University College London (UCL) and the Zoological Society of London (ZSL)

The sustainability of deep-sea fishing in Greenland from a benthic ecosystem perspective: the nature of habitats, impacts of trawling and the effectiveness of governance

PhD Thesis

Stephen Long

I, Stephen Long, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis text.

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Abstract

The deep sea (>200 m) is the world's least explored and largest biome, covering ~65% of the earth's surface, it is increasingly subject to anthropogenic disturbance from fishing. The offshore Greenland halibut (*Reinhardtius hippoglossoides*) fishery, west Greenland, employs demersal trawl gear at depths of 800-1,400 m. Recent Marine Stewardship Council (MSC) certification of this fishery highlighted the paucity of knowledge of benthic habitats and trawling impacts. This interdisciplinary thesis employs a benthic video sled to investigate deep-sea habitats and trawling impacts and conducts a critical analysis of the fishery's governance, with reference to the role of the MSC certification.

The results provide new insights into this poorly known region of the Northwest Atlantic, including identifying four candidate vulnerable marine ecosystems (VMEs). Imagery obtained demonstrates that chronic trawling has had extensive impacts on the seafloor, which are significantly associated with the benthic communities observed. Further, trawling effort is shown to have a significant negative association with the abundance of some VME indicator taxa.

The governance case study finds an effective system of state-led governance, supported by scientific, certification and industry actors. Outcomes directly attributable to engagement with the MSC certification include the introduction of a management plan and new benthic research programmes. However, questions are raised about the MSC certification, providing case study examples of existing criticisms. Assessments are weak with respect to benthic habitats and over-reliant on the definitive, expert judgement of Conformity Assessment Bodies (CABs), whose independence is questioned. The assurance offered by the MSC certification in terms of the sustainability of trawling impacts on benthic ecosystems is found to seriously lack credibility.

Findings are of direct relevance to the management of deep-sea fisheries in Greenland and elsewhere. Widely applicable critical insights into deep-sea fishery governance are presented, including into the role of eco-labels as a market-mechanism to promote sustainable fishery management.

Impact Statement

The research has addressed knowledge gaps relating to: i) the nature of deep-sea benthic ecosystems in Northwest Atlantic, including the distribution of vulnerable marine ecosystems (VMEs); ii) the benthic ecosystem impacts of trawling in the study region; iii) the role of the MSC certification in fishery governance. Four peer-reviewed scientific papers have arisen from this research (three published and one in review).

Working with partners at the Greenland Institute of Natural Resources (GINR), ecological findings have been proactively communicated to fishery management authorities and the relevant Ministries in Greenland. This includes notification of new evidence for four candidate vulnerable marine ecosystems (VMEs) that have been identified. This has informed the revision of the management plan for offshore Greenland halibut fishery, west Greenland. Further, it is understood that spatial management measures to afford protection to candidate VMEs identified are under consideration at present.

The programme of ecological research has directly contributed to the Marine Stewardship Council (MSC) certification annual surveillance audits of two components of the west Greenland offshore Greenland halibut fishery. Specifically, these are the West Greenland Offshore Greenland Halibut Fishery (WGOGHF) and Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF). It is anticipated that the results of this research will be of material importance to future MSC re-assessments of the certified components of the fishery.

In a broader sense, the quantitative descriptions of deep-sea benthic ecosystems will provide helpful reference points against which to benchmark future discoveries in the deep seas of the North Atlantic. In particular, the approach adopted was intended to best contribute to the revision, interpretation and application of the FAO VME definition elsewhere.

The critical analysis of the offshore Greenland halibut fishery and the role of the MSC certification provides insights that are of direct relevance to fishery management in Greenland and elsewhere. The research makes a valuable contribution to the wider discourse on the effectiveness of the MSC certification as a market-based mechanism to promote sustainable fishery management. Specific recommendations for improvements are made.

Throughout the research the author has been engaged in a number of outreach and communication activities, specifically this has included: at the Royal Society Summer Science Exhibition (July 2018);

at the Polar Fish Trade Fair, Greenland (September 2018); at the Aurora House School Outreach Day (January 2019); and through the use of digital platforms. Digital platforms utilised include: Twitter, Skyping Schools, 360 degree virtual reality videos from research cruises and a browser-based educational game ‘Tricky Trawling’ available in three languages (Greenlandic, Danish and English) (ZSL, 2018). These efforts have shared findings with diverse audiences of all ages in Greenland and the UK. Collectively these resulted in the author winning the Royal Society of Biology’s ‘New Researcher Outreach and Engagement Award’ in 2019.

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List of papers

The following have arisen from the research undertaken as part of this PhD and are listed in order of publication date. A copy of each is included in Appendix I to Appendix IV. The relationship between these and the following chapters is briefly described.

Paper I

The following paper served as a test case for adapting and applying the Marine Protected Area Governance (MPAG) framework to a fishery, as opposed to a marine protected area. This informed the development and description of the methodology presented in Chapter 4.

Long, S., Randriana, Z., Hadj-Hammou, J. and Jones, P.J.S. (2021) Governance analysis of a community managed small-scale crab fishery in Madagascar: novel use of an empirical framework. *Marine Policy* 127. doi: 10.1016/j.marpol.2017.11.022

Paper II

The results presented in the following paper are detailed in Chapter 5, whilst the methodology is described in Chapter 4.

Long, S., Sparrow-Scinocca, B., Blicher, M.E., Hammeken Arboe, N., Fuhrmann, M., Kemp, K.M., Nygaard, R., Zinglersen, k., Yesson. C. (2020). Identification of a Soft Coral Garden Candidate Vulnerable Marine Ecosystem (VME) Using Video Imagery, Davis Strait, West Greenland. *Frontiers in Marine Science* 7(460). doi: 10.3389/fmars.2020.00460.

Paper III

The results and discussion in the following paper are presented in Chapter 7, whilst the methodology is described in Chapter 4.

Long, S. and Jones, P.J.S. (2021). Greenland's offshore Greenland halibut fishery and role of the Marine Stewardship Council certification: A governance case study. *Marine Policy* 127. doi: j.marpol.2020.104095.

Paper IV

The results presented in the following paper are detailed in Chapter 6, whilst the methodology is described in Chapter 4.

Long, S., Blicher, M.E., Hammeken Arboe, N., Fuhrmann, M., Kemp, K.M., Nygaard, R., Zinglersen, k., Yesson. C. (2021) Deep-sea benthic habitats and trawling impacts in the offshore Greenland halibut fishery, Davis Strait, west Greenland. *ICES Journal of Marine Science* 78(8), 274. doi: 10.1093/icesjms/fsab148

List of acronyms

The following acronyms are used in this thesis.

ABNJ	Areas beyond national jurisdiction
AI	Artificial intelligence
ASI	Assurance Services International
AUV	Autonomous underwater vehicle
BBDW	Baffin Bay Deep Water
BIIGLE	Bio-Image Indexing, Graphical Labelling and Exploration
CAB	Conformity assessment body
CBD	Convention on Biological Diversity
CFP	Common Fisheries Policy
CPRDR	Client and Peer Review Draft Report
CPUE	Catch per unit effort
CSR	Corporate social responsibility
CTD	Conductivity, temperature and depth
DFO	Department of Fisheries and Oceans Canada
DKK	Danish krone
DSWGHF	Doggerbank Seefischerei West Greenland Halibut Fishery
EEZ	Exclusive economic zone
EGC	East Greenland Current
EIA	Environmental impact assessment
ETP	Endangered, threatened and protected
EU	European Union
EUNIS	European Nature Information System
FAO	Food and Agriculture Organisation
FDR	Final Draft Report
FIP	Fisheries improvement project
FOV	Field of view
FSC	Forest Stewardship Council
FSR	Fisheries Standard Review
GBP	British pound sterling
GDP	Gross domestic product
GE	Grønlands Erhverv/Sulisitsisut (Greenland Business Association)
GFLK	Grønlands Fiskerilicenskontrol (Greenland Fisheries Licence Control)
GINR	Greenland Institute of Natural Resources
GLM	General linear model
GOODS	Global Open Oceans and Deep Seabed
GRT	Gross registered tonnage
GSSI	Global Sustainable Seafood Initiative
GUI	Graphical user interface
HCR	Harvest control rules
HDI	Human development index
IC	Irminger Current

ICES	International Council for the Exploration of the Sea
ISO	International Standards Organisation
ITQ	Individual transferable quotas
KANUKOKA	Kalaallit Nunaanni Kommunit Kattuffiat (Association of Municipalities)
KNAPK	Kalaallit Nunaanni Aalisartut Piniartullu Kattuffiat (the Fishers' and Hunters' Association of Greenland)
LM	Linear model
MAM	Minimum adequate model
MFHA	Ministry of Fisheries Hunting and Agriculture
MPA	Marine protected area
MPAG	Marine Protected Area Governance (MPAG) framework
MSC	Marine Stewardship Council
NAFO	Northwest Atlantic Fisheries Organization
NB GLM	Negative binomial general linear model
NEAFC	North East Atlantic Fisheries Commission
NGO	Non-governmental organisation
NMDS	Non-metric multidimensional scaling
NUSUKA	Nunaqavissut Suliffiutillit Kattuffiat (Employers' Association)
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic or OSPAR Convention
P2	Principle 2 of the MSC's Fishery Standard
PCDR	Public Comment Draft Report
PCR	Public Certification Report
PI	Performance Indicator
PSC	Port state control
RFB	Regional fishery bodies
RFMO	Regional fisheries management organisations
ROV	Remote operated vehicle
SAI	Serious or adverse impacts
SES	Social-ecological systems
SFG	Sustainable Fisheries Greenland
SIK	Sulinermik Inuussutissarsiuteqartut Kattuffiat (Employees' Union)
TAC	Total allowable catch
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNGA	United Nations General Assembly
USD	United States dollar
VME	Vulnerable marine ecosystem
WGC	West Greenland Current
WGIW	West Greenland Intermediate Water
WGOGHF	West Greenland Offshore Greenland Halibut Fishery
WoRMS	World Register of Marine Species
WWF	World Wildlife Fund
ZSL	Zoological Society of London

1. Introduction

The deep sea (>200m) is the largest and least explored biome on earth. 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 (Ramirez-Llodra *et al.*, 2010). In recent decades, the simultaneous declines of continental shelf stocks and advances in fishing technologies have seen the development of commercial deep-sea fisheries (Koslow *et al.*, 2000, 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).

Eco-labelling has been identified as a market-based mechanism with the potential to promote sustainable fishery management (Ward and Phillips, 2009), including in the deep-sea. The most established seafood eco-label, the Marine Stewardship Council (MSC) certification, was founded in 1997 and now certifies 15% of global wild-capture seafood (MSC, 2020). However, there are growing and high-profile criticisms from environmental NGOs (Various, 2018b) and scientists (Jacquet *et al.*, 2010, Christian *et al.*, 2013, Bailey *et al.*, 2018). A key concern is the habitat impacts of certified fisheries, particularly those employing towed demersal gears, especially in poorly known deep-sea ecosystems, where recovery can be extremely slow (Roberts, 2018, Various, 2018b). There is therefore a need to critically assess the role of the MSC certification in the governance of deep-sea fisheries.

