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

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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, especially 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 (Paug 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 90% 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 km² Exclusive Economic Zone (EEZ) is ~4.5%, comprised of exclusively 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 km² 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 (Umbelula 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 surveys 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 (Keratosis 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...
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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/km$^2$). 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 manufacturer’s specifications this provides the same plane angle0.1%; pitch-roll accuracy0.1°) 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 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).

**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; ±0.025°C) 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 detailed description of the sled’s movements on the seabed.

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 (WOGHFF), 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 WOGHFF MSC certificate, to incorporate a single long-line 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).

**Image processing**

**Image extraction**

Still images were extracted for quantitative analysis from ‘usable 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 Biolmage 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 Ascidiaacea.

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 sub-classes [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 useable 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/km², 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 m²) (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–Curtis 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 m² (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 (°C) |       |       |     |
| 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 Gravely mud (gM) | 4.0 | 3.3 | 3.5 |
| A6.2.2 Gravely 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 $\sim$ 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 ‘countrreg’ (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, heteroscedasticity, 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 UNEP 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 m² 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 (0.7°C) being colder than in the south (3.6°C). 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/m² across the image set, compared with just 0.15 annotations/m² 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 Actinaria, Spirula 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, Ophiomus娅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 Halipiteris finmarchica, exhibited a density greater than one individual or colony per m² 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 indicator 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/m²
was seen, which was higher in individual images with a maximum of 5.10 individuals/m². Conversely, *H. finnmarchica* was absent from the majority of stations, being recorded at just nine. A maximum of 3.47 *H. finnmarchica*/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. finnmarchica* observations with both stations exhibiting densities > 1 colony/m²) (Figure 6b).

Excluding, *F. alabastrum* and *H. finnmarchica* 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 videosled 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 Keratoisisspp., despite the proximity of the northern portion of the study area to the Disko Fan Conservation Area from which dense Keratoisisspp. 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 (0.7°C) is much colder than in the southern area (3.6°C). 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/m$^2$ and 3-4 F. alabastrum/m$^2$), 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...
lower temperature boundary for *F. alabastrum* to 3.7°C, 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

