Original Article

Deep-sea benthic habitats and the impacts of trawling on them in the offshore Greenland halibut fishery, Davis Strait, west Greenland

Stephen Long [1,2,*], Martin E. Blicher[3], Nanette Hammeken Arboe[3], Mona Fuhrmann[2], Michael Darling[1], Kirsty M. Kemp[2], Rasmus Nygaard[3], Karl Zinglersen[3], and Chris Yesson [2]

[1]*Department of Geography, University College London (UCL), London WC1E 6BT, United Kingdom*
[2]*Institute of Zoology (IoZ), Zoological Society of London, London NW1 4RY, United Kingdom*
[3]*Greenland Institute of Natural Resources, Nuuk 3900, Greenland*

Corresponding author: tel: +44 (0) 20 7449 6369; e-mail: stephen.long.16@ucl.ac.uk

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The offshore Greenland halibut (*Reinhardtius hippoglossoides*) fishery, west Greenland, employs demersal trawl gear at depths of 800–1400 m. In contrast to many deep-sea fisheries, the target stock appears stable and the fishery is of significant economic importance. Recent Marine Stewardship Council certification of this fishery highlighted the paucity of knowledge of benthic habitats and trawling impacts, which this study aimed to address using a towed benthic video sled. The spatially discrete northern and southern areas of the fishery were found to be distinct in terms of the communities present, which non-metric multidimensional scaling suggests is primarily driven by temperature. Extensive physical evidence of trawling was observed. Trawling effort was significantly linked with community composition, with a negative association between trawling effort and abundance of some taxa, including some vulnerable marine ecosystem (VME) indicator species. Three potential VMEs are identified: (i) *Flabellum alabastrum* cup coral meadows; (ii) a *Halipteris finmarchica* sea pen field; and (iii) areas exhibiting mixed assemblages of VME indicators. Of immediate conservation concern is a *H. finmarchica* field, which seems to be at least regionally rare, is situated within the fringes of existing trawling effort and is currently afforded no protection by management measures.

Keywords: Arctic, cup coral meadow, image analysis, sea pen field, vulnerable marine ecosystem

Introduction

Declines in shallow water stocks and improving technology have led to the expansion of deep-sea fisheries in recent decades (Morato *et al.*, 2006). The sustainability of deep-sea fisheries has been repeatedly questioned, both in terms of the impacts on the target stock and the wider ecosystem (e.g. Koslow *et al.*, 2000; Roberts, 2002). The life history of deep-sea fauna is typically characterised by slow growth, late-maturity, and longevity, which can render populations, communities and habitats sensitive to physical disturbance, espe-

cially vulnerable marine ecosystems (VMEs) (FAO, 2009; Ramirez-Llodra *et al.*, 2010). Given that deep-sea fisheries contribute <0.5% to global fisheries landings it has been argued that their economic importance is trivial (Victorero *et al.*, 2018), especially when many deep-sea fleets rely heavily on subsidies to be economically viable (Sumaila *et al.*, 2010; Norse *et al.*, 2012). Clark's Law, coined by Norse *et al.* (2012), observes that where commercial deep-sea species are abundant, the combination of high biomass and low productivity creates a strong economic incentive to maximise catches in the short-term rather than sustainably exploit stocks over

longer time-scales. Frequently, high initial catches have been followed by stock collapse, with numerous well-documented examples of this 'boom and bust' cycle in deep-seas (e.g. Sasaki, 1986; Clark, 1999; Baker *et al.*, 2009).

Deep-sea fisheries predominantly employ demersal otter trawls, in which the depth necessitates heavy gear with trawl doors weighing 2–5 tonnes each and sometimes more (Roberts, 2002; Clark and Koslow, 2007; Clark *et al.*, 2016). The ecosystem effects of these gears have been likened to clear cutting of forests (Watling and Norse, 1998) and ploughing of agricultural land (Puig *et al.*, 2012). The effects of trawl gear on the seabed include mixing of sediments; physical trawl scars or tracks; increased turbidity; displacement of glacial dropstones or boulders; and seafloor homogenization (Watling and Norse, 1998; Thrush and Dayton, 2002; Pusceddu *et al.*, 2014). Benthic faunal impacts include removal or in-situ mortality; smothering; displacement; and structural damage to biogenic habitat (e.g. cold-water coral reefs) (Koslow *et al.*, 2000; Gage *et al.*, 2005; Hall-Spencer *et al.*, 2007). The longevity of these impacts is likely to be significant with recovery estimated to take decades, centuries or even longer, particularly in the case of VMEs (Roberts, 2002). Accordingly, depth-based management measures are increasingly being introduced, including in the northeast Atlantic, the prohibition of demersal trawling below 800 m in all European Union waters (European Union, 2016). Despite recent major advances in ecological research, including new and improving technologies for sampling in the deep-sea, we still lack the knowledge to effectively manage extractive resource use (e.g. fisheries and mining) in these ecosystems (Danovaro *et al.*, 2017). Fundamental challenges include the logistics of accessing deep-sea environments and the sheer scale – the deep-sea (depths >200 m) accounts for more than 99% of the global ocean volume (Costello *et al.*, 2010) and covers 65% of the planet's surface (Danovaro *et al.*, 2017). *In situ* observations of deep-sea habitats often require costly research vessel time and expensive technologies to cope with the depth and pressure. Accordingly, there is a paucity of knowledge in terms of the nature and distribution of deep benthic habitats and their responses to physical disturbance, particularly in comparison with shallower marine habitats.

Deep-sea Greenlandic waters in the northwest Atlantic represent one such knowledge gap. At present, Marine Protected Area (MPA) coverage in the 2.2 million km^2 Exclusive Economic Zone (EEZ) is ~4.5%, comprised of exclusively in inshore waters (UNEP-WCMC, 2019). There are no MPAs affording protection to known VMEs, although measures introduced by Executive Orders have prohibited the use of bottom-contact fishing gears in two areas to protect VME indicator species. These are an ~6.5 km^2 area in southwest Greenland associated with an observation of *Desmophyllum pertusum* (Government of Greenland, 2017; Kenchington *et al.*, 2017) and 11 discrete areas in Melville Bay closed to demersal trawling 'based on significant observations of sea pens' (*Umbellula sp*). (Cappell *et al.*, 2018; Government of Greenland, 2018). The limited spatial management measures to protect deep-sea ecosystems is principally due to a lack of knowledge about the nature and distribution of habitats and VMEs within the Greenlandic EEZ (Long *et al.*, 2020), including in the Davis Strait where this study is focussed. In contrast, more comprehensive research has been undertaken on the Canadian side of the Davis Strait, using trawl survey, fishery bycatch, and image data (e.g. Gass and Willison, 2005; Wareham and Edinger, 2007; Kenchington *et al.*, 2016), which has informed management. Notable findings include an area of dense bamboo coral (*Keratoisis sp.*) forests at depth >900m (de Moura Neves *et al.*, 2015a), which has been closed to trawling as part of

the Disko Fan Conservation Area (de Moura Neves *et al.*, 2015a; Hiltz *et al.*, 2018). Whilst known aggregations of coral, sponge and sea-pens support the prohibition on the use of bottom-contact gear in the Davis Strait Conservation Area further to the south (Kenchington *et al.*, 2016; Hiltz *et al.*, 2018). A recent analysis of the North Atlantic by Morato *et al.* (2021) using VME records and fishing effort data identified the southern Davis Strait as an area where there is a high risk of serious adverse impacts on VMEs, with high confidence in Canadian waters supported by good data (but low confidence and very limited data within the Greenlandic EEZ).
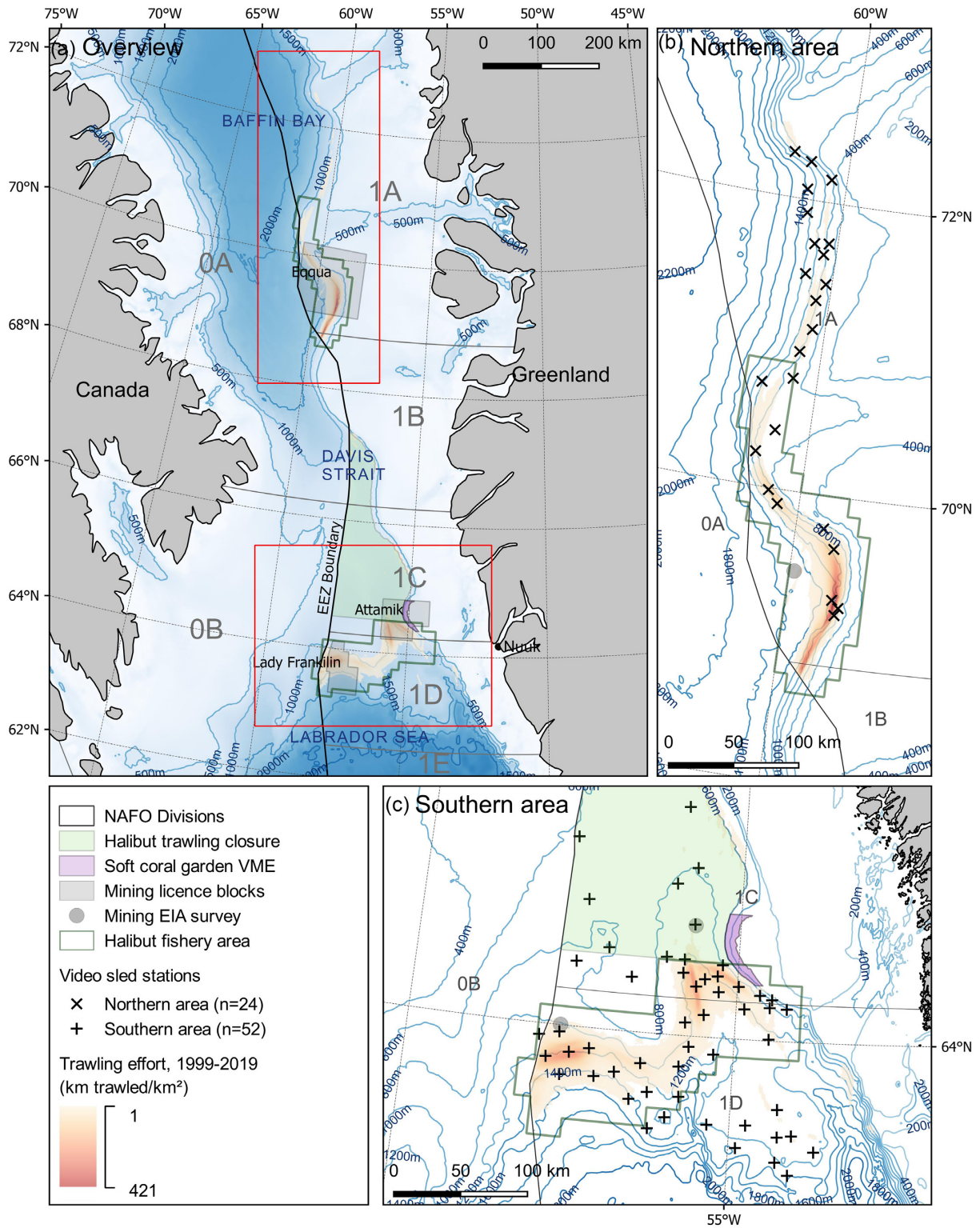
The offshore Greenland halibut (*Reinhardtius hippoglossoides*) fishery in the Davis Strait, west Greenland (NAFO 1A-D, offshore), employs demersal trawl gear at depths of 800–1400 m. It is a rare exception among deep-sea fisheries, in terms of its stock stability and economic importance. Contrary to the typical 'boom and bust' pattern, the fishery continues to be productive and the stock stable (Jacobsen *et al.*, 2018), despite a long history of exploitation. In 2017, Greenlandic vessels in the fishery obtained Marine Stewardship Council (MSC) certification (Cappell *et al.*, 2017), followed by German in 2019 (Cook *et al.*, 2019). The halibut fishery is of considerable importance to the Greenlandic economy. Greenland's fishing industry accounts for 80–95% of the country's export income (Mortensen, 2014; The Economic Council, 2017; Jacobsen, 2018). Some 30% of this fisheries' export income is from halibut (inshore and offshore catches) making it the second most important stock after coldwater prawns (The Economic Council, 2017).

Annual stock assessments, made by the North Atlantic Fisheries Organisation (NAFO) using survey data, provide information on the stock status and trends in the offshore Greenland halibut fishery. However, there is little understanding of the nature of benthic habitats in this area of Greenlandic waters and of the fishery's impacts. Limited existing research has relied on bycatch data from stock assessment surveys to assess the impacts on non-target fish (Jørgensen *et al.*, 2014) and the distribution of corals and sponges (Jørgensen *et al.*, 2013; Blicher and Hammeken Arboe, 2021). The NAFO stock assessment notes that with regards benthic habitats there is: "*no specific information available*" and that "*general impacts of bottom trawl gear on the ecosystem should be considered*" (NAFO, 2019). Long and Jones (2020) critically assessed the governance of this fishery and raised significant concerns about the robustness of the MSC certification process, specifically with regards the assessment of benthic habitat impacts, which are poorly known. This study aims to characterise the benthic habitats and make a preliminary assessment of the impacts of trawling in the west Greenland offshore halibut fishery. This is achieved by sampling across a spectrum of fishing effort, using a low-cost benthic video sled.