Greenland offers a unique and important context in which to consider the sustainability of deep-sea fisheries and the role of MSC certification. Greenland's undiversified economy is heavily reliant on MSC certified deep-sea fisheries for its foreign exchange income. The recent MSC certification of the offshore Greenland halibut (*Reinhardtius hippoglossoides*) fishery highlighted the paucity of knowledge about the nature and distribution of deep-sea habitats and the impacts of trawling in this poorly known region of the northwest Atlantic (Cappell *et al.*, 2017, Cook *et al.*, 2019).

The timing is pertinent as the Arctic region has seen the greatest observed warming globally (Hoegh-Guldberg and Bruno, 2010), with significant reductions in sea ice cover (Stroeve *et al.*, 2012) and reports of impacts on the marine ecosystem (Wassmann *et al.*, 2011). In response, species and their fisheries are shifting polewards (Cheung *et al.*, 2013), including Greenland halibut, with the potential for fisheries expanding into previously untrawled areas (Christiansen *et al.*, 2014, Vihtakari *et al.*, 2021).

1.1. Aims

This thesis adopts an interdisciplinary approach to examine the sustainability of Greenland's economically important deep-sea fishery for Greenland halibut. The study has a particular focus on the benthic ecosystem impacts and the role of the Marine Stewardship Council certification in its governance. The findings will have direct applications to the management of deep-sea fisheries in Greenland and beyond, whilst yielding critical insights into the effectiveness of eco-labelling in promoting sustainable management and governance. Specific aims of this research are:

- Use a towed benthic video sled to acquire imagery of poorly known deep-sea benthic habitats in the Davis Strait, west Greenland.
- Describe the epi-faunal communities and their distribution in relation to the footprint of the fishery and intensity of trawling effort.
- Identify differences, if any, between communities in the spatially discrete northern and southern areas of the fishery.
- Describe the distribution of vulnerable marine ecosystems (VMEs) indicator species.
- Identify any previously unknown VMEs and highlight conservation priorities.
- Model the role of temperature, depth and the availability of hard substrates in determining the composition of communities.
- Model the impact of demersal trawling on communities and faunal abundance, with particular reference to VME indicator species.
- Adapt the Marine Protected Area Governance (MPAG) framework to create a tool to support a structured, empirical approach to critically analysing the governance of the fishery.
- Through the MPAG case study, critically analyse the role of the Marine Stewardship Council certification in the fishery's management and governance.
- Provide a holistic assessment of the sustainability of a deep-sea trawl fishery, combining interdisciplinary insights from the ecological and social science approaches, with reference to the definition of sustainability set out by the MSC certification.

1.2. Structure of this thesis

The aims of the study are set out in this chapter. Chapter 2 reviews the existing literature relating to deep-sea fisheries; their impacts on benthic ecosystems, management and governance. Chapter 2 also provides an overview of the Marine Stewardship Council (MSC) seafood eco-label. Chapter 3 provides background to the study: introducing the Greenland context, describing engagement of the Greenlandic fishing industry with the MSC certification and introducing the offshore Greenland halibut fishery, west Greenland. Chapter 4 describes the ecological and social science methods employed in this interdisciplinary study. Chapter 5 uses towed benthic video sled imagery to describe a previously unknown soft coral garden candidate vulnerable marine ecosystem (VME), which is immediately adjacent to the offshore Greenland halibut fishery. Chapter 6 presents imagery data obtained from sampling across a spectrum of fishing effort in the halibut fishery, including untrawled areas outside of the fishery footprint. These data provide new insights into the benthic habitats and the impacts of trawling. Chapter 7 presents a critical analysis of the governance of the halibut fishery, with specific reference to the role of the MSC certification. Chapter 8 discusses the conclusions arising from the research presented in this thesis.

2. Literature review

2.1. Deep seas

The Earth's largest biome is the ocean, which has a surface area of over 360 million km^2 and a volume exceeding 1.33 billion km^3 (Costello *et al.*, 2010, Costello *et al.*, 2015). By far the largest component of this biome are the deep seas, defined here as deeper than 200m, which account for more than 99% of the global ocean volume (Costello *et al.*, 2010) and cover 65% of the planet's surface (Danovaro *et al.*, 2017).

In these deep seas, temperatures are typically below 4˚C, sunlight is absent and hydrostatic pressure increases by one atmosphere every ten metres (Danovaro *et al.*, 2014). For a time, the prevailing assumption was these deep, dark, cold waters were devoid of life, encapsulated by Edward Forbes's 1843 Azoic hypothesis, which predicted life would cease to exist below 550m (Anderson and Rice, 2006). The Azoic hypothesis was only slowly rejected, in the face of inescapable and growing evidence of life in samples recovered from the deep seafloor. Today, deep seas are recognised as being home to a significant diversity of marine life, indeed it has been theorised life on earth may have originated in deep-sea hydrothermal vents (Martin *et al.*, 2008).

Departing in 1872, the three and a half year voyage of *HMS Challenger* sought to undertake *"the examination of the physical and biological conditions of the great ocean basins"* (Thomson *et al.*, 2015), and is often cited as the birth of deep-sea science and exploration, though contributions were made by many countries and expeditions. Covering some 68,000 nautical miles, the *Challenger* and its crew circumnavigated the globe, deploying dredges and sounding equipment in every ocean except the Arctic (noting that only the very southern extremity of the Indian Ocean was visited). The expedition report filled some 50 volumes, providing systematic insights into the diversity of deep-sea habitats and fauna. This was by no means the only dedicated deep-sea exploration and research undertaken in this era. For example, other key contributors, vessels and expeditions include: the Norwegian Michael Sars; Alphonse Milne-Edwards' work aboard the French vessels the *Travailleur* and the *Talisman*; surveys conducted by Prince Albert I of Monaco's vessels the *Hirondelle* and the *Princesse Alice*; the Danish Ingolf expedition; the Dutch Siboga expedition led by Max Weber; the German Valdivia Expedition; and surveys by American naval vessels, such as the *USS Albatross*, the *USS Enterprise* (Gage and Tyler, 1991*)*. It should be acknowledged that in some cases the motivation and purpose for this early exploration extended beyond scientific research, to including commercial, military and arguably colonial objectives.

The topographic diversity of the deep-sea floor is fundamentally determined by the interaction between tectonic processes and sedimentation, giving rise to a range of habitats, including: canyons, seamounts, abyssal plains, continental slopes, oceanic ridges, trenches, hydrothermal vents and methane seeps (Gage and Tyler, 1991). These benthic environments and the pelagic waters above combine to form the physical extent of the deep-sea biome. This deep-sea biome supports a significant diversity of species, contributing to total marine species richness estimated to be between 0.5 and 2.2 million species (Costello *et al.*, 2011, Mora *et al.*, 2011, Appeltans *et al.*, 2012). It has even been suggested that deep-sea diversity may exceed that of shallow seas (Levin *et al.*, 2001, Valentine and Jablonski, 2015).

A number of competing hypotheses have emerged to explain the apparent paradox of deep-sea species richness in environmental conditions that might be expected to inhibit, rather than promote, diversity (McClain and Schlacher, 2015). The first of these to emerge was Sanders (1969) ‘stability-time hypothesis’, which posits that the environmental stability of the deep sea over evolutionary timescales allows competitive interactions to drive speciation through high levels of niche differentiation. A further equilibrium explanation, is that the comparative stability of the deep-sea means that biogenic structures (e.g. reefs, burrows, foraminifera tests) persist for much longer timescales than in shallower high energy environments. These biogenic structures result in persistent small-scale habitat heterogeneity, where competition can drive niche specialisation (Jumars, 1975). Conversely, Grant (2000) have argued, based on observations in shallow-water sediments, that competition is not important in structuring communities and thus alternative hypotheses are required. Disequilibrium type explanations, apply the intermediate disturbance hypothesis, where diversity is greatest at intermediate levels of disturbance (Connell, 1978). Dayton and Hessler (1972) suggested biological disturbance in the form of predation by epibenthic ‘croppers’ depresses the abundance of potential competitors, preventing competitive exclusion. Grassle and Sanders (1973) observe the deep-sea floor is a mosaic of habitats created by sporadic and patchy organic input along with small scale-disturbance. This ‘patch-mosaic model’ proposes that diversity is maintained through the concurrent existence of distinct assemblages at different phases of succession. Ultimately, the practical challenges inherent in observing and conducting *in situ* deep-sea experiments mean that these hypotheses remain largely untested, relying on inference from more accessible but inevitably dissimilar ecosystems (Gage and Tyler, 1991, Grant, 2000). Thus, at present the drivers of the considerable species richness in the deep sea remain unresolved.

Beyond a depth of 200 m the lack of sunlight prevents photosynthetic primary production, rendering these habitats largely heterotrophic and exhibiting low productivity (Thistle, 2003, Ramirez-Llodra *et* *al.*, 2010). Adapted to the low productivity, the life-histories of deep-sea species are typically characterised by; slow growth, delayed onset of maturity and extreme longevity (Koslow *et al.*, 2000, Devine *et al.*, 2006). Slow growing sessile species, such as cold-water corals and sponges, are ecologically important, introducing structural heterogeneity and providing biotic habitats (Buhl-Mortensen *et al.*, 2010).

