Greenland halibut fishery benthic habitats and trawling impacts: interim report

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Purpose

ZSL (Zoological Society of London) have worked in partnership with the Greenland Institute of Natural Resources (GINR) since 2011. The focus of this collaboration has been to deploy imaging technologies (still and video cameras) to understand the nature and distribution of deep-sea benthic habitats and how they are impacted by commercial trawling, in west Greenland.

This interim report is intended to provide an overview of this research and preliminary results. This is provided with a view to informing the West Greenland Offshore Greenland Halibut Fishery (WGOGHF) Marine Stewardship Council (MSC) annual surveillance audit. The management implications of the findings are discussed briefly.

The results presented here are preliminary and subject to ongoing analyses. The final results will be presented in a paper (Long et al., in prep.), expected to be completed in spring 2021.

1. Methodology

Seafloor imagery has been obtained using a towed benthic video sled (Fig. 1). The benthic video sled was equipped with an oblique angled centrally mounted video camera, lights, scaling lasers (two green dots with 20cm separation), temperature data logger (recording every 10 seconds; ±0.025˚C) and an echo sounder unit (depth; ± 0.1 m). A full description of the rig is provided by Long et al. (2020). On bottom contact the sled was towed at a target speed of 0.8-1 knots for a minimum of 15 minutes.

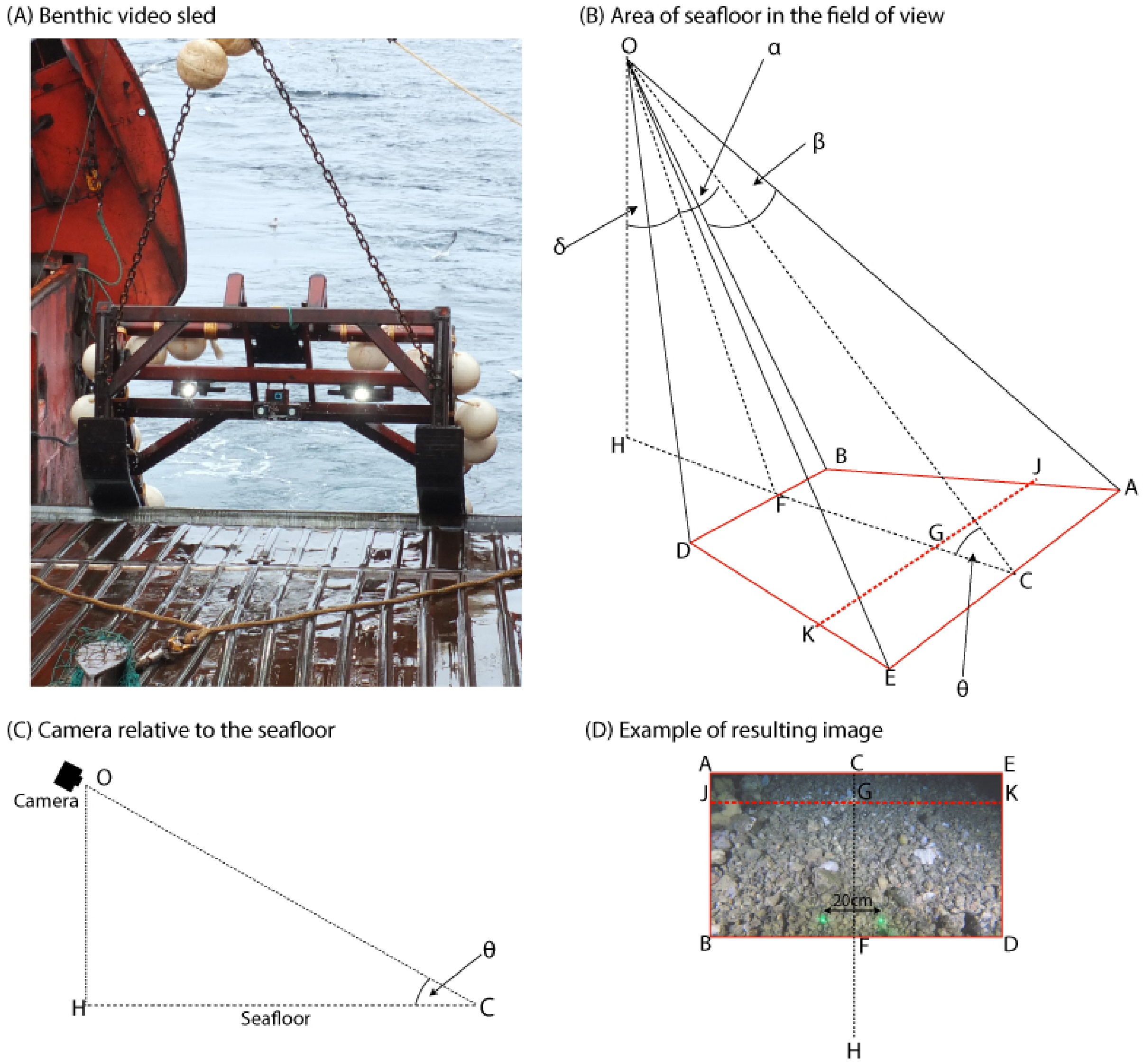


Figure 1: (A) Picture of the towed benthic video sled being deployed from the *RV Paamiut*. The camera, lights and scaling lasers (20cm separation) are visible. (B-D) Diagrammatic representation of the benthic video sled camera for determining the area of the field of view. (B) Shows the camera position, aperture angles and area of seafloor (*ABDE*) in the camera's FOV (red line); with a cut-off line JK to exclude the portion of the image unsuitable for analysis (red dashed line). (C) Shows the camera orientation relative to the seafloor. (D) Shows an example image of the seafloor, in relation to (B) and (C), for which the area *JBDK* is calculated and used in the estimation of fauna density. Adapted from: Nakajima et al. (2014). Reproduced from: (Long et al., 2020).

Deployments were made opportunistically from the *RV Paamiut* (PA), *RV Sanna* (SA) and *MT Helga Maria* (HM), during four stock assessment survey cruises (2017_PA_07, 2018_SA_11, 2019_HM_02 and 2019_HM_04) undertaken by GINR. The study area included the northern and southern portion of the fishery and areas outside of the existing footprint for comparison. The sled was deployed at a total of 76 stations (52, southern area: 24, northern area) across a spectrum of fishing effort, from depths of 649 to 1,476 m, covering the depth range at which the fishery operates (Fig. 2).

