large phytoplankton only. Provide examples of the metrics for selected sea areas, and recommendations for interpretation

2.4 Industrial zonation of fishing

Work by Piet & Hintzen (2012) and Jennings *et al* (2012) suggested that most of the fishing effort is concentrated in relatively small area of the sea floor. For instance, Piet & Hintzen indicated that 95–90–85% of the effort result in, respectively, 42–31–24% of the Dutch EEZ being fished over. Conversely then, that suggests that only 15% of the effort is spread across 76% of the sea area. This raises the possibility of designating some percentage of the sea area for fishing, and the rest being left alone. This is like the reverse of MPAs, where we designate free-fishing areas. We have VMS and landings data to identify the key areas We could then evaluate how much of each predominant habitat type was “protected” through such an approach. Such an approach should also minimize the effort displacement issue that has plagued many fishery based MPAs. Without a concomitant reduction of effort, equivalent to that deployed within the MPA prior to being established, the gains from an MPA can be very limited or even counter-productive.

This can also be related to MSP and particularly in the context of rapid expansion of Offshore Renewable Energy (ORE). ORE developments are being proposed widely, and will certainly reduce the areas available for fishing. If these are sited in major fishing areas, then the effort displacement issue will be amplified. Alternatively, ORE could be sited where fishing was minimal, and designated fishing areas could be protected. As a bonus, the ORE sites represent de facto MPAs, or at the least, refugia.

The call for MPAs to address international targets for biodiversity, food and climate adaptation (Sala *et al*.) from a fisheries perspective could also link to this idea, picking MPAs that avoid the conflicts between fisheries and ecosystem conservation.

WGECO should develop advice on the knowledge and analyses needed for such an approach, including revisiting the work of Piet & Hintzen (2012) and Jennings *et al* (2012). This could also include issues with, say, *nephrops* grounds, and for SSF, and possible adaptations for these.

There will be strong links to WKTRADE and WGECO should consider that such zonation may limit fisher's options into the future – "freezing the footprint". In both France & the Netherlands there is interest in linking this with Offshore Renewable Energy sites, their impacts on fishing opportunities and the statutory requirements for 30% MPA in Europe

Jennings, S., Lee, J., and Hiddink, J. G. 2012. Assessing fishery footprints and the trade-offs between landings value, habitat sensitivity, and fishing impacts to inform marine spatial planning and an ecosystem approach. – ICES Journal of Marine Science, 69: 1053–1063.

Piet, G. J., and Hintzen, N. T. 2012. Indicators of fishing pressure and seafloor integrity. – ICES Journal of Marine Science, 69: 1850–1858.

Sala, E., J. Mayorga, *et al*. (2021). "Protecting the global ocean for biodiversity, food and climate." Nature 592: 397–402.

Suggested ToR:

Develop an overview of the spatial distribution of fishing activity (hot spots), and in relation to proposed Offshore Renewable Energy (ORE) locations. Consider whether explicit fishing and ORE development could also be synergistic with the need for increases in offshore MPAs, and whether these are mutually compatible. This would be a 3 year ToR.

2.5 B_{MSY}

B_{MSY} is a concept ICES does not tend to use, and uses the possibly contentious $MSY_{btrigger}$ instead. However, B_{MSY} is used in the NOAA advice as mandated by the Magnuson-Stevens Act: https://www.fisheries.noaa.gov/national/population-assessments/status-us-fisheries

It is also very popular as a concept with eNGOs, for instance the Pew Trusts: https://www.pewtrusts.org/-/media/assets/2015/03/turning_the_tide_msy_explained.pdf

WGECO, with representatives from both sides of the Atlantic would be well placed to critique both B_{MSY} and $MSY_{btrigger}$ and indicate what they are each good for, or not, and whether there may be a better way of expressing a biomass reference point. This could also consider the meaning and value of $B_{escapement}$, and provide advice on its use.