2.1.1. Vulnerable marine ecosystems (VMEs)

In 2004 and 2006, the United Nations General Assembly (UNGA) resolutions 59/25 and 61/105 called upon states and regional fisheries management organisations (RMFOs), to protect vulnerable marine ecosystems (VMEs) in deep seas from serious adverse impacts, caused by destructive fishing practices, including demersal trawling (UNGA, 2004, UNGA, 2006). The resolutions called for:

i. *"the identification of VMEs, supported by increased scientific research, data collection and sharing;*
ii. *the provision of technical guidance by the Food and Agriculture Organisation (FAO), on the identification and protection of VMEs;*
iii. *the adoption of management and conservation measures to protect VMEs;*
iv. *the prohibition of demersal trawling where VMEs are known to occur;*
v. *the execution of impact assessments for high seas trawl fisheries, to determine whether serious or adverse impacts (SAIs) on VMEs are likely to occur;*
vi. *the cessation of fishing activities where VMEs are encountered;*
vii. *the reporting of VME encounters by fisheries."*

Following a period of consultation, the FAO issued guidelines (FAO, 2009), which sought to provide a scientific basis for identifying VMEs, conducting impact assessments and determining what constitutes serious adverse impacts. In these guidelines, VMEs were defined as exhibiting one or more of the following five criteria:

1) *Uniqueness or rarity – an area or ecosystem that is unique or that contains rare species whose loss could not be compensated for by similar areas or ecosystems. These include:*
    a) *habitats that contain endemic species;*
    b) *habitats of rare, threatened or endangered species that occur only in discrete areas; or*
    c) *nurseries or discrete feeding, breeding, or spawning areas.*
2) *Functional significance of the habitat – discrete areas or habitats that are necessary for the survival, function, spawning/reproduction or recovery of fish stocks, particular life-history stages (e.g. nursery grounds or rearing areas), or of rare, threatened or endangered marine species.*

3) *<u>Fragility</u> – an ecosystem that is highly susceptible to degradation by anthropogenic activities.*

4) *<u>Life-history traits of component species that make recovery difficult</u> – ecosystems that are characterized by populations or assemblages of species with one or more of the following characteristics:*

    a) *slow growth rates;*

    b) *late age of maturity;*

    c) *low or unpredictable recruitment; or*

    d) *long-lived.*

5) *<u>Structural complexity</u> – an ecosystem that is characterized by complex physical structures created by significant concentrations of biotic and abiotic features. In these ecosystems, ecological processes are usually highly dependent on these structured systems. Further, such ecosystems often have high diversity, which is dependent on the structuring organisms.*

Subsequently, the term VME has been applied globally to a wide variety of deep-sea habitats, in both areas beyond national jurisdiction (ABNJ) and within exclusive economic zones (EEZs). Frequently, the identification of VMEs has been based on the occurrence of VME indicator species, such as cold-water corals or sponges at sufficient density to result in the VME criteria being met. The level of abundance of VME indicator taxa, either individually or collectively, that constitutes a VME is a matter of expert judgement in the absence of explicit thresholds in the FAO guidance (Auster *et al.*, 2010). A further challenge, is determining what spatial extent is required to qualify as an 'ecosystem' rather than simply a habitat. To date, this latter issue has received relatively little consideration in the wider literature (Watling and Auster, 2020). There have been efforts to establish a more consistent, quantitative and systematic basis for identifying VMEs (Ardron *et al.*, 2014, Morato *et al.*, 2018), though none have been widely adopted. To operationalise the VME definition, some RMFOs have developed regionally specific lists of VME indicator taxa and VME habitat types, though there are some inconsistencies between these in the taxa selected (Bell *et al.*, 2019)

Fundamentally, adoption of a consistent systematic approach requires a sound understanding of the underlying nature and distribution of VMEs and indicator species globally. Currently, biases in survey effort mean that regions such as the Northeast Atlantic have received considerable attention (e.g. Muñoz and Sayago-Gil, 2011, Buhl-Mortensen *et al.*, 2015, Huvenne *et al.*, 2016), whilst others remain comparatively poorly known.

2.1.2. Camera-based surveys of deep-sea benthic habitats

Simple methods of obtaining physical samples including dredges, as employed on the Challenger expedition, have been the mainstay of deep-sea biology (Roberts, 2002). These are increasingly supplemented and replaced by sophisticated technological approaches. Remotely operated vehicles

(ROVs), autonomous underwater vehicles (AUVs), bottom landers, submersibles, multi-beam sonar and side-scanning sonar are all used to provide new insights into the nature of deep-sea ecosystems, recovering samples, taking measurements and capturing imagery.

The history of deep-sea imagery is relatively short. The first images were obtained via the porthole of a bathysphere in 1933 (Beebe, 1934), followed by the development of purpose-built deep-sea camera systems at the Woods Hole Oceanographic Institution in the 1940s (Ewing *et al.*, 1967). It was only from the 1970s onwards that the use of deep-sea cameras has greatly increased (Howell *et al.*, 2020). Survey approaches which yield quantifiable seafloor imagery by employing ROVs, drop-cameras, manned submersibles or towed cameras are now commonly used for exploring deep-sea benthic environments. Morato *et al.* (2018) observe that the cost of obtaining and deploying equipment capable of imaging deep-sea environments is limiting, with only a minute fraction of the deep-sea floor having been surveyed to date. Indeed, Roberts (2002) estimates that biological science has so far only touched a millionth of the deep-sea floor.

The geographic expanse of the deep sea and the paucity of existing knowledge provide a strong rationale for the development and deployment of low-cost imaging approaches. Towed cameras, deployed from a ship which is drifting or moving under power, are technologically the simplest platforms for imaging the deep sea and are thus relatively cheap (Jones *et al.*, 2009). Early platforms consisted of a photographic camera and flash, triggered on contact with the seafloor, an approach which has been used in west Greenland to study habitats and trawling impacts from 61 to 725 m (Yesson *et al.*, 2015, Gougeon *et al.*, 2017, Yesson *et al.*, 2017).

Towed platforms can be separated into: those that are ‘flown’ blind with data being obtained following retrieval (e.g. Jones *et al.*, 2009); and those with real-time data transfer to the ship, usually via a fibre optic cable (e.g. Purser *et al.*, 2018). The latter are generally more expensive. The camera(s) are either mounted on a platform designed to be ‘flown’ above the seabed or on a sled towed across the seafloor (Jamieson *et al.*, 2013, Bowden and Jones, 2016). More advanced systems can include video camera(s), lighting rigs, scaling lasers, conductivity temperature and depth (CTD) data loggers, altimeters and other sensors. Compared with ROVs, AUVs and submersibles, the fundamental simplicity of towed cameras provides several advantages in terms of cost, robustness, operation, maintenance and risk (Bowden and Jones, 2016). However, there are also several inherent limitations in this simple design. Surveys are generally basic transects, without the ability to follow specific features, pause, or zoom-in on objects of interest, whilst the direct link to the towing vessels means the quality of imagery is directly related to the sea state at the surface (Bowden and

Jones, 2016). Further, towed cameras, especially bottom contacting sleds, are unsuitable for rough terrain or complex topography (Jamieson *et al.*, 2013) and can physically impact seafloor biota.

A key step in the use of imagery to investigate deep-sea benthic habitats is the processing of the data rich images or video. This includes the annotation of fauna or features of interest and the classification of habitats and substrates. There are a growing number of software platforms specifically designed to facilitate such processing of marine imagery. Gomes-Pereira *et al.* (2016) compare some 23 different platforms including: Bio-Image Indexing, Graphical Labelling and Exploration (BIIGLE) (Ontrup *et al.*, 2009); Video Annotation & Reference System (VARS) (Schlining and Stout, 2006); and SQUIDLE+ (Friedman *et al.*, 2016); which have all been applied to deep-sea research. Previous studies analysing deep-sea imagery in Greenland have employed Poseidon, which was specifically developed to support that work (Yesson *et al.*, 2015, Yesson *et al.*, 2017). These platforms are essentially graphical user interfaces (GUIs) linked to a database, allowing images and/or video to be viewed and annotated in real-time, or retrospectively. Additional features available in some platforms include the ability to: import, develop and modify annotation/classification schemes; estimate sizes/areas; perform quality control tasks; attach image metadata; collaborate with multiple users; query the database; and implement artificial intelligence (AI) based automation.

To assist image processing and aid standardisation, a number of classification schemes for habitats and substrates have been developed. Some of these are specific to particular biogeographic contexts, such as north-eastern North American sublittoral marine habitats (Valentine *et al.*, 2005). In contrast, the European Nature Information System (EUNIS) (Davies *et al.*, 2004) is a wide ranging classification that can be applied broadly, with the advantages of enabling comparisons between different studies. Addressing limitations identified by (Galparsoro *et al.*, 2012), a modified version of this latter scheme has been used in the Arctic region to classify benthic habitats in depths of 61-725m (Gougeon *et al.*, 2017).

Image processing requires both a significant investment of time and skilled labour, which creates a bottleneck. There are also challenges associated in achieving consistency of interpretation within and between different individuals processing imagery. Accordingly, there is growing interest in the potential for AI automation of image annotation and classification, stemming from the rapidly developing field of computer vision, though this largely remains at the developmental stage (Schoening *et al.*, 2012, Durden *et al.*, 2016). Where such approaches have been successfully implemented, they are reliant on the availability of training data of sufficient quality and volume, typically hundreds or thousands of reference images per target (Piechaud *et al.*, 2019). A key challenge for automated image processing is to develop methods that are sufficiently transferable so they can be applied to imagery from novel contexts, thus removing the bottleneck for deep-sea image based research.

2.1.3. Governance of the deep sea

The United Nations Convention on the Law of the Sea (UNCLOS) grants maritime countries an exclusive economic zone (EEZ), which extends up to 200 nm from the shoreline, less if two maritime countries are separated by <400 nm, in which case a median line divides their EEZs. Within EEZs, natural resources and their management, including deep seas, are the responsibility of nation states. Outside of EEZs, areas beyond nation jurisdiction (ABNJs) make up 61% of the surface of the planet's oceans and are subject to limited and somewhat haphazard legal frameworks (Baker *et al.*, 2020). Regional coordination across EEZs and ABNJ is in part achieved through regional fishery bodies (RFBs). RFBs are a mechanism through which states and other entities work together towards the conservation, management and/or development of fisheries. For example, the International Council for the Exploration of the Sea (ICES) is an RFB whose goal is to advance and share scientific understanding of marine ecosystems, including in the Atlantic Ocean and extending into the Arctic. RFBs with a management mandate are termed regional fisheries management organisations (RFMOs). RFMOs of relevance in the North Atlantic (including in Greenlandic waters) are the North Atlantic Fisheries Organisation (NAFO) and North East Atlantic Fisheries Commission (NEAFC). Within their respective regions, these RFMOs are directly responsible for management of fisheries in ABNJs, whilst performing advisory and coordination functions for states and their respective EEZs.

2.2. Deep-sea fisheries

Historic data shows that centuries of over-fishing has reduced previously abundant coastal fish stocks with profound ecosystem effects (Jackson *et al.*, 2001). Despite increasing effort and technological advances, global captures from marine fisheries are now thought to be in decline (Pauly and Zeller, 2016). Simultaneous declines in continental shelf stocks and advances in fishing technologies have seen fisheries expand into deeper waters (Koslow *et al.*, 2000, Morato *et al.*, 2006). The expansion of fisheries into the deep sea is a recent development; with the exception of a few traditional fisheries, all major deep-sea fisheries were developed since World War II (Koslow *et al.*, 2000, Gage *et al.*, 2005). At a global scale, fisheries have been shown to be operating at increasing depth and to have shifted to targeting deeper water species, since the 1970s (Morato *et al.*, 2006). However, the economic importance of these fisheries is limited. Deep-sea fisheries (predominantly demersal trawling) account for less than 0.5% of the global estimated catch for all fisheries (Victorero *et al.*, 2018), whilst, the depth, distance from ports and heavy gears required can render profitability marginal. Indeed, Sumaila *et al.* (2010) conclude that the majority of deep-sea trawl fisheries operating in the high-seas are only made economically viable by government subsidies, particularly in the form of fuel subsidies.