Methodology

The study area

In west Greenland, a wide continental shelf extends upwards of 100 km from shore, beyond which the continental slope descends to depths >2000 m (Jørgensen *et al.*, 2018). The Davis Strait acts as a bathymetric bottleneck between the deeper Labrador Sea and Baffin Bay basins (Figure 1), forming a topographic barrier to currents and water masses, thus shaping the hydrographic conditions (Tang *et al.*, 2004; Cuny *et al.*, 2005). The cold East Greenland Current (EGC) and Warmer Irminger Current (IC) combine to form the West Greenland Current (WGC) flowing northwards over the west Greenlandic shelf (Myers *et al.*, 2007). Most of the warmer IC current water, constrained by the shallowing bathymetry, crosses

Figure 1. 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 500 m intervals in (a) and 200 m intervals in (b) and (c), using the IBCAO Version 3500-m grid (Jakobsson et al., 2012). For clarity this bathymetric raster is included in (a) but not (b) and (c). Halibut fishing activity is restricted to the halibut fishery area (polygon green outline), introduced in 2021 (MFHA, 2021). Prior to this and at the time of the study, there were no spatial restrictions other than the halibut trawling closure (polygon light green fill). Oil exploration licence blocks subject to EIAs are drawn and named, with the site of benthic surveys indicated. Trawling effort represented by a 1 km grid, is based on haul by haul logbook data from 1999 to 2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.

the mouth of the Davis Strait and turns south flowing along the Labrador coast (Hamilton and Wu, 2013; Yang *et al.*, 2016). In Baffin Bay, warm West Greenland Intermediate Water (WGIW) formed from the WGC, is found from 300–800 m, below this temperature declines with depth in the cold water mass known as Baffin Bay Deep Water (BBDW). Since the sill depth of the Davis Strait is shallower than 700m, this cold deep water does not have direct access to the Labrador Sea to the south. Accordingly, there are significant water differences between the southern Baffin Bay and the Labrador Sea at the depth range of the halibut fishery. The southern area of the fishery experiences warmer bottom temperatures, whilst the northern area is significantly colder. The Global Open Oceans and Deep Seabed (GOODS) biogeographic classification system identifies lower bathyal provinces (800 to 3000 m) globally. The two separate areas of the fishery fall into different provinces (southern area, Northern North Atlantic province; northern area, Arctic province) (Vierros *et al.*, 2009).

There is some background information on the nature of the habitats in the study area (the fishery and adjacent areas within Greenlandic waters). Environmental Impact Assessments (EIAs) were undertaken for three spatially discrete mining exploration blocks, which overlap the fishery (Figure 1) (BSL, 2011a, b, c). They also provide the only existing seabed imagery (prior to this study), albeit of limited quality and spatial extent. At present, there is no mining, exploration, EIAs or pending applications within the fishery footprint. Across the whole fishery, the seafloor consists of unconsolidated sediments overlying soft clay (BSL, 2011a, b, c; Jørgensbye and Wegeberg, 2018). Icebergs deposit terrigenous sediments and dropstones (Gutt, 2002; Streuff *et al.*, 2017), the latter provides sparse hard substrates on otherwise soft sediments. Trawling occurs on only the gently sloping areas of the continental slope, which per the EIAs, appear to have gradients of <1å (BSL, 2011a, b, c). Reportedly, steeper areas of the slope are associated with rockier ground and are not trawled (Cappell *et al.*, 2017).

Currently, there are no reports of VMEs within the fishery footprint (the area trawled, see Figure 1). However, several VME indicator taxa are known to be present including Alcyonacea, Gorgonacea, Pennatulacea, Scleractinia, Antipatharia (Jørgensen *et al.*, 2013; Blicher and Hammeken Arboe, 2021). A soft coral garden VME was recently identified immediately adjacent to the southern area of the fishery in shallower water from 300 to 600 m (Long *et al.*, 2020) (Figure 1).

In offshore Greenland halibut fishery, commercial catches were first reported in 1964 (NAFO, 2019), since when it has been continuously exploited. Currently, the stock is considered to be stable and fished at a sustainable level (Jacobsen *et al.*, 2018), since 1995 catches have been near the total allowable catch (TAC), which has been steadily increased (Treble and Nogueira, 2018). Over the past decade, annual catches have been around 15,000 tonnes (ICES, 2018). A detailed account of the fishery, its management and governance is provided by Long and Jones (2020). Vessels principally employ bottom trawls with rock hopper gear and heavy trawl doors (each >2 tonnes) (Cappell *et al.*, 2017). Nets are required to use a minimum of 100 mm mesh in the wings and 140-mm mesh in the cod-end (MFHA, 2016). Some vessels employ twin-rigged nets, separated by a heavy roller clump or rolling shoe (Long and Jones, 2020), the weight of this gear component is not specified, though in the shallower west Greenland prawn fishery these reportedly weigh 2-9 tonnes (Cappell and Powles, 2016). To date, there has been limited long-lining by Norwegian vessels (Jacobsen *et al.*, 2018). In 2017, the Greenlandic portion of the fleet, consisting of 6 vessels

known as the West Greenland Offshore Greenland Halibut Fishery (WGOGHF), was certified sustainable by the Marine Stewardship Council (MSC) (Cappell *et al.*, 2017). This was followed by 2 German vessels forming the Doggerbank Seefischerei West Greenland Halibut Fishery, which was first MSC certified in 2019 (Cook *et al.*, 2019). In March 2020, a scope extension was obtained for the WGOGHF MSC certificate, to incorporate a single longline vessel (Chaudhury *et al.*, 2020). Demersal trawling is prohibited between 64°30'N and 68°00'N to protect juvenile halibut (MFHA, 2016) (Figure 1). The spatial distribution of trawling effort is shown in Figure 1. In 2021, subsequent to this study, a revised management plan for the fishery, restricts halibut fishing to a defined area, which encompasses the vast majority of prior trawling effort (Figure 1) (MFHA, 2021).

Benthic video sled

Imagery was obtained using a towed benthic video sled, deployed semi-opportunistically from the *RV Paamiut* (PA), *RV Sanna* (SA), and *MT Helga Maria* (HM), during four stock assessment survey cruises undertaken by Greenland Institute of Natural Resources (GINR), during the summer months of 2017 to 2019. In so far as was possible, stations were selected to cover the depth range of the fishery, be evenly spatially distributed and sample across a spectrum of fishing effort, including untrawled areas. The sled was deployed at a total of 76 stations (52, southern area: 24, northern area), from depths of 649 to 1476 m.

The benthic video sled was equipped with an oblique angled centrally mounted video camera, lights, scaling lasers (two green dots with 20 cm separation), temperature data logger (recording every 10 s; ±0.025åC) and a Marport Trawl Explorer sensor (depth accuracy 0.1%; pitch-roll accuracy 0.1°) providing a live view of the sled's movements on the seabed. A full description of the rig is provided by Long *et al.* (2020). On the bottom contact, the sled was towed at a target speed of 0.8–1 knots for a minimum of 15 minutes. Longer tow times, to a maximum of 31 minutes, were used to ensure adequate footage was obtained when there were potential issues during deployment. For example, rough seas can cause the sled to briefly lift clear of the bottom.

Video was recorded with a GoPro action camera in Group-Binc housings. A GoPro4 recording 1920 × 1080 pixels at 48 frames per second (fps) was used in 2017. Subsequently, a GoPro5 was used, recording at the same aspect ratio (16 × 9) but higher resolution of 2704 × 1520 pixels at 60 fps. The 'Medium FOV' setting was used, which per the manufacturer's specifications this provides the same field of view (FOV) in both cameras. The area of the FOV was calculated to be 8.23 m², with a horizontal width of the FOV at the midline of 1.49 m. A detailed description of the method of FOV estimation and accompanying equations is provided by Long *et al.* (2020).

Image processing
Image extraction
Still images were extracted for quantitative analysis from 'useable segments' of videos, where the sled was proceeding smoothly along the bottom with a clear image. Stills were sampled every 15 seconds, selecting the frame with the sharpest focus, following Long *et al.* (2020).

Image annotation

The images were uploaded to BioImage Indexing, Graphical Labelling and Exploration 2.0 (BIIGLE 2.0), which is a browser based annotation platform (Ontrup *et al.*, 2009; Langenkämper *et al.*, 2017). BIIGLE allows the annotation of images and/or features within images with labels from custom made hierarchical trees.

Prior to commencing annotation, a representative subset of the images was reviewed by the team to agree on a consistent approach. This was informed by previous collective experiences of image and physical sampling surveys in west Greenland. To ensure consistency a single author made all annotations of fauna and substrates.

Fauna annotation

Benthic invertebrate fauna were initially annotated at the highest taxonomic resolution and then aggregated to the Order level to achieve consistency within and between images. Only taxa where discrete individuals or discrete colonies (i.e. colonial organisms that form discrete unit e.g. a sea pen) could be identified were annotated, to allow density estimation. In practice, taxa <5 cm were generally not annotated, except where their gross morphology is sufficiently distinct to allow consistent identification. Highly mobile taxa were not analysed. Three Porifera taxa were relatively common and have a gross morphology that allowed consistent identification across the image set. All other Porifera were annotated according to their size (longest visible dimension), based on the laser scaling dots. Only two size classes were used given the crudeness of this size estimation. Porifera smaller than 5 cm were not annotated they could not be consistently distinguished from other fauna present, especially small Ascidiacea.

Substrate annotation

Substrates were annotated at the level of the image. The revised EUNIS Habitat Classification (Davies *et al.*, 2004), which includes deep-sea specific categories, was previously adapted by Gougeon *et al.* (2017) and further by Long *et al.* (2020), for classifying substrates in imagery from west Greenland. In this study, two new subclasses [A6.5.1 Mud (M) and A6.5.2 Mud with boulders (Mb)] are employed, examples and description of the substrate classes are provided (Supplementary Material, Table 1 and Figure 1). Additionally, images containing apparent evidence of trawling in the form of disturbed/overturned sediments or regular linear features, were annotated by means of a label at the image level.

Video fauna counts

For selected fauna, counts were made from the video (in addition to image annotation). Selected taxa were VME indicators (and abundant non-VME indicator taxa for comparative purposes) that could be consistently identified across the video imagery. This more resource-intensive approach utilises more of the available information in the video imagery. This provides the most accurate estimate of faunal density for the selected taxa and supports taxa-specific modelling for a limited subset of fauna. The useable segments of videos were viewed and selected fauna counted as they crossed a horizontal midline superimposed onto the video. Boulders (rocks >20 cm) were also counted. The estimated 'swept area' in the usable segments from each station was calculated based on the duration of useable segments, mean speed and the width of the FOV at the superimposed midline. The counts and estimated swept area were used to estimate densities.

Fishing Effort

A 1 × 1 km resolution grid of trawling effort was used, based on haul-by-haul logbook data for halibut fishery trawls between 1999 and 2019 (data provided by Greenland Fishery Licence Control). The grid represents km trawled/km^2, bounded by 72.5°N and 62°N; the 500 m depth cline; and the Greenlandic EEZ. A full description is provided by (Long *et al.*, 2020).

Station metadata

The sled position was inferred trigonometrically from the ship's position, direction, water depth, and length of towing cable (Long *et al.* 2020). Seabed temperature values were based on a mean of all data logger readings taken between the start and end of the tow. A depth value was obtained as the mean of depths recorded at the start and the end of the tow. Trawling effort ('effort') for each station was based on cross-referencing survey positions with the effort raster (see, 2.4 Mapping), using a mean of all cells crossed by the sled's path.

Statistical approach

Data processing and analysis was undertaken in R (R Core Team, 2013). Non-metric multidimensional scaling (NMDS) was used to identify patterns in the benthic communities. Specifically, to determine if the stations were arranged in distinct clusters, suggesting spatial variation in communities across the study area. The NMDS ordination technique, which uses rank order to collapse information from multiple dimensions to allow visualisation and interpretation, is commonly used in the analysis of benthic communities (de Carvalho *et al.*, 2015). The number of images obtained from each station varied according to the length of tow and the duration of useable segments (see, 2.3.1 Image processing). Therefore, image annotation count data were normalised to the median area imaged across all stations (403 m^2) (i.e. the counts for each station were adjusted to the median area for all stations, according to the area imaged at that station). The analysis was conducted at the Order level, with the following exceptions. Porifera that could not be classified to the Order level were grouped into two size classes (see 2.3.2.1 Fauna annotation). Gastropoda were included at the Class level as a greater level of taxonomic detail could not be reliably achieved. The 'metaMDS' function of the vegan community ecology package (Oksanen *et al.*, 2019), was used to find the optimal ordination solution with the lowest stress value. The count data were log(x+1) transformed prior to NMDS, this transformation yields the lowest stress value. The solution was optimised using Bray–Cutis dissimilarity. The significance of the fitted environmental vectors was assessed using a permutation procedure (9999 permutations), using the 'envfit' function of the vegan package, which independently assesses each variable and allows them to be visualised as vectors on the NMDS ordination plot (Oksanen *et al.*, 2019). Environmental vectors were considered significant where $p < 0.05$.

There were only sufficient stations to support taxa-specific modelling in the southern area of the fishery ($n = 52$), using the video count data. The video count data were normalised to the mean 'swept area' of 433.6 m^2 (standard deviation = 210.3) (i.e.

Table 1. Summary statistics at the station level.

