Imperial College London

Use of deep-sea imagery to understand ecosystem dynamics and to investigate the potential classification of a vulnerable marine ecosystem (VME) in the Davis Strait, Greenland

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Declaration

The benthic imagery data for my project was collected by researchers at the Zoological Society of London (ZSL) and the Greenland Institute of Natural Resources (GINR) off the West Coast of Greenland, beginning in 2011.

I analyzed all of the videos for useable segments and I extracted the stills using an R script created by my supervisor Stephen Long. The process for calculating the area of the field of view was created by Stephen Long and Aamal Hussain, and calculated by Chris Yesson.

The data for environmental variables and fishing effort was calculated and provided by Chris Yesson and Stephen Long, Zoological Society of London.

My supervisors Chris Yesson and Stephen Long, Zoological Society of London, provided advice on identification and the correct statistical analyses to conduct. Stephen Long provided feedback on drafts of my dissertation.

All identifications of taxa and habitat classifications were determined and annotated by myself using an online annotating platform called BIGGLE 2.0. In this report, I am responsible for all of the writing, data-processing and model development in the analysis.

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Abstract
The deep sea represents the most expansive habitat on our planet and yet the ecosystem dynamics and community associations of these cold-water species are still poorly understood. Cold water coral and sponge communities have been shown to provide a diverse array of essential ecosystem services. These specialized habitats are becoming increasingly threatened by deep sea fishing activities. Bottom trawling gear used in deep sea fisheries has been shown to cause irreparable damage to these fragile and slow growth ecosystems. Classifying these areas as vulnerable marine ecosystems (VMEs), under guidelines created by the United Nations is key to protecting these areas and the marine resources they provide. A low-cost benthic video sled was used to collect imagery from several stations spanning a bank in the Davis Strait off the West Coast of Greenland in order to describe the community composition and environment of a potential VME. High densities of Nephtheidae, Actiniarians, Crinoids, *Anthomastus sp.* and Porifera were found at 11 out of 14 stations sampled along this bank. It was found that Nephtheidae, Actiniarians and Crinoids occurred at higher densities in coarse rocky ground habitats. Densities of Porifera massive were highest in gravelly mud habitats. Densities of Nephtheidae, our coral garden indicator species, significantly varied with depth and fishing effort. We defined the extent of this coral garden habitat which we believe should be classified as a vulnerable marine ecosystem and closed to fishery activity. Understanding what environmental conditions and anthropogenic stressors affect the densities of these important taxa is crucial to inform future management practices and ensure the sustainably of deep-sea fisheries into the future.
Keywords: VMEs, trawling, Greenland, marine invertebrates, deep-sea fisheries, conservation

Introduction
The deep sea covers ~65% of the earth's surface, and yet it is not as well studied as other habitats (Roberts 2002; Victorero et al. 2018; Danovaro et al. 2017). Our understanding of the impacts of anthropogenic stressors on the deep sea has been greatly limited by the challenges involved in accessing and monitoring these areas (Ardron et al. 2014). Many species found in these habitats are extremely vulnerable to physical disturbance and can take a long time to recover due to their fragile structures and life history traits (Koslow et al. 2000; Gordon 2001; FAO 2008). Cold water corals and sponges present in these habitats have been shown to provide a diverse array of ecosystem services. These services range from storing carbon and cycling nutrients throughout the ecosystem to providing structural complexity in the habitat, associated with increased levels of biodiversity (Oanta 2018; Milligan et al. 2016; Linley et al. 2017). Currently deep sea habitats are becoming increasingly threatened by anthropogenic activities, including deep sea fishing (Armstrong et al. 2019).

Recognizing the value and importance of these threatened deep sea ecosystems, the Food and Agricultural Organization of the United Nations (FAO) created the 'Technical Consultation on International Guidelines for the Management of Deep-sea Fisheries in the High Seas'(FAO 2008). This defined the term vulnerable marine ecosystems (VMEs), as areas exhibiting one or more of the following traits: unique or rare; functionally significant; fragile; structurally complex; and containing species that possess life history traits characterized by slow growth, late age of maturity and low recruitment (FAO 2008). Species dynamics and community associations are still poorly known in deep-seas and this can make it challenging to apply this definition (Oanta 2018).

Economically, Greenland depends on deep sea fishing, in particular prawn, *Pandalus borealis,* (150-600m) and halibut, *Reinhardtius hippoglossoides* (400-1400 m) fisheries in the western exclusive economic zone (EEZ) (OCED 2005; Jorgensen at al. 2014; Yesson et al. 2017). Fishery activities account for 92% of Greenland's total exports. Shrimp fisheries directly represent approximately 60% of these total exports (OCED 2005). Trawlers use bottom-contacting gear which can result in significant levels of impact on the benthic habitat (Eigaard et al. 2017). With the climate warming rapidly, and Greenland reaching record setting high temperatures, it is important to have a better understanding of these Northern Atlantic ecosystems before they incur increased exploitation (Armstrong et al. 2019). Greenland has few formally recognized Marine Protected Areas (MPAs) covering only ~4.5 % of its EEZ, all of which are found in inshore and coastal waters (UNEP-WCMC 2019). Additionally, a few areas are closed to fishing by 'Technical Conservation Measures' introduced by Executive Orders. Only two of these areas are closed in order to protect known populations of VME species. A closure in the southwest of Greenland was based on a single observation of the cold water coral *Desmophyllum pertusum* (Government of Greenland 2017). A set of 11 discrete areas closed to trawling in offshore waters in Melville Bay were created to protect the sea pen *Umbellula sp* (Acoura Marine 2018).

Since 2011 a programme of benthic research employing drop cameras and a benthic video sled has sought to map habitats and quantify the impacts of trawling on these ecosystems and inform management practices (Yesson et al. 2017; Yesson et al. 2015; Gougeon et al. 2017). This ongoing work by the Greenland Institute of Natural Resources (GINR) and the Zoological Society of London (ZSL) has gathered imagery from a series of stations off of the west coast of Greenland between ~ 30 to 1500 m. The stations are distributed across the prawn and halibut fisheries and adjacent areas. Imagery from a subset of stations, 250m – 700m, shows a coral garden habitat on a stony substrate along the continental slope of Toqqusaq Bank, which may represent a VME. These stations are found in an area that has experienced limited fishing effort to date.

This study considers this subset of images to describe the habitat, assemblages and abundance of VME indicator taxa in this region of the Davis Strait, Greenland. Densities of VME indicator taxa were considered in relation to VME guidelines (FAO 2008), as interpreted by the North Atlantic Fisheries Organization (NAFO) and International Council for the Exploration of the Sea (ICES), and in addition to the wider related literature (NAFO 2019; ICES 2019). The impact of environmental variables including depth, current, sea-bed temperature, slope, topographic ruggedness index (TRI), topographic position index (TPI) and the distribution of fishing effort on the densities of VME related species, is modelled. This study aims to address the following three hypotheses:

1) The habitat in this subset of stations meets the criteria to be considered a VME.
2) Taxa densities in this ecosystem are not homogenous, but vary with substrate type.
3) Nephtheidae density is influenced by fishing effort.

This project aims to provide a comprehensive description of a candidate VME habitat within the Greenlandic EEZ. This will have direct applications for Greenland, including informing management of deep sea fisheries. Further knowledge and understanding of the nature and distribution of VMEs in the North Atlantic is essential in order to support sustainable fisheries practices. Exploring these concepts will allow us to have a clearer understanding of how these deep-sea ecosystems function, and learn the best way to conserve and protect the ecosystem services they provide.

Methods

1. Data Collection

1.1 *Study Site*

Benthic imagery from drop and sled stations was collected from 2011 to 2019. A subset of 14 video and 5 drop cameras appear to display a soft coral garden habitat on a stony substrate. These 19 stations (250m to 700m deep) are between 64.75˚N and 64.18˚N, spanning ~100 km of the western slope of the Toqqusaq Bank, Davis Strait (Figure 1). This analysis focuses on the information rich videos obtained from the video sled. Drop camera stations were not quantitatively analyzed, but exhibited coral garden VME assemblages and were included in proposing the minimal extent of this habitat. A list of the subset of stations can be found in Table 1, which includes information about each station and which videos were used in this study.