It has been shown that as depth increases, the fish species encountered exhibit increasing longevity, later maturity, decreasing fecundity and thus a slower potential rate of population increase (Drazen and Haedrich, 2012). Accordingly, deep-sea fish are vulnerable to over-exploitation (Koslow *et al.*, 2000, Victorero *et al.*, 2018). 'Clark's Law', coined by Norse et al. (2012), observes that where deep-sea fish 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). Often this has been on seamounts, which provide easily identifiable hotspots that can be intensively trawled, resulting in collapse of targets such as orange roughy (*Hoplostethus atlanticus*) (Francis and Clark, 2005, Clark and Koslow, 2007). Indeed, Merrett and Haedrich (1997) suggest that *"the deep-sea fishery should not be considered a fishery at all. There is a much stronger analogy to a mining operation wherein an ore body is exploited to depletion and then new sources (mines, virgin stocks) are sought*". Thus, purely from a stock perspective, many deep-sea fisheries are considered unsustainable; the controversy associated with these fisheries being compounded by concerns around wider ecosystem impacts.

2.2.1. Benthic impacts of deep-sea demersal fisheries

The nature of the impacts of trawling on benthic ecosystems in the deep sea are broadly similar to those seen on the shelf, as the same types of gear are used in both cases (Clark *et al.*, 2016). 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 homogenisation (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); and alteration of trophic structures where disturbance differentially impacts different species (for example negative impacting long-lived sessile species with low resilience to disturbance whilst promoting mobile scavengers and opportunistic species) (Watling and Norse, 1998, Koslow *et al.*, 2000, Gage *et al.*, 2005, Hall-Spencer *et al.*, 2007).

However, two important factors are thought to render the magnitude of these impacts greater in deeper seas. Firstly, the gear required in these deeper waters is significantly heavier. Steel trawl doors can weigh over 5 tonnes each, with sweeps, bridles and ground gear spanning 80-200m (or more in the case of twin rigged nets) (Victorero *et al.*, 2018). Additional weight is added by rock-hopper gear, consisting of steel bobbins and stiff-rubber discs designed to 'roll' over the bottom, minimising snagging in rough ground (Clark and Koslow, 2007). Secondly, fauna in the deep sea are adapted to a comparatively low disturbance regime (Grassle and Sanders, 1973), making them more sensitive to the physical impacts of towed gears and slower to recover (Jones, 1992). One exception to this may be in polar regions, in those seabed areas subject to disturbance by iceberg scouring, which has been observed as deep as 600 m (Gutt, 2002).

The inherent vulnerability of deep-sea fauna, heavy gear, and high bycatch rates have led to the sustainability of deep-sea fisheries being questioned from a benthic ecosystem perspective. Deep-sea demersal trawling has been likened to ploughing (Puig *et al.*, 2012) and clear-cutting forests (Watling and Norse, 1998), in terms of the considerable ecosystem impacts. 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).

2.2.1.1. Measuring the impacts of trawling

Studies of the effects of trawling on the benthos are highly context dependent (Thrush and Dayton, 2002). The physical impacts of trawling will depend on factors including: weight of the gear, trawl speed, type of gear, frequency, substrate, sediment composition, natural disturbance and seabed topography (Jones, 1992, O'Neill and Ivanović, 2016). Experimental studies in deep-sea environments are rare (Clark *et al.*, 2016). Such studies are limited by their scale, making it hard to extrapolate findings to the ecosystem scale at which fisheries operate (Hinz *et al.*, 2009). Most studies are of the ‘compare and contrast type’, examining the benthic ecosystem in areas that have been subject to differing levels of fishing intensity. Fishing effort data can be obtained from logbooks and or vessel monitoring systems (VMS), with the latter having high spatial and temporal resolution (though this may be restricted by providers). Fishing effort data is then typically rasterised to support further analyses. Obtaining data from points or along transects, across sites positioned on a spectrum of known or measured fishing effort, enables inferences of the impacts of trawling on benthic ecosystems to be made. Data may be obtained by side-scanning sonar, imagery, direct sampling (e.g. research trawls, grab sampling) or fishery bycatch data.

A number of studies (e.g. De Leo *et al.*, 2016) have used side-scanning sonar to identify trawling marks or scars on the seabed, both to gain insights into fishing effort and impacts on the seafloor. Post-processing of sonar scans enables trawl marks to be counted, and their location and orientation recorded (De Leo *et al.*, 2016). An alternative is to use camera-based approaches (see, 2.1.2 Camera-based surveys of deep-sea benthic habitats). Side scanning sonar and video, as methods for determining fishing impacts on the seafloor, are compared by Smith *et al.* (2007). They report that at speeds of 2-3 knots, side scanning sonar can image a tract 200 m wide with a resolution ~20 cm and is capable of identifying trawl doors marks. In comparison, a video system towed at 1 knot images a tract of only 1-2 m in width but at a resolution of 1-2 cm. This allows identification of trawl door marks, scrape marks, bioturbation features, and crucially faunal observations. An advantage of side scanning sonar over video, is that the data produced are not affected by turbidity (Smith *et al.*, 2007).

Bycatch sampling from stock assessment (Wareham and Edinger, 2007) and commercial trawls (Hall–Spencer *et al.*, 2002) has been used to determine the presence and distribution of coral megafauna in the deep-sea. It can also be used as a method for assessing the impacts of trawling. Cryer *et al.* (2002) examined bycatch in research trawls off north eastern New Zealand in depths of 200-600 m, having indexed the intensity of previous commercial fishing activity. They attributed 11-40% of total variation to fishing, concluding that trawling probably reduced biodiversity and changed benthic community structure at a large spatial scale. However, sampling epi-benthic invertebrates from bycatch may be unrepresentative. Freese *et al.* (1999) compared density estimates made using photographic and bycatch sampling approaches in deep (206-274 m) waters off southeast Alaska. Estimates of densities using bycatch data were lower for: asteroids, echinoids and molluscs (<1%); and holothurians (4.6%). It was not possible to make estimates for octocorals or sponges; it was thought that the size and fragility of the species present meant they were not retained in the cod-end of the trawl gear. Thus there is a clear selection bias with this approach. Williams *et al.* (2015) also compared camera and benthos sampling-sled approaches on seamounts off Tasmania. They found the techniques provided complementary but not interchangeable outputs. Obtaining physical samples detected a greater number of species and allowed further analysis of collected material, whilst imagery provided higher estimates of megabenthos abundance and had lower environmental impacts. Selection of sampling approaches should therefore depend on the objectives and be made with a consideration of the trade-offs.

2.2.1.2. Physical impacts on the seafloor

The direct physical impacts of towed bottom gears on the seabed are the ploughing or scraping of the seabed, resulting in the homogenisation and resuspension of sediments, which can perturb chemical fluxes (Jones, 1992) (Table 2.1). Prominent deep grooves are caused by the heavy otter boards, though nets and other gear components are also known to leave distinct impressions on the seabed (Gage *et al.*, 2005, Buhl-Mortensen *et al.*, 2016). The persistence and biological consequences of these impacts will depend on the sediment type and the natural disturbance regimen (Roberts *et al.*, 2000, Buhl-Mortensen *et al.*, 2016). Marks are known to persist for at least 10 years in some conditions (Roberts *et al.*, 2000). Trawl gear has been reported to disturb partially buried glacial drop stones and boulders in the Northeast Atlantic (Gage *et al.*, 2005, Hall-Spencer *et al.*, 2007) and Gulf of Alaska (Freese *et al.*, 1999). The chemical composition and flux of the upper sediment layers can be altered by disturbance, especially in the more stable environments of the deep-sea (Jones, 1992, Puig *et al.*, 2012); the impacts on ecosystem functioning are not known.

Table 2.1 Studies reporting effects of deep-sea trawling on benthic ecosystem in the deep seas of the Northwest Atlantic and Arctic region.

Impact type	**Key findings**	**Ecosystems component(s)**	**Location**	**Depth (m)**	**Method**	**Reference**
Abiotic habitat alteration	High-frequency of trawl markings on sediments; deep cuts and linear features	Seafloor	Southern Barents Sea	~400	Towed video camera	(Jensen *et al.*, 2009)
	Trawls scars, furrows up to 20cm deep	Seafloor	North-west Norway	200-300	Towed video camera	(Buhl-Mortensen *et al.*, 2013)
	Trawl scars 30-40 cm deep, persistence is dependent of substrate	Seafloor	Southwestern Barents Sea	50-2000	Towed video camera	(Buhl-Mortensen *et al.*, 2016)
	Boulders (with attached epifauna) were displaced by a single trawl pass	Seafloor boulders	Gulf of Alaska	206-274	Remote operated vehicle (ROV) camera	(Freese *et al.*, 1999)
Damage to habitat forming species	Trawl areas characterised by: sparse living coral; broken, dislodged and partially buried coral, coral rubble; reduced structural complexity of habitat; and trawl scars (5-10cm deep)	*Desmophyllum pertusum* reefs	West Norway	200	ROV camera	(Hall–Spencer *et al.*, 2002)
	Significant reduction in heights of coral colonies (*D. pertusum* and *Paragorgia sp.)* in trawled areas	*D. pertusum* reef, *Paragorgia sp.* corals	North-west Norway	200-300	Towed video camera	(Buhl-Mortensen *et al.*, 2013)
	30-50% of reefs in the study area were damaged by trawling. Fishers report catches are lower in areas of damaged coral.	*D. pertusum* reefs	Norwegian Sea	200-400	ROV camera, fisher knowledge	(Fosså *et al.*, 2002)
	Estimated that 8–17% of sponges exposed to fishing pressure were removed in a three year period, with negative impacts on ecosystem functioning.	Sponges	Flemish Cap, Northwest Atlantic	50-2,000	Trawl bycatch	(Pham *et al.*, 2019)
Impacts on benthic communities	Density of 79 out of 97 common taxa was negatively correlated with fishing intensity. Sponges (*Craniella zetlandica* and *Phakellia/Axinella*) were particularly vulnerable. Asteroids, lamp shells and small sponges showed a positive correlation.	Megabenthos	Southwestern Barents Sea	50-2,000	Towed video camera	(Buhl-Mortensen *et al.*, 2016)

	Significant decreases in the density of sponges and anthozoans (evidence of damage) in trawled areas	Megabenthos	Gulf of Alaska	206-274	ROV camera	(Freese *et al.*, 1999)
	Trawling intensity is a significant factor in the abundance, diversity and assemblage of benthic organisms. Sessile erect organisms (including Anthozoa and Porifera) showed significant negative responses to trawling. Soft sediment communities showed higher resilience.	Megabenthos	West Greenland	61-725	Drop-camera	(Yesson *et al.*, 2017)
	Physical disturbance by bottom trawling negatively correlated with evenness and diversity and reduces functional diversity in peracarid crustacean communities	Megabenthos	Northwest Atlantic	582-2294	Box corer	(Ashford *et al.*, 2018, Ashford *et al.*, 2019)
	Reduced biomass reported for 11 out 13 epibenthic species	Epibenthos	Barents Sea	300-400	Trawl bycatch	(Denisenko, 2007, cited by Clark et al. 2016)

2.2.1.3. Impacts on benthic fauna

Hard bottoms provide a substratum for a rich diversity of sessile epifauna, the effect of trawls on these being relatively easy to interpret, whereas it has been more difficult to document damage to soft bottom associated sessile epifauna (Gage *et al.*, 2005). A study in the Gulf of Alaska has shown a single trawl pass to cause significant damage to sponges and anthozoans (Freese *et al.*, 1999). Yesson *et al.* (2017) investigated impacts of northern prawn trawling in the waters off the west coast of Greenland at depths of 150-600 m, and found significant impacts on abundance, diversity and community composition on muddy and rocky substrates. They reported sessile protruding taxa were most vulnerable, including Anthozoa and Porifera, showing a significant negative response to cumulative trawling (Yesson *et al.*, 2017). In the Barents Sea at depths of 300-400 m the biomass of 11 out of 13 epibenthic species examined was reported to be reduced in trawled areas (Denisenko, 2007, cited by Clark et al. 2016). The displacement of glacial drop stones and boulders will impact sessile, attached organisms unable to respond to a change in orientation; and continued disturbance of boulders may inhibit re-colonisation (Gage *et al.*, 2005).