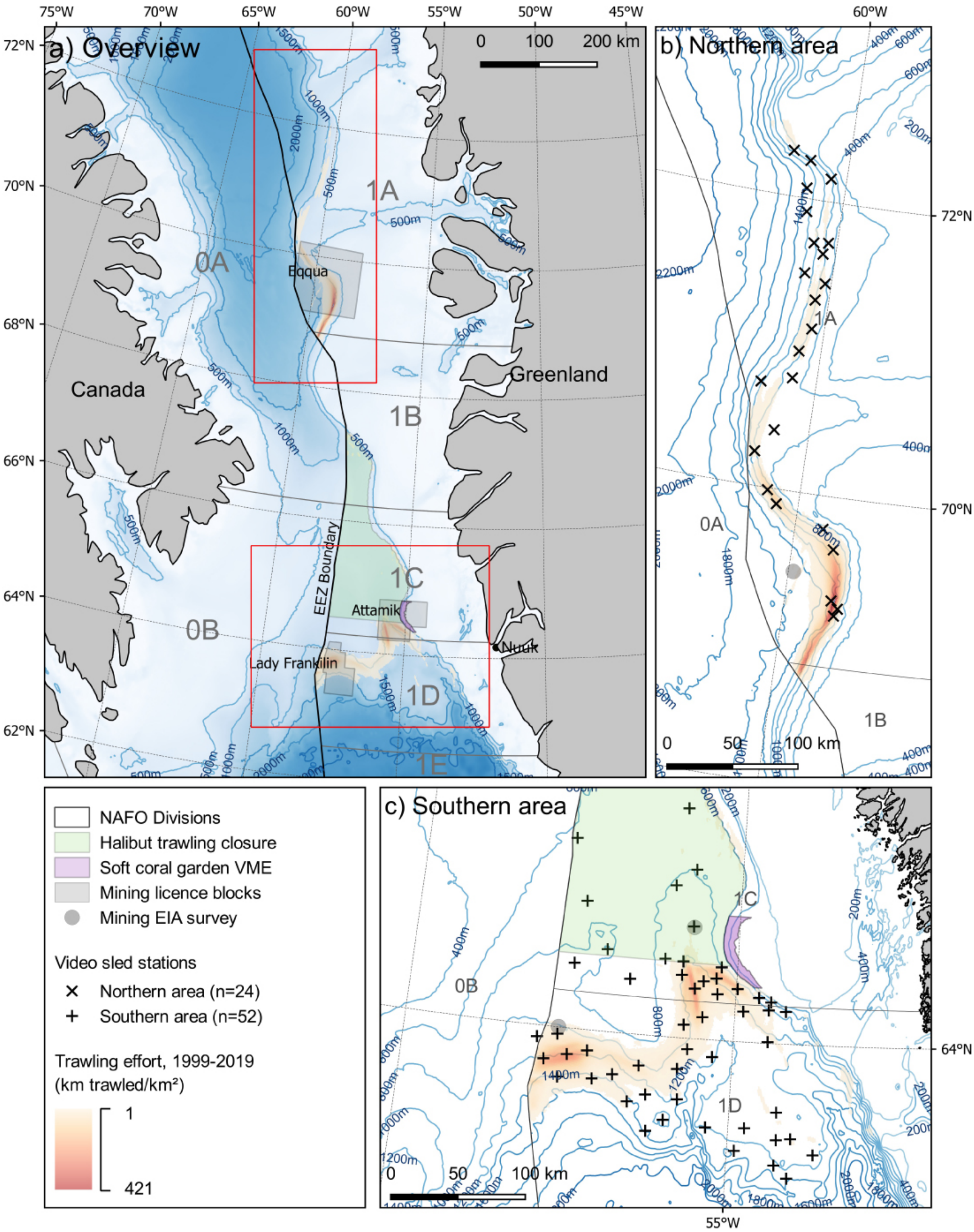


Figure 2: Map showing: a) the offshore Greenland halibut fishery, west Greenland; b) the northern area of the fishery; and c) the southern area of the fishery. The position of video sled stations (n=76) is shown in b) and c). Bathymetric contours are drawn at 500m intervals in a) and 200m intervals in b) and c), using the IBCAO Version 3 500m grid (Jakobsson et al., 2012). For clarity this bathymetric raster is included in a) but not b) and c). Trawling effort represented by a 1km grid, is based on haul by haul logbook data from 1999-2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.

Additionally a separate set of 18 stations video sled stations along the Toqqusaq Bank at depths of 274m to 585m, have been used to describe a candidate soft coral garden vulnerable marine ecosystem (VME). This analysis is considered complete and the results published by Long et al.

(2020). A summary of these results previously shared with the Government of Greenland and SFG are included here for reference (Appendix I), along with the paper (Appendix II). These findings are referred to in the discussion of VMEs.

In the current study, video imagery from the 76 stations was reviewed and sampled at 15 seconds intervals from the useable sections of video. This yielded 3,504 images (north: 981; south: 2,523). It is estimated that the area in the field of view (FOV) is 8.23 m², thus the still images represent 28,838 m² (=0.029 km²) of seafloor. Images were uploaded to BIIGLE (Langenkämper et al., 2017), a browser based annotation platform. Fauna in images were annotated, yielding 13,062 annotations (north: 1,184; south: 11,878). Fauna annotations were limited to those taxa that could be consistently and reliably identified across the image set. Annotations were made at the taxonomic level of Order, with some exception for reasons of pragmatism, e.g unidentified Porifera were annotated according to size classes (small = 5cm < Porifera ≤ 10cm; large = Porifera > 10cm). Additionally, substrates and evidence of trawling ('trawl evidence', in the form of disturbed/overturned sediments or regular linear features), were annotated at the image level. This image annotation data was used for community level analyses.

Video imagery from the southern area was reviewed to count occurrences of selected taxa, specifically VME indicator species and highly abundant fauna. The useable segments of video covered a mean of 492.4 m² per station. The total area in useable segments of videos from the southern portion of the study area was 25,607 m² (=0.026 km²). This video count data supports a more accurate estimate of fauna density for taxa of interest. Individuals were counted as they crossed a horizontal midline superimposed on the video. The estimated width of the FOV at the midline is 1.49m (Fig. 1). The duration of each video and the mean tow speed was used to estimate the area covered at each station and therefore the density of taxa. This approach was also used to quantify the density of boulders (rocks >20 cm) at each station. This video count data was used for taxa specific modelling and density maps. Video counts data from the northern area are in the process of being collected.

Fishing effort is represented by a 1x1 km resolution grid of trawling effort, based on haul-by-haul logbook data for halibut fishery trawls between 1999-2019 (data provided by Greenland Fishery Licence Control). The grid represents distance trawled/km², bounded by 72.5°N and 62°N; the 500m depth cline; and the Greenlandic EEZ. A full description is provided by (Long et al., 2020). The path of the sled was estimated trigonometrically from the ship's position during each sled tow. A value for fishing effort was assigned to each station calculated as the mean value for all effort raster cells crossed by the sled path.

2. Results

2.1. Physical trawling impacts

Evidence of trawling impact on the seabed was observed in the images (Figure 3). The variety of impacts observed being the product of the interaction of the seabed substrate with different components of trawling gear. These included: large, deep single furrows or scars, thought to be caused by trawl doors (Fig. 3a); overturned sediments (Fig. 3c); parallel grooves, caused by bobbins or rollers on rock hopper gear (Fig. 3d); small regular grooves, perhaps from the bottom of the net, cod-end or roller clump (Fig. 3e); and displaced, dragged or overturned rocks (Fig. 3f). There was a strong correlation between the trawling evidence observed in images and the logbook fishing effort data (Figure 3a). This suggests these are both reasonable measures of effort and confirms the validity of our existing understanding about the distribution of fishing effort. The maximum level of trawling evidence intensity observed at northern and southern stations was broadly similar, both in terms of the evidence observed in the imagery and logbook fishing effort data