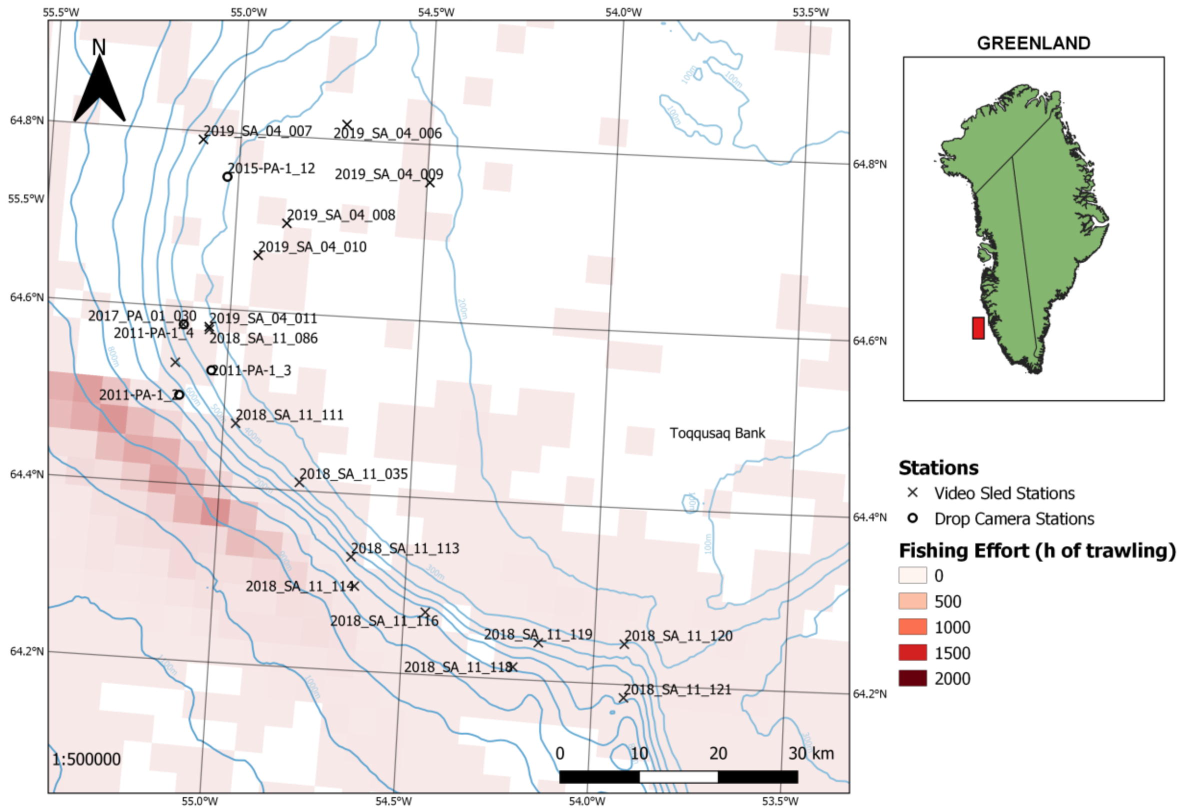


Figure 1 | Benthic imagery was collected from 19 stations (250m to 700m deep) which are between 64.75˚N and 64.18˚N, the western slope of the Toqqusaq Bank, Davis Strait. Video (x) and drop camera (open circle) are drawn and labelled (Year_Ship_Leg_Station_Number). Bathymetry is drawn at 100m intervals. Trawling effort from Global Fishing Watch (GFW) is the hours of trawling inferred from AIS transmissions from 2012 to 2016 inclusive, aggregated to a 3.5km grid (Global Fishing Watch, 2017).

Table 1| Description of stations sampled from video sled and drop camera stations from the Toqqusaq Bank, Davis Strait, Greenland.

Station	Depth (m)	Year	Analysed	Gear Type	Images Extracted
PA_01_02	321	2011	No	Drop	-
PA_01_03	349	2011	No	Drop	-
PA_01_04	397	2011	No	Drop	-
PA_01_12	390	2015	No	Drop	-
PA_01_05	400	2017	No	Drop	-
PA_01_030	411	2017	Yes	Sled	23
SA_11_035	445	2018	Yes	Sled	44
SA_11_086	321	2018	Yes	Sled	128
SA_11_087	585	2018	Yes	Sled	133
SA_11_111	391	2018	Yes	Sled	77
SA_11_113	561	2018	Yes	Sled	84
SA_11_119	412	2018	Yes	Sled	108
SA_11_120	326	2018	Yes	Sled	106
SA_11_121	366	2018	Yes	Sled	37
SA_04_006	276	2019	Yes	Sled	60
SA_04_007	395	2019	Yes	Sled	59
SA_04_008	287	2019	Yes	Sled	63
SA_04_010	293	2019	Yes	Sled	53
SA_04_011	314	2019	Yes	Sled	56

1.2 *Benthic Sled Video Collection*

Imagery was collected using a towed sled with an oblique angled front facing action camera (GoPro), two lights and a scaling laser. Once the sled landed on the seabed it was pulled along behind the ship for approximately 10-30 mins at a tow speed of 1 knot. Start and end position were recorded for the path of sled tow. The area of the field of view was calculated trigonometrically to be 8.23 m^2 (Millard and Seaver 1990; Treibitz et al. 2012; Nakajima et al. 2015). The process conducted to determine the area of the field of view is explained in detail in the supplementary information.

2. Image Selection

2.1 *Extraction of Stills for Annotation*

Quantitative analysis was based on stills extracted from videos. All footage was reviewed and useable video segments identified. Segments of video were excluded when: 1) floating debris or dust covered more than 5% of the screen; 2) the light from the sled was blocked or unevenly distributed across the frame/seabed; 3) the sled was not level with the seabed; or 4) the sled was stationary or moving more quickly than the average speed. Stills were extracted at 15 second intervals, from the useable segments. An algorithm selected the most in focus frame from the first 48 frames (GoPro 4) and 60 frames (GoPro 5) at each time point. These images were reviewed and any unsuitable images, as per the criteria above, were excluded. This produced 1037 images. The start and end location, speed, bearing, depth, wire length, and time within tow were used to estimate the location of each still using trigonometry. The images were then uploaded to BioImage Indexing, Graphical Labelling and Exploration 2.0 (BIIGLE) an online browser based annotation program (Langenkämper et al. 2017).

3. Annotation of Images

3.1 *Identification of taxa for annotation*

The abundance and density of taxa in the imagery, and the fact that not all of the taxa could be consistently identified with confidence, meant a pragmatic approach to annotation was required. This was informed by the FAO's VME guidelines and NAFO and ICES interpretation of this, in addition to the wider literature (FAO 2008; NAFO 2019; ICES 2019). The taxa selected for annotation met at least one or more of the following requirements: 1) currently classified as VME indicators by NAFO and/or ICES; 2) large enough in size for consistent annotation/identification in all images; 3) form structurally significant components of their habitats; 4) present commonly across the image set. These criteria gave 20 taxa selected for annotation (Table 2).

Table 2 | A compiled list of species that were annotated in this study. Taxa were chosen as VME indicators species for this study with reference to NAFO and ICES VME guidelines (NAFO 2019; ICES 2019).