However, not all fauna will be negatively impacted. Trawled areas can show increased abundance of rapid colonists and scavengers (Jones, 1992, Thrush and Dayton, 2002). On muddy substrates at depths of 183-361 m off the west coast of North America, communities heavily disturbed by trawling are dominated by mobile scavengers (sea urchins, hermit crabs and sea stars) (Hixon and Tissot, 2007). Increased abundance of scavengers in areas exposed to trawling has also been reported in the Norwegian Sea (Buhl-Mortensen *et al.*, 2013). In trawled areas of the Gulf of Alaska, Freese *et al.* (1999) did not detect damage or density changes in motile invertebrates.

Perhaps the most concern has been directed at the impact of trawling on slow growing deep-sea corals and sponges (Gage *et al.*, 2005). These are regarded as ecosystem engineers and play a keystone role in deep-sea benthic ecosystems (Buhl-Mortensen *et al.*, 2010). Considerable attention has been given to the impacts of trawling on *Desmophyllum pertusum*, a cold-water coral. It has a cosmopolitan distribution, including in the Arctic region, is common in the Norwegian Sea and is typically found at depths of 200-400 m (Fosså *et al.*, 2002, Davies *et al.*, 2008). *D. pertusum* forms reefs that can be over 40 m tall and extend for several kilometres (Rogers, 1999, Davies *et al.*, 2008). These bioherms (large biological structures) grow at rates of just millimetres a year (Mortensen, 2001) and are often thousands of years old (Hall-Spencer *et al.*, 2007). The structural complexity provides numerous habitat niches. In the Northeast Atlantic over 1,300 different species have been found living on *D. pertusum* reefs (Roberts *et al.*, 2006). In Norwegian waters, it is estimated that 30-50% of coral bioherms have been damaged by fishing, with fishers claiming that catches are lower in damaged areas (Fosså *et al.*, 2002). There are reports of fishers using heavy chains and other gears to clear areas of coral before fishing to prevent the loss of nets (Fosså *et al.*, 2002, Roberts, 2002, Gage *et al.*, 2005). Trawling can also cause dislocation, altering the fine-scale spatial distribution of species. In the deep waters of the Barents Sea, *Geodia* and *Stetleta* sponges were found to have been re-organised into lines filling the trenches left by trawl doors (Buhl-Mortensen *et al.*, 2016). Corals and sponges are caught in large quantities as bycatch. In Alaskan fisheries around the Aleutian Islands over 4,000 tonnes of corals and sponges were caught between 1996 and 2002, around 90% of which was from demersal trawling (NMFS, 2004).

In addition to direct physical impacts, the resettling of suspended material caused by towed gears may indirectly impact epifauna. Sediment plumes have the potential to impact fauna over a greater area than the immediate path of trawl. Research on the impacts of deep-sea mining for manganese nodules has predicted effects of re-suspended sediments on seafloor communities across an area 2-5 times greater than that physically disturbed by mining (Smith *et al.*, 2008). Recent work by Muñoz-Royo *et al.* (2021), estimated that sediment suspended by mining can be readily transported 1,000 km. It is known that cold-water corals such as *D. pertusum* can be smothered by as little as a few millimetres of sediment, inhibiting expansion and recovery (Rogers, 1999) . Laboratory experiments on the deep-water sponge *Geodia barretti*, which can be found at high densities in the Arctic, showed that it physiologically shuts down when exposed to suspended sediments but is able to recover after exposure (Tjensvoll *et al.*, 2013). However, this study did not assess the impact of repeated exposure over the long-term as may be expected in a fishery context. Sponges play a key role in benthic-pelagic coupling (Pile and Young, 2006), therefore sedimentation impacts may have cascading ecological effects (Bell, 2008).

In shallow water, the impacts of fishing disturbance on infauna have been well studied (Collie *et al.*, 2000, Kaiser *et al.*, 2000, Kaiser *et al.*, 2002, Hinz *et al.*, 2009). However, in the deep sea there is limited knowledge on the impacts on infauna (Leduc and Pilditch, 2013), even less than for epifauna, presumably due to the challenges of sampling and the costs of conducting experiments. Given that the deep-sea environment is thought to be more stable than in shallow waters, it is expected that disturbance will affect more species, with resulting declines in abundance, richness and functional diversity (Grassle and Sanders, 1973, Ashford *et al.*, 2018, van der Grient and Rogers, 2021).

The penetration of trawl gears into the seabed is known to be significant i.e. >30 cm (Buhl-Mortensen *et al.*, 2013). Laboratory experiments have shown disturbance can affect the composition and distribution of infauna in deep-sea sediment cores (Leduc and Pilditch, 2013). A study was conducted into the effects of chronic trawling, at depths of 200-800 m, on the sediments of the continental slope in the north-western Mediterranean Sea (Pusceddu *et al.*, 2014). It was found that trawled areas were characterised by having lower organic matter content and reduced carbon turnover, with reductions in meiofauna (80%) and species richness (25% fewer nematode species). A similarly comprehensive study has not been conducted in Arctic waters, though the authors concluded that similar effects are likely in other deep-sea environments. Burrowing organisms that leave casts or holes on the seabed can offer insights which can be gained from photographic or video techniques. In the Barents Sea at depths of over 400 m, (Jensen *et al.*, 2009) report that there is a lack of burrows in those areas where trawl marks are present, in comparison with unmarked areas. Changes to the abundance and assemblage of burrowing infauna will likely affect rates of bioturbation - a key process controlling cycling of nutrients and chemical flux in sediments (Smith, 1992).

2.2.2. Management of the benthic impacts of deep-sea fisheries

Given the vulnerability and extremely slow recovery of deep-sea benthic ecosystems, it is imperative that effective management measures are identified. Restoration approaches are unlikely to be feasible, it having been estimated that the costs and timescales of restoration projects in the deep sea are orders of magnitude greater than in shallow water (Van Dover *et al.*, 2014).

There are a variety of technical modifications to demersal trawl gear to minimise impacts. These include reducing bottom contact and reducing the overall weight of gear, particularly trawl doors but also ground ropes (Mounsey and Prado, 1997, Linnane *et al.*, 2007, Rose *et al.*, 2010). Some have argued that these modified demersal gears are unlikely to substantially reduce the impacts on highly vulnerable, sessile, erect, epibenthic fauna (Clark *et al.*, 2016). Trawling on the seabed could be replaced by mid-water trawls designed to fish close to, but not directly on the seabed, reducing impacts and increasing fuel efficiency, as has been shown for targeting cod (Jørgensen and Valdemarsen, 2010). However, many species have a dive response when disturbed, so trawling above the seabed leaves an escape route that may reduce catches (Clark *et al.*, 2016). An alternative solution is to transition to lower impact fishing methods (traps, pots and longlines), which can also be less fuel intensive than towed gears (Suuronen *et al.*, 2012). This involves trade-offs between financial costs, bottom impacts and catch, which will dictate where this approach is adopted (Clark *et al.*, 2016). It should be recognised that whilst demersal trawling can be used for a broad range of targets, not all lower impact gears are suitable for specific targets (e.g. long-lining is not suitable for prawns). Adoption of gear with reduced environmental impact requires strong incentives or pressures to ensure widespread uptake. These can include: gear-dependent access rights; market-based pressures (e.g. eco-labelling); bycatch limits and regulations; and grants or subsidies (Jennings and Revill, 2007).

States and regional fisheries management organisations (RFMOs) have adopted differing approaches for both identifying VMEs (Ardron *et al.*, 2014) and implementing measures to protect them (Rogers and Gianni, 2011), which includes bycatch thresholds and move-on rules (Auster *et al.*, 2010). These work on the basis that where a vessel exceeds a predetermined bycatch threshold for an indicator species, it must move a set distance away before resuming fishing. The obligation to report encounters, which trigger move-on rules is intended to contribute to developing knowledge on the distribution of VME indicator species. Auster *et al.* (2010) identify a number of problems with move-on rules, including: i) the relationship between biomass and bycatch is not known, meaning thresholds are arbitrary; ii) the triggering of 'move-on' rules will be highly dependent on catchability, many species being likely to be damaged but not retrieved by gears; iii) VMEs are patchily distributed, it is not known at what point on any given trawl the bycatch occurred; iv) moving may displace fishing effort increasing the total area impacted; and v) fishers can increase the number but decrease the duration of tows to avoid triggering thresholds. Others have echoed concerns about these significant problems, with Rogers and Gianni (2011) highlighting that thresholds set by RMFOs are so high that they are unlikely to result in the cessation of fishing in the vicinity of VMEs. For the move-on rules to be effective, these challenges will need to be adequately addressed and improved regulations implemented.

Some have argued that spatial management is the most effective and pragmatic strategy, restricting the distribution of fishing, as this may be the only way to protect highly vulnerable fauna (Clark and Dunn, 2012, Clark *et al.*, 2016). This zoning approach, including the designation of deep sea marine protected areas (MPAs), allows exploitation in some areas whilst protecting at least a portion of, vulnerable species and habitats. Such spatial restrictions also allow for a more holistic approach, where management of fisheries can be coordinated with other extractive activities, such as deep-sea mining (Wedding et al., 2013).