	Study area		
	North	**South**	**ALL**
Data collection			
Number of stations	24	52	76
Number of images	981	2,523	3,504
Area in images (m²)	8074	20764	28838
Number of fauna annotations	1184	11878	13062
Annotations /m²	0.15	0.57	0.45
Depth (m)			
Minimum	653	649	649
Maximum	1353	1476	1476
Mean (± SD)	923 (184)	1058 (214)	1015 (214)
Temperature (åC)			
Minimum	0.0	3.3	0.0
Maximum	1.6	4.3	4.3
Mean (± SD)	0.7 (0.4)	3.6 (0.2)	2.6 (1.4)
Substrate (% of images)			
A6.2.1 Gravelly mud (gM)	4.0	3.3	3.5
A6.2.2 Gravelly mud with boulders (gMb)	1.8	1.7	1.7
A6.5.1 Mud (M)	92.0	87.1	88.5
A6.5.2 Mud with boulders (Mb)	2.1	7.9	6.3
Trawling evidence (% of images)			
Minimum	0	0	0
Maximum	55	59	59
Median	2	0	0
Fishing effort (km trawled/km²)			
Minimum	0	0	0
Maximum	298	215	298
Median	1.0	0.6	0.8

the counts for each station were adjusted to the mean area for all southern stations, according to the area imaged at that station). Four potential explanatory variables were investigated: (i) depth; (ii) bottom temperature; (iii) boulder occurrence; and (iv) effort. Correlation between explanatory variables was assessed using the Pearson correlation coefficient. Depth and temperature were strongly correlated ($r = -0.67$), so the latter was excluded as depth is more readily interpreted from a management perspective. Removing highly correlated variables reduces the risk of overfitting models. The Pearson correlation coefficients for the remaining variables used in the full model were $|r| < 0.2$. Transformations were used to improve normality of effort and boulder occurrence and address outliers, in order to avoid violating model assumptions (Zuur *et al.*, 2010). Effort (plus the minimum positive value of effort) was log-transformed and boulder occurrence was square-root transformed.

Full models were in the form *normalised taxa count ~ depth + boulder prevalence + effort*. The minimum adequate model (MAM) was identified by step-wise model simplification. Variables were considered significant where $P < 0.05$. The count data for some taxa was zero inflated and/or overdispersed, arising from large variation in the positive count data. Following Zuur *et al.* (2009), depending on the distribution of the count data and degree of zero-inflation,

the following models were implemented: linear model (LM), Poisson general liner model (Poisson GLM), quasi-Poisson GLM and negative binomial GLM (NB GLM). For LMs, where appropriate, log-transformation was used to improve the normality of the response variable.

Standard approaches to model validation and assessing the goodness of fit were employed. Specifically, this involved visually inspecting plots of residuals versus fitted values and quantile-quantile plots of randomized quantile residuals. Additionally, model validation and selection employed rootograms – a graphical tool originally developed by Tukey (1977) and extended by Kleiber and Zeileis (2016). The R package 'countreg' (Zeileis and Kleiber, 2018) was used to implement 'hanging' rootograms to identify underfitting or overfitting and compare models for goodness of fit. Validation of LMs used: (i) the gvlma function of R package 'gvlma' (Slate and Pena, 2019) to implement five tests of the validity of assumptions (skewness, kurtosis, heteroscedascity, validity of link function and a global validity of model) (Pena and Slate, 2006); and (ii) the ncvTest function of the R package 'car' (Fox *et al.*, 2012) to test constancy of error variance. Tests for overdispersion (in quasi-Poisson GLM and NB GLM models) and zero-inflation (in Poisson, quasi-Poisson GLM and NB GLM models) were implemented using the R package 'performance' (Lüdecke *et al.*, 2020).

Assessment of potential VMEs

The United Nations General Assembly (UNGA) Resolution 61/105 called upon States to take action to protect VMEs (UNGA, 2006), subsequently defined as meeting one or more of the following criteria: (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). To operationalise this definition regional fisheries management organisations (RFMOs) have developed regionally specific lists of VME indicator taxa and VME habitat types, though there are some inconsistencies between these (Bell *et al.*, 2019; Long *et al.*, 2020). The extent to which the presence of one or more VME indicator taxa result in these criteria being met is density dependent, though at present there are no universally agreed thresholds or standards (Auster *et al.*, 2010). A further difficulty is determining when the spatial extent is sufficient to constitute an ecosystem, this latter problem appears to have received relatively little attention in the VME related literature (Watling and Auster, Accepted). In this study, the approach taken is to review the data to identify instances where the observed density of taxa warrant consideration as evidence of a potential VME. Each case is considered in the discussion, with reference to: the observed distribution and density of the taxa; the UN-FAO VME definition; RFMO guidance and the wider literature. For clarity, the five VME definition criteria are italicised.

Results

A total of 3504 images covering 28838 m^2 were obtained from 76 stations (Table 1). The depth range in the northern and southern stations was similar (Table 1). There was no overlap in the range of temperatures observed in the north and south, the mean temperature in the north (0.7åC) being colder than in the south (3.6åC). The dominant substrate throughout the study area was EUNIS substrate class A6.5 Deep-sea mud found in 94.8% of images (Table 1). Limited hard substrates were available in the form of gravelly mud and occasional boulders, the latter being more prevalent in stations adjacent to the continental slope in the southern portion of the study area (Supplementary Material Figure 17).

Trawl evidence

Evidence of trawling impact on the seabed was observed in the images (Figure 2). 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 (Figure 2b); overturned sediments (Figure 2c); parallel grooves, caused by bobbins or rollers on rock hopper gear (Figure 2d); small regular grooves, perhaps from the bottom of the net, cod-end or roller clump (Fig 2e); and displaced, dragged or overturned rocks (Figure 2f). There was a strong correlation between the trawling evidence observed in images and the logbook fishing effort data (Figure 2a). The maximum level of trawling 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 (Table 1).

Community composition

For the purposes of this study by 'community', we refer to the assemblage of different taxa quantified in the imagery. The community composition differed between the northern and southern area indicated by two distinct clusters in the nMDS ordination plot (Figure 2). Temperature (envfit, $p < 0.001$), depth (envfit, $p < 0.001$), visual trawl evidence (envfit, $p = 0.017$), and the prevalence of boulders (envfit, $p < 0.001$) were all significant (Figure 3). Community composition was not significantly related to fishing effort extracted from the trawl raster layer (envfit, $p = 0.180$), though the direction of the fitted vector was similar to that of trawling evidence. Temperature appears to be the primary environmental driver for the separation of the northern and southern sites, which occurs along the temperature vector. The communities also varied between stations, both within and between the two areas (Figure 4). Figure 5 provides some examples of communities observed.

Taxa observations

A total of 13062 fauna observations were made in the images. The density of fauna was greatest in the south where there were 0.57 annotations/m^2 across the image set, compared with just 0.15 annotations/m^2 in the north (Table 1). Fauna is notably sparser in the images from the northern area, both in terms of abundance and diversity, with the majority of annotations being of Actiniaria, Spirularia and Sabellida. Of the 36 taxa, 34 were seen in the images from the south and 21 were seen in the images from the north (Table 2). The most abundant taxa were the brittlestar, *Ophiomusa lymani* and the cup coral, *Flabellum alabastrum,* which were seen almost exclusively in the south. There was only a single observation of *O. lymani* in images from the northern area (Table 2), though this was not registered in the video annotation (Table 3). Potentially, this is because the nature of the rig means objects in the uppermost corners of an image may not cross the horizontal midline of the video.

A total of 37088 observations of selected taxa were made in the videos (Table 3). Three taxa, *O. lymani, F. alabastrum* and *Halipteris finmarchica*, exhibited a density greater than one individual or colony per m^2 at some stations (Table 3). Locally even higher densities of these taxa were seen within individual images, see examples in Figure 5a–c.

VME indicator taxa

A total of 14 VME indictor taxa (as recognised by either, the NAFO, or NEAFC guidance) were identified in the imagery across the study area. Of these, 14 were present in the south and 9 of were present in the north (Tables 2 and 3). Maps of the observed densities of those 11 VME indicator taxa counted in the videos are provided (Supplementary Material). The prevailing trend is that the highest densities of VME indicator species were seen outside of the trawled area. However, for many of the VME indicator taxa, there were too few observations of these sparsely distributed fauna to support taxa specific modelling.

The VME indicator taxa were generally observed at low abundance. The presence of VME indicator taxa at low densities, individually or collectively, does not constitute a VME (Auster *et al.*, 2010; Morato *et al.*, 2018; Watling and Auster, 2020). There were no instances in the northern area where, in the opinion of the authors, the individual or collective density of VME indicators was notable. Only *F. alabastrum* and *H. finmarchica* were observed individually at significant densities at some stations in the southern area. *F. alabastrum* were present at the majority of southern stations, 44 of 52 stations (Table 3), though typically at low abundance (Figure 6a). At the station level, a maximum density of 4.64 *F. alabastrum*/m^2
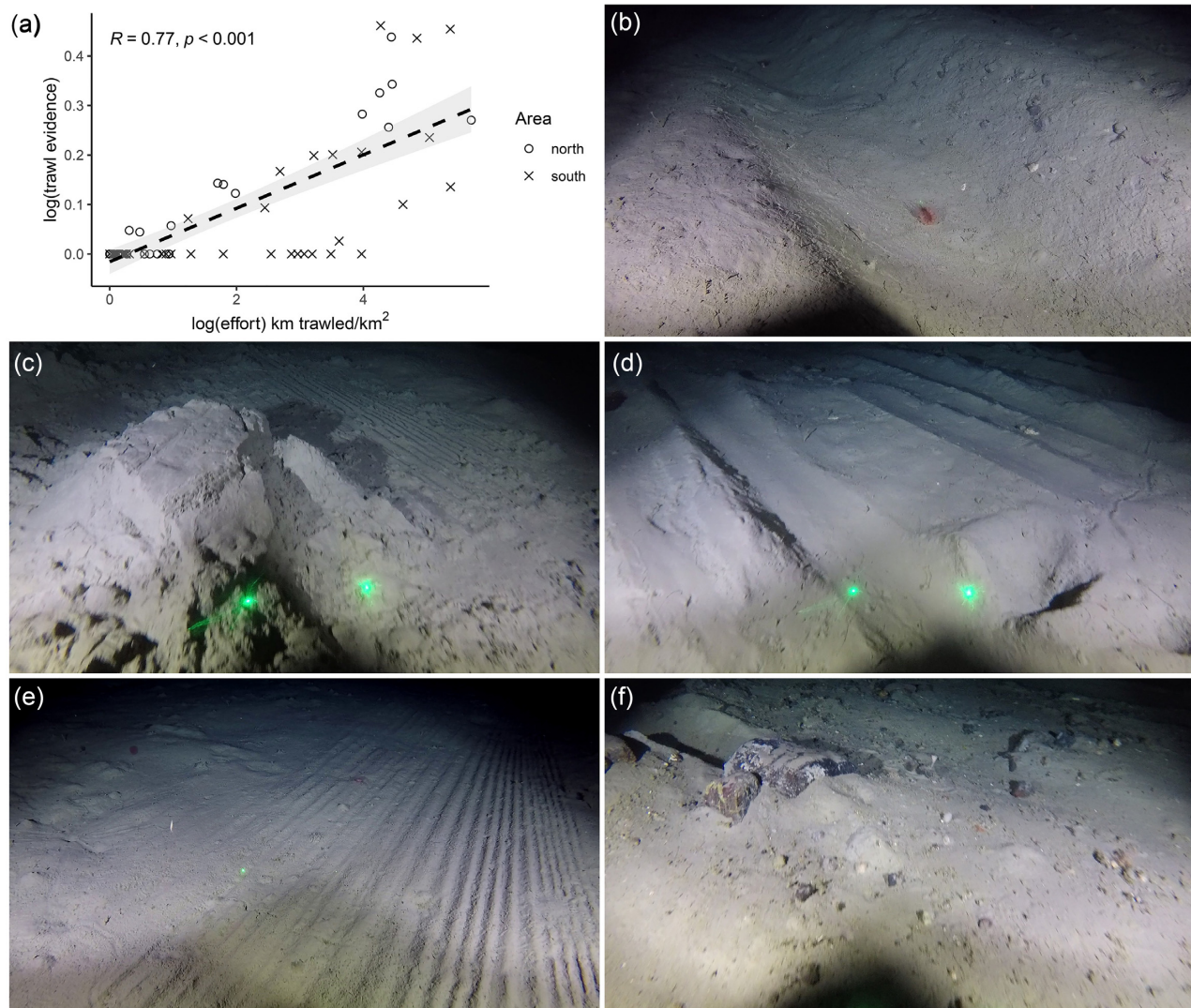
Figure 2. Panel (a) Relationship between the proportion of images observed with trawl evidence and effort at video sled stations. Where, effort is determined by sampling along the sled path from a raster derived from logbook trawling effort data from 1999-2019 (see, 2.4 Mapping and 2.5 Station metadata). Panels (b)–(f) Examples of the range of physical evidence of trawling observed in images. Where present, laser dots (green) are 20 cm apart.

was seen, which was higher in individual images with a maximum of 5.10 individuals/m². Conversely, *H. finmarchica* was absent from the majority of stations, being recorded at just nine. A maximum of 3.47 *H. finmarchica*/m² were observed at the station level with the maximum within an image being 4.50 individuals/m². Two stations, at the edge of but within the existing fishing effort footprint, contained 95% of the *H. finmarchica* observations with both stations exhibiting densities >1 colony/m²) (Figure 6b).

Excluding, *F. alabastrum* and *H. finmarchica* which were both locally highly abundant, Figure 6c, presents the abundance of all other VME taxa counted in the videos. This identifies a cluster of stations in the southeast of the study area where the mixed assemblage of VME indicators is at a density greater than seen across the rest of the study area.