Common name of taxonomic group	Phylum	Annotation Label	NAFO VME Indicator	ICES VME Indicator
Anemones	Cnidaria	Actinaria	No	Yes
Gorgonian corals	Cnidaria	Acanthogorgiidae	Yes	Yes
	.	Paragorgiidae	Yes	Yes
		Plexauridae	Yes	Yes
		Primnoidae	Yes	Yes
Soft corals	Cnidaria	Anthomastus sp.	No	Yes
		Nephtheidae	No	Yes
Hydrozoans	Cnidaria	Aglaopheniidae	No	Yes
Sea pens	Cnidaria	Pennatulidae	Yes	Yes
Sea lilies	Echinodermata	Crinoidea	Yes	Yes
Brittle stars	Echinodermata	Ophiuroidea	No	Yes
Sponges	Porifera	Axinellidae	Yes	Yes
		Geodiidae	Yes	Yes
		Polymastiidae	Yes	Yes
		Rossellidae	Yes	Yes
		Porifera massive <10cm	N/A	N/A
		Porifera massive >10cm		
		Porifera branching <10cm	N/A	N/A
		Porifera branching >10cm		
Bryozoans	Bryozoa	Reteporella sp.	No	No

3.2 *Still annotation*

Stills were annotated using BIGGLE 2.0. In this program the user can select an image from a volume and annotate images using coloured labels that note specific taxa found in an associated label tree. Each image was first reviewed at the whole image level and annotated. Images were then reviewed using lawnmower mode which allows the user to zoom in one level (to ~ 25% of the image on screen) and cycle through the full image to annotate any taxa missed (Langenkämper et al. 2017). When necessary, video was reviewed alongside images to provide a better view of the individual taxa to aid identification. All images were reviewed at the end of this process and image annotations checked to ensure the consistency of the identification of taxa across all stations. Substrate classifications were then made at the whole image level using an adapted version of the EUNIS habitat classifications (Galparsoro et al. 2012) for deep sea habitats originally modified by Gougeon et al. (2017) and further customized to be applicable here (Galparsoro et al. 2012). Each image was labelled as either coarse rocky ground (R), coarse rocky ground with boulders (Rb), gravelly mud (gM), or gravelly mud with boulders (gMB) (Figure 2).

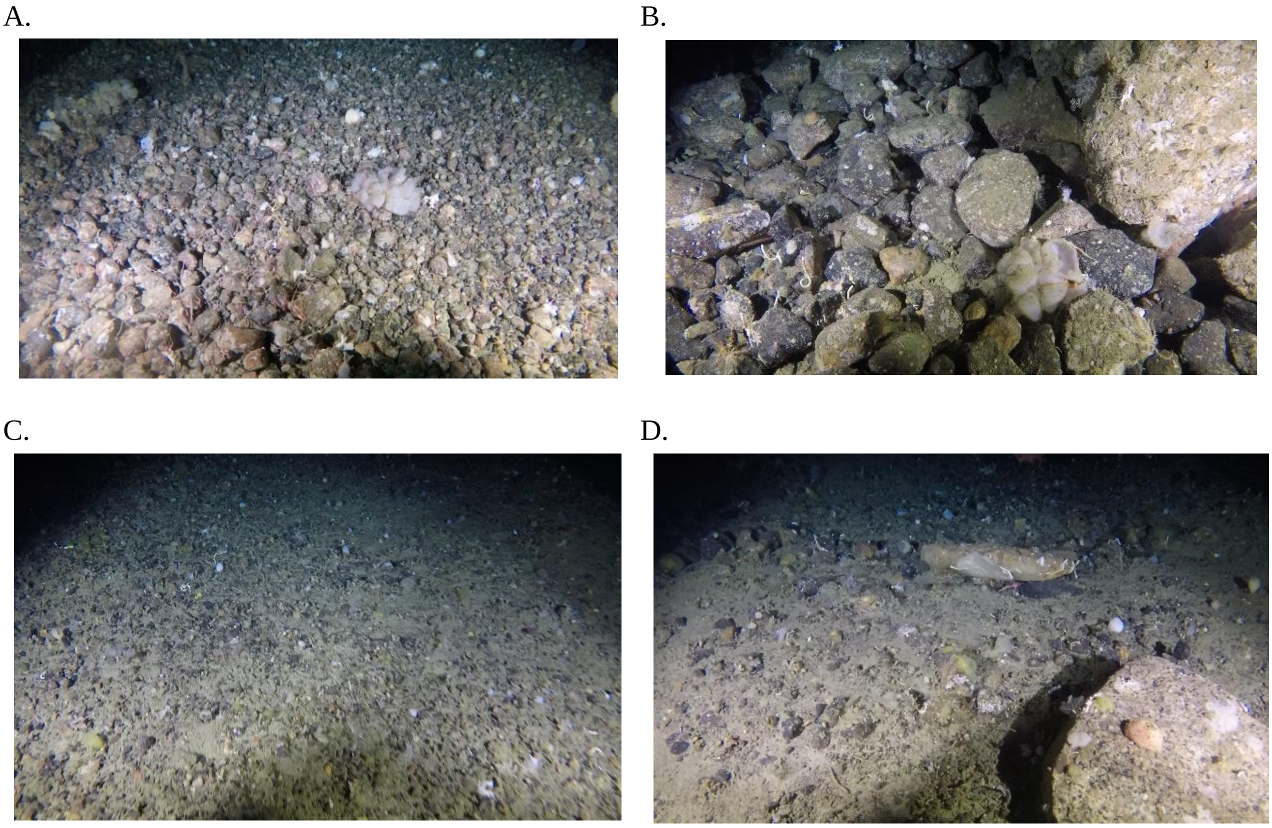


Figure 2| This figure displays the habitat types categorized in this study which are adapted from the EUNIS habitat classifications originally modified by Gougeon et al. 2017 and customized further for this study. **(A)** Represents a *coarse rocky ground (R)* habitat defined as areas of rocky ground with no consolidated sediments visible. **(B)** Represents a *coarse rocky ground with boulders (Rb)* habitat defined by areas of rocky ground with no consolidated sediments, and with at least one or more boulders (≥20cm). **(C)** Represents a *gravelly mud* (gM) habitat defined as areas of consolidated mud with small pieces of gravel (≤ 4 cm) scattered within the mud. **(D)** Represents a *gravelly mud with boulders (gMb)* habitat defined by areas of gravelly mud with at least one or more boulders (≥20cm). Stills were taken from benthic video sled imagery collected in the Davis Strait, Greenland.

4. Data Analysis

All data analysis was conducted using R version 3.5 (R Core Team 2019). I used the following R packages to conduct the following analysis: dplyr (Wickham et al. 2019), tidyverse (Wickham 2017), ggplot2 (Wickham 2016), ggpubr (Kassambara 2018) and lattice (Sarkar 2008). I considered results statistically significant where $p \leq 0.05$.

4.1 *Density calculations*

Annotation data extracted from BIGGLE 2.0 was used to estimate density of the important groups of taxa. For each station I calculated the mean and standard deviation of the density of each taxa group (taxa per m^2) (Table 3). Maximum and minimum mean densities for each taxa group across stations were reported (Table 3). Based on personal communications and unpublished data from scientists working on deep sea ecosystems in the North Atlantic Ocean, we concluded that any taxa found in densities above 2 per m^2 were considered to display a VME level density.

4.2 *Comparisons of taxa and substrate classifications*

Using the image level substrate classifications, I calculated the proportion of different substrate types at each station. A substrate classification was then assigned at the station level based on the most prevalent habitat type found at each station.

To test whether substrate type influenced the densities of specific taxa groups, I created a boxplot, where taxa density (m^2) was the response variable and substrate type the explanatory variable. For each taxa group I conducted an ANOVA to determine if there was a difference between the densities of taxa found on each substrate type. If groups were shown to be significantly different from each other, a subsequent regression was performed on the ANOVA tests for each taxa group to investigate the effects of substrate types on taxa density. Following this I was able to determine on which substrate type each taxa group of interest was most commonly found.

4.3 *Environmental factors influencing taxa densities*

To learn more about what drove the densities of Nephtheidae, the main coral garden indicator family, at different stations I ran a linear mixed model including several environmental variables. Environmental variables were calculated using a process outlined in a study by Yesson et al. 2017. I took into account the effects of depth, fishing effort, current, sea-bed temperature, slope, topographic ruggedness index (TRI) and topographic position index (TPI) when trying to describe what effects the density of the group of interest. Each environmental variable was checked for normality and those that did not meet this assumption were log transformed before being further analyzed. Fishing effort, depth and TPI were log transformed to meet this assumption. Depth was known to have a non-linear relationship in relation to density and this was accounted for in the mixed linear model. I conducted a stepwise model selection to remove variables which had no effect to produce the minimum adequate model (MAM). I visually inspected the residual plots of this analysis to assess that the assumptions of this model were not violated. The minimum adequate model included depth as a polynomial parameter and fishing effort.