Ideally, spatial management would be informed by a sound understanding of the nature and distribution of habitats and ecosystems. However, the scale of the deep sea and the current knowledge gaps present significant challenges. In the absence of specific knowledge, spatial management can be premised on introducing measures that provide a minimum protection across gradients of depth, temperature or latitude, prioritising those areas most likely to be vulnerable. Using trawl data from the Northeast Atlantic, Clarke *et al.* (2015) found that between 600 and 800 m the negative ecological impacts of trawling began to outweigh the commercial value of catches. Accordingly, depth-based management measures have subsequently been introduced prohibiting demersal trawling in European Union waters below 800 m (European Union, 2016).

2.3. The Marine Stewardship Council certification

Market-based mechanisms have been identified as one way to steer fisheries towards sustainable practice. Recent years have seen the emergence of eco-labelling schemes to set standards and influence the governance of the fisheries sector (Ward and Phillips, 2009). To some extent, these mirror eco-labelling approaches already employed in terrestrial settings, such as the Forest Stewardship Council (FSC), which was initiated in 1993 (Gulbrandsen, 2006). The most established and globally recognised seafood eco-label is the Marine Stewardship Council (MSC) certification scheme (Gulbrandsen, 2009, Jacquet *et al.*, 2010). Today 15% of global wild-capture seafood carries the MSC certification (MSC, 2020).

2.3.1. History

The first eco-labels that emerged in the fisheries sector were focussed on single species, most notably 'dolphin-safe' tuna labels, but these did little to address the wider and significant impacts of the global fishing fleet (Gulbrandsen, 2009). In response, the aspiration for the MSC eco-label was to harness market forces to promote changes on the water, which ensured the long-term viability of target stocks and the ecosystems on which they depended (Sutton, 1996).

The MSC was jointly founded in 1997 by the World Wildlife Fund (WWF, an international environmental organisation) and Unilever (then the world's largest buyer of frozen fish) (Gulbrandsen, 2009, Agnew *et al.*, 2014), building on the model of the FSC. In Unilever, WWF were seeking a partner able to facilitate the adoption and promotion of certified products among retailers and consumers (Gulbrandsen, 2006). The MSC developed its principles and criteria between 1997 and 1999, through a series of international meetings, drawing on expert opinion and stakeholder input (Agnew *et al.*, 2014).

To ensure its credibility as a neutral body, the MSC became a fully independent non-profit entity from 1999 (Fowler and Heap, 2000, Ponte, 2012). Subsequent reforms have resulted in a governance structure with a Board of Trustees, Stakeholder Advisory Council, Technical Advisory Council along with various subsidiary boards and committees (Gulbrandsen, 2009).

2.3.2. The Theory of Change

The MSC certifies fisheries as meeting the MSC Fisheries Standard ("the Standard"). For a seafood product to display the MSC eco-label, all entities in the supply chain (buyers, distributors, retailers etc.), must be certified against the MSC's Chain of Custody Standard, which is intended to provide full traceability from source to plate. The MSC's Theory of Change is a cyclical model (Figure 2.1). To pick an arbitrary starting point in this Theory of Change, market demand for certified sustainable seafood leads to fisheries engaging with the MSC certification and making the necessary changes to ensure practices meet the MSC's definition of sustainable. The intention is that a virtuous cycle is created, where supply and demand for certified sustainable seafood is mutually self-supporting, throughout the supply chain, driving actual changes on the water (Arton *et al.*, 2020). To be effective, the MSC certification needs to offer a benefit to fishers, either by creating a price premium (Roheim *et al.*, 2011), and/or by providing access to markets. Whilst it is accepted that access to markets is being provided through retailers increasingly choosing to stock only MSC certified products, the relative role of pressure from consumers, environmental groups and states in driving this is debated (Gulbrandsen, 2006, Ponte, 2012).

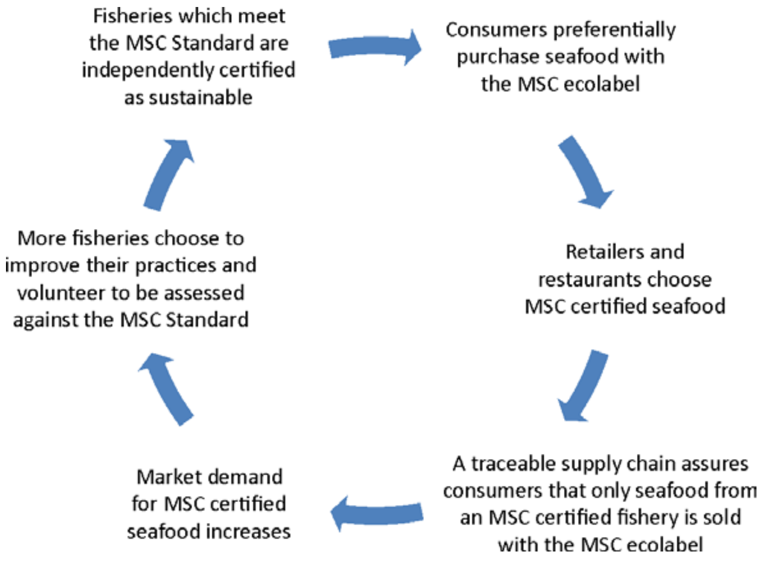


Figure 2.1 The Marine Stewardship Council (MSC) Theory of Change (ToC). Adapted from: Arton *et al.* (2018)

2.3.3. Defining sustainable: the MSC Fishery Standard

Fisheries are highly complex systems, the product of the interactions between ecological and socio-economic processes. What is meant by 'sustainable' in such systems? In reality there are a multitude of different meanings of sustainability and definitions of sustainable seafood (Hilborn *et al.*, 2015). Since it is the *development* (or extraction of natural resources) for human use that modifies ecosystems, the widely adopted Brundtland Commission's definition of sustainable development is a common starting point. "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Kates *et al.* (2005) observe that this definition is "*creatively ambiguous"*, its flexibility may yield some insight into its widespread adoption. Clearly, a universal definition is problematic. What sustainable eco-labels and certifications seek to do is provide a definition and assurance that products meet this definition.

The MSC Fisheries Standard ("the Standard") offers a definition of sustainable that is principally focussed on environmental sustainability (Arton *et al.*, 2020). Agnew *et al.* (2014), in relating their experiences of establishing the certification, identified two challenges that the MSC has faced since inception. These are:

> 1) *"how to develop specific operational interpretations of a sustainability standard that are valid in all fishery conditions; and*
> 2) *how to maintain a credible and reliable standard as scientific understanding and accepted best practice management change over time"*

The MSC Fisheries Certification Requirements and Guidance v2.0 (MSC, 2014) defines the Standard and the process by which fisheries should be assessed[1]. The Standard complies with the UN (United Nations) FAO's Code of Conduct for Responsible Fishing, Global Sustainable Seafood Initiative (GSSI) guidance, ISEAL codes and relevant International Standards Organisation (ISO) standards. The Standard is comprised of three core principles, of which Principles 2 and 3 are of direct relevance to this thesis:

> *"Principle 1: Sustainable target fish stocks*
>
> > *A fishery must be conducted in a manner that does not lead to over-fishing or depletion of the exploited populations and, for those populations that are depleted, the fishery must be conducted in a manner that demonstrably leads to their recovery.*
>
> *Principle 2: Environmental impact of fishing*
>
> > *Fishing operations should allow for the maintenance of the structure, productivity, function and diversity of the ecosystem (including habitat and associated dependent and ecologically related species) on which the fishery depends.*
>
> *Principle 3: Effective management*
>
> > *The fishery is subject to an effective management system that respects local, national and international laws and standards and incorporates institutional and operational frameworks that require use of the resource to be responsible and sustainable."*
>
> MSC (2014)

---

[1] Throughout this thesis, where reference is made to the MSC Fisheries Standard and the assessment process, this refers to that detailed in the MSC Fisheries Certification Requirements and Guidance v2.0, which was applied to the two certified components of Greenland's offshore Greenland halibut fishery. Specifically, these are the West Greenland Offshore Greenland Halibut Fishery (WGOGHF) and the Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF). The MSC Fisheries Standard and assessment process has been subject to subsequent revision, see MSC Fisheries Standard and Guidance v2.01 and MSC Fisheries Certification Process and Guidance v2.2. The revisions are technical in nature rather than a wholesale revision of the MSC Fishery Standard or assessment process.

The Standard and assessment process are subject to review on a five-year cycle, a process which external parties are invited to contribute to.

2.3.4. The assessment process

The MSC very clearly defines its role as a standard setter, with assessments undertaken and certificates awarded by independent third parties, known as Conformity Assessment Bodies (CABs) (Agnew *et al.*, 2014, MSC, 2018). The CABs themselves are subject to oversight by an accreditation body Assurance Services International (ASI). Fisheries are represented by fishery clients, which can be private, non-governmental organisations (NGOs) or governments. Entrance into the certification process is voluntary. Fishery clients are responsible for contracting a CAB to conduct the assessment, with subsequent annual surveillance audits and full-reassessment every five years. The costs of assessment are borne by the organisation representing the fishery that is seeking certification and are about 15,000 to 120,000 USD, additionally there are costs associated with annual audit and 5-year review (Christiansen *et al.*, 2014).

Hønneland (2020) provides a comprehensive description of the certification process, which is summarised here. The CAB performs an initial assessment of the fishery, which is informed by: a site visit(s); the available literature and data; and interviews with actors (fishers, managers, scientists, NGOs etc.) (Hønneland, 2020). The information gathered is used to make an assessment in relation to the three principles. The three principles are assessed by 28 performance indicators (PIs) for which a score between 0 and 100 is given. Ultimately, scoring below 60 for any PI results in failure, whilst scores from 60-79 attract a condition requiring a specified improvement within a set timeframe. The average of PIs for each principal must exceed 80 for a fishery to be certified. The CAB produces a Client and Peer Review Draft Report (CPRDR), which details the scoring and any conditions that have arisen. This is subject to review by both the fishery client and the MSC Peer Review College. The CAB is required to respond to comments arising from this review and produces the Public Comment Draft Report (PCDR), which is made publicly available via the MSC’s website. Stakeholders are invited to comment on the PCDR for a period of 30 days. At this stage, the PCDR is returned to the Peer Review College for further comment and also in selected cases subject to Technical Oversight by the MSC. Comments from the second round of peer review, stakeholders and the MSC Technical Oversight are responded to by the CAB, resulting in the Final Draft Report (FDR). The FDR is made publicly available and there is a 15 day window for stakeholders to submit an objection, within a rigorously defined procedure. In the event of no objections, or following the conclusion of that process, for fisheries that have ‘passed’, the fishery is then deemed certified and the final Public Certification Report (PCR) is made publicly available. Fisheries are then required to make progress towards specific milestones relating to any conditions attached to the certificate. Progress is assessed at annual surveillance audits, along with monitoring for any significant changes in the fishery. Failure to reach milestones and conditions within specified timeframes can result in suspension and removal of the certification by the CAB. The certificate is valid for 5 years, after which full re-assessment is required. The resulting assessment, surveillance and reassessment reports typically consist of 500-1,000 pages for each fishery's five-year certification period (Hønneland, 2020).