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**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).
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 taxa 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? | Number of stations present at | Maximum observed density |
|-------------|-------------|-------------------------------|----------------|-----------------------------|--------------------------|
|             |             |                               | NAFO | NEAFC | North (n = 24) | South (n = 52) | All (n = 76) | North | South | All | Image level | Station level | Area |
| Phylum      |             |                               |      |       |                |                |              |       |       |    |             |                |      |
| Porifera    |             |                               |      |       |                |                |              |       |       |    |             |                |      |
| Hexactinellida |             | Lyssacinosida                  |     | Yes   | 0             | 14            | 14           | 0     | 36   | 36 | 0.36         | 0.02          | S    |
| DemOSPONGe |             | Polymastiida                   |     | Yes   | 5             | 13            | 18           | 18    | 25   | 43 | 0.36         | 0.02          | N    |
| Suberitida  |             | Stylocordyla borealis          |     | No    | 10            | 6             | 16           | 72    | 14   | 86 | 0.49         | 0.07          | N    |
| Size Classes |             | Other small 5 cm < Porifera ≤ 10 cm | No  | No    | 4             | 27            | 31           | 25    | 224  | 249| 0.73         | 0.08          | S    |
|             |             | Other large Porifera > 10 cm   |     | Yes   | 6             | 19            | 25           | 33    | 67   | 100| 0.61         | 0.04          | N    |
| Cnidaria    |             | Actiniaria                     |     | No    | 18            | 35            | 53           | 448   | 108  | 556| 1.46         | 0.39          | N    |
| Anthozoaa   |             | Acanella arbuscula             |     | No    | 1             | 28            | 29           | 1     | 387  | 388| 0.97         | 0.23          | S    |
| Actiniaria  |             | No                            |     | No    | 0             | 7             | 7            | 0     | 8    | 8  | 0.12         | 0.00          | S    |
| Alcyonacea  |             | Yes                           |     | Yes   | 5             | 5             | 10           | 9     | 12   | 21 | 0.36         | 0.01          | S    |
|             |             | Yes                           |     | Yes   | 0             | 2             | 2            | 0     | 4    | 4  | 0.24         | 0.01          | S    |
|             |             | Yes                           |     | Yes   | 6             | 32            | 38           | 10    | 411  | 421| 0.97         | 0.23          | N    |
| Antipatharia|             | Stauropathes arctica          |     | Yes   | 0             | 14            | 14           | 0     | 30   | 30 | 0.36         | 0.01          | S    |
| Spirularia  |             | ??†                          |     | Yes   | 10            | 25            | 35           | 250   | 152  | 402| 0.97         | 0.22          | N    |
| Corallimorphia |             | Corallimorphia                |     | No    | 0             | 5             | 5            | 0     | 7    | 7  | 0.12         | 0.01          | S    |
| Pennatulacea|             | Anthoptilum grandiflorum      |     | Yes   | 6             | 21            | 27           | 7     | 62   | 69 | 0.24         | 0.04          | S    |
|             |             | Helipteris finmarchica        |     | Yes   | 0             | 5             | 5            | 0     | 645  | 645| 4.50         | 1.69          | S    |
|              |             | Pennatula spp.                |     | Yes   | 1             | 10            | 11           | 38    | 47   | 85 | 0.49         | 0.18          | N    |
|              |             | Umbellula sp.                 |     | Yes   | 3             | 0             | 3            | 3     | 0    | 3  | 0.12         | 0.00          | N    |
|              |             | All Pennatulacea              |     | Yes   | 7             | 27            | 34           | 48    | 754  | 802| 4.50         | 1.73          | S    |
| Sceleractinia|             | Flabellum alabastrum          |     | No    | 0             | 43            | 43           | 0     | 3566 | 3566| 5.10         | 2.23          | S    |
### Table 2. Continued