Results

4. Data Analysis

4.1 *Density calculations*

A total of 14 stations were analysed in this study with 1037 images extracted from the imagery collected. More than 43 000 taxon observations were annotated from the imagery collected at these sites. As seen in Table 3, six taxon groups were found to have densities at or higher than 2 individuals per m^2 (Figure 3). Nephtheids were found at all stations in noticeable densities and at significant VME densities in 6 stations. Actiniarians, *Anthomastus sp*, globular sponges, branching sponges and crinoids were not found as consistently as Nephtheids across all stations, but were all present in at least one station at a VME level densities (Table 3, Figure 5).

Table 3| Displays the minimum, maximum, mean and standard deviation of the density of each taxa group over the 14 stations sampled on a bank from the Davis Strait, Greenland. The gorgonian coral taxa group consists of 4 VME indicator families: *Acanthogorgiidae, Paragorgiidae, Plexauridae, Primnoidae.* The porifera massive taxa group consists of 3 VME indicator families: *Polymastiidae, Geoiidae, Axinellidae* and any other sponges of less than or greater than 10 cm.

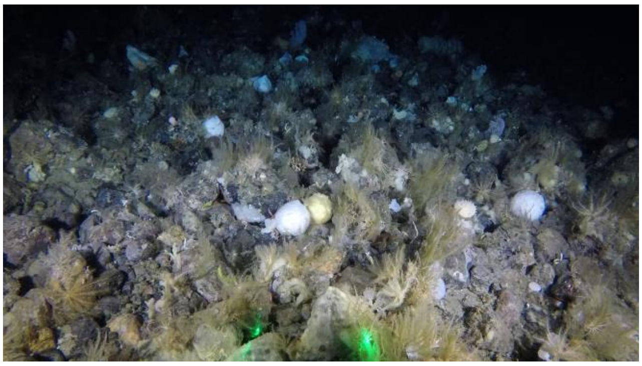
VME Taxa	Minimum per m^2	Maximum per m^2	Mean per m^2	Standard Deviation	Stations where taxa present	Stations with VME Densities
Actiniaria	0.12 (St. 6, 8, 10, 119,121)	10.93 (St. 11)	1.60	3.54	14	2
Agalophenidae	0	0.43 (St. 119)	0.31	0.12	8	0
Anthomastus sp.	0	2.19 (St. 87)	0.67	0.86	5	1
Crinoidea	0	2.30 (St. 87)	0.44	0.65	11	1
Gorgonian Corals	0	0.49 (St. 120)	0.24	0.11	9	0
Nephtheidae	0.16 (St. 8)	2.91 (St. 30)	1.28	1.05	14	6
Porifera branching	0.12 (St. 10)	2.36 (St. 120)	0.52	0.73	11	2
Porifera massive	0	1.62 (St. 30)	0.91	0.38	14	2
Reteporella	0.18 (St. 119)	0.87 (St. 111)	0.49	0.25	14	0

Eleven out of fourteen stations had indicator taxon groups found at VME level densities (Figure 4). Six of these stations, which are Nephtheid dominated represent potential VME coral garden habitats. Two more stations in which Actiniarians are found at very high densities likely also represent variations of this coral garden habitat. Three more stations represent sponge dominated habitats. Potential VME habitats were mostly found within the 350-500 m depth range along Toqqusaq Bank (Figure 4).

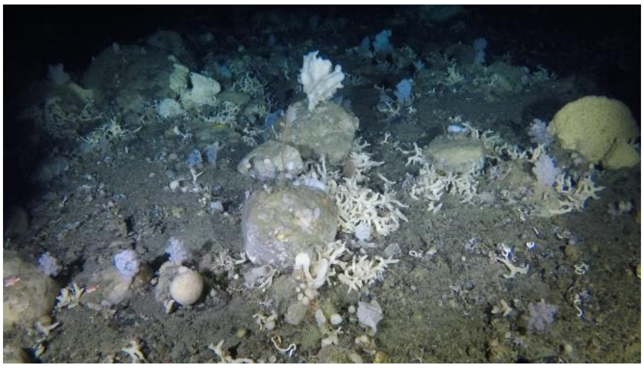
A. Nephtheidae Density= 6.2 per m^2

B. Actinarian Density = 12.15 per m^2

C. Crinoidea Density= 6.61 per m^2



D. Porifera = 5.34 per m^2



E. Anthomastus Density= 13 per m^2

F. Porifera branching = 5.12 per m^2

Figure 3| This figure displays example stills of VME level density areas described in this study. Densities listed above each image display the density of taxa group present in that image. (A) Cauliflower Coral Garden (*Nephtheidae*); (B) Anemone Fields (*Actiniaria*); (C) Crinoid Meadow; (D) Globular Sponge Area (*Porifera massive*); (E) Anthomastus Bed; (F) Branching Sponge Area (*Porifera branching*). Stills were taken from benthic video sled imagery collected in the Davis Strait, Greenland.

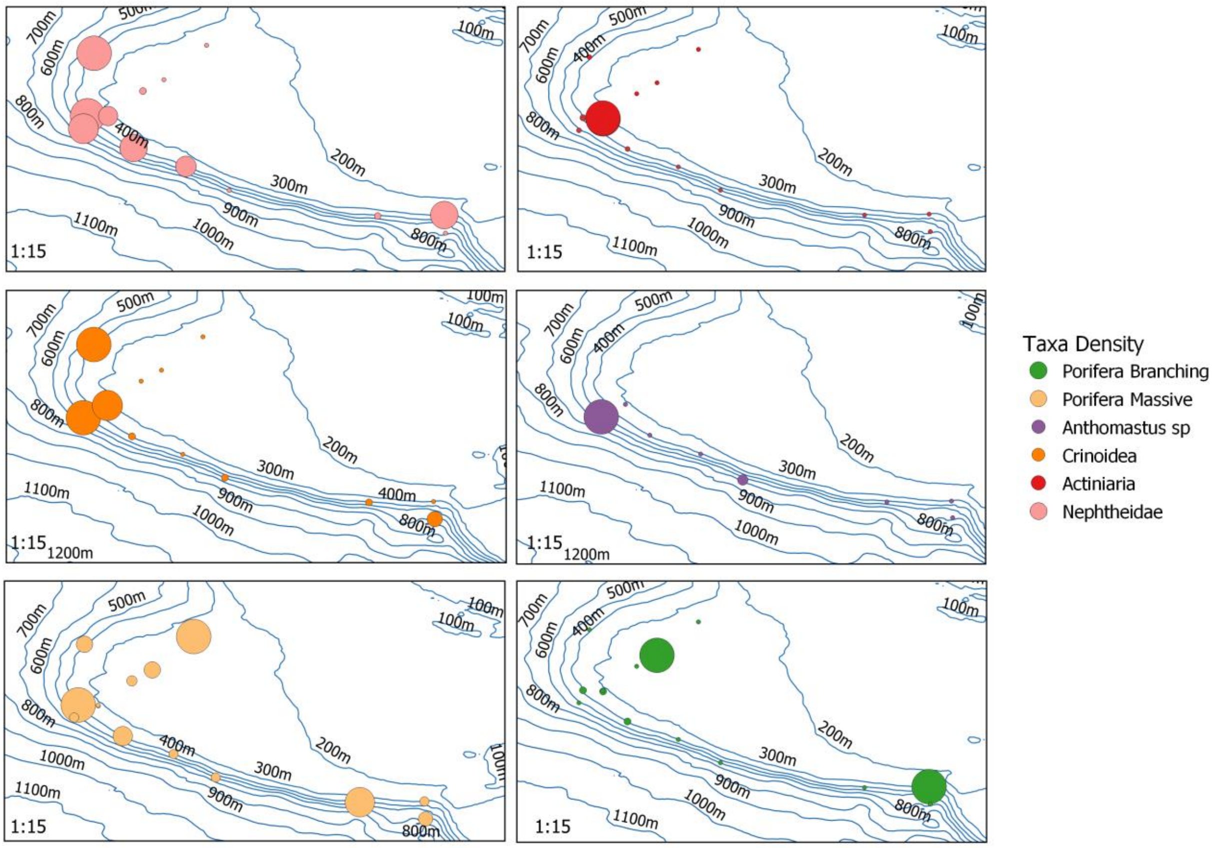


Figure 4| Displays taxa densities of our 6 VME level density taxa. Size of dots is relative to density of taxa. Data was collected from stills which were taken from benthic video sled imagery collected in the Davis Strait, Greenland.