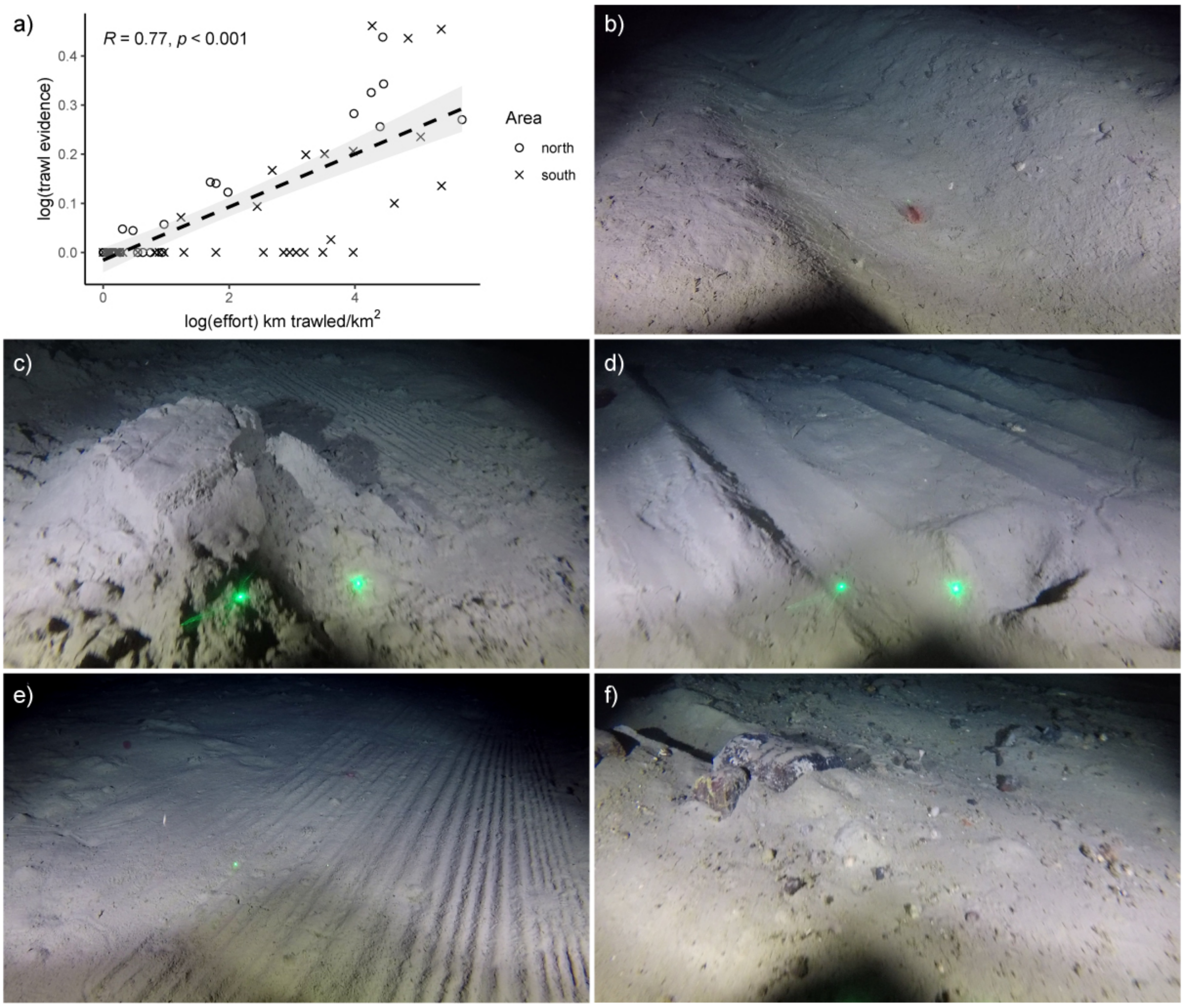


Figure 3: a) Relationship between log-transformed trawling evidence (proportion of images at each station showing physical evidence of trawling) and log-transformed fishing effort (from logbook trawling data 1999-2019) at video sled stations. Examples of the range of physical evidence of trawling observed in images are shown b) to f). Where present, laser dots (green) are 20cm apart.

2.2. Community composition

The northern stations were considerably colder (0.0 – 1.6˚C) than the southern stations (3.3 - 4.3˚C), despite covering a similar depth range (north: 653 - 1,353m ; south: 649 – 1,476 m). In general, a lower diversity and abundance of taxa was observed at the northern stations. The difference in the community composition between the northern and southern area is indicated by two distinct clusters in the non-metric multi-dimensional scaling plot (Figure 4). The strong correlation between the ordination of stations and the temperature gradient appears to make a significant contribution in explaining the separation between the northern and southern areas, which was in the same direction as the temperature vector. The effects of temperature, depth, trawl evidence and the presence of boulders were all significant. Whilst the effect of fishing effort was not significant in the model the direction of the fitted vector was closely aligned with that of trawl evidence. This suggests trawling has an effect on the community composition.

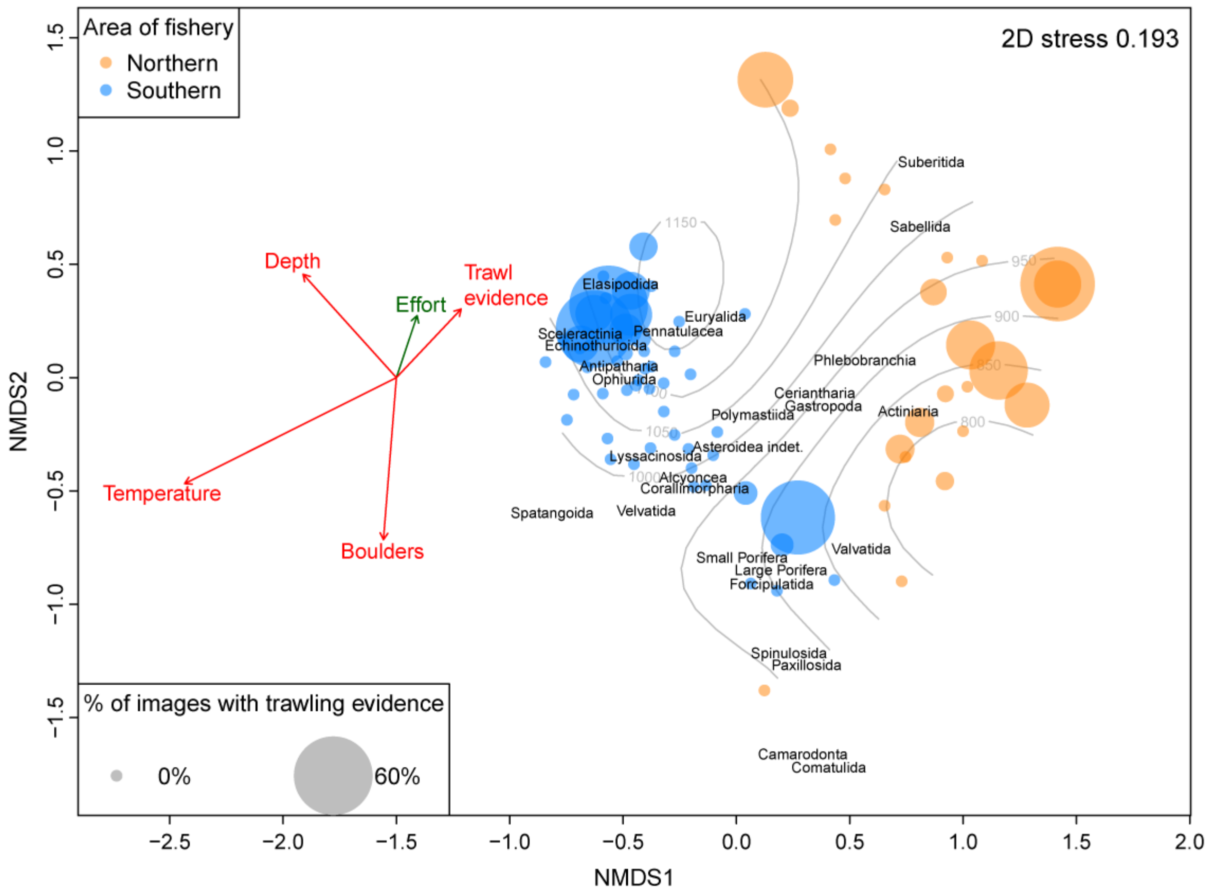


Figure 4: Non-metric multi-dimensional scaling (NMDS) ordination of the benthic fauna assemblage observed in video sled imagery. Stations are positioned by independent metrics of faunal similarity, with nearby stations being compositionally similar. Stations (filled circles, n=76), from the northern (yellow, n=24) and southern (blue, n= 52) areas are scaled by trawling evidence observed at each station. Fitted vectors of environmental variables are drawn in red (envfit, p<0.05) and green (envfit, p>0.05), offset from the origin for clarity. Effort is inferred from logbook data. Trawl evidence is the proportion of images from each station in which trawl evidence was observed. Boulders is the proportion of images at each station in which boulders were present. Depth fitted as a smooth surface, is indicate by 50m contours (grey).