Taxa abundance models

The nature of the video count data (high variance, zero inflation and small sample size) meant that models could only be implemented and validated for a limited set of taxa (Table 4). Depth, boulder prevalence and fishing effort were found to have significant associations with the abundance of some taxa (Table 4). Notably, fishing effort was significantly negatively associated with the abundance of *Acanella arbuscula*, Large Porifera and Other VME indicator taxa. Pennatulacea were typically absent at the majority of stations but locally abundant (Table 3 and Supplementary Material Figures 9–12). This meant Pennatulacea could not be modelled individually and were not included in the Other VME indicator taxa model, as this resulted in a highly skewed distribution, unsuitable for the modelling approaches employed.
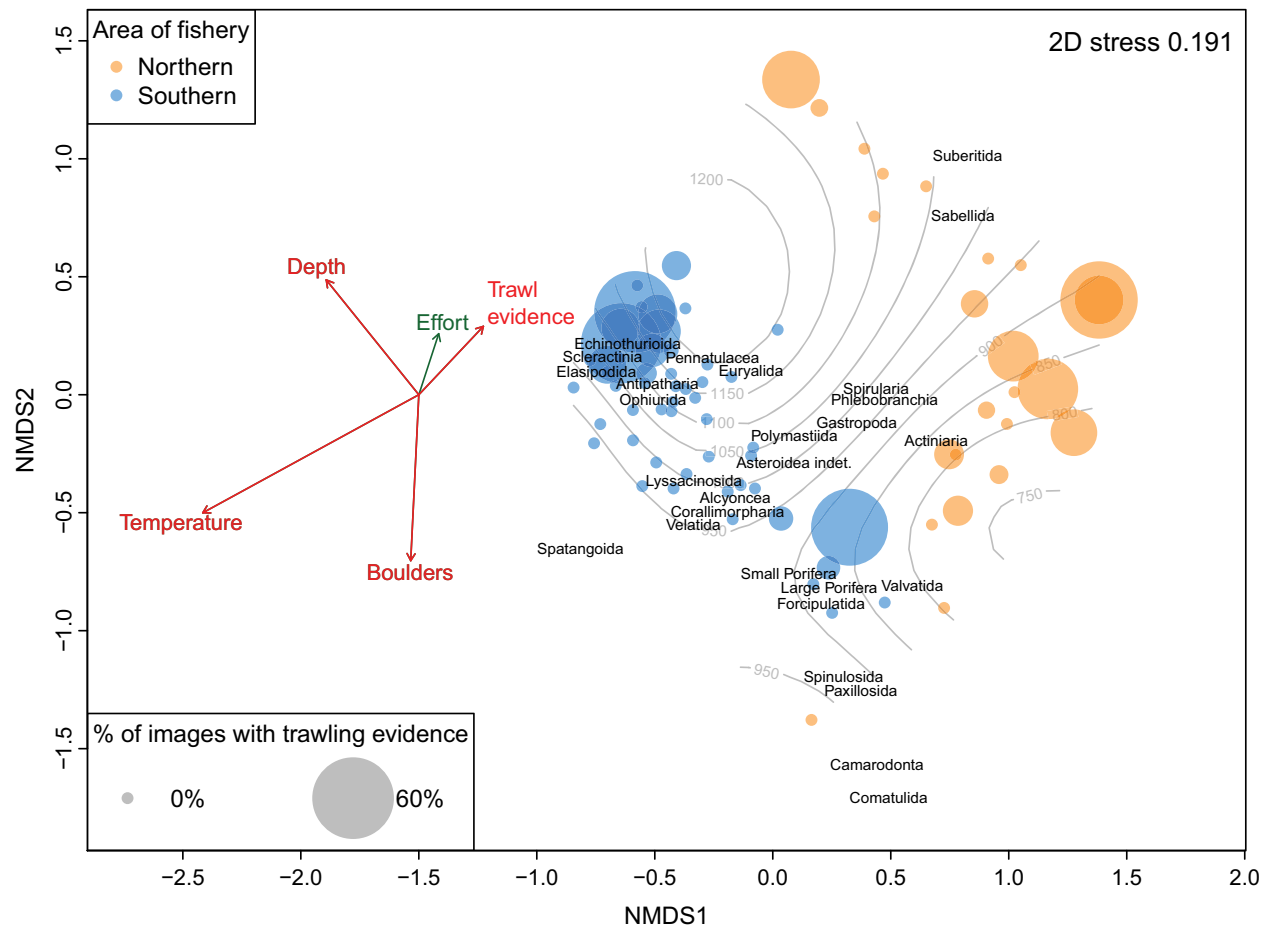
Figure 3. NMDS ordination of the benthic fauna assemblage observed in video sled images. Stations (filled circles, $n = 76$), from the northern (yellow, $n = 24$) and southern (blue, $n = 52$) areas are scaled by trawling evidence observed at each station. Fitted vectors of environmental variables are drawn in red (envfit, $p < 0.05$) and green (envfit, $p > 0.05$), offset from the origin for clarity. Effort is trawling effort inferred from logbook data. Trawl evidence is the proportion of images from each station in which trawling evidence was observed. Boulders is the proportion of images at each station in which boulders were present. Depth fitted as a smooth surface, is indicated by 50 m contours (grey).

Discussion

Communities

The taxa observed were consistent with those previously reported in adjacent Canadian waters of the Davis Strait (Wareham and Edinger, 2007; Kenchington *et al.*, 2016), with no taxa being identified in the imagery that had not previously been reported from this region. We did not observe any *Keratoisis spp.*, despite the proximity of the northern portion of the study area to the Disko Fan Conservation Area from which dense *Keratoisis spp.* forest have previously been reported (de Moura Neves *et al.*, 2015a). Despite the homogeneity of substrates, the communities observed differed considerably both within and between the northern and southern areas. The northern and southern areas exhibited different communities in terms of the composition, abundance and diversity. In general a greater abundance and diversity of fauna was observed in the south, including VME indicators. In the previous EIAs, NMDS of community data obtained by grab sampling, also showed clear differentiation between the community in the Eqqua block (northern area) and the Lady Franklin and Atammik blocks (southern area) (BSL, 2011b), which concurs with the findings here. The available evidence suggests that both the in- and epi-faunal communities are different in these two spatially separate areas of the fishery. This concurs with these two deep-sea areas being assigned to separate biogeographic provinces within the GOODS classification system (Vierros *et al.*, 2009). These insights provide new site-specific descriptions of the benthic communities in the halibut fishery addressing the knowledge gap identified by NAFO and highlighted by the pan North Atlantic analysis of Morato *et al.* (2021).

These two areas are physically separated by the shallowing bathymetry of the Davis Strait, which separates the warmer mater masses to the south from those in the north (Tang *et al.*, 2004; Cuny *et al.*, 2005). Accordingly and as observed in this study, the mean temperature in the northern area (0.7åC) is much colder than in the southern area (3.6åC). Results from the NMDS suggest that temperature is a significant factor driving differentiation of these communities. As expected from fundamental ecological understanding (e.g. Roberts *et al.*, 2009; Ramirez-Llodra *et al.*, 2010), other environmental variables, specifically depth and the availability of hard substrates in the form of boulders were also significantly associated community composition. This was shown by both the NMDS ordination plot and the taxa-specific modelling.

The most abundant species found in the study were the brittlestar *O. lymani*, and the solitary cup coral *F. alabastrum,* both widely distributed in the southern stations and absent from the
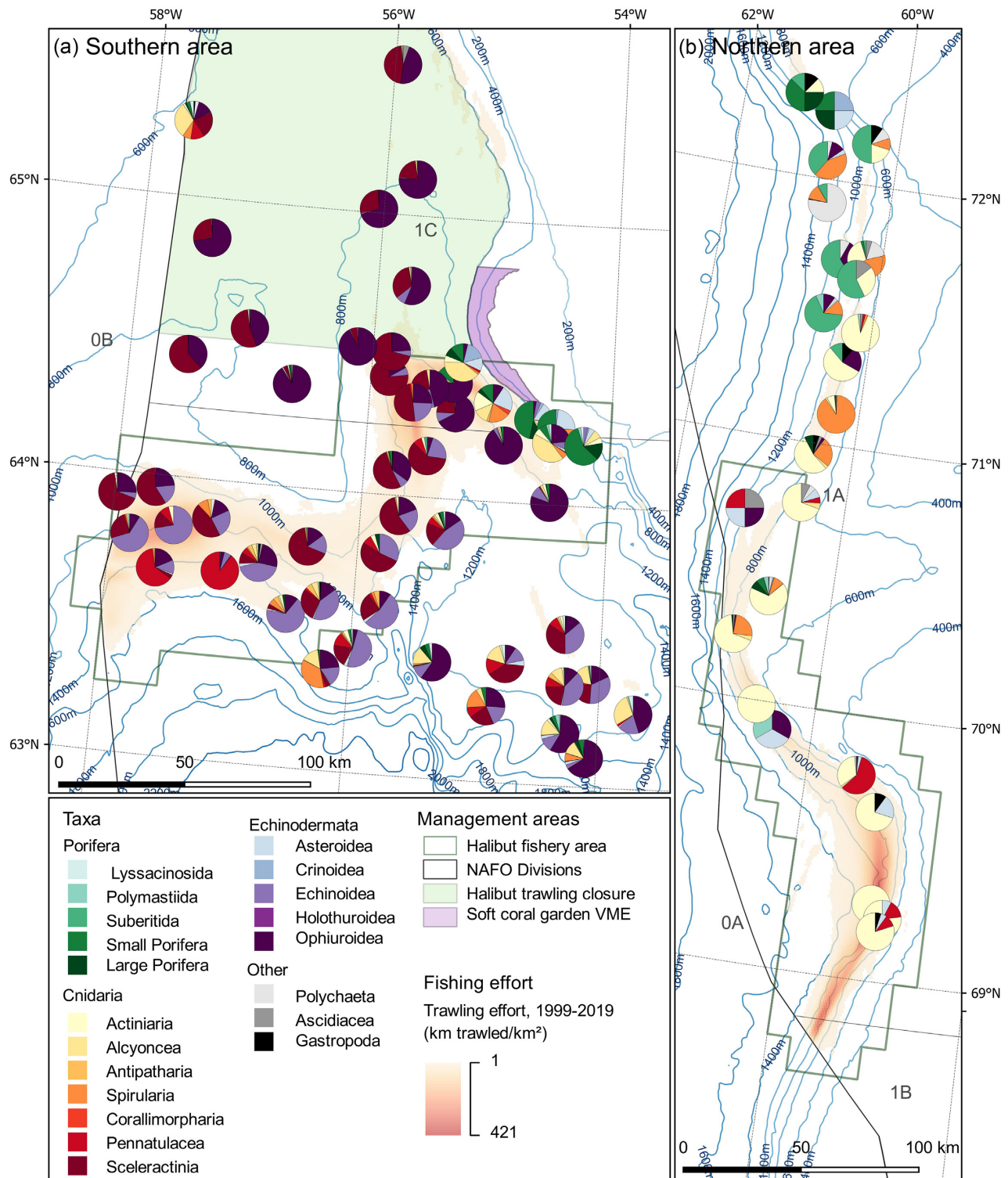
Figure 4. Community composition by station from image annotation data. Classes containing VME indicator taxa are presented at the Order level, all other taxa are aggregated to the Class level.

northern ones. The EIA conducted in the southern area (Lady Franklin and Atammik blocks) also reported that these were the most abundant taxa, reporting similar densities (1 *O. lymani*/m² and 3-4 *F. alabastrum*/m²), to those observed in this study