| Phylum | VME Indicator? | Number of stations present at | Number of observations | Maximum observed density (taxa/m²) | Image level | Station level | Area |
|--------|----------------|-----------------------------|------------------------|-------------------------------|-------------|--------------|------|
|        |                | North (n = 24) | South (n = 52) | All (n = 76) | North | South | All |
| **Echinodermata** | | | | | | | | |
| Asteroidea | | | | | | | | |
| Valvatida | No | No | 3 | 9 | 12 | 4 | 13 | 17 | 0.12 | 0.01 | N |
| Spinosoida | No | No | 0 | 8 | 8 | 0 | 15 | 15 | 0.12 | 0.01 | S |
| Forcipulata | No | No | 0 | 6 | 6 | 0 | 7 | 7 | 0.12 | 0.00 | S |
| Carterida | No | No | 0 | 2 | 2 | 0 | 2 | 2 | 0.12 | 0.00 | S |
| Indet. | No | No | 9 | 26 | 35 | 13 | 60 | 73 | 0.24 | 0.02 | S |
| **Crinoidea** | | | | | | | | |
| Comatulida | Yes | Yes | 1 | 4 | 5 | 1 | 13 | 14 | 0.73 | 0.02 | S |
| **Echinoida** | | | | | | | | |
| Echinostribrida | 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 | Elapsopida | Ophiura borealis | No | No | 8 | 20 | 10 | 15 | 2 | 17 | 0.12 | 0.02 | N |
| Ophiuroidea | Ophiura | Ophiurina | 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 | S |
| All Ophiurida | No | No | 9 | 48 | 57 | 18 | 5452 | 5470 | 3.28 | 1.82 | S |
| **Annelida** | | | | | | | | |
| Sabellida | No | No | 7 | 3 | 10 | 223 | 10 | 233 | 1.94 | 0.68 | N |
| **Chordata** | | | | | | | | |
| Phlebobranchia | No | No | 9 | 6 | 15 | 12 | 33 | 45 | 0.36 | 0.05 | S |
| **Mollusca** | | | | | | | | |
| 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) |
|------------------|----------------|-------------------------------|------------------------|-----------------------------------|
|                  | NAFO | NEAFC | North (n = 24) | South (n = 52) | All (n = 76) | North | South | All | Area |
| **Porifera**     |      |       |                |                  |                  |       |       |     |      |
| Demospongiae     |      |       |                |                  |                  |       |       |     |      |
| Polymastiidae    | Yes  | Yes   | 7              | 24               | 31               | 32    | 93    | 125 | 0.03 | N   |
| Polymastiidae    | Yes  | Yes   | 13             | 42               | 55               | 61    | 459   | 520 | 0.13 | S   |
| Large            |      |       |                |                  |                  |       |       |     |      |
| All Porifera > 10 cm | Yes  | Yes   | 7              | 24               | 31               | 32    | 93    | 125 | 0.03 | N   |
| 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   |
| Heliptera finmarchica | Yes  | Yes   | 0              | 9                | 9                | 0     | 2015  | 2015 | 3.47 | S   |
| Pennatula sp.    | Yes  | Yes   | 3              | 18               | 21               | 113   | 121   | 234 | 0.61 | N   |
| Umbellula sp.    | Yes  | Yes   | 6              | 0                | 6                | 14    | 0     | 14  | 0.03 | N   |
| Sceleractinia    |      |       |                |                  |                  |       |       |     |      |
| Flabellum alabasterum | No   | Yes   | 0              | 44               | 44               | 0     | 11764 | 11764 | 4.64 | S   |
| Echinodermata    |      |       |                |                  |                  |       |       |     |      |
| Echinoidea       |      |       |                |                  |                  |       |       |     |      |
| Echinothurioidea | No   | No    | 0              | 48               | 48               | 0     | 2558  | 2558 | 0.32 | S   |
| Ophiuroidea      |      |       |                |                  |                  |       |       |     |      |
| Ophiuroida       | No   | No    | 16             | 0                | 16               | 67    | 0     | 67  | 0.08 | N   |
| Ophioplaeus borealis | No   | No    | 16             | 0                | 16               | 67    | 0     | 67  | 0.08 | N   |
| Ophioplaeus lymani | No   | No    | 0              | 50               | 50               | 0     | 18029 | 18029 | 4.11 | S   |

*aInferred 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).
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 dragging. 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/m², whilst 8 have a density >0.9/m². 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 finnarchica** (*sea pen*) field

Sea pen fields and *H. finnarchica* are recognised as VME habitats and indicator species by both NAFO and NEAFC (NAFO, 2012; NEAFC, 2014). *H. finnarchica* 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. finnarchica* 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. finnarchica* 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. finnarchica* 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. finnarchica* 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. finnarchica* fields from imagery. Nevertheless, there were numerous examples where Gorgonocoelophus brittlestars (Class: Ophiuroidea) were seen wrapped around this sea pen in the video footage. Wareham and Edinger (2007) have observed commensal sea anemones *Stephanoegia 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 (Blancher and Hammeken Arboe, 2021). Malecha and Stone (2009) showed that trawling induced breakage of H. wille-mosii 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/m²) 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 subject 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. alabasterm 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., Polymastidiidae, 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 substrates 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 (Blancher and Hammeken Arboe, 2021).

There are no commonly agreed density thresholds for mixed assemblages. The maximum density observed is 0.65 individuals/m², which is notable, especially in relation to the background abundance across the study area. Furthermore, this excludes the VME indicators F. alabasterm 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 WGOGHFMSC assessment reports that the total area trawled by the Greenlandic halibut fleet in a three year period was 14963 km² (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. finnarchica 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. finnarchica 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. finnarchica 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. finnarchica 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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