2.3. Taxa specific models

The small sample size (n=76), zero-inflation (where taxa were absent from stations) and high variance presents considerable challenges for modelling. Given the known differences between the northern and southern area modelling was restricted by area, with models produced using normalised video count data for the southern area only (n=52). Table 1 presents preliminary results of modelling for 5 taxa. This demonstrates that the abundance of some taxa, including VME indicator species (Large porifera and *A. arbuscula*), has been negatively impacted by demersal trawling. The abundance of the VME indicator species *F. alabastrum* (cup corals) did not appear to be significantly affected by trawling.

Table 1: Abundance models for selected taxa, using normalised count data as the response variable, in the southern area of the GHL fishery.

Taxa	Model	Variable	Estimate	Std. error	Significance	Variable effect on abundance
O. lymani						
	linear*	Intercept	5.271	0.389		
		Boulders	-0.170	0.070	($F_{1, 49}$ = 5.88, p = 0.019)	-
		Effort	-0.209	0.090	($F_{1, 49}$ = 5.450, p = 0.024)	-
P. placenta						
	linear*	Intercept	-2.188	0.755		
		Depth	0.005	0.001	($F_{1, 50}$ = 54.749, p < 0.001)	+
F. alabastrum						
	linear*	Intercept	7.964	0.927		
		Depth	-0.002	0.001	($F_{1, 49}$ = 5.987, p = 0.018)	-
		Boulder	-0.490	0.049	($F^{1, 49}$ = 100.03, p < 0.001)	-
A. arbuscula						
	linear*	Intercept	1.469	0.244		
		Boulder	0.172	0.044	($F_{1, 49}$ = 15.149, p < 0.001)	+
		Effort	-0.281	0.056	($F_{1, 49}$ = 24.919, p < 0.001)	-
Large Porifera						
	linear*	Intercept	0.754	0.159		
		Boulder	0.217	0.029	($F_{1, 49}$ = 57.196, p < 0.001)	+
		Effort	-0.137	0.037	($F_{1, 49}$ = 14.029, p < 0.001)	-

* Response variable log-transformed

2.4. Vulnerable marine ecosystems (VMEs)

The United Nations General Assembly (UNGA) Resolution 61/105 called upon States to take action to protect vulnerable marine ecosystems (VMEs) (UNGA, 2006). The UN-FAO defined VMEs as exhibiting one or more of the following characteristics: i) unique or rare; ii) functionally significant, iii) fragile, iv) containing component species whose life-history traits make recovery difficult; or v) structurally complex (FAO, 2009).

The term VME has been widely implemented by states and regional fisheries management organisations (RMFOs), including the North Atlantic Fisheries Organisation (NAFO) and North East Atlantic Fisheries Commission (NEAFC). VMEs are also explicitly incorporated in the Marine Stewardship Council (MSC) Fishery Standard and assessment process (MSC, 2014).

There is an important distinction between VME indicator species and VMEs. VME indicator species are taxa which have the potential to result in an ecosystem exhibiting one or more of the five characteristics listed above. The presence of one or more VME indicator species can signal the occurrence of VME, where an individual indicator species or community of indicator species, are sufficiently abundant. In the absence of any specific thresholds, this is open to interpretation by scientists, states and regional fisheries management authorities (RMFOs) (e.g. NAFO and NEAFC). Thresholds that have been applied or proposed elsewhere vary between VME indicator species and habitats but are helpful to contextualise new findings.

There is no formal process for the designation of VMEs either in national or international waters. Typically VMEs are recognised either by RMFOs, states and/or by scientific consensus. In this research the available evidence is considered and where appropriate the term 'potential' or 'candidate' VME is used, recognising that this is an opinion. These should be considered professional and evidence-based opinions.

2.4.1. Vulnerable marine ecosystems (VME) indicator species

A total of 14 VME indicator species have been identified in the still images. Of these, 13 were present in the south, 9 in the north and 8 in the north and the south (Table 2). This reinforces the finding that the northern and southern areas have different communities. At some stations the density of these VME indicator species (either individually or collectively) warrant careful consideration. This is where the observed densities are in the region of thresholds, which according to the literature, are indicative of VMEs.

Table 2: Shows the presence at stations, number of annotations and maximum observed densities for VME indicator taxa based on image annotation data. For each taxon guidance from NAFO (2012) and NEAFC (2014) was consulted to determine if the taxon is considered a VME indicator. The maximum observed density area column reports the area in which the station with the observed maximum density is found.

Phylum			**VME Indicator?**		**Number of stations present at**			**Number of annotations**			**Maximum observed density (taxa/m²)**		
Class	**Order**	**Taxa**	NAFO	NEAFC	North (n=24)	South (n=52)	All (n=76)	North	South	All	Image level	Station level	Area
Porifera													
Hexactinellida	Lyssacinosida	*Asconema foliatum*	Yes	Yes	0	14	14	0	36	36	0.36	0.02	S
Demospongiae	Polymastiida	Polymastiidae	Yes	Yes	5	13	18	18	25	43	0.36	0.02	N
Large (>10cm)	Large	Porifera > 10cm	Yes*	Yes*	6	19	25	33	67	100	0.61	0.04	N
Cnidaria													
Anthozoa	Alcyonacea	*Acanella arbuscula*	Yes	Yes	1	28	29	1	387	388	0.97	0.23	S
		Nephtheidae	No	Yes	5	5	10	9	12	21	0.36	0.01	S
		Paramuricea sp.	Yes	Yes	0	2	2	0	4	4	0.24	0.01	S
	Antipatharia	*Stauropathes arctica*	Yes	Yes	0	14	14	0	30	30	0.36	0.01	S
	Ceriantharia	All Ceriantharia	?†	Yes	10	30	40	250	174	424	0.97	0.22	N
	Pennatulacea	*Anthoptilum grandiflorum*	Yes	Yes	6	21	27	7	62	69	0.24	0.04	S
		Halipteris finmarchica	Yes	Yes	0	5	5	0	645	645	**4.50**	**1.69**	S
		Pennatula spp.	Yes	Yes	1	10	11	38	47	85	0.49	0.18	N
		Umbellula sp.	Yes	Yes	3	0	3	3	0	3	0.12	0.00	N
	Sceleractinia	*Flabellum alabastrum*	Yes	Yes	0	43	43	0	3566	3566	**5.10**	**2.23**	S
Echinodermata													
Crinoidea	Comatulida	Antedonidae	?‡	Yes	1	4	5	1	13	14	0.73	0.02	S

* Inferred based on taxa listed as VME indicator species

?† Tube dwelling anemones (family: Cerianthidae) are included in NAFO VME indicators guidance but only *Pachycerianthus borealis* is listed there

‡ Crinoids (family: Antedonidae) are included in NAFO VME indicators guidance but only *Trichometra cubensis* is listed there