2.3.5. Impacts of the MSC certification

Since its inception, the MSC has grown exponentially, in terms of the number of fisheries certified, its market share of global wild-caught seafood and uptake by retailers and consumers (Ponte, 2012). The MSC reported that the number of different products that have carried the eco-label increased 34 times between 2008 and 2019 to over 37,000 (MSC, 2019b), with 18,735 products available on shelves in 2020 (MSC, 2020). The MSC is credited with almost single-handedly creating a mainstream market for sustainable seafood in little over a decade (Ponte, 2012). In the financial year 2019-20, it reported an income of £29.3 million, the majority (80.5%) of which was revenue from the licensing of the MSC eco-label (MSC, 2020). MSC certification of fisheries is now utilised as an indicator for the Convention on Biological Diversity's (CBD) Aichi Targets 4 and 6 (OECD, 2019).

Accordingly, as the market leading seafood ecolabel, it has attracted considerable attention from the scientific research community. The fundamental question being: what have the actual impacts of this certification been? However, studies are typically qualitative and rarely involve a longitudinal component, few are able to draw on counterfactuals or have a quasi-experimental design (Arton *et al.*, 2020). Nevertheless, case-studies are a useful tool for examining the role of MSC certification of fisheries across the broad range of contexts in which it has been applied. The utility of case-studies is greatly improved where their study design allows replication in both time and space to facilitate comparison. Reviews have attempted to synthesise findings from multiple studies, though in each case a significant proportion of the available literature does not meet the inclusion criteria (Dilley *et al.*, 2012, Komives *et al.*, 2018, Arton *et al.*, 2020). In the most recent and comprehensive of these reviews, Arton *et al.* (2020) mapped studies and found that the available evidence for impacts fell into the following categories: economic (38%), environmental (25%), governance (29%), and social (8%). They found a considerable diversity of reported outcomes with the most common relating to price premiums, market access, changes in stock health, ecosystem impacts and fisheries management changes. However, this review does not explicitly identify to what extent outcomes in the literature reviewed were positive or negative. They also identify key knowledge gaps, with few studies examining the effects on the supply chain and some geographic biases, the latter in part arising from the geographic bias in certification uptake in the northern hemisphere. Outside of the academic literature, in 2019, the UK Parliament's Environmental Audit Committee completed its Sustainable Seas inquiry, which specifically examined the MSC certification, drawing on evidence from a diverse range of stakeholders (House of Commons Environmental Audit Committee, 2019). The report found that the MSC certification, *"is driving incremental change towards sustainable fish stocks through improvements in fishing practices"*. Table 2.2 provides examples of the range of positive impacts associated with MSC certification reported in the literature.

Table 2.2 Examples of positive impacts associated with engagement with the MSC certification.

Category of impacts	**Fishery(-ies) and area**	**Positive impact(s) identified**	**Reference**
Governance	Various, Arctic region	Management regimes were improved as a direct result of engaging in certification, specifically the incorporation of biological reference points and harvest control rules.	Hønneland (2020)
Environmental	Patagonian Toothfish, South Georgia	Reduction in seabird bycatch.	(Agnew *et al.*, 2006)
Economic	Hake trawl, South Africa	The economic value of the certification to the fishery in terms of access to markets was found to be significant.	(Lallemand *et al.*, 2016)
Governance	Tuna purse seine, Oceania	Engagement with certification reinforced state agency in the value chain.	(Adolf *et al.*, 2016)
Social and Governance	Various, Australia	Improved social licence to operate, greater efficiency in governance processes.	(van Putten *et al.*, 2020)
Economic and governance	Various, Russia	Price premiums, increased transparency.	(Lajus *et al.*, 2018)
Environmental	Lobster, Western Australia and Mexico	Improved monitoring and understanding of: target stocks; bycatch; and endangered, threatened and protected (ETP) species.	(Bellchambers *et al.*, 2016b)
Social	Lobster trap fishery, Mexico	Empowerment of communities and fishing cooperatives, which has strengthened co-management.	(Pérez-Ramírez *et al.*, 2012b)

2.3.6. Criticisms

Unsurprisingly, giving the scale of uptake for the certification and its growing monopoly as the dominant wild-caught seafood eco-label, the MSC certification has attracted growing and high-profile criticisms from environmental NGOs (Various, 2018b, Various, 2018a), including original founders WWF (WWF, 2018) and scientists (Jacquet *et al.*, 2010, Christian *et al.*, 2013, Bailey *et al.*, 2018). Ponte (2012) argues that as a response to the global fisheries crisis, *"the MSC seems to be better tuned to the creation of a market for 'sustainable fish' rather than 'sustainable fisheries'".* In 2016, a highly critical internal report produced by WWF – a co-founder of the MSC – was leaked (WWF, 2016). More recently in 2018, a detailed open letter to the MSC written by NGOs and academics, called for revisions to the Standard and the assessment process to address concerns that principally related to the ecosystem impacts of certified fisheries (i.e. Principle 2) (Various, 2018b, Various, 2018a). The Sustainable Seas inquiry identified a number of criticisms and made recommendations that the MSC addressed these through revision of the Standard (House of Commons Environmental Audit Committee, 2019).

Perhaps the most fundamental criticisms are that the certification has been awarded to fisheries that are unsustainable in terms of the impacts on target stocks or the wider ecosystem. Such criticisms stem from the belief that: either, the Standard itself is inadequate (i.e. it is not a definition of sustainable) (e.g. Froese and Proelss, 2013); or, the process of assessment lacks sufficient rigour. In the case of the former, the Standard explicitly excludes from scope destructive fishing practices (e.g. dynamiting) that, in the eyes of the MSC, are inherently destructive (MSC, 2014). However, some argue that gears such as demersal trawls and dredges have significant destructive impacts (especially in deep-sea contexts) and that the Fishery Standard sets the bar too low for these high-impact fisheries (Roberts, 2018, Various, 2018b, Various, 2018a). Pragmatic observers note that the line has to be drawn somewhere and that what is key is that assessments are transparent and robust. Here, a second tranche of criticisms arises, where various authors have reported loose or generous interpretations in fishery assessments (Jacquet *et al.*, 2010, Froese and Proelss, 2012, Christian *et al.*, 2013). In reviewing the effects of MSC certification of Canadian fisheries, Arnold and Roebuck (2017) found that *"time extensions and lenient guidance allows fisheries too much flexibility for completion of conditions",* which has eroded the potential for positive environmental outcomes.

By design, the objections process offers recourse where stakeholders believe that there has been an error in an assessment. However, the effectiveness of the MSC's objections process has been questioned, with some accusing it of being, costly, bureaucratic, and narrowly defined (Jacquet *et al.*, 2010, Christian *et al.*, 2013). Objectors are required to pay costs of up to 5,000 GBP (Brown *et al.*, 2016), which can act as a major barrier or disincentive. Christian et al. (2013) report that only one out of 19 formal objections was upheld, which may discourage future objections and undermine faith and confidence in the process.

Where stakeholders have questioned the rigour of assessments, it is often accompanied by questions around conflicts of interest. The MSC has sought to minimise the potential for conflicts of interest by tightly defining its role as standard-setter, with assessments conducted by an independent third-party (CAB) (Agnew *et al.*, 2014). Nevertheless, critiques highlight that the MSC's licensing based funding model is directly linked to the number of fisheries certified and that achieving a sufficient supply of certified seafood was critical to mainstreaming eco-labelled seafood (Ponte, 2012). The direct financial relationship between CABs and the fishery clients that contract them is arguably more problematic. Jacquet *et al.* (2010) describe the potential conflict of interest in simple terms: *"certifiers that leniently interpret existing criteria might expect to receive more work and profit from ongoing annual audits"*.

An additional fundamental criticism is that there is relatively little empirical evidence supporting the MSC theory of change, in terms of positive impacts on stocks and ecosystems. A number of authors have highlighted that engagement with certification does not necessarily lead to changes on the water (Arnold and Roebuck, 2017). Despite over two decades of operation, examples of positive environmental impacts that can be directly attributed to MSC certification are relatively rare (Gulbrandsen, 2009). However, this may in part be attributed to challenges in measuring environmental impacts and establishing causal relationships, see discussion above (2.3.5 Impacts of the MSC certification).

Many have highlighted that the MSC certification process favours large-scale, commercial fisheries with small-scale fisheries and/or those in developing countries unable to obtain certification (Bailey *et al.*, 2016, Stratoudakis *et al.*, 2016). This arises from the significant costs associated with pursuing certification and the data-poor nature of fisheries in those contexts (Bellchambers *et al.*, 2016a). The effect of the growth of certification has therefore been to marginalise fisheries in the global south, especially those in low income countries (Ponte, 2012). This is compounded by the fact that the certification is increasingly a pre-requisite for market access. It has been argued that, paradoxically, the eco-label is biased against small-scale fisheries, which are often inherently low-impact and sustainable, in favour of large-scale industrial fisheries (Bailey *et al.*, 2018). Le Manach *et al.* (2020) observe that the MSC has relied on driving the certification of large-scale fisheries in order to certify a significant part of global fisheries catch and establish its eco-label as the market leader.

Some accuse the MSC of exploiting a gap between the public perception of what 'sustainable' means and what the MSC certification actually delivers. An analysis by Le Manach *et al.* (2020) neatly demonstrates this, by showing that the MSC's promotional material disproportionately features small-scale fisheries and passive gears, whilst the majority of certified catch comes from large scale vessels deploying active gears. Perhaps counterintuitively, especially for those who see demersal trawling and dredging as inherently destructive, bottom trawling accounts for a greater proportion of MSC certified catch than any other gear type (Arton *et al.*, 2020).

Ultimately, in order to understand the impacts of certification and whether criticisms are justified in any given fishery, in-depth interdisciplinary research is required, combining ecological data with the perspectives of stakeholders. This is rarely done, making it difficult to make a holistic assessment of the effectiveness of the MSC certification. Such assessments should be made in order to identify if this is an effective approach and offer insights into how to improve eco-labelling approaches to better promote the sustainability of fisheries.

3. Background: Greenland, engagement with the MSC certification and the offshore Greenland halibut fishery

Driven by anthropogenic climate change, the Arctic is one of the fastest changing regions of the planet (Hansen et al., 2006), with rising sea temperatures, ice-retreat (Stroeve et al., 2012) and shifting distributions of marine species (Wassmann et al., 2011). These changes present new opportunities for the development and (potentially sustainable) exploitation of natural resources, heralding a new era for geo-political cooperation or conflict in the polar north (Berkman and Young, 2009, Dodds, 2010, Brosnan et al., 2011).

Greenland, as a constituent of the Kingdom of Denmark, is part of the eight Arctic Nations (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, United States), represented by the Arctic Council. The country has a small population of ~56,000, living in relatively isolated coastal communities (Bendixen *et al.*, 2019). The Home Rule Act 1979 and Self-Rule Act 2009, transferred legislative and executive power to Greenland, granting the right to manage all natural resources in Greenland and its exclusive economic zone (EEZ) (Rosing et al., 2014).