Much of this depends on the way the B reference point is used e.g. hinge point on the HCR, where the precise value is probably not critical, but this would be more important if it is used as a management indicator, as in the USA. Consider how biomass reference points can be used "constructively". Consider concepts for defining Blim, which can be seen as poorly substantiated and consistent.

Suggested ToR:

No suggested ToR at this time, but keep as a watching brief

2.6 The elephant in the room, selectivity

Numbers of questions have been raised about the issue of selectivity in stock assessment and how it is calculated and used. This was raised at the OFI workshop on reference points and by WKRPchange. It was also discussed by Cronin-Fine & Punt (2021).

WGECO could explore this issue and provide advice on what could and should be done in the future on this key parameter. Selectivity is also a function of the commercial fishing gears used, and WGECO has access to a number of experts in this field, and more generally with links to WGFTFB.

Cronin-Fine, L. and A. E. Punt (2021). Modelling time-varying selectivity in size-structured assessment models. Fisheries Research 239: 105927

Suggested ToR:

No suggested ToR at this time, but keep as a watching brief

2.7 Linking benthic knowledge to fisheries advice

Good progress has been made on understandings of benthic indicators in the DPSIR context, although this has yet to resolve how to link deep and shallow area approaches. However, there has been no progress on how to make the crucial link to fishery advice, or how to resolve how to link deep and shallow area approaches. This links to recent WGECO work on the deep sea access regulation (see WKEUVME report and advice), as well as information from WKTRADE3 workshop work (still ongoing in the advice process).

Suggested ToR:

No suggested ToR at this time, but keep as a watching brief and consider evaluating developments in other Expert Groups as they emerge

2.8 Shared-Socioeconomic-Pathways

WGECO could develop and advise on the common framework on Shared-Socioeconomic-Pathways (SSPs) as described in the CERES project and in Pinnegar *et al*. (2021) from an ICES perspective.

Pinnegar, J. K., K. G. Hamon, *et al*. (2021). "Future Socio-Political Scenarios for Aquatic Resources in Europe: A Common Framework Based on Shared-Socioeconomic-Pathways (SSPs)." Frontiers in Marine Science 7(1096).

Suggested ToR:

No suggested ToR at this time, but keep as a watching brief

2.9 Fisheries and blue carbon sequestration

Mariani *et al* (2020) suggested that fishing could be considered as a route for preventing dead fish etc. becoming, functionally, sequestrated carbon. This is a very definite Ecosystem Effect of Fishing, and we would propose that WGECO keep a watching brief on this subject, and recommend a way forward on this within ICES. In the Mariani paper, the conclusion is that “subsidized” fisheries would be a major target for reduction, but there is a significant role for areas without subsidies, i.e. most ICES waters. The paper also convolves this sequestration issue with fuel use. The role for WGECO would be to evaluate the scale of this issue in ICES waters and the validity of the claim by Mariani *et al*. It is, for instance arguable that dead fish sinking in continental shelf waters are not necessarily sequestrated, and would be consumed by detritivores

Mariani, G. l., W. W. L. Cheung, *et al*. (2020). "Let more big fish sink: Fisheries prevent blue carbon sequestration - half in unprofitable areas." Science Advances 6(44): eabb4848.

Suggested ToR:

No suggested ToR at this time, but consider a recommendation to SciCom to develop a more targeted response to this emerging issue e.g. via a theme session, workshop, or WG.

3 Tor e: Review the sensitive species list prepared by WKCOFIBYC (Workshop on Fish of Conservation and Bycatch Relevance). This is in response to some discrepancies between the list of sensitive species produced by WGBYC and conclusions from a review by WGECO 2019. In 2021, WKCOFIBYC re-evaluated the list of species to be monitored under protection programmes in the Union or under international obligations (COMMISSION IMPLEMENTING DECISION (EU) 2016/1251) to determine which of the bony fish species are considered sensitive bycatch and hence relevant to the work of WGBYC. This list will be included in the fisheries overviews. WGECO is requested to: 1). Review the criteria used to develop the final list of fish species of bycatch concern and comment on the methodology used; and 2). Provide feedback in relation to: species not listed in a particular ecoregion but are actually present in that ecoregion; species listed in ecoregions where they do not actually occur; and any discrepancies that may be found in the current versus 2019 lists.