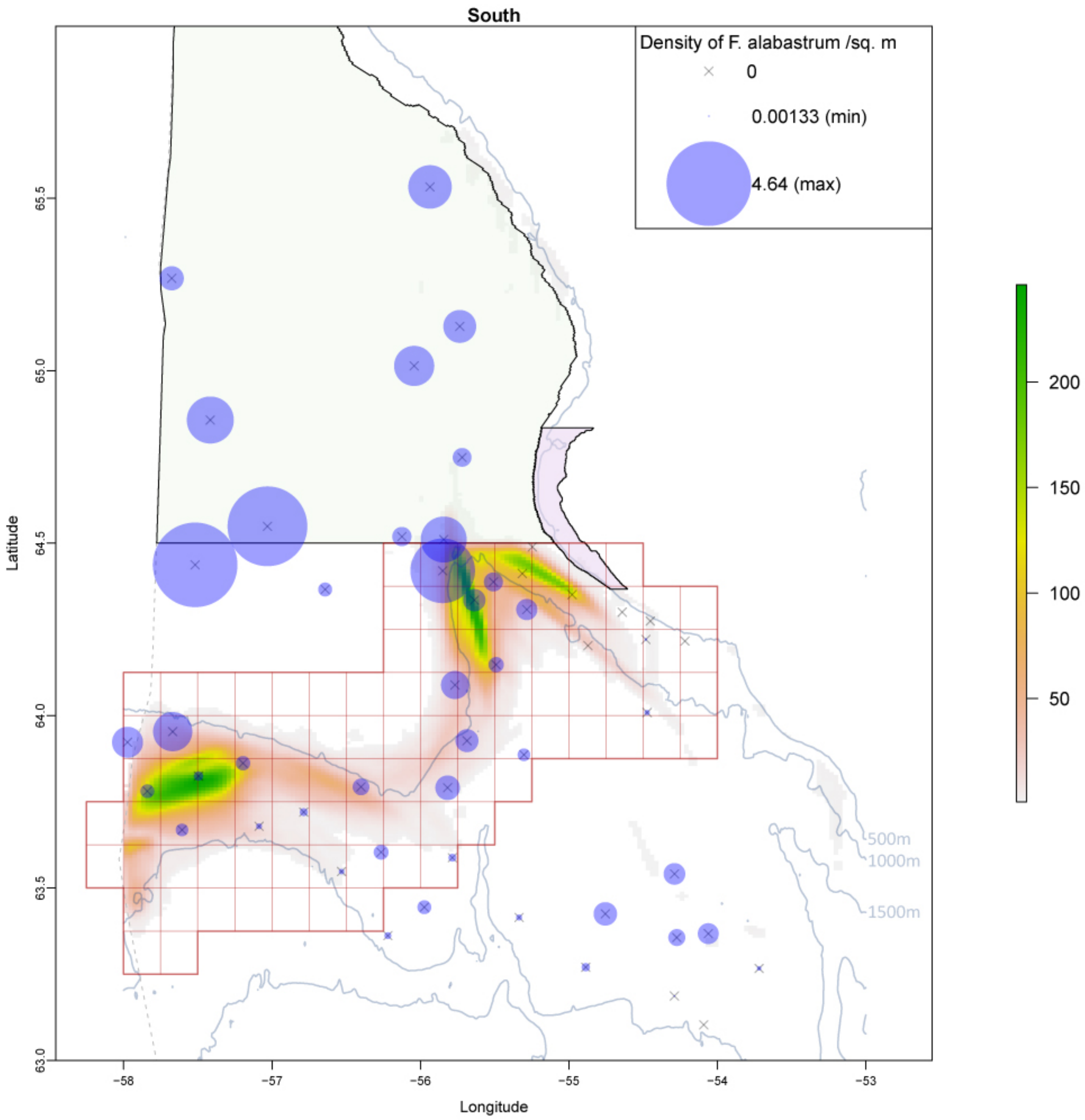
2.4.2. Potential vulnerable marine ecosystems (VMEs)

In our dataset, there are four cases where VME indicators species are observed at a density that may constitute a VME, these are:

1. *Flabellum alabastrum* (cup corals)
2. *Halipteris finmarchica* (sea pen)
3. Areas exhibiting high combined density of corals, sea pens and sponges
4. Toqqusaq Bank soft coral garden candidate VME

Each of these cases is considered below, with reference to: the observed distribution and density; the UN-FAO VME definition; and the wider literature. Management implications in each case are briefly discussed.

2.4.2.1. *Flabellum alabastrum* (cup coral) meadow



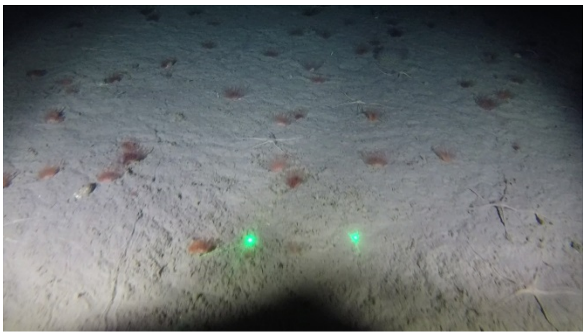


Figure 5: Map of observed density of *F. alabastrum* (scaled circles) at stations (n=52, 'x') in the southern area. The halibut trawling ban area (green polygon) and the proposed soft coral garden VME are shown (purple polygon). The revised Halibut Management Plan fishery area is shown divided by field code areas (red outline). Bathymetric contours are drawn at 500m intervals. Trawling effort represented by a 1km grid, is based on haul by haul logbook data from 1999-2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.

VME criteria	Likely to meet criteria?	Rationale
1. Uniqueness or rarity	No	Locally widespread and abundant and there are lots of records in the North Atlantic.
2. Functional significance	?	It is difficult to infer from imagery, there is limited information in the existing literature.
3. Fragility	No?	They appear to survive within the fishery footprint and are seen in images with trawling evidence. Modelling does not provide any evidence that fishing effort had a negative effect on abundance. However, it should be noted that the highest densities are only observed outside of existing fishing effort. The skeleton is somewhat fragile, individuals may be at risk of burial or impacted by suspended sediment. In some images cup corals were seen to have aggregated in trawl scars. The reason for this is not known but may indicate trawl scars represent a barrier to movement in an otherwise largely flat environment.
4. Life history traits that make recovery difficult	Yes	Growth rates are slow ~1-5mm/year; they are reasonably long lived (at least 45 years) (Hamel et al., 2010); and fecundity is positively correlated with size (Waller and Tyler, 2011).
5. Structural complexity	Yes?	At significant densities they add some structural complexity to otherwise homogenous muddy sediments.

F. alabastrum are widespread among stations in the southern area, being present in 43 of 52 stations, but are absent from the northern area (Table 2). The maximum observed density at a station was 4.64/m² (based on video counts).

There is no commonly agreed density threshold for what constitutes a cup coral meadow VME. In UK waters, NE Atlantic, Lea-Anne and Roberts (2014) propose a threshold of 0.1 - 0.9 /m² (for *Caryphyllia* cup corals at depths of 1069-1769m). In this study, multiple stations in the southern area exceed this threshold; 31 stations have a density >0.1/m², whilst 8 have a density >0.9/m². The maximum density observed being an order of magnitude greater than the upper value of this threshold. The available evidence suggests that there are *F. alabastrum* meadows VMEs in this area. This candidate VME and its interaction with the fishery is not of immediate conservation concern given that the species: i) is widespread in the study area; ii) is found at high density and multiple sites; and iii) the available image data does not show a significant negative response to trawling. Maintaining the existing effort footprint would likely ensure adequate protection of this candidate VME.

However, it should be acknowledged that there remains some uncertainty about the fragility of this species in terms of its response to trawling (see comments in table above). Further research is also advisable in those areas outside of the existing effort footprint but within the fishery area defined in the revised management plan), as there are few stations there.