4.2 *Comparisons of Taxa and Substrate Classifications*

All stations exhibited more than one substrate type (Figure 5). Seven stations exhibited only coarse rocky ground and coarse rocky ground with boulders habitats. Two stations exhibited only gravelly mud and gravelly mud with boulder habitat types. Five stations were determined to be a mix of all different habitat types.

An analysis of variance conducted on the four most prevalent groups of taxa showed that the effect of substrate type on the number of taxa found in an image was significant (Table 4, Figure 6). Nephtheids ($F(3,814 = 44.84)$, $p<0.01$), Actiniarians ($F(3,443 = 8.09)$, $p<0.01$), and Crinoids ($F(3,190 = 6.46)$, $p<0.01$), were significantly found most often in coarse rocky ground and coarse rocky ground with boulder habitats. Whereas globular sponges (Porifera massive) ($F(3,634 = 19.67)$, $p<0.01$) were significantly found most often in gravelly mud type habitats. Both *Anthomastus sp*. ($F(3,324 = 6.46)$, $p=0.116$) and branching sponges (Porifera branching) ($F(3,63 = 2.04)$, $p=0.314$) were seen at VME level densities but did not show a significant preference for any substrate type (Table 4, Figure 4). Table 4, displays results of linear models for each taxa group, comparing the mean number of taxa per image by substrate type. The mean number of taxa in coarse rocky ground habitats represents the intercept of this model and estimates of the mean number of taxa for the other substrate types are noted in comparison to the intercept. Positive estimate values indicate they have a higher number of taxa in comparison to coarse rocky ground, and negative estimate values indicate they have a lower number of taxa in comparison to coarse rocky ground habitats. The value of the estimate describes to what degree higher or lower the mean number of taxa is in comparison to the coarse rocky ground habitat (Table 4).

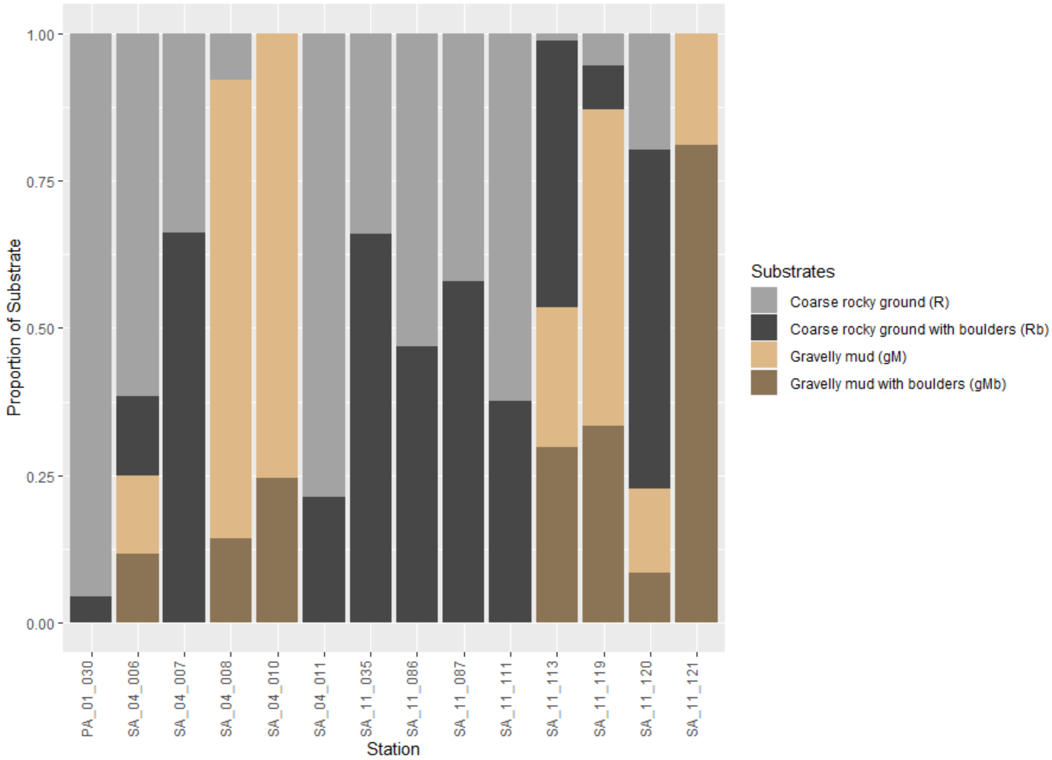


Figure 5| Stacked bar chart showing proportion of all four substrate types identified from a series of still images subsampled from 14 stations. 1037 stills were taken from benthic video sled imagery collected in the Davis Strait, Greenland. Substrate types categorized using modified EUNIS habitat classifications.

Table 4| Displays results of linear models for each taxa group, comparing the mean number of taxa per image by substrate type. The intercept of this model represents the mean number of taxa found in the coarse rocky ground habitat to which all other substrate types are compared.

Taxa Group	Substrate Type	Estimate	Standard Error	t value	p
Nephtheidae	Coarse rocky ground (R)	12.4803	0.67	18.51	<0.01
	Coarse rocky ground with boulders (Rb)	4.3393	0.93	4.67	<0.01
	Gravelly mud (gM)	-8.7864	1.36	-6.44	<0.01
	Gravelly mud with boulders (gMb)	-7.7239	1.49	-5.18	<0.01
Actinarians	Coarse rocky ground (R)	41.363	2.80	14.77	<0.01
	Coarse rocky ground with boulders (Rb)	-12.028	3.99	-3.02	<0.01
	Gravelly mud (gM)	-40.181	12.69	-3.17	<0.01
	Gravelly mud with boulders (gMb)	-40.196	12.18	-3.30	<0.01
Crinoidea	Coarse rocky ground (R)	9.76	2.25	4.34	<0.01
	Coarse rocky ground with boulders (Rb)	5.01	2.64	1.90	> 0.05
	Gravelly mud (gM)	-7.23	4.27	-1.69	> 0.05
	Gravelly mud with boulders (gMb)	-4.62	3.27	-1.41	> 0.05
Porifera massive	Coarse rocky ground (R)	2.33	0.16	14.14	<0.01
	Coarse rocky ground with boulders (Rb)	0.12	0.23	0.57	> 0.05
	Gravelly mud (gM)	1.77	0.27	6.49	<0.01
	Gravelly mud with boulders (gMb)	1.22	0.29	4.18	<0.01