(BSL, 2011c). The absence of these taxa from the northern may be explained by environmental drivers identified in this study, given the marked difference, temperature would be a strong candidate. For example, a study by Baker *et al.* (2012) extended the known
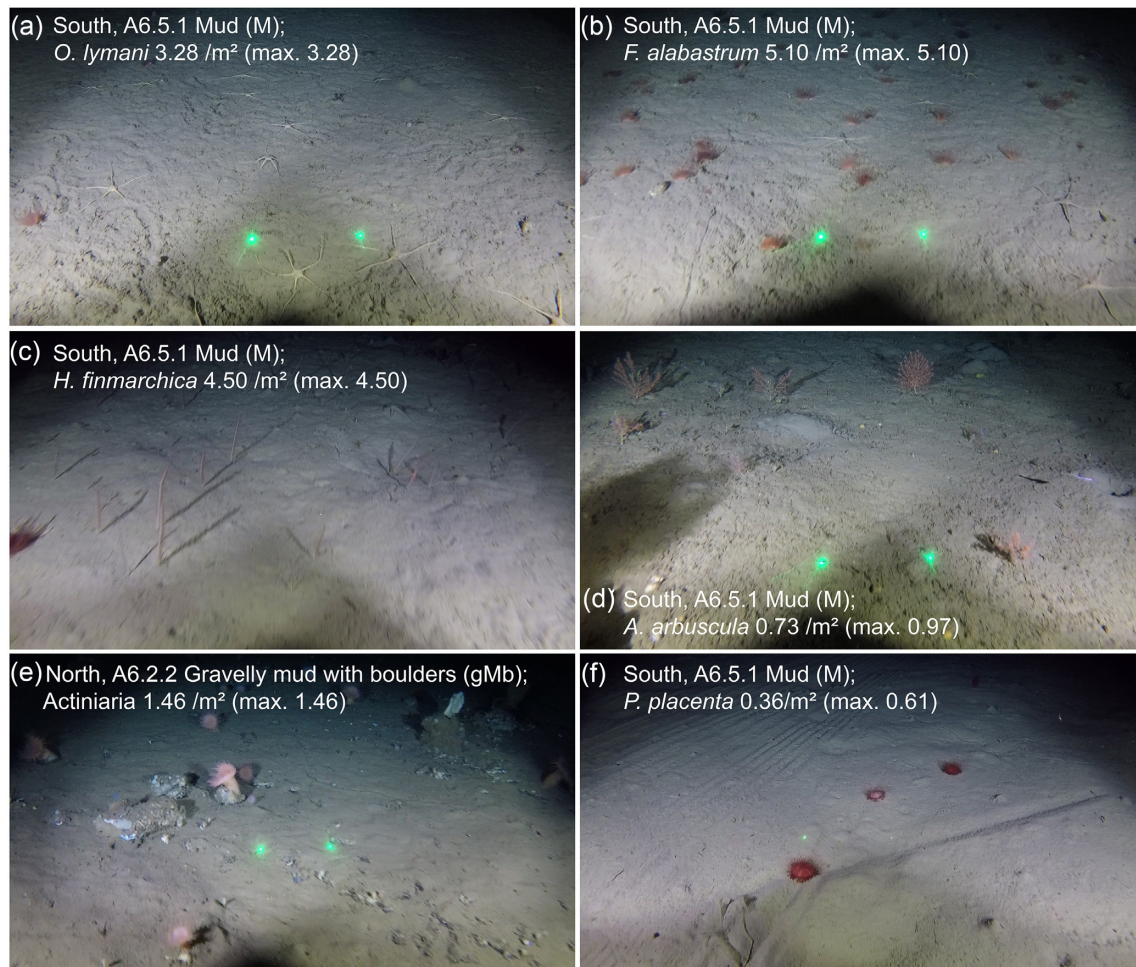
Figure 5. Example images of different communities seen in the imagery. The area from which the image was obtained is indicated along with the substrate type. The density of dominant or notable taxa in each image is shown, followed, in parentheses, by the maximum density observed in any image for reference. Note, the presence of physical evidence of trawling in panel f).

lower temperature boundary for *F. albastrum* to 3.7åC, which overlaps with conditions in the southern but not northern area in this study. However, other processes and drivers may be at work.

In comparison to the southern area, the abundance and diversity of fauna in imagery from the northern area was notably sparse. The previous EIA in this northern area also reported finding an impoverished community both in terms of richness and abundance and noted this depauperate community was "*unlike any other recorded within the western Greenland area*" (BSL, 2011b). Within the impoverished communities of the northern area the majority of fauna observations were from just three taxa Actiniaria, Sabellida and Spirularia. The latter appeared to be solely comprised of a single taxon of tube dwelling anemone (cf. Cerianthidae), though this may be a sampling bias. This taxon was also present in the south, though at lower densities. The translucent nature of this taxon and its retraction in response to disturbance means that it was not selected for video fauna counts and observations in the images likely result in an underestimate of density. It was previously reported that the most dominant non-worm in-faunal taxon in this northern area was a burrowing anemone (*Edwardsia sp.*) (BSL, 2011b). Observations here of a tube-dwelling anemone (Order: Spirularia), may refer to the same taxon as that identified as *Edwardsia sp.* in the

EIA, though there is insufficient information available to resolve this. Taxonomic uncertainty aside, the comparatively high densities of tube-dwelling anemones may play an important ecological role in terms of sediment dynamics, bioturbation, and nutrient cycling in these impoverished communities. Indeed, it is for these reasons that tube-dwelling anemones have been suggested as potential VME indicator taxa (NAFO, 2012; NEAFC, 2014). This taxon and its response to trawling disturbance may therefore warrant further investigation in this northern area.

Vulnerable marine ecosystems
The opinion of the authors' is that there are three instances where the observed density of taxa warrant consideration as evidence of a potential VME.

Flabellum alabastrum (cup coral) meadows
Soft-bottom cup coral meadows featuring Flabellidae are specifically recognised as a VME habitat type and indicator species by NEAFC (NEAFC, 2014) but conversely not by NAFO (NAFO, 2012). A previous study using species distribution modelling has

Table 2. Data derived from annotating images, showing the presence at stations, number of observations, and maximum observed densities at the Order level for annotated fauna (36 distinct taxa). Sub-Order level detail is provided where: individual taxa were highly abundant; to draw distinction between taxa within an Order that were predominantly found in one area; annotations were of a single taxon within an Order; and/or for VME indicator taxa. 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 ('S', southern area; 'N', northern) in which the station with the observed maximum density is found.

Class	Order	Taxa	VME Indicator? NAFO	VME Indicator? NEAFC	Number of stations present at North (n = 24)	South (n = 52)	All (n = 76)	Number of observations North	South	All	Maximum observed density (taxa/m²) 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
	Suberitida	*Stylocordyla borealis*	No	No	10	6	16	72	14	86	0.49	0.07	N
Size classes	Other small	5 cm < Porifera ≤ 10 cm	No[a]	No[a]	4	27	31	25	224	249	0.73	0.08	S
	Other large	Porifera > 10 cm	Yes[a]	Yes[a]	6	19	25	33	67	100	0.61	0.04	N
Cnidaria													
Anthozoa	Actiniaria		No	No	18	35	53	448	108	556	1.46	0.39	N
	Alcyonacea	*Acanella arbuscula*	Yes	Yes	1	28	29	1	387	388	0.97	0.23	S
		Alcyoniidae	No	No	0	7	7	0	8	8	0.12	0.00	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
		All Alcyonacea	Some	Some	6	32	38	10	411	421	0.97	0.23	S
	Antipatharia	*Stauropathes arctica*	Yes	Yes	0	14	14	0	30	30	0.36	0.01	S
	Spirularia		?†[b]	Yes	10	25	35	250	152	402	0.97	0.22	N
	Corallimorpharia	Corallimorpharia	No	No	0	5	5	0	7	7	0.12	0.01	S
	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
		All Pennatulacea	Yes	Yes	7	27	34	48	754	802	4.50	1.73	S
	Scleractinia	*Flabellum alabastrum*	No	Yes	0	43	43	0	3566	3566	5.10	2.23	S

Table 2. Continued

Phylum / Class	Order	Taxa	VME Indicator? NAFO	VME Indicator? NEAFC	Number of stations present at North (n = 24)	South (n = 52)	All (n = 76)	Number of observations North	South	All	Maximum observed density (taxa/m²) Image level	Station level	Area
Echinodermata													
Asteroidea	Valvatida		No	No	3	9	12	4	13	17	0.12	0.01	N
	Spinulosida		No	No	0	8	8	0	15	15	0.12	0.01	S
	Paxillosida		No	No	0	3	3	0	3	3	0.12	0.00	S
	Velatida		No	No	0	6	6	0	7	7	0.12	0.00	S
	Forcipulatida		No	No	0	2	2	0	2	2	0.12	0.00	S
	Indet.		No	[c]	9	26	35	13	60	73	0.24	0.02	S
Crinoidea	Comatulida		[c]	Yes	1	4	5	1	13	14	0.73	0.02	S
Echinoidea	Echinothurioida	*Phormosoma placenta*	No	No	0	41	41	0	854	854	0.61	0.14	S
	Spatangoida		No	No	0	1	1	0	1	1	0.12	0.00	S
	Camarodonta		No	No	0	2	2	0	2	2	0.12	0.00	S
Holothuroidea	Elasipodida		No	No	0	2	2	0	2	2	0.12	0.00	S
Ophiuroidea	Ophiurida	*Ophiopleura borealis*	No	No	8	2	10	15	2	17	0.12	0.02	N
		Ophiomusa lymani	No	No	1	48	49	1	5450	5451	3.28	1.82	S
		Indet. spp.	No	No	2	0	2	2	0	2	0.12	0.00	N
		All Ophiurida	No	No	9	48	57	18	5452	5470	3.28	1.82	S
	Euryalida		No	No	1	2	3	1	3	4	0.12	0.01	S
Annelida													
Polychaeta	Sabellida		No	No	7	3	10	223	10	233	1.94	0.68	N
Chordata													
Ascidiacea	Phlebobranchia		No	No	9	6	15	12	33	45	0.36	0.05	S
Mollusca													
Gastropoda	Indet.		No	No	7	9	16	8	14	22	0.12	0.01	S

[a] Inferred based on taxa listed as VME indicator species.
[b] Tube dwelling anemones (Order: Spirularia) are included in NAFO VME indicators guidance but only *Pachycerianthus borealis* specifically is listed there.
[c] Crinoids (Order: Comatulida) are included in NAFO VME indicators guidance but only *Trichometra cubensis* specifically is listed there.

Table 3. Data derived from count observations in videos, showing the presence at stations, number of observations and maximum observed densities for selected taxa. Selected taxa were VME indicators (and abundant non-VME indicator taxa for comparative purposes) that could be consistently identified across the video imagery. 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 ('S', southern area; 'N', northern) in which the station with the observed maximum density is found.

Phylum			VME Indicator?		Number of stations present at			Number of observations			Maximum observed density (taxa/m²)	
											At the station level	Area
Class	Order	Taxa	NAFO	NEAFC	North (n = 24)	South (n = 52)	All (n = 76)	North	South	All		
Porifera												
Demospongiae	Polymastiida	Polymastiidae	Yes	Yes	7	24	31	32	93	125	0.03	N
	Large	All Porifera > 10 cm	Yes[a]	Yes[a]	13	42	55	61	459	520	0.13	S
Cnidaria												
	Alcyonacea	*Acanella arbuscula*	Yes	Yes	0	44	44	0	1300	1300	0.54	S
		Nephtheidae	No	Yes	11	8	19	33	18	51	0.03	N
		Paramuricea sp.	Yes	Yes	11	8	19	33	18	51	0.01	S
	Antipatharia	*Stauropathes arctica*	Yes	Yes	0	17	17	0	93	93	0.03	S
	Pennatulacea	*Anthoptilum grandiflorum*	Yes	Yes	6	32	38	16	251	267	0.08	S
		Halipteris finmarchica	Yes	Yes	0	9	9	0	2015	2015	3.47	S
		Pennatula spp.	Yes	Yes	3	18	21	113	121	234	0.61	N
		Umbellula sp.	Yes	Yes	6	0	6	14	0	14	0.03	N
	Scleractinia	*Flabellum alabastrum*	No	Yes	0	44	44	0	11764	11764	4.64	S
Echinodermata												
Echinoidea	Echinothurioida	*Phormosoma placenta*	No	No	0	48	48	0	2558	2558	0.32	S
Ophiuroidea	Ophiurida	*Ophiopleura borealis*	No	No	16	0	16	67	0	67	0.08	N
		Ophiomusa lymani	No	No	0	50	50	0	18029	18029	4.11	S

[a] Inferred based on taxa listed as VME indicator species.
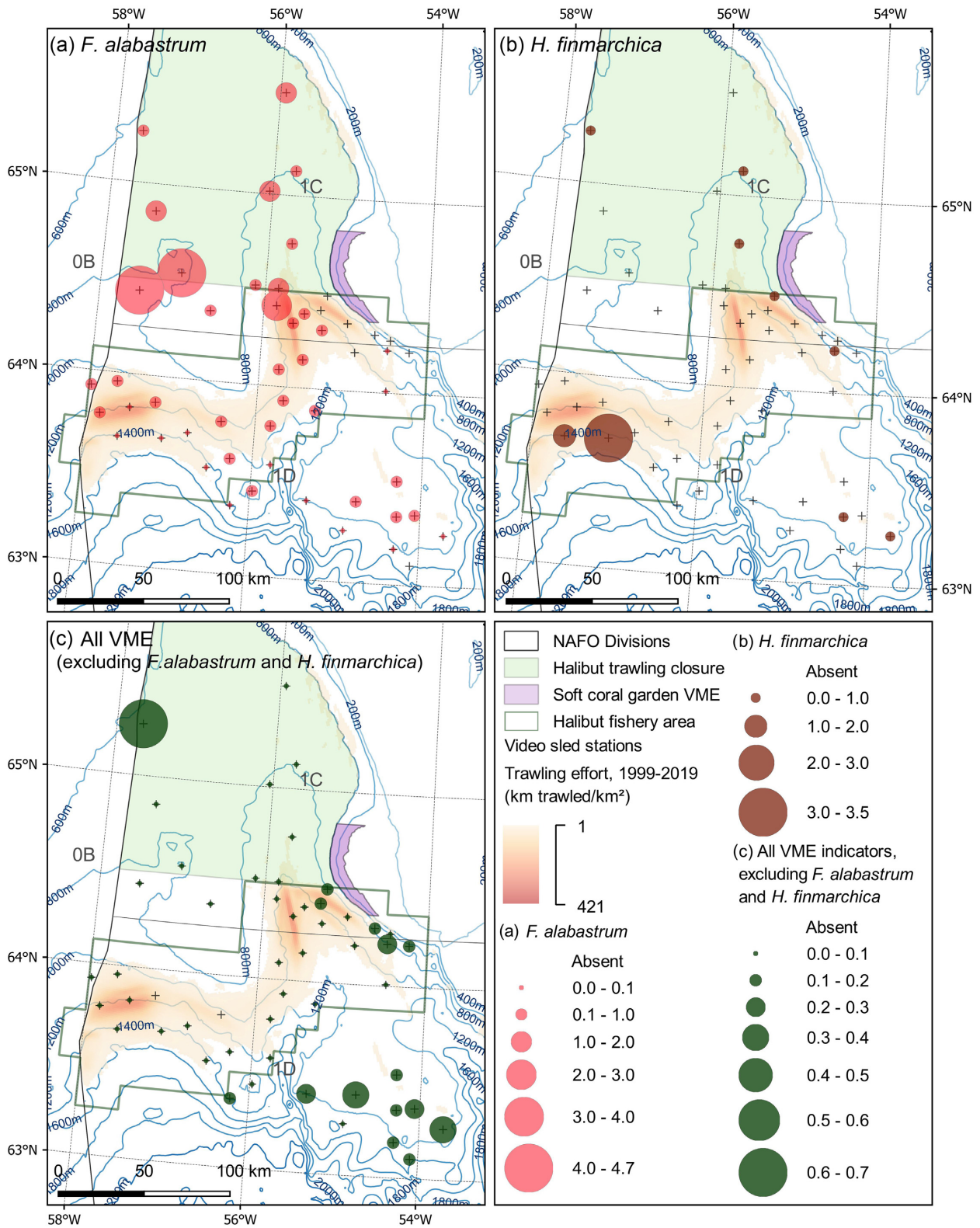
Figure 6. Map showing the density (individuals or colonies /m²) at stations in the southern area ($n = 52$) for: (a) *F. alabastrum*; (b) *H. finmarchica*; and (c) all VME indicators (excluding *F. alabastrum* and *H. finmarchica*). The EEZ is drawn (solid black line).