2.4.2.2. *Halipteris finmarchica* (sea pen) field

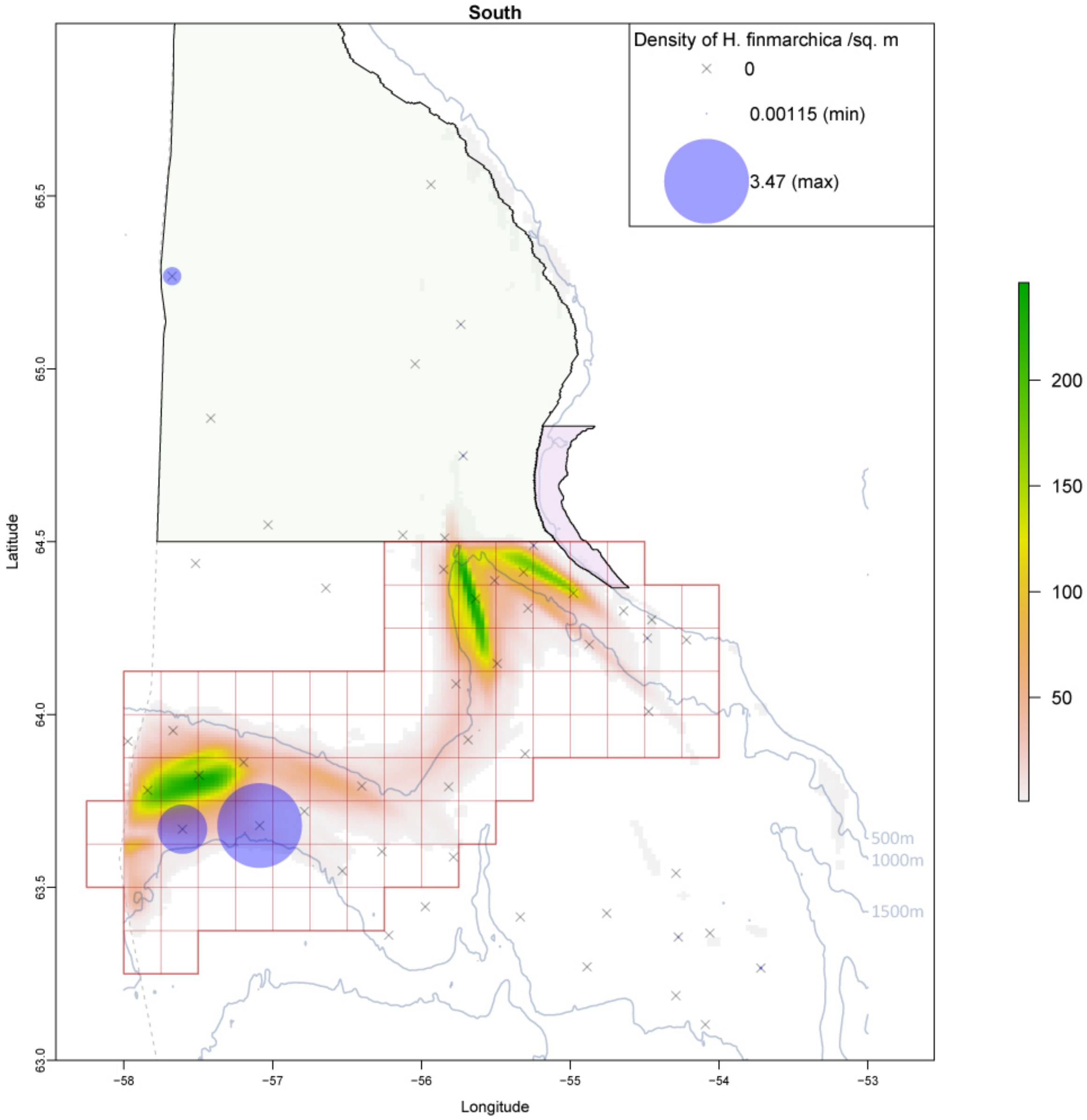
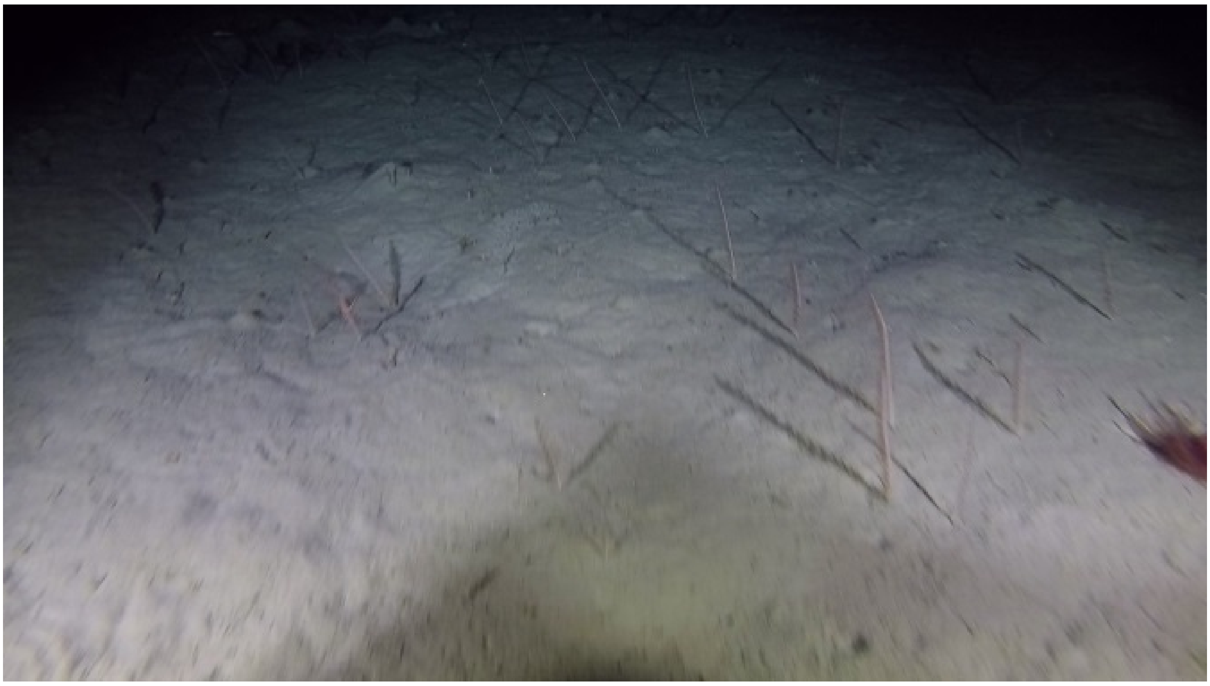


Figure 6: Map of observed density of *H. finmarchica* (scaled circles) at stations (n=52, 'x') in the southern area. The halibut trawling ban area (green polygon) and the proposed soft coral garden VME are shown (purple polygon). The revised Halibut Management Plan fishery area is shown divided by field code areas (red outline). Bathymetric contours are drawn at 500m intervals. Trawling effort represented by a 1km grid, is based on haul by haul logbook data from 1999-2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.