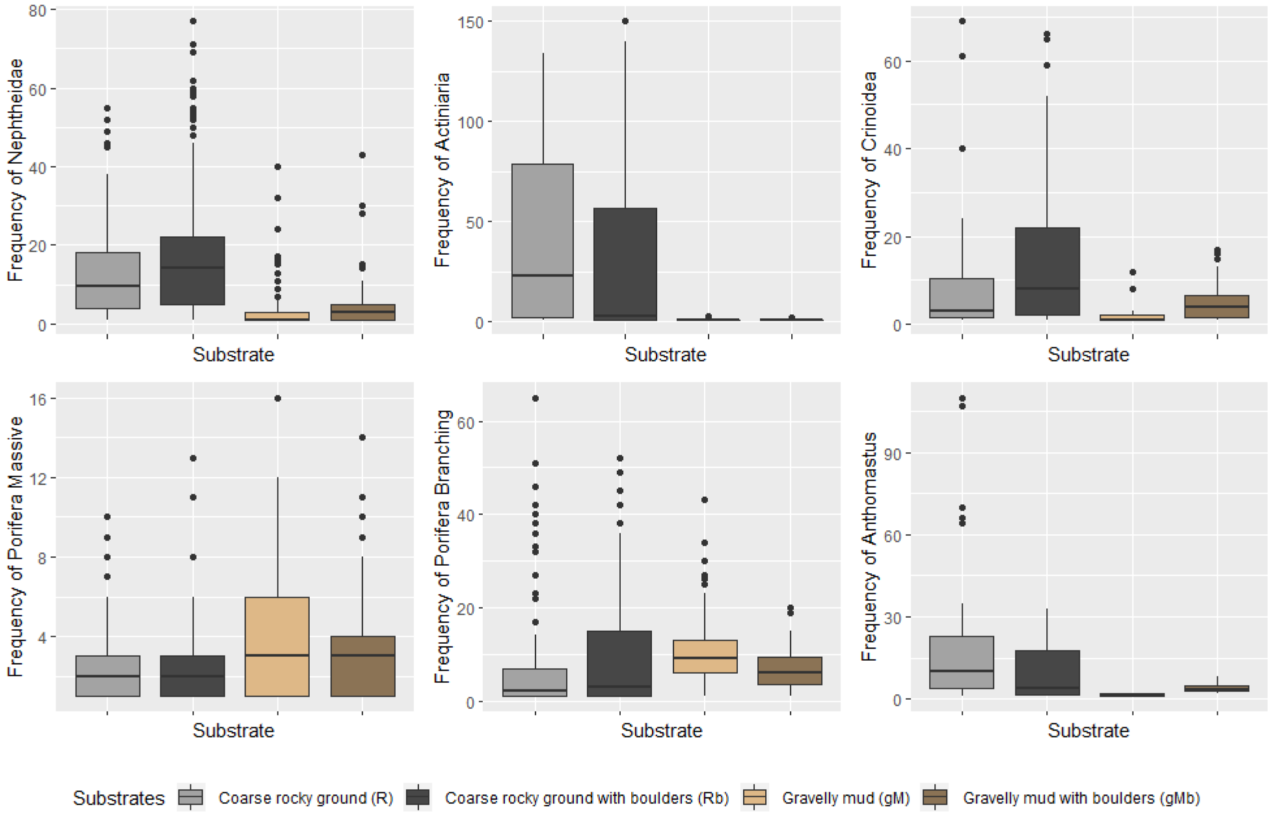


Figure 6| Boxplots displaying the frequency of various taxa groups per image by substrate type. Substrate types categorized using modified EUNIS habitat classifications.

4.3 *Environmental Factors Influencing Taxa Densities*

A linear model including all environmental variables was subjected to stepwise deletion to determine the minimum adequate model (Figure 7). Depth, fishing effort and the interaction between them were found to have a significant effect on Nephtheidae density ($F(3,10)=4.082$, $p < 0.05$) with an R^2 of 0.4157.

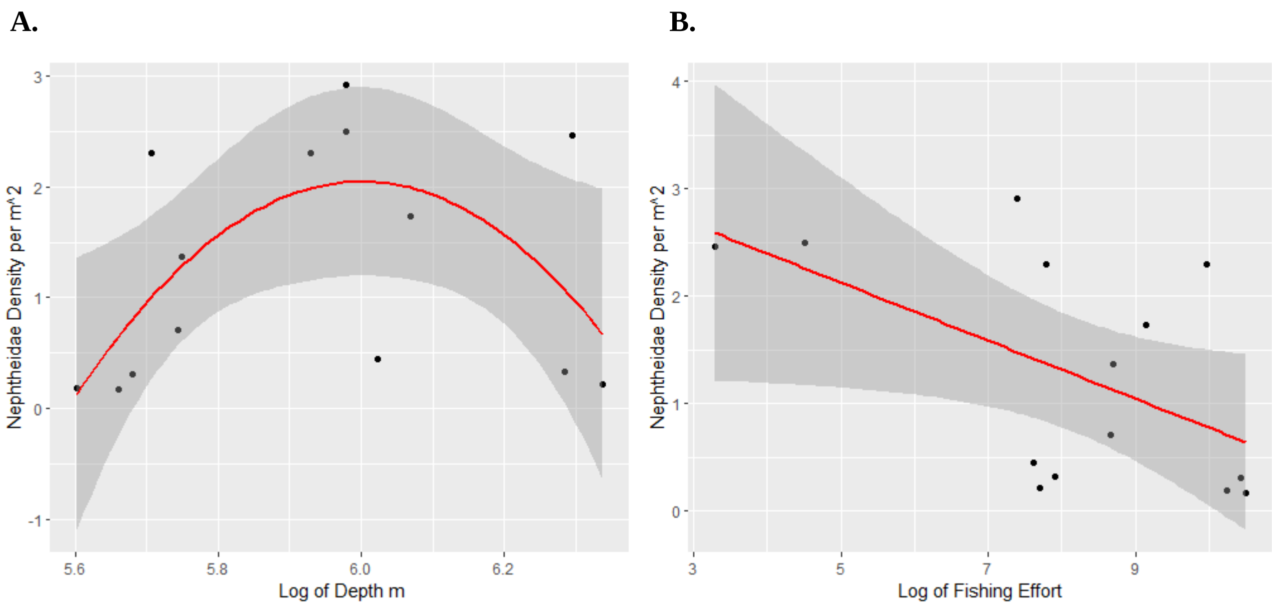


Figure 7| A) Displays a linear model of Nephtheidae density by depth. B) Displays a linear model of Nephtheidae density by the log of fishing effort. For both graphs the red line represents a line of best fit and the grey band represents standard error.

Discussion

As the climate warms and technology improves, many deep sea environments are becoming more accessible to the expansion of fishery activities. In order to improve the management of deep sea ecosystems, and protect the essential functions that these ecosystems provide, we must develop a standardized system to identify vulnerable marine ecosystems and protect them. Understanding what factors affect the abundance of the organisms which comprise these deep sea communities is a crucial step in predicting where vulnerable marine ecosystems will occur. Quantifying the impacts of anthropogenic stressors on cold-water coral communities will help us understand the best way to mitigate these stressors. In this project we aimed to address these issues, and identify a potential vulnerable marine ecosystem off of the West Coast of Greenland.

In this study we estimated VME level densities of a variety of species from several stations spanning the Toqqusaq Bank in Greenland. High abundances of anemones (Actinaria), soft corals (Nephtheids), feather stars (Crinoids) and sponges indicate the presence of a coral garden habitat along the bank from 350m to 500m in depth. Based on the observations of these habitats, I would suggest that the area outlined in Figure 8 represents the minimal extent of this coral garden VME. Closing this area to fishery activities would protect species in this habitat from being damaged as it has been shown that once cold-water habitats are damaged they are unlikely to recover (Huvenne et al. 2016). In consideration of precautionary management, we should likely be protecting the whole depth zone from 350m to 500m on this bank, as conditions would suggest the coral garden habitat likely spans farther than what we have sampled.