Table 4. Summary of abundance models, using normalised video count data. The model type, estimated regression parameters, standard errors, test statistics, and pass rate of validation tests are reported.

Taxa	Model type	Variable	Estimate	Std. error	Significance	Tests
F. alabastrum						
	Linear[a]	Intercept	8.025	0.877		6/6
		Depth	-0.002	0.001	($F_{1,49} = 7.86, p = 0.007$)	
		Boulder	-0.501	0.047	($F_{1,49} = 112.06, p < 0.001$)	
A. arbuscula						
	Linear[a]	Intercept	1.361	0.239		5/6
		Boulder	0.160	0.045	($F_{1,49} = 12.79, p < 0.001$)	
		Effort	-0.228	0.048	($F_{1,49} = 22.74, p < 0.001$)	
Large Porifera (>10 cm)						
	Linear[a]	Intercept	1.361	0.239		6/6
		Boulder	0.160	0.045	($F_{1,49} = 46.06, p < 0.001$)	
		Effort	-0.228	0.048	($F_{1,49} = 9.40, p = 0.004$)	
Other VME taxa[b]						
	NB GLM	Intercept	-0.097	0.264		2/2
		Boulder	0.236	0.042	($X^2 = 19.67, df = 49, p < 0.001$)	
		Effort	-0.115	0.049	($X^2 = 4.19, df = 49, p = 0.041$)	

[a]Response variable log transformed.
[b]All other NAFO VME indicator taxa, this excludes those modelled individually above and all Pennatulacea. Thus, Other VME taxa consists of the combined abundance of Nephtheidae, *Paramuricea sp.*, *Stauropathes arctica*, and Polymastiidae.

identified the potential for *F. alabastrum* meadow VMEs to be present in this area (Jørgensbye, 2017).

There is no evidence that these cup coral meadows meets the *unique or rare* criteria. Within the southern portion of the study area these were widespread and abundant, similarly there are numerous records across the region (e.g. Wareham and Edinger, 2007) and North Atlantic (ICES, 2020). It is difficult to infer the *functional significance* of *F. alabastrum* from the imagery (i.e. the image resolution does not permit close inspection of individuals) and there is limited available information in the literature.

In terms of *fragility*, *F. alabastrum* are clearly present within the fishery footprint, including in the areas of most intense effort and are seen in images that show trawling evidence. Modelling does not provide any evidence that fishing effort has a significant negative relationship with abundance. Nevertheless, it should be noted that the highest densities are only observed outside of existing fishing effort. The skeleton is somewhat fragile, and individuals are at risk of burial or being impacted by sediment suspended by bottom trawling. In some images this species was seen to have aggregated in trawl scars, the driver of this is not known. *F. alabastrum* have been observed to move slowly, it has been suggested that this movement is facilitated by expanding the poly volume to increase buoyancy and drag (Buhl-Mortensen *et al.*, 2007). Potentially, trawl scars represent a barrier to this semi-passive movement in an otherwise largely flat environment.

F. alabastrum do exhibit *life-history traits that make recovery difficult*: 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). They were typically observed on flat muddy sediments devoid of other features, modelling showed a significant negative relationship with boulders. In this context, at the densities observed, it could be argued that their presence makes a significant contribution to the *structural complexity* of the benthic environment.

There is no commonly agreed density threshold for what constitutes a cup coral meadow VME. In the NE Atlantic, Lea-Anne and Roberts (2014) propose a threshold of 0.1–0.9 /m² (for *Caryophyllia*

cup corals on mixed substrates at depths of 1069-1769 m). In this study, multiple stations in the southern area, both inside and outside of the fishery footprint, exceed this threshold; 31 stations have a density $>0.1/m^2$, whilst 8 have a density $>0.9/m^2$. The observed maximum density at the station level (4.64 individuals/m²; Table 3) being an order of magnitude greater than the upper value of this threshold. The available evidence suggests that the cup coral habitat observed here is a strong candidate for a VME. The habitat meets at least one of the VME criteria, has a considerable spatial extent and the densities observed are comparable to what is considered a cup coral VME elsewhere.

Halipteris finmarchica (sea pen) field

Sea pen fields and *H. finmarchica* are recognised as VME habitats and indicator species by both NAFO and NEAFC (NAFO, 2012; NEAFC, 2014). *H. finmarchica* was only seen at densities that could be described as a 'sea pen field' at two stations in the southwestern corner of the study area, where the maximum station level density was 3.47 colonies/m². Occasional *H. finmarchica* individuals were seen at seven other southern stations and it was absent in the north. Thus, this species can be described as locally rare, with fields being rarer still. Blicher and Hammeken Arboe (2021) report *H. finmarchica* bycatch records from a confined area in the Davis Strait sill region between 65°N and 66°N at depths of 600-800 m. There are a limited number of observations of *H. finmarchica* in the Canadian waters adjacent to the study area (Wareham and Edinger, 2007; Beazley *et al.*, 2016), though these are sparse and densities are not provided. The apparent rarity of *H. finmarchica* fields in this region of the NW Atlantic suggests the observations presented here may meet the *uniqueness or rarity* criteria of the VME definition.

It is difficult to infer the *functional significance* of these *H. finmarchica* fields from imagery. Nevertheless, there were numerous examples where Gorgonocephalus brittlestars (Class: Ophiuroidea) were seen wrapped around this sea pen in the video footage. Wareham and Edinger (2007) have observed commensal sea anemones *Stephanauge nexilis* firmly attached to the rachis, whilst

Baillon *et al.* (2014) found six species on *H. finmarchica* specimens of which five were close associates or symbionts. *H. finmarchica* is also known to provide nursery habitats for larval fish (Baillon *et al.*, 2012). Sea pens more generally are known to be a food source for a range of invertebrate predators (Birkeland, 1974; Krieger and Wing, 2002). The two stations with a high density of *H. finmarchica* were found on otherwise homogenous muddy sediments, contributing significantly to the *structural complexity* of the habitat.

A thin, erect, sea pen reaching lengths of 140 cm (Murillo *et al.*, 2018), is likely to physically interact with trawl gear. Bycatch observations in stock assessment trawls suggest it can be removed by trawling (Blicher and Hammeken Arboe, 2021). 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. The slow growth and longevity (>20 years) of this species means recovery from damage is likely to be at decadal scales (de Moura Neves *et al.*, 2015b; Murillo *et al.*, 2018). The effect of trawling on abundance could not be modelled but all observations are outside of the areas of highest trawling intensity. However, the two stations with the greatest density of *H. finmarchica* are within the fishery footprint, albeit in an area of lower intensity trawling, despite the evidence of their vulnerability in the wider literature. This may highlight limitations in the study arising from the spatio-temporal resolution of the fishing effort data. First, the accuracy of logbook positioning data, combined with the rasterization process makes it difficult to be certain whether a specific sampling locality within low-intensity areas has been trawled or not. In other words, the path of the sled may not overlap with the path of trawl gear within the 1 km fishing effort raster cells that have only been subject to limited effort. A further limitation is that there is no temporal component to the fishing effort raster used, which combines logbook data from 1999 to 2019. In the case of the high density *H. finmarchica* observations, examination of the underlying logbook records suggests that this area has not been trawled for over 10 years. These limitations are less significant at the macro-level but present challenges when considering the high density *H. finmarchica* observations at just two stations. It may be the case that these observations: (a) are from untrawled patches of seabed within an area of low trawling intensity; (b) represent a population in recovery following earlier trawling; or (c) indicate a degree of resilience to trawling disturbance. The latter seems unlikely given the evidence of *fragility* elsewhere in the literature.

There is no commonly agreed density threshold for what constitutes a sea pen field and 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 at the two stations is comparable. The highest densities of *Anthoptilum grandiflorum* (0.08 colonies/m^2) were also observed co-occurring at these two stations, though it was widespread and at lower densities elsewhere (Supplementary Material Figure 9).

The imagery from these two adjacent stations provide strong evidence of a potential VME, meeting some if not all of the five VME criteria. What is not clear is the likely spatial extent of the sea pens fields observed. Clearly, the habitat is absent immediately to the north, where three stations were undertaken in areas subjected to a high intensity of fishing effort. Further work should seek to determine whether the habitat is continuous between these two stations and extends further to the south, where no trawling has occurred.

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

Coral, sponge and sea-pen VME indicators species were observed in mixed assemblages at some stations. Figure 6c 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 500 and 1000 m contours, to the south of the soft coral garden VME. Both these clusters of stations exhibit a higher diversity of taxa than generally seen elsewhere.

VME indicator species as recognized by both NEAFC and NAFO contributing to this higher collective density include: *A. arbuscula*, large Porifera (>10 cm), *Paramuricea sp.*, Pennatula spp., Polymastiidae, and *Stauropathes arctica*. These areas are associated with some of the higher densities of boulders (Supplementary Material Figure 17). This may partially explain the higher densities observed as some of these indicator species are dependent upon rocky substrate for attachment. Previously, Jørgensen *et al.* (2013) used bycatch data from stock assessment trawls to identify an area with a relatively high diversity and high density of corals at depths of 1000–1500 m from 63°N to 64°N and 54°W to 56°W, which aligns with the findings here. A more recent analysis of bycatch data confirms the presence of this mixed assemblage, highlighting that this area yielded the largest bycatch records for Ostur sponges in West Greenland, represented by Geodiidae, Ancorinidae, and Theneidae (Blicher and Hammeken Arboe, 2021).

There are no commonly agreed density thresholds for mixed assemblages. The maximum density observed is 0.65 individuals/m^2, which is notable, especially in relation to the background abundance across the study area. Furthermore, this excludes the VME indicators *F. alabastrum* and *H. finmarchica*, which are also present in these stations. There is no evidence to suggest that this mixed assemblage is especially *unique or rare*. However, it can reasonably be assumed that collectively the species present at the densities observed meet the remaining four criteria in the VME definition.

Management implications

Trawling has had extensive physical effects on the seafloor, which was also noted in the limited video imagery obtained during the EIAs in southern area (BSL, 2011c, a). Imagery was not obtained from the EIA in the northern area (BSL, 2011b). The physical evidence of trawling in images was strongly correlated with fishing effort derived from logbooks. It can therefore be assumed that the fishery's footprint as represented by the effort raster gives a good indication of the spatial extent of seabed modification by physical disturbance. The WGOGHF MSC assessment reports that the total area trawled by the Greenlandic halibut fleet in a three year period was 14963 km^2 (Cappell *et al.*, 2017). It should be acknowledged that the area imaged is very small, relative to the fishery footprint. The 76 stations are distributed across a significantly larger area, as the study was designed to provide insights into both areas within the fishery and those that have not been subject to trawling. Consequently, only limited inferences can be made about the nature of the benthic habitats between the stations, not least because of the observed heterogeneity within and between areas.

The benthic communities in northern and southern areas of the fishery are different and within these two discrete areas there is considerable heterogeneity. This may have important implications for

management in terms of informing future decisions about spatial restrictions and fishery expansion. The existing WGOGHF MSC certification assessment of habitat impacts was premised on the assumption that the habitats in these two areas were the same (Cappell *et al.*, 2017), which should be revised in light of findings presented here.

A critical goal for the management of any deep-sea fishery is to ensure that serious or irreversible harm is not caused to VMEs. Move-on rules, which are employed in Greenland, aim to afford protection where there is insufficient information on the nature and distribution of VMEs. The move-on rules in effect here require vessels to cease fishing and move a minimum of 2 nm if >60 kg or corals or 300 kg of sponges are taken in a single haul (Government of Greenland, 2017). The efficacy of such move-on rules has been previously questioned elsewhere (Auster *et al.*, 2010). In the context of this fishery, given the large mesh size (≥100 mm) and the small size and fragility of many VME indicator species in this area, a few individuals in a haul may indicate a relatively high abundance on the seafloor but thresholds are unlikely to be reached. Indeed, there has not been a single report of the move-on rules being triggered in this fishery to date (Cappell *et al.*, 2017; Cook *et al.*, 2019; Long and Jones, 2020).