VME criteria	Likely to meet criteria?	Rationale
1. Uniqueness or rarity	?	Locally rare, found only at 9 stations in the southern videos, and only at a significant density (>1/m²) at two stations.
2. Functional significance	Yes?	It is difficult to infer from imagery. Nevertheless, there were numerous examples where Gorgonocephalus brittlestars (class: Ophiuroidea) were seen wrapped around this sea pen. Baillon et al. (2014) reports that 6 species were found on *H. finmarchica* of which 5 were close associates or symbionts. Further, it has been reported that *H. finmarchica* provides essential larval fish habitat (Baillon et al., 2012).
3. Fragility	Yes	This is a thin, erect sea pen, which can extend upwards of 1m from the seafloor. It is therefore likely to physical interact with trawl gear. Bycatch observations in stock assessment trawls suggest it can be removed by trawling. Malecha and Stone (2009) showed that trawling induced breakage of *H. willemoesi* made them more susceptible to predation. Further, they reported that although dislodged sea pens were able to rebury in the sediment, they subsequently became dislodged even without further contact.
4. Life history traits that make recovery difficult	Yes	de Moura Neves et al. (2015) report slow growth rates and estimate longevity of >20 years. Though longevity is less than other deep-water corals they caution that recovery from damage is likely to be at decadal scales.
5. Structural complexity	Yes	At significant densities they add structural complexity to otherwise homogenous muddy sediments.

H. finmarchica sea pens were rare among stations in the southern area and were absent from the northern area (Table 2). They were only observed at a notable density (>1/m²) at two stations. The maximum observed density of 3.47/m² was observed at 2017_PA_07_061, with a density of 1.2/m² at 2019_HM_04_32. The highest densities of the sea pen *Anthoptilum grandiflorum* was also observed co-occurring at these stations (2017_PA_07_061: 0.08/m² ; and 2019_HM_04_32: 0.08/m²), though it was widespread at lower densities elsewhere.

There is no commonly agreed density threshold for what constitutes a sea pen field. The authors are not aware of any published accounts of *H. finmarchica* fields with densities of colonies reported. However, in comparing the imagery from this study with other available imagery (Fuller et al., 2008), we note that the density observed here is similar or indeed exceeds that of imagery from elsewhere.

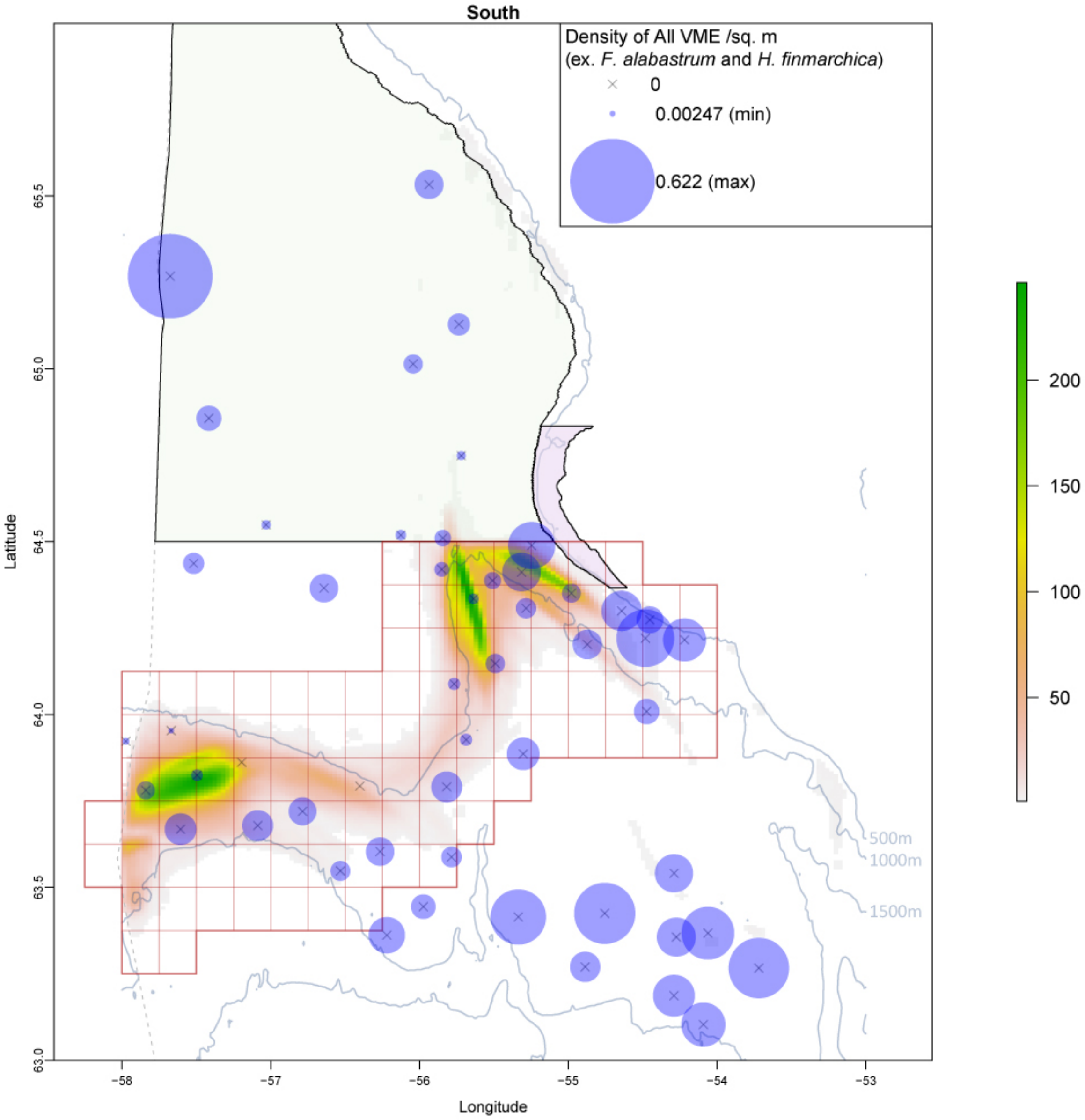
The two stations in the south western corner of the southern study area are evidence of a potential *H. finmarchica* fields VME. The habitat in the imagery potentially meets multiple VME criteria, specifically: i) the rarity (at least locally); ii) functional significance, as the density provides a biogenic habitat; iii) the fragility to trawling disturbance; iv) life history, in terms of relatively slow growth and longevity; and v) structural complexity, again a result of the density.

It is difficult to determine the spatial extent of these *H. finmarchica* fields, or to infer whether the habitat is continuous between these two stations. Further sampling in this area would be valuable, especially to the south of these stations outside the fishery footprint, from where there is currently no imagery. Review of stock assessment trawl bycatch records may also be informative (Blicher and Hammeken Arboe, 2021, in prep.).

These two stations are 2017_PA_07_061 and 2019_HM_04_32, with the former having the greatest density. These stations overlap with the logbook data fishing effort raster. The calculated value for fishing effort is 11.7 and 36.2 km trawled/km² respectively, which are at the low effort end of the spectrum (maximum: 214 km trawled/km²). Due to the resolution of the logbook data, raster generation process and sled path estimation process it cannot be determined whether trawling has or has not occurred in the sled path of these videos.

This potential VME is of immediate conservation concern. It is located very close to, or within, existing fishing effort. Maintaining the existing effort footprint (or expansion to fully utilise the fishery area in the revised management plan) would likely result in serious or irreversible harm to the habitat observed at these two stations. These two stations currently represent the only known examples of high density *H. finmarchica* fields in the Greenlandic exclusive economic zone (EEZ), pending further research it would be advisable to consider spatial management measures for this candidate VME.