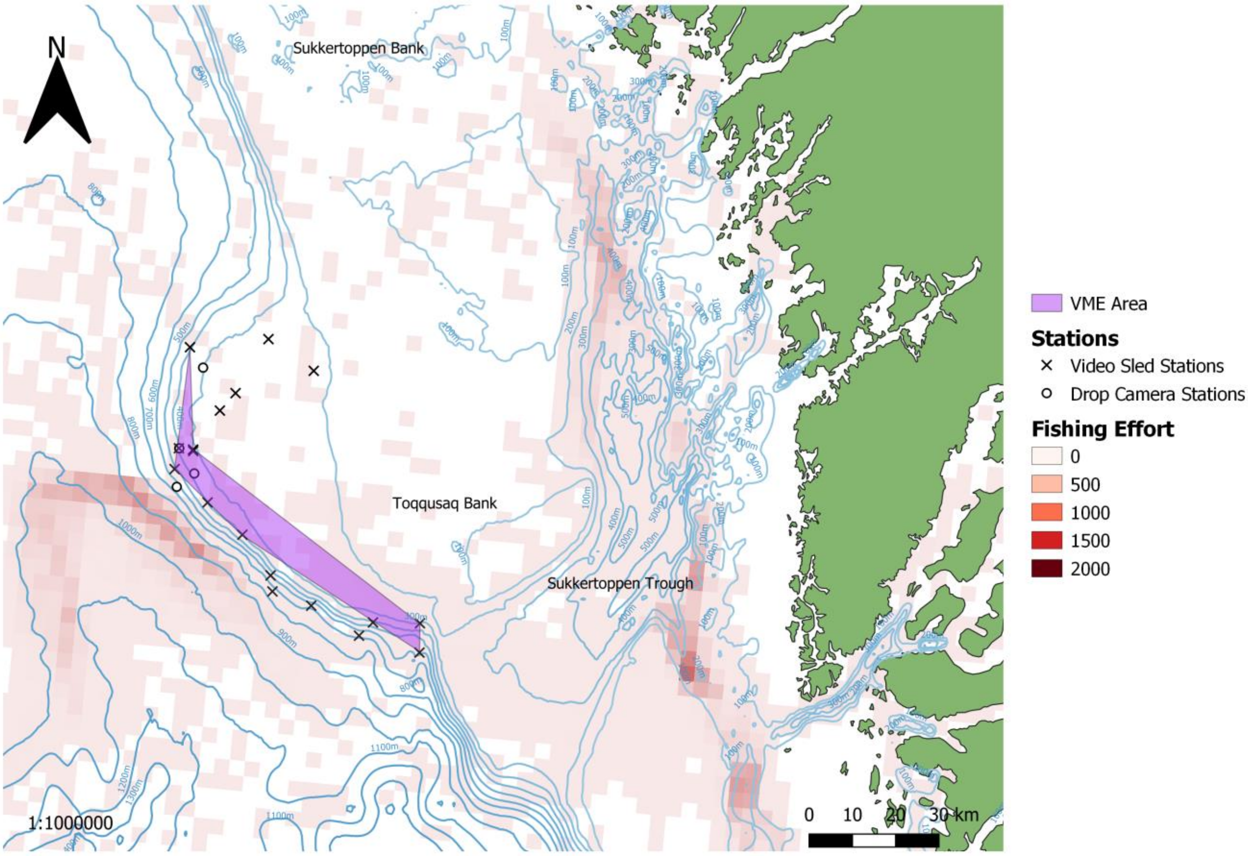


Figure 8| The proposed VME area determined from this study is outlined in purple. Benthic imagery was collected from 19 stations (250m to 700m deep) which are between 64.75˚N and 64.18˚N, the western slope of the Toqqusaq Bank, Davis Strait. Video (x) and drop camera (open circle) are drawn and labelled (Year_Ship_Leg_Station_Number). Bathymetry is drawn at 100m intervals. Trawling effort from Global Fishing Watch (GFW) is the hours of trawling inferred from AIS transmissions from 2012 to 2016 inclusive, aggregated to a 3.5km grid (Global Fishing Watch 2017).

In accordance with the most recent list of deep water VMEs characterized by the International Council for the Exploration of the Seas (ICES), we have identified two different subtypes of a coral garden habitat, and also deep sea sponge and anemone aggregations (ICES 2019). The VME area outlined in this study contains multiple species of Nephtheids and *Anthomastus sp*. displaying a soft bottom coral garden habitat. Within this same area we found evidence of extremely dense anemone aggregations displaying another type of VME habitat. Habitats in this area contain many VME indicator species such as: *Asconema foliatum, Polymastida spp., Geoidia spp., Anthomastus spp., Paramuricea spp.* and *Acanthogorgia spp.* These structurally complex habitats also showed a diversity of other species such as sea stars, brittle stars, prawn, crabs and several different types of fish. We noted three potential VME sponge dominated habitats which fell outside of our coral garden habitat depth range. If more data was analyzed from those regions, they would likely represent a different type of vulnerable marine ecosystem.

Many different habitats form the large expanse of the deep sea and it can be extremely challenging to document all of these areas using video imagery. However, learning about which habitat types and environmental conditions support high densities of important taxa can allow us to predict where VME areas will occur using existing data on deep-sea environmental conditions. Anemones, Nephtheids and Crinoids were all found at higher densities in rocky ground habitats. Mud dominated habitats tend to support higher densities of deep sea sponges. We have also discovered that both depth and fishing effort have a significant effect on the density of Nephtheidae, our primary coral garden species. Work is currently being conducted to map the habitat types of the seabed off the West Coast of Greenland (Gougeon et al. 2017). Combining all of this information will allow us to predict the full extent of our VME habitat and determine where new ones may exist.

Identifying and documenting the prevalence of these deep sea habitats is only the first step in protecting the ecosystem services they provide. In order to protect VME areas from further damage, managers must introduce measures to close off these areas to deep sea fishing activities. The efficiency and efficacy of these processes vary greatly depending on the country, their governmental policies, and the degree to which people in the country rely on the services they will lose if these areas are closed. Currently the habitat outlined in this study borders an area that is highly fished for prawn and halibut on the West Coast of Greenland (Figure 9). It is not clear whether the majority of this habitat falls in an area that has a lower fishing effort because it is unsuitable habitat to use for fishing gear, or simply because it has not been exploited yet. It is possible that because this area is currently not as highly used it could be more easily closed to fisheries as it would not immediately affect a large portion of the fishery activities. It is important to note that both the prawn and halibut fisheries on the West Coast of Greenland have been certified as 'sustainable fisheries' by the Marine Stewardship Council (MSC) (Acoura Marine 2018; Cappell et al. 2017). One requirement of obtaining this certification is that these fisheries must minimize their environmental impact (Acoura Marine 2018). Discovering and protecting ecosystems like this would be in the best interest of the fishery industries as it would be economically beneficial to maintain this certification into the future. Habitats with VME indicator species have been shown to support a highly diverse array of species in comparison to surrounding habitats without these species (Linley et al. 2017). Species of sponges in the Northwest Atlantic have already been shown to increase the prevalence and diversity of small crustaceans in comparison to habitats where they were not present (Ashford et al. 2019). Recovery rates of highly impacted deep sea ecosystems that were later protected has been shown to be very low, which highlights the importance of preventative measures (Huvenne et al. 2016). Protecting these VME areas will likely help sustain the prosperity and diversity of these types of ecosystems. Therefore, not only will protecting these ecosystems provide an economic benefit, but it will ensure the sustainability of both the prawn and halibut populations into the future.

The protocol of documenting and describing taxa and assessing the effects of both environmental factors and anthropogenic stressors on deep sea ecosystems can be used as a template for the identification and protection of VMEs around the world. Using a cost-effective technology to document these ecosystems will hopefully lead to more deep sea exploration in areas of the world which have less financial resources to support this type of research. Displaying the prevalence of soft corals in deep sea ecosystems and the habitats which they can support will help update current lists of VME indicators species to help formalize their importance in deep sea ecosystems. Standardizing the process of finding and protecting vulnerable marine systems will help us protect the marine resources that our deep ocean environemnts can provide.

There is still the potential to save these deep sea coral and sponge habitats but we must act quickly and work with states and regional fisheries management organizations (RFMOs) to inform management practices.

In the future it is important to improve on how we classify vulnerable marine ecosystems and how we measure both environmental variables and anthropogenic stressors. In this study, based on personal communications with other scientists working on VMEs in the North Atlantic Ocean, we chose a VME density threshold of over 2 taxa per m^2. As we learn more about these organisms it would likely be best to have particular VME level density thresholds that are taxa specific. For this study we used environmental variables and fishing effort data. It is crucial to note that the spatial resolution of these limits the model. Therefore there can be discrepancies in specific environmental conditions that we are unable to account for. Higher resolution environmental data will be key to understanding fine-scale variation within the coral garden habitat. Previous studies have used fishing effort provided by industry or managers which does not have the spatial resolution necessary to study these impacts on a taxa specific level (Chris Yesson et al. 2017; Pauly and Zeller 2016). Moving forward there are efforts to use AIS satellite data, as in this study leading to obtaining a higher resolution systematic fishing effort data. Increasing the accuracy of our measurements of environmental variables and anthropogenic stressors combined with increasing the amount of area that is sampled will allow us to have a more reliable estimate of the full extent of our VME ecosystems.

Human overexploitation of our environment is a prominent issue in our world today and if we do not begin to protect important habitats, we will quickly lose all of the ecosystem services they provide. Through continued efforts to identify, describe and manage vulnerable marine ecosystems we can ensure the health of populations of species that many species on which deep sea fisheries depend. Sustainable management practices informed by scientific research are needed to protect the essential marine resources that deep ocean ecosystems provide.