The most effective approaches to preventing harm to known VMEs is perhaps the use of spatial management measures. In Greenland, an Executive Order makes provision for the closure of areas to bottom gears where VMEs are identified (Government of Greenland, 2017). Given the observed heterogeneity in communities and patchy nature of VMEs, a 'footprint freeze' may be the most pragmatic approach, limiting effort to those areas already impacted. At the time of the study, the fishery's extent was not restricted, except for the prohibition on trawling in the shallower waters between the northern and southern portions of the fishery. Reportedly, this footprint has remained static, as these areas continue to be productive (Cappell *et al.*, 2017; Cook *et al.*, 2019). In 2021, a revised halibut fishery management plan came into force, limiting the maximum spatial extent of the fishery to two discrete areas (Figure 1, green outline) (MFHA, 2021). This new halibut fishery area encompasses, and significantly exceeds, the existing trawling footprint and so allows for a considerable expansion of fishing effort into previously unimpacted areas.

This study identifies three candidate VMEs: (i) *F. alabastrum* cup coral meadows; (ii) *H. finmarchica* sea pen fields; and (iii) a mixed assemblage of VME indicator taxa (including Porifera, Alcyonacea, Antipatharia, Pennatulacea, and Sceleractinia). It is therefore important to consider the extent to which the existing management measures afford protection to these. The *F. alabastrum* cup coral meadows are of least concern as they are widespread in the southern area of the study area, including in trawled areas, while the greatest densities were observed outside of the newly introduced halibut fishery area. Similarly, the stations in the southeast corner of the study area exhibiting the highest density of mixed VME indicator taxa are outside of the halibut fishery area. However, the potential impact of the fishery on the *H. finmarchica* sea pen fields is of significant concern. The two stations where this potential VME was observed are on the fringes of the existing fishing footprint and well within the recently defined halibut fishery area. There is therefore scope for serious or irreversible harm in the future. Indeed, the observations made here may represent an already partially degraded VME and/or one in recovery having not been trawled for over a decade. Employing the precautionary principle, given the apparent rarity of the *H. finmarchica* fields,

protection should be afforded to these until the spatial extent of this habitat can be determined and adequate management measures introduced. The fishery area defined by the revised management plan (MFHA, 2021) does not afford this potential VME any protection.

Conclusion

This research is a positive step in addressing the significant knowledge gaps in the nature and distribution of deep-sea benthic habitats in west Greenland. Trawling has resulted in physical modification of the seabed, likely over a significant area given the reported ~15000 km² size of the footprint (Cappell *et al.*, 2017). The data show that trawling appears to affect the community composition and reduce the abundance of some taxa, including some VME indicator taxa. The research identifies three candidate VMEs. Further research is required to understand the spatial extent of the candidate VMEs identified with a view to informing sustainable management. Of immediate conservation concern is the identification of a candidate *H. finmarchica* field VME on the fringes of the existing fishing footprint, which is not protected by existing management measures.

Supplementary Data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Data availability

Where possible, the data underlying this paper will be shared on a reasonable request to the corresponding author. The logbook fishing effort data were provided by Greenland Fishery Licence Control (GLFK) and will only be shared with their prior permission.

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References

Auster, P. J., Gjerde, K., Heupel, E., Watling, L., Grehan, A., and Rogers, A. D. 2010. Definition and detection of vulnerable marine ecosystems on the high seas: problems with the "move-on" rule. ICES Journal of Marine Science, 68: 254–264.

Baillon, S., Hamel, J.-F., and Mercier, A. 2014. Diversity, distribution and nature of faunal associations with deep-sea pennatulacean corals in the Northwest Atlantic. Plos One, 9.

Baillon, S., Hamel, J.-F., Wareham, V. E., and Mercier, A. 2012. Deep cold-water corals as nurseries for fish larvae. Frontiers in Ecology and the Environment, 10: 351–356.

Baker, K. D., Devine, J. A., and Haedrich, R. L. 2009. Deep-sea fishes in Canada's Atlantic: population declines and predicted recovery times. Environmental Biology of Fishes, 85: 79.

Baker, K. D., Wareham, V. E., Snelgrove, P. V., Haedrich, R. L., Fifield, D. A., Edinger, E. N., and Gilkinson, K. D. 2012. Distributional patterns of deep-sea coral assemblages in three submarine canyons off Newfoundland, Canada. Marine Ecology Progress Series, 445: 235–249.

Beazley, L., Murillo, F., Kenchington, E., Guijarro, J., Lirette, C., Siferd, T., Treble, M. et al. 2016. Species Distribution Modelling of Corals and Sponges in the Eastern Arctic for Use in the Identification of Significant Benthic Areas, Fisheries and Oceans Canada (DFO).

Bell, J., Guijarro, E., and Kenny , A. 2019. Demersal fishing in areas beyond national jurisdiction: A comparative analysis of Regional Fisheries Management Organisations. Frontiers in Marine Science, 6: 596.

Birkeland, C. 1974. Interactions between a sea pen and seven of its predators. Ecological monographs, 44: 211–232.

Blicher, M., and Hammeken Arboe, N. 2021. Atlas of Vulnerable Marine Ecosystem (VME) indicators observed on Trawl Assessment Surveys in Greenland waters during 2015-2019. Technical Report no. 113.

BSL. 2011a. Environmental baseline survey Atammik block AT7 well, report for Capricorn Greenland Exploration No.1 Ltd. Benthic Solutions Limited (BSL). 170pp.

BSL. 2011b. Environmental baseline survey Eqqua block Gamma A and B wells, report for Capricorn Greenland Exploration No.1 Ltd. Benthic Solutions Limited (BSL). 172pp.

BSL. 2011c. Environmental baseline survey Lady Franklin block LF7C well, report for Capricorn Greenland Exploration No.1 Ltd. Benthic Solutions Limited (BSL). 157pp.

Buhl-Mortensen, L., Mortensen, P. B., Armsworthy, S., and Jackson, D. 2007. Field observations of Flabellum spp. and laboratory study of the behavior and respiration of Flabellum alabastrum. Bulletin of marine science, 81: 543–552.

Cappell, R., Lassen, H., Holt, T., and Bekkevold, S. 2017. Public Certification Report for the initial assesment of the west Greenland offshore Greenland halibut fishery. https://cert.msc.org/FileLoader/FileLinkDownload.asmx/GetFile?encryptedKey=v3PzrM1Zdtdb5FcYfeh4g/IMH5mPotqa29IvKlRAiSo+EaSQK3MDfinW61RUuuC2. [Accessed 2 August 2021].

Cappell , R., Mouat, B., and Hambrey, J. 2018. West Greenland Coldwater prawn fishery: Public Certification Report.

Cappell, R., and Powles, H. 2016. Onsite Surveillance Visit – Report for West Greenland Coldwater Prawn Fishery, Third Surveillance Audit. https://cert.msc.org/FileLoader/FileLinkDownload.asmx/GetFile?encryptedKey=kPRvQDp68Pb80bsR1fQ0bGE7KaGVAtJLD0mVMcr/0a14iwHWwCDX+3Gi85SI98ys. [Accessed 6 October 2020].

Chaudhury, S., Lassen, H., and Huntington, T. 2020. Public certification report for the scope extension of the West Greenland offshore Greenland halibut fishery. 177pp.

Clark, M. 1999. Fisheries for orange roughy (Hoplostethus atlanticus) on seamounts in New Zealand. Oceanologica Acta, 22: 593–602.

Clark, M. R., Althaus, F., Schlacher, T. A., Williams, A., Bowden, D. A., and Rowden, A. A. 2016. The impacts of deep-sea fisheries on benthic communities: a review. ICES Journal of Marine Science: Journal du Conseil, 73: i51–i69.

Clark, M. R., and Koslow, J. A. 2007. Impacts of fisheries on seamounts. Seamounts: ecology, fisheries, and conservation, 12: 413–441.

Cook, R., Gaudian, G., Honneland, G., and Seip-Markensteijn, C. 2019. Marine Stewardship Council (MSC) Public Certification Report: Doggerbank Seefischerei West Greenland Halibut Fishery. https://cert.msc.org/FileLoader/FileLinkDownload.asmx/GetFile?encryptedKey=bQzmevYgfqx3o9HgDfm1hzRxon2R2ia0BhCRUgrOINzN5IuFDFDpDDikcUeg/+5p. [Accessed 2 August 2021].

Costello, M. J., Cheung, A., and De Hauwere, N. 2010. Surface area and the seabed area, volume, depth, slope, and topographic variation for the world's seas, oceans, and countries. Environmental science & technology, 44: 8821–8828.

Cuny, J., Rhines, P. B., and Kwok, R. 2005. Davis Strait volume, freshwater and heat fluxes. Deep Sea Research Part I: Oceanographic Research Papers, 52: 519–542.

Danovaro, R., Aguzzi, J., Fanelli, E., Billett, D., Gjerde, K., Jamieson, A., Ramirez-Llodra, E. et al. 2017. An ecosystem-based deep-ocean strategy. Science, 355: 452–454.

Davies, C. E., Moss, D., and Hill, M. O. 2004. EUNIS habitat classification revised 2004. European Environment Agency-European Topic Centre on Nature Protection and Biodiversity: 127–143.

de Carvalho, G. C., de Sá-Neto, R. J., and Barros, F. 2015. Thirty years of use of multivariate quantitative methods in benthic community ecology of marine and coastal habitats: looking to the past to planning the future. Scientometrics, 105: 593–610.

de Moura Neves, B., Edinger, E., Hillaire-Marcel, C., Saucier, E. H., France, S. C., Treble, M. A., and Wareham, V. E. 2015a. Deep-water bamboo coral forests in a muddy Arctic environment. Marine Biodiversity, 45: 867–871.

de Moura Neves, B., Edinger, E., Layne, G. D., and Wareham, V. E. 2015b. Decadal longevity and slow growth rates in the deep-water sea pen Halipteris finmarchica (Sars, 1851) (Octocorallia: pennatulacea): implications for vulnerability and recovery from anthropogenic disturbance. Hydrobiologia, 759: 147–170.

European Union 2016. Regulation (EU) 2016/2336 of the European Parliament and of the Council of 14 December 2016 establishing specific conditions for fishing for deep-sea stocks in the north-east Atlantic and provisions for fishing in international waters of the north-east Atlantic and repealing Council Regulation (EC) No 2347/2002. http://data.europa.eu/eli/reg/2016/2336/oj. [Accessed 2 August 2021].

FAO. 2009. Report of the Technical Consultation on International Guidelines for the Management of Deep-sea Fisheries in the High Seas. FAO Fisheries and gariculture Repport, 881: 86pp.

Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., Firth, D. et al. 2012. Package 'car'. Vienna: R Foundation for Statistical Computing.

Fuller, S., Murillo, F. J., Wareham, V., and Kenchington, E. 2008. Vulnerable marine ecosystems dominated by deep-water corals and sponges in the NAFO convention area. NAFO SCR Doc. 08/22.

Gage, J., Roberts, J., Hartley, J., and Humphery, J. 2005. Potential impacts of deep-sea trawling on the benthic ecosystem along the northern European continental margin: a review. In American Fisheries Society Symposium, p. 503. AMERICAN FISHERIES SOCIETY.

Gass, S. E., and Willison, J. M. 2005. An assessment of the distribution of deep-sea corals in Atlantic Canada by using both scientific and local forms of knowledge. *In* Cold-water corals and ecosystems, pp. 223–245. Springer: Berlin.

Government of Greenland. 2018. Beskyttelse af de sårbare og tidligere uberørte havmiljøområder i Melvillebugten. https://naalakkersuisut.gl//da/Naalakkersuisut/Nyheder/2018/01/2301_melvillebugten. (Accessed 22 August 2019).

Government of Greenland. 2017. Selvstyrets bekendtgørelse nr. 4 af 30. marts 2017 om tekniske bevaringsforanstaltninger i fiskeriet. Government of Greenland Executive Order no. 4 of 30 March 2017 on technical conservation measures in fishing. Nuuk.

Gougeon, S., Kemp, K., Blicher, M., and Yesson, C. 2017. Mapping and classifying the seabed of the West Greenland continental shelf. Estuarine, Coastal and Shelf Science, 187: 231–240.

Gutt, J. 2002. On the direct impact of ice on marine benthic communities, a review. *In* Ecological Studies in the Antarctic Sea Ice Zone, pp. 157–168. Springer.

Hall-Spencer, J., Rogers, A., Davies, J., and Foggo, A. 2007. Deep-sea coral distribution on seamounts, oceanic islands, and continental slopes in the Northeast Atlantic. Bulletin of marine science, 81: 135–146.

Hamel, J. F., Sun, Z., and Mercier, A. 2010. Influence of size and seasonal factors on the growth of the deep-sea coral Flabellum alabastrum in mesocosm. Coral Reefs, 29: 521–525.

Hamilton, J., and Wu, Y. 2013. Synopsis and trends in the physical environment of Baffin Bay and Davis Strait, Fisheries and Oceans Canada (DFO).

Hiltz, E., Fuller, S. D., and Mitchell, J. 2018. Disko Fan Conservation Area: a Canadian case study. PARKS, 24: 17.

ICES 2018. In Report of the North-Western Working Group (NWWG), 26 April–3 May, 2018. ICES HQ: Copenhagen, Denmark. ICES CM 2018/ACOM:09. 733pp.

ICES 2020. ICES VME Portal. International Council for the Exploration of the Seas (ICES). https://vme.ices.dk/map.aspx. [Accessed 2 August 2020].

Jacobsen, R. B. 2018. The sustainability of what? Stocks, communities, the public purse? *In* The Politics of Sustainability in the Arctic, pp. 33–47. Ed. by Gad, U. P., and Strandsbjerg, J.. Routledge.

Jacobsen, R. B., Hedeholm, R. B., Robert, D., and Wheeland, L. 2018. 6.4 Sustainable fisheries. In Adaptation actions for a changing Arctic: perspectives from the Baffin Bay/Davis Strait Region, pp. 162–176. Ed. by AMAP. Arctic Monitoring and Assessment Progrmme (AMAP), Oslo, Norway.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H. *et al.* 2012. The international bathymetric chart of the Arctic Ocean (IBCAO) version 3.0. Geophysical Research Letters, 39.

Jørgensbye, H. 2017. Vulnerable marine ecosystems in West Greenland: Identification and distribution. National Institute of Aquatic Resources (DTU Aqua).

Jørgensbye, H., and Wegeberg, S. 2018. Mapping of marine sediments on the Greenland West Coast: contributions of fishers' ecological knowledge. ICES Journal of Marine Science.

Jørgensen, L. L., Blicher, M., Bluhm, B., Christiansen, J. S., Fredriksen, R., Hammeken, N., Logerwell, L. *et al.* 2018. Detecting changes in the Arctic Ecosystem–Long-Term Benthos Monitoring network for detecting changes in the Arctic benthic ecosystem (LTM-Benthos) 2017-2020. https://hdl.handle.net/10037/14243. [Accessed 2 August 2021].

Jørgensen, O. A., Bastardie, F., and Eigaard, O. R. 2014. Impact of deep-sea fishery for Greenland halibut (Reinhardtius hippoglossoides) on non-commercial fish species off West Greenland. ICES Journal of Marine Science: Journal du Conseil, 71: 845–852.

Jørgensen, O. A., Tendal, O. S., and Arboe, N. H. 2013. Preliminary mapping of the distribution of corals observed off West Greenland as inferred from bottom trawl surveys, 2010–2012.

Kenchington, E., Beazley, L., Lirette, C., Murillo, F. J., Guijarro, J., Wareham, V., Gilkinson, K. *et al.* 2016. Delineation of coral and sponge significant benthic areas in Eastern Canada using Kernel Density Analyses and Species Distribution Models. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/093. vi + 178p.

Kenchington, E. Yashayaev, I. Tendal, O. S., and Jørgensbye, H. 2017. Water mass characteristics and associated fauna of a recently discovered Lophelia pertusa (Scleractinia: Anthozoa) reef in Greenlandic waters. Polar Biology, 40: 321–337.

Kleiber, C., and Zeileis, A. 2016. Visualizing count data regressions using rootograms. The American Statistician, 70: 296–303.

Koslow, J. A., Boehlert, G. W., Gordon, J. D. M., Haedrich, R. L., Lorance, P., and Parin, N. 2000. Continental slope and deep-sea fisheries: implications for a fragile ecosystem. ICES Journal of Marine Science, 57: 548–557.

Krieger, K. J., and Wing, B. L. 2002. Megafauna associations with deepwater corals (*Primnoa* spp.) in the Gulf of Alaska. Hydrobiologia, 471: 83–90.

Langenkämper, D., Zurowietz, M., Schoening, T., and Nattkemper, T. W. 2017. BIIGLE 2.0 – Browsing and Annotating Large Marine Image Collections. Frontiers in Marine Science, 4.

Lea-Anne, H., and Roberts, J. M. 2014. Developing an interim technical definition for Coral Gardens specific for UK waters and its subsequent application to verify suspected records, Joint Nature Conservation Committee. https://hub.jncc.gov.uk/assets/72060f25-76ff-454a-b980-4afc8de4c490. [Accessed 3 August 2021].

Long, S., and Jones, P. J. 2020. Greenland's offshore Greenland halibut fishery and role of the Marine Stewardship Council certification: A governance case study. Marine Policy.

Long, S., Sparrow-Scinocca, B., Blicher, M. E., Hammeken Arboe, N., Fuhrmann, M., Kemp, K. M., Nygaard, R. *et al.* 2020. Identification of a soft coral garden candidate vulnerable marine ecosystem (VME) using video imagery, davis strait, west greenland. Frontiers in Marine Science, 7.

Lüdecke, D., Makowski, D., Waggoner, P., and Patil, I. 2020. Performance: Assessment of Regression Models Performance. R Package.

Malecha, P. W., and Stone, R. P. 2009. Response of the sea whip Halipteris willemoesi to simulated trawl disturbance and its vulnerability to subsequent predation. Marine Ecology Progress Series, 388: 197–206.

MFHA. 2016. Management plan for trawl fishing for Greenland halibut off west Greenland. Ministry of Fishing, Hunting and Agriculture (MFHA). Government of Greenland.

MFHA. 2021. Forvaltningsplan for Fiskeriet efter havgående hellefisk ved Vestgrønland 2021 – 2025 (Management plan for trawl fishing for Greenland halibut off west Greenland 2021–2025). Ministry of Fishing, Hunting and Agriculture (MFHA). Government of Greenland. https://naalakkersuisut.gl/~/media/Nanoq/Files/Attached%20Files /Fiskeri_Fangst_Landbrug/Eng/2021/forvaltningsplan%20hellefisk%20en.pdf [Accessed 2 August 2021].

Morato, T., Pham, C. K., Fauconnet, L., Taranto, G. H., Chimienti, G., Cordes, E., Dominguez-Carrió, C. *et al.* 2021. North Atlantic Basin-Scale Multi-Criteria Assessment Database to Inform Effective Management and Protection of Vulnerable Marine Ecosystems. Frontiers in Marine Science, 8.

Morato, T., Pham, C. K., Pinto, C., Golding, N., Ardron, J. A., Muñoz, P. D., and Neat, F. 2018. A multi criteria assessment method for identifying Vulnerable Marine Ecosystems in the North-East Atlantic. Frontiers in Marine Science, 5: 460.

Morato, T., Watson, R., Pitcher, T. J., and Pauly, D. 2006. Fishing down the deep. Fish and Fisheries, 7: 24–34.

Mortensen, B. O. G. 2014. The quest for resources – the case of Greenland. Journal of Military and strategic Studies, 15.

Murillo, F., MacDonald, B., Kenchington, E., Campana, S., Sainte-Marie, B., and Sacau, M. 2018. Morphometry and growth of sea pen species from dense habitats in the Gulf of St. Lawrence, eastern Canada. Marine Biology Research, 14: 366–382.

Myers, P. G., Kulan, N., and Ribergaard, M. H. 2007. Irminger water variability in the West Greenland Current. Geophysical Research Letters, 34.

NAFO 2012. Report of the Scientific Council Meeting. NAFO SCS Doc 12/19.

NAFO 2019. Stock advice for greenland halibut in SA 0+ Div. 1A offshore + Div. 1B-1F. North Atlantic Fisheries Organisation (NAFO).

NEAFC. 2014. Recommendation on the protection of vulnerable marine ecosystems in the NEAFC Regulatory Area. https://www.neafc.org/system/files/Rec19-Protection-of-VMEs_0.pdf. [Accessed 2 August 2021].

Norse, E. A., Brooke, S., Cheung, W. W., Clark, M. R., Ekeland, I., Froese, R., Gjerde, K. M. *et al.* 2012. Sustainability of deep-sea fisheries. Marine Policy, 36: 307–320.

Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P. R. *et al.* 2019. vegan: Community Ecology Package. R package version 2.5-6. https://CRAN.R-project.org/package=vegan. 10: 719. [Accessed 2 August 2021].

Ontrup, J., Ehnert, N., Bergmann, M., and Nattkemper, T. W. 2009. BIIGLE-Web 2.0 enabled labelling and exploring of images from the Arctic deep-sea observatory HAUSGARTEN. OCEANS 2009-EUROPE, 2009. pp. 1–7, https://doi.org/10.1109/OCEANSE.2009.5278332.

Pena, E. A., and Slate, E. H. 2006. Global validation of linear model assumptions. Journal of the American Statistical Association, 101: 341–354.

Puig, P., Canals, M., Company, J. B., Martín, J., Amblas, D., Lastras, G., Palanques, A. *et al.* 2012. Ploughing the deep sea floor. Nature, 489: 286–289.

Pusceddu, A., Bianchelli, S., Martín, J., Puig, P., Palanques, A., Masqué, P., and Danovaro, R. 2014. Chronic and intensive bottom trawling impairs deep-sea biodiversity and ecosystem functioning. Proceedings of the National Academy of Sciences, 111: 8861–8866.

R Core Team 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Ramirez-Llodra, E., Brandt, A., Danovaro, R., De Mol, B., Escobar, E., German, C., Levin, L. *et al.* 2010. Deep, diverse and definitely different: unique attributes of the world's largest ecosystem. Biogeosciences, 7: 2851–2899.

Roberts, C. M. 2002. Deep impact: the rising toll of fishing in the deep sea. Trends in ecology & evolution, 17: 242–245.

Roberts, J. M., Wheeler, A., Freiwald, A., and Cairns, S. 2009. Coldwater corals: the biology and geology of deep-sea coral habitats. Cambridge University Press: Berlin.

Sasaki, T. 1986. Development and present status of Japanese trawl fisheries in the vicinity of seamounts. Environment and Resources of Seamounts in the North Pacific. NOAA Technical Report NMFS, 43: 21–30.

Slate, E. H., and Pena, E. A. 2019. gvlma: Global Validation of Linear Models Assumptions. R Package version 1.0.0.3. https://CRAN.R-project.org/package=gvlma. [Accessed 2 August 2021].

Streuff, K., Cofaigh, C. Ó., Hogan, K., Jennings, A., Lloyd, J. M., Noormets, R., Nielsen, T. *et al.* 2017. Seafloor geomorphology and glacimarine sedimentation associated with fast-flowing ice sheet outlet glaciers in Disko Bay, West Greenland. Quaternary Science Reviews, 169: 206–230.

Sumaila, U. R., Khan, A., Teh, L., Watson, R., Tyedmers, P., and Pauly, D. 2010. Subsidies to high seas bottom trawl fleets and the sustainability of deep-sea demersal fish stocks. Marine Policy, 34: 495–497.

Tang, C. C., Ross, C. K., Yao, T., Petrie, B., DeTracey, B. M., and Dunlap, E. 2004. The circulation, water masses and sea-ice of Baffin Bay. Progress in Oceanography, 63: 183–228.

The Economic Council. 2017. Nunatta aningaasaqarnera: Greenland's Economy. 1–51pp. https://naalakkersuisut.gl/~/media/Nanoq/Files/Attached%20Files/Finans/ENG/GOR%202017%20rapport%20ENG.pdf. [Accessed 2 August 2021].

Thrush, S. F., and Dayton, P. K. 2002. Disturbance to marine benthic habitats by trawling and dredging: implications for marine biodiversity. Annual Review of Ecology and Systematics, 33: 449–473.

Treble, M. A., and Nogueira, A. 2018. Assessment of the Greenland Halibut Stock Component in NAFO Subarea 0 + Division 1A (Offshore) + Divisions 1B-1F. ICES Document NAFO SCR Doc.18/040. 32pp.

Tukey, J. W. 1977. Exploratory data analysis, Reading, MA.

UNEP-WCMC. 2019. Protected Area Profile for Greenland from the World Database of Protected Areas, October 2019. https://www.protectedplanet.net/country/GL. [Accessed 25 October 2019].

UNGA. 2006. Resolution 61/105. Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of straddling Fish Stocks and Highly Migratory Fish Stocks, and related instruments. UNGA A/RES/61/105. 21pp.

Victorero, L., Watling, L., Deng Palomares, M. L., and Nouvian, C. 2018. Out of sight, but within reach: a global history of bottom-trawled deep-sea fisheries from > 400 m depth. Frontiers in Marine Science, 5: 98.

Vierros, M., Cresswell, I., Briones, E. E., Rice, J., and Ardron, J. 2009. Global open oceans and deep seabed (GOODS) biogeographic classification, UNESCO.

Waller, R. G., and Tyler, P. A. 2011. Reproductive patterns in two deepwater solitary corals from the north-east Atlantic—Flabellum alabastrum and F. angulare (Cnidaria: anthozoa: scleractinia). Journal of the Marine Biological Association of the United Kingdom, 91: 669–675.

Wareham, V. E., and Edinger, E. N. 2007. Distribution of deep-sea corals in the Newfoundland and Labrador region, Northwest Atlantic Ocean. Bulletin of marine science, 81: 289–313.

Watling, L., and Auster, P. J. 2021. Vulnerable Marine Ecosystems, Communities, and Indicator Species: Confusing Concepts for Conservation of Seamounts. Frontiers in Marine Science. 8. https://doi.org/10.3389/fmars.2021.622586.

Watling, L., and Norse, E. A. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conservation Biology, 12: 1180–1197.

Yang, Q., Dixon, T. H., Myers, P. G., Bonin, J., Chambers, D., van den Broeke, M. R., Ribergaard, M. H. *et al.* 2016. Recent increases in Arctic freshwater flux affects Labrador Sea convection and Atlantic overturning circulation. Nature Communications, 7: 10525.

Zeileis, A., and Kleiber, C. 2018. countreg: Count data regression. R package version 0.2–1.

Zuur, A. F., Ieno, E. N., and Elphick, C. S. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution, 1: 3–14.

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., and Smith, G. M. 2009. Mixed effects models and extensions in ecology with R, Springer, New York, NY.

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