2.4.2.3. Areas exhibiting high combined density of corals, sea pens and sponges



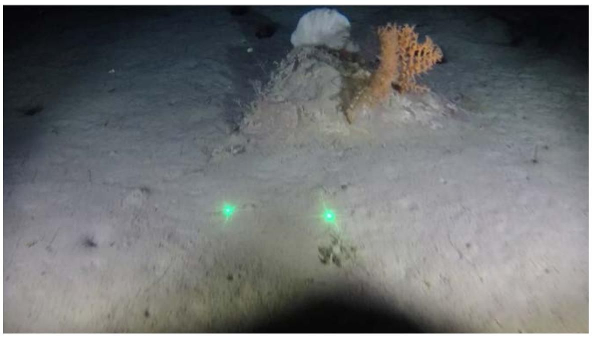


Figure 7: Map of observed density of all VME indicator taxa, excluding *F. alabastrum* and *H. finmarchica* (scaled circles), at stations (n=52, 'x') in the southern area. The halibut trawling ban area (green polygon) and the proposed soft coral garden VME are shown (purple polygon). The revised Halibut Management Plan fishery area is shown divided by field code areas (red outline). Bathymetric contours are drawn at 500m intervals. Trawling effort represented by a 1km grid, is based on haul by haul logbook data from 1999-2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.

VME criteria	Likely to meet criteria?	Rationale
1. Uniqueness or rarity	No	No evidence that the assemblages or densities observed are unique or rare.
2. Functional significance	Yes?	Mixed assemblages provide habitat heterogeneity, the diversity of species are likely to collectively be of functional significance.
3. Fragility	Yes	There is a range of species but the corals in particular have hard fragile skeletons which are erect from the seafloor. Many of these species rely on hard substrates (boulders) for attachment which are known to be displaced or overturned by fishing gear.
4. Life history traits that make recovery difficult	Yes	There is a range of species present but the corals in particular are long-lived and slow growing making recovery difficult. Recovery timescales are likely to in the order of several decades or more.
5. Structural complexity	Yes	At significant densities they add structural complexity to otherwise homogenous muddy sediments.

A number of coral, sponge and sea-pen VME indicators species are observed in mixed assemblages at some stations. Figure 7 shows there to be a cluster of stations in the south east corner of the study area that consistently have higher collective densities of VME indicator species (excluding *F. alabastrum* and *H. finmarchica*). There is also a smaller cluster on the bottom of the continental slope, between the 500m and 1000m contours, to the south of the proposed soft coral garden VME (purple polygon).

The VME indicator species contributing to this higher collective density include: *Acanella arbuscula (bamboo coral), Asconema foliatum* (a glass sponge), other large Porifera (other sponges >10cm), Nephtheidae (cauliflower corals), *Paramuricea sp.* (small gorgonian coral), *Pennatula spp.* (seapens), Polymastiidae (a family of sponges) and *Stauropathes arctica* (a black coral). These areas are associated with some of the higher densities of boulders. Some of these indicator species are dependent upon rocky substrate for attachment (e.g. black corals & many sponges).

There are no commonly agreed density thresholds for individual taxa and mixed assemblages provide an even greater challenge. The maximum density observed is 0.6/m², which is notable, especially in relation to the background abundance across the study area.

There is reasonable evidence to consider these areas of higher density mixed VME indicator species to be a candidate VME. Continued sampling over the wider area would help contextualise and interpret these findings. Review of stock assessment trawl bycatch records may also be informative. Indeed, Jørgensen et al. (2013) used bycatch data to identify '*a small area between 63°N and 64°N and at 1000-1500 m depth was there a relatively high density and diversity of corals*', which is the same area as the larger cluster of stations described here. GINR's recent trawl bycatch data confirm this occurrence of corals in vicinity of the largest records of indicators of the Ostur Sponge Aggregation VME habitat type in West Greenland, represented by sponge families Geodiidae, Ancorinidae and Theneidae (Blicher and Hammeken Arboe, 2021, in prep.).

Maintaining the existing effort footprint (and even expansion to fully utilise the fishery area in the revised management plan) would likely ensure adequate protection of the southern cluster.

The smaller cluster of stations on the continental slope are adjacent to the existing fishing effort and within the revised management plan fishery area. GINR's trawl bycatch data suggests this area of high collective VME indicator species density likely expands further south (Blicher and Hammeken Arboe, 2021, in prep.). There is therefore potential for detrimental interactions.

It may be the case that the highest densities are associated with more steeply sloping areas and/or areas with significant concentrations of boulders, which are not sampled in this study. Such conditions are unfavourable for trawling and thus may potentially afford some natural protection.

2.4.2.4. Toqqusaq Bank soft coral garden VME

The Toqqusaq Bank soft coral garden candidate VME is described by Long et al. (2020) (Appendix II). A summary of these findings has previously been shared with the Greenlandic Government and SFG (Appendix I). These findings are not repeated and discussed here.

However, it is worth highlighting that the fishery area in the revised management plan significantly overlaps this candidate VME (Figure 7). This area is immediately adjacent to the halibut trawling footprint (and other fisheries, including the MSC certified prawn fishery). There are currently no restrictions preventing trawling by the halibut or any other fishery in this area, such trawling would likely cause serious or irreversible harm. Therefore there is compelling case to prioritise the development of spatial management measures, though we recognise that the halibut fishery currently operates below the depth of this candidate VME (300-600m).

3. Conclusion

The halibut fishery does not operate in one single habitat. The northern and southern areas are clearly distinct, with differing fauna assemblages. Within these areas there is considerable heterogeneity, with stations exhibiting different assemblages and densities of VME indicator species. The initial assessment of the halibut fishery made the assumption, in lieu of further information, that the whole fishery could be considered one habitat (Cappell et al., 2017). This should be reconsidered in light of the information now available.

The imagery collected provides evidence that trawling has direct physical impacts on the seafloor. This is shown to affect associated fauna communities. The abundance of some taxa, including some VME indicator species is negatively affected by trawling.

This research is a positive step in addressing the significant knowledge gaps in the nature and distribution of deep-sea benthic habitats in Greenland. However, the area imaged is comparatively very small. The fishery footprint is reportedly ~15,000 km² (Cappell et al., 2017), the 76 stations are distributed across a significantly larger area, as the study was designed to provide insight in areas that have not been subject to trawling (Figure 1). Consequently, little can be said about the nature of the areas between the stations. The research identifies some areas where VME are present but it does not identify any areas where VMEs are absent. In short, an absence of evidence does not equal evidence of absence.

VME indicator species are present in the fishery and adjacent areas. To date we have identified four potential candidate VME: i) *F. alabastrum* cup coral meadows; ii) *H. finmarchica* sea pen fields; iii) Mixed coral, sea pen and sponge assemblages; and iv) the Toqqusaq Bank soft coral garden VME. Of these the *H. finmarchica* sea pen fields are of immediate conservation concern with the potential for serious or irreversible harm from the halibut fishery. We suggest there is a need for the introduction of spatial management measures and further work to determine the extent of this potential VME. Additionally, we suggest there is a need to introduce spatial management measures to afford protection to the Toqqusaq Bank soft coral garden VME, which significantly overlaps the halibut fishery area as defined by the revised halibut fishery management plan.

We support reactive fishery management measures where new information becomes available, particularly with regards benthic habitat impacts and VMEs. Accordingly we hope the final version of this research should help inform future management decisions. The results should be considered alongside analysis of stock assessment trawl bycatch data and any other sources of data. We suggest future expansions of the fishery should be contingent on targeted research, using the available data and supplementary sampling prior to expansion. This is necessary to confirm that there is no risk of serious or irreversible harm to VMEs.

Finally, as previously indicated in a joint memorandum with GINR (Appendix III), we recommend the development of an overarching plan for the management and conservation of benthic habitats in Greenland. Such a plan would make provision for all benthic habitats, ensuring that a minimum proportion of every habitat type is afforded adequate protection. In addition it would ensure that there is a systematic approach to the identification and conservation of ecologically important and sensitive habitats, such as VMEs. This should establish a consistent basis for the protection of Greenlandic benthic habitats, whilst establishing a framework for sustainable management and exploitation of marine resources. We feel an over-arching plan would be more effective, fair and transparent than working on a case-by-case, industry-specific and/or fishery-specific basis, as is current practice.

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