Data Code and Availability Statement

Data from this project belongs to the Zoological Society of London and the Greenland Institute of Natural Resources. The data from this project is available upon request of examiners but will not be shared publicly pending its publication in the fall. The full R code for this project is available at: https://www.dropbox.com/s/f7ws18dalotwtez/Sparrow-Scinocca_Bridget_EECMSc_2019.R?dl=0. In combination with the data this R script would allow for the full replication of my results.

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Supplementary Information

1. Information on the Benthic Video Sled

A benthic video sled set with a centrally mounted oblique angled video camera, echo sounder unit, scaling lasers and lights was used to collect underwater imagery. Positioned 20 cm apart below the camera were a pair of green Z-bolt lasers (wavelength=515nm), used to indicate scale. Lights placed on either side of the camera were Group-Binc Nautilux 1750m LED Torches, which were angled to achieve the best illumination possible of the camera's field of view. A Marport Trawler Explorer (echo sounder unit) fixed to the top of the sled was used to monitor the position of the sled relative to the seafloor and measure depth (± 0.1m) and temperature (± 0.1˚C). The sled was towed for 15-30 min at ~ 1 knot once it had made contact with the sea floor.

A GoPro action camera contained in Group-Binc housing, which has a flat acrylic port was used to record video of the sea floor. In 2017, a GoPro4 recording 1920x1080 pixels at 48 frames per second (fps) was used. Following 2017, a GoPro5 recording at the same pixel ratio (16x9) but higher resolution of 2704x1520 pixels and at 60fps was used.

Both cameras were set to 'Medium FOV' while recording footage. This setting, as described by the manufacturer, provides the same field of view (FOV), with vertical (αair) and horizontal (βair) aperture angles in air of 55˚ and 94.4˚ respectively. These values were corrected for refraction according to Snell's Law of refraction using a similar process as described in Treibetiz et al. (2011), where it is necessary to correct for refraction by the bulk medium (seawater) but not the acrylic lens of the housing. Vertical (α) and horizontal (β) aperture angles in seawater were determined by using Equations 1 and 2.

$$\alpha = 2.\sin^{-1}\left(\frac{\sin(0.5\times\alpha_{air})}{r}\right) \quad \text{Equation 1}$$

$$\beta = 2.\sin^{-1}\left(\frac{\sin(0.5\times\beta_{air})}{r}\right) \quad \text{Equation 2}$$

Where, *r* is the refractive index of seawater, for which based on the range of depth, temperature, salinity encountered in this study a value of 1.34 was used (Millar and Seaver, 1990). The values calculated were α=40.3˚ β=66.4˚.

The way that the camera is angled means that the very top part of the image can be difficult to interpret due to taxa appearing smaller because they are furthest from the camera and lacking light. All 43 000 annotations made in this study were below the top hundredth of the image. Removing this area from the analysis prevents the underestimation of the density of taxa. Therefore the area of seafloor in the FOV is calculated for JBDK, a subset of ABDE, where length JB is 0.99 of the length AB (Figure 9).

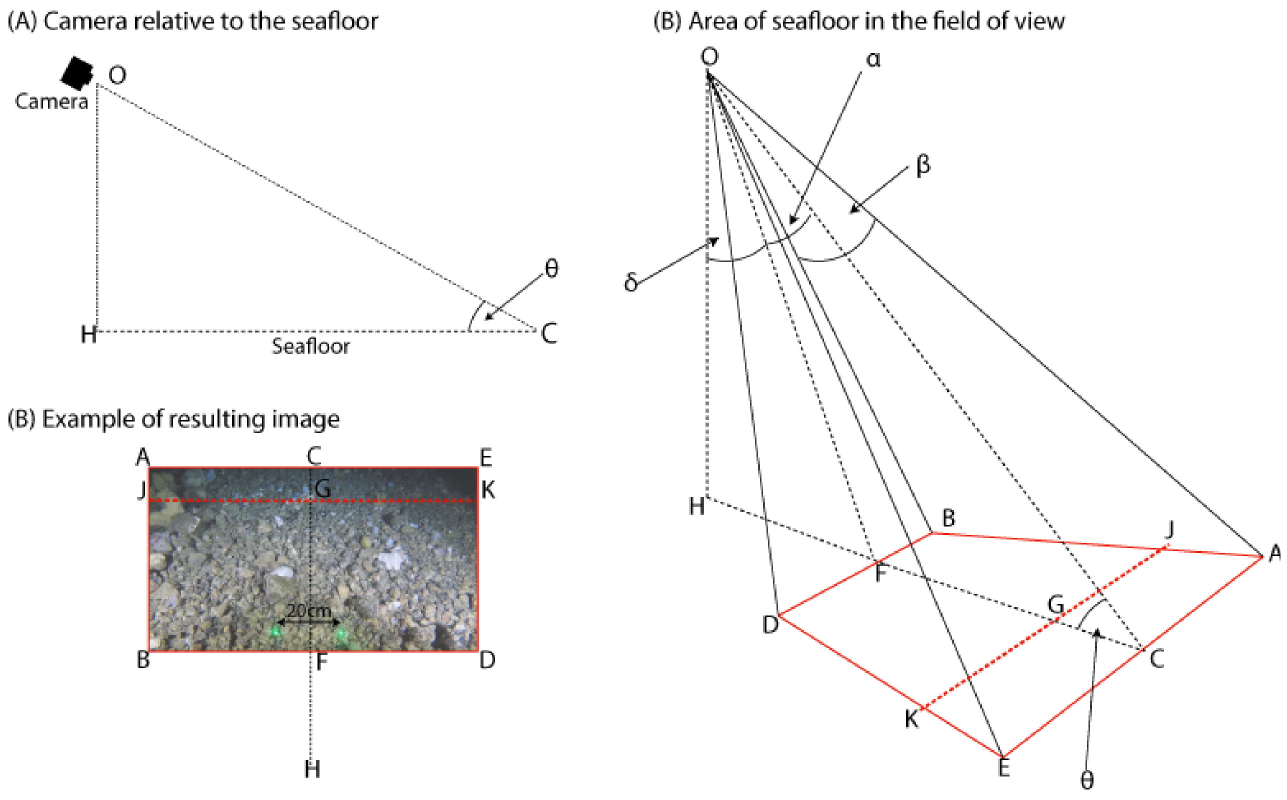

Figure 9| This figure displays a diagram of the benthic video sled camera used to determine the area of the field of view. (A) Shows the orientation of the camera relative to the seafloor. (B) Shows the position of the camera, aperture angles and area of seafloor (*ABDE*) in the camera's FOV (red line), with a cutoff line JK to exclude the portion of the image unsuitable for this analysis (red dashed line). (C) Displays an example image of the seafloor, in relation to (A) and (B), for which the area JBDK is calculated and used in the estimation of fauna density. Adapted from: (Nakajima et al. 2015)

The method described by Nakajima et al. (2015) is modified to allow the estimation of the area *JBDK* (Equations 3-8).

$$\delta = \pi - \left(\frac{\pi}{2} + \theta + \alpha\right) \qquad \text{Equation 3}$$

$$\gamma = 0.99\alpha \qquad \text{Equation 4}$$

$$JK = 2\tan\left(\frac{\beta}{2}\right) \times \frac{OH}{\cos(\delta+\gamma)} \qquad \text{Equation 5}$$

$$BD = 2\tan\left(\frac{\beta}{2}\right) \times \frac{OH}{\cos(\delta)} \qquad \text{Equation 6}$$

$$GF = OH(\tan(\delta+\gamma) - \tan(\delta)) \qquad \text{Equation 7}$$

$$JBDK = \frac{(JK+BD)}{2} \times GF \qquad \text{Equation 8}$$

The height of the camera *OH* was 0.55m. θ the angle of incidence with the seafloor was 28.8° and the aperture angles (α and β) are determined as above (Equations 1 and 2). The area of the seafloor in each image using this analysis (*JBDK*) was estimated to be 8.23m^2. This value was used in this analysis to calculate the densities of all taxa groups used in this study.