In Greenland, the economic, political, social and cultural importance of fishing cannot be overstated. The past century has seen a transition from subsistence hunting and fishing to an economy based on the public sector and commercial export fisheries (Bendixen *et al.*, 2019). Greenlandic fisheries can be divided into the inshore and offshore sectors, which are spatially discrete and have very different management and social-economic contexts (Jacobsen, 2018). In simple terms, the labour intensive, low productivity inshore fishery employs small vessels with catches landed and processed locally, whilst the high-capital, high productivity, offshore fishery consists of factory trawlers (Christian Jervelund, 2013), which land the majority of catch overseas. Both inshore and offshore fisheries contribute to seafood exports, which accounts for 80 to 95% of the country's export income (Mortensen, 2014, Jacobsen, 2018, The Economic Council, 2017). The most important fisheries are for prawns (*Pandalus borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*), which both operate in deep seas, with an inshore and offshore component.

Despite having an EEZ of over 2.2 million km^2, Greenland has few Marine Protected Areas (MPAs). These are exclusively in inshore waters, totalling ~4.5% of the EEZ (UNEP-WCMC, 2019), with none designated to protect deep-sea habitats or known VMEs. This is some way behind the Convention of

Biological Diversity's (CBD) Aichi Target 11 of at least 10% of marine and coastal areas being conserved through effective and equitably managed protected areas by 2020 (CBD, 2010) and a long way behind the 30% by 2030 target. A number of 'Technical Conservation Measures' introduced by Executive Orders have been used to limit the use of bottom-contact fishing gears in some areas, of these only two are associated with the presence of VME indicator species. Specifically, there is a ~6.5 km^2 area in southwest Greenland bounding a single observation of *Desmophyllum pertusum* (Government of Greenland, 2017, Kenchington *et al.*, 2017) and 11 discrete areas within the offshore region of Melville Bay closed to bottom trawling '*based on significant observations of sea pens*' (*Umbellula sp*). (Cappell *et al.*, 2018, Government of Greenland, 2018). This paucity of spatial management measures to protect VMEs is principally due to a lack of knowledge about the nature and distribution of VMEs within the Greenlandic EEZ, representing a knowledge gap in the North Atlantic.

3.1. Emergence of MSC certification in Greenland

Figure 3.1 provides an overview for the engagement with the MSC certification in Greenland. In 2008, Sustainable Fisheries Greenland (SFG) was formed. This industry consortium's purpose was to pursue MSC certification of Greenlandic fisheries, acting as the 'fishery client' in the MSC certification process. This was the first step in the subsequent extensive engagement of the Greenland fishing industry with the MSC certification.

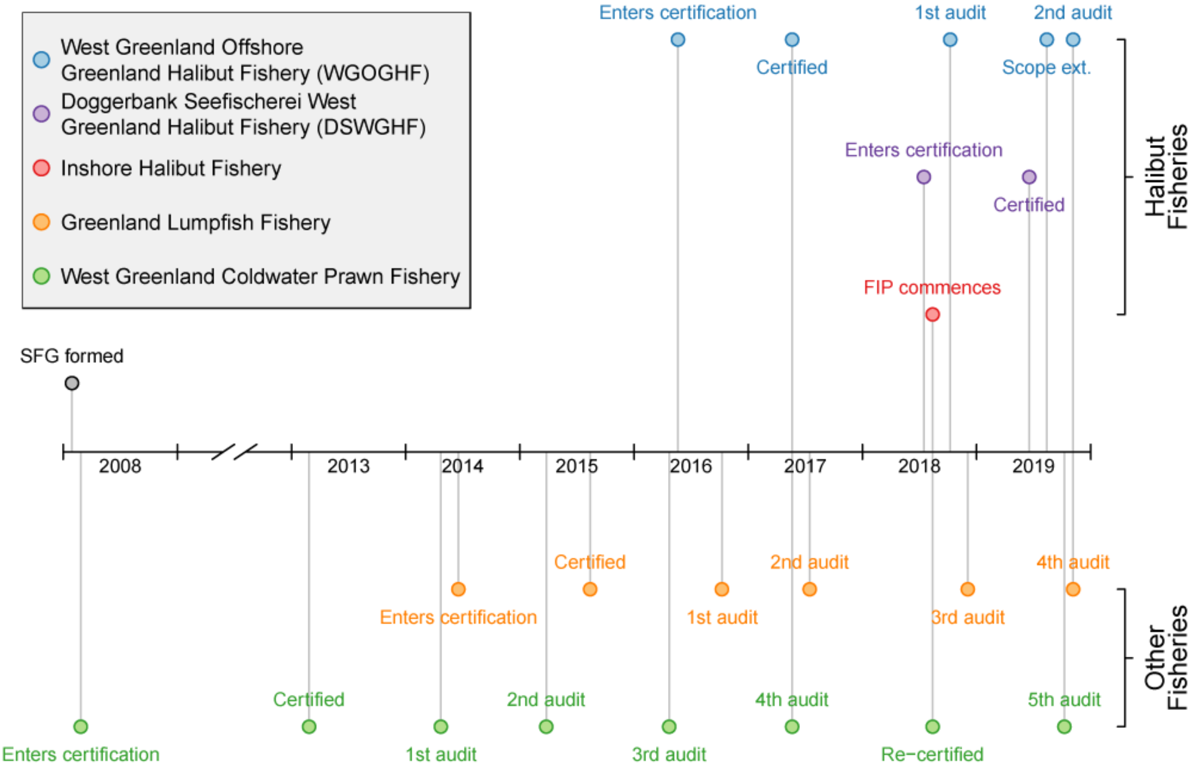


Figure 3.1 Timeline showing the development of MSC certification in Greenlandic fisheries.

The formation of Sustainable Fisheries Greenland (SFG), a consortium of Greenlandic fishing industry representatives is indicated.

The first target for certification was the West Greenland Coldwater Prawn Fishery. The fishery employs demersal trawls for cold-water prawns (*Pandalus borealis*) from the southern end of the continental shelf to 74˚N at depths of 150–600 m (Yesson *et al.*, 2017). The process began in 2008 and led to the fishery first becoming certified in 2013 (Lassen *et al.*, 2013a). Following this initial success, the Greenland Lumpfish Fishery, which employs gillnets inshore to catch lumpfish (*Cyclopterus lumpus)* for their roe, achieved certification in 2015 (Lassen *et al.*, 2015). Two separate components of the offshore Greenland halibut fishery (*Reinhardtius hippoglossoides*) have obtained certification. The Greenlandic portion of the offshore fleet, known as the West Greenland Offshore Greenland Halibut Fishery (WGOGHF), was first certified in May 2017 (Cappell et al., 2017b). This was followed by the German vessels in June 2019, which form the Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF) (Cook et al., 2019). The original certification of the WGOGHF was for Greenlandic trawlers only. In August 2019 a scope extension was granted to also include catch from a single Greenlandic longline vessel (Cappell *et al.*, 2020). At the time of writing a number of other Greenlandic fisheries are engaged with the MSC certification (K. Guldbæk, pers. comm.).

In addition to the certified fisheries, the inshore halibut fishery has been the subject of a fisheries improvement project (FIP) since 2018 (SFG, 2020). The FIP seeks to improve understanding and management of the inshore fishery with a view to pursuing MSC certification in the future, acknowledging that at the outset there were several challenges, including overfishing, the lack of a management plan and gaps in the scientific knowledge.

Since the initial certification of the prawn fishery, the industry has driven the fairly rapid engagement of a significant proportion of the Greenlandic fisheries sector with the MSC certification, across a spectrum of fisheries from passive inshore gears to offshore deep-sea trawl fisheries. SFG report that *"In all cases, Greenland have benefitted economically from the certifications. For that reason, there is both a political and a commercial wish to certify more fisheries"* (SFG, 2020).

It would also appear that, from the MSC's perspective, the Greenland story is seen as something of a success. The certification of Greenlandic fisheries, in particular the prawn and halibut fisheries, have repeatedly been highlighted by the MSC in press releases and their annual reports (e.g. MSC, 2019a). The MSC has been particularly keen to highlight new research into deep-sea habitats that has arisen from the engagement with certification. For example, in evidence submitted to the Sustainable Seas inquiry, the MSC described how a partnership between the Zoological Society of London and SFG resulted in camera surveys of benthic habitats and supported the creation of *“a Marine Protected Area equal to the area enclosed by the M25, to protect coldwater coral [Umbellula sp. sea pens]” (House of Commons Environmental Audit Committee, 2019).*

It may surprise some to see demersal trawl fisheries, employing heavy gear in poorly known deep seas, held up as flagship examples of sustainability. The halibut fishery, for example, could not operate within EU waters, being below the 800 m limit on trawling introduced to avoid unsustainable ecosystem impacts (European Union, 2016). Yet, the MSC has very deliberately highlighted the halibut (and prawn) fishery as examples where certification has driven new research into benthic habitats and led to changes on the water to protect vulnerable habitats.

The economic importance of fishing in Greenland and the significant engagement with the MSC certification make it an important test-case for the eco-label. There can be few, countries, if any, with a higher proportion of their gross domestic product (GDP) MSC certified. However, to date there have been no studies examining the impacts of certification in Greenland, whilst there are studies focusing on other geographic contexts, e.g.: Russia (Lajus *et al.*, 2018); Japan (Blandon and Ishihara, 2021); and Argentina (Pérez-Ramírez *et al.*, 2012a). In Greenland, where deep-sea fisheries are central to the economy, it is critical to understand whether the certification makes a positive contribution to the governance framework. Does certification support the sustainable management of marine resources; particularly from a benthic ecosystem perspective given inherent vulnerability of deep-sea habitats and species?

3.2. The offshore Greenland halibut fishery

Some 30% of Greenland’s fisheries’ export income is from halibut (inshore and offshore catches), making it the second most important stock after coldwater prawns (The Economic Council, 2017). The inshore fishery accounts for a greater proportion of the halibut catch (Pedersen and Zeller, 2001); landings of 38,192 tonnes of halibut in 2017 were split between 24,790 tonnes inshore and 13,402 tonnes offshore (Ministry of Finance, 2019).

This offshore Greenland halibut fishery (NAFO 1A-D, offshore) employs demersal trawl gear at depths of 800-1,400 m in the Davis Strait, west Greenland (Figure 3.2). Trawling occurs in two spatially discrete northern and southern areas, in which there has also been some limited longline fishing by Norwegian and Greenlandic vessels (Jacobsen, 2018). Bi-lateral agreements provide quota to vessels from Norway, Russia, Faroe Islands and some EU member states (European Union, 2015, Cappell *et al.*, 2017, Cappell *et al.*, 2018, Ministry of Finance, 2019).