3.1 General Remarks

A request by the Workshop on Fish of Conservation and Bycatch Relevance (WKCOFIBYC) to review the criteria used to develop the final list of fish species of bycatch concern ("sensitive species") was not adopted by WGECO as a ToR in 2021. A similar review from the Working Group on Bycatch of Protected Species (WGBYC) was completed by WGECO in 2019 (ICES 2019) and conclusions regarding sensitive species were shown to differ between the two working groups. WGECO members felt there would be little utility in re-reviewing another sensitive species list given the likelihood of complete agreement among several working groups was low. WGECO would be willing to consider this for future work if a means for handling potentially ongoing conflicting outcomes is resolved, the need is relevant, and member interest strengthens.

3.1.1 References

ICES. 2019. Working Group on the Effects of Fishing Activities (WGECO). ICES Scientific Reports. 1:27. 148 pp. http://doi.org/10.17895/ices.pub.4981.

Annex 1: List of participants

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Annex 2: Resolutions

2020/OT/HAPISG03 The Working Group on the Ecosystem Effects of Fishing Activities (WGECO), chaired by Tobias van Kooten, NL and Brian Smith, USA, will meet by correspondence, 13 April—24 June 2021 to:

a) Investigate the ecological consequences of stock rebuilding, with particular emphasis on benthivorous fish and invertebrates: 1) Make first-order estimates of predation pressure on benthos; 2) Examine evidence of food limitation and density-dependent growth; 3) Compare the footprints of trawling to the footprints of predation pressure on benthos.

b) As potential input for the Ecosystem overviews, WGECO will develop spatial distribution indicators for survey data (fish and benthos) across marine ecosystems and analyse trends in these indicators in relation to climate change, abundance change and large-scale fisheries closures.

c) Conduct a "reality check" and horizon scanning survey within WGECO. The aim is to develop a consensus view of the major emerging issues in relation to fisheries and ecosystems, and on which WGECO could focus future work. WGECO members will provide a list of emerging issues (horizon scanning), that would benefit from scrutiny by WGECO. This list will be collated and used as material for a plenary discussion, and with the aim of producing a perspectives paper in the ICES JMS or Fish and Fisheries.

d) Prioritize indicators (one or more than one) from a set of indicators from current and earlier work by WGECO or its participants (including particularly those from ToR d of WGECO 2018), which can be estimated on a routine basis and are applicable across several ecoregions. For each prioritized indicator, supply a short explanatory text for justification of the prioritization, identify the required steps to operationalize their use in the ICES fisheries and/or ecosystem overviews, and outline how WGECO or ICES can support their implementation over the next three years.

e) Review the sensitive species list prepared by WKCOFIBYC (Workshop on Fish of Conservation and Bycatch Relevance). This is in response to some discrepancies between the list of sensitive species produced by WGBYC and conclusions from a review by WGECO 2019. In 2021, WKCOFIBYC re-evaluated the list of species to be monitored under protection programmes in the Union or under international obligations (COMMISSION IMPLEMENTING DECISION (EU) 2016/1251) to determine which of the bony fish species are considered sensitive bycatch and hence relevant to the work of WGBYC. This list will be included in the fisheries overviews. WGECO is requested to: 1). Review the criteria used to develop the final list of fish species of bycatch concern and comment on the methodology used; and 2). Provide feedback in relation to: species not listed in a particular ecoregion but are actually present in that ecoregion; species listed in ecoregions where they do not actually occur; and any discrepancies that may be found in the current versus 2019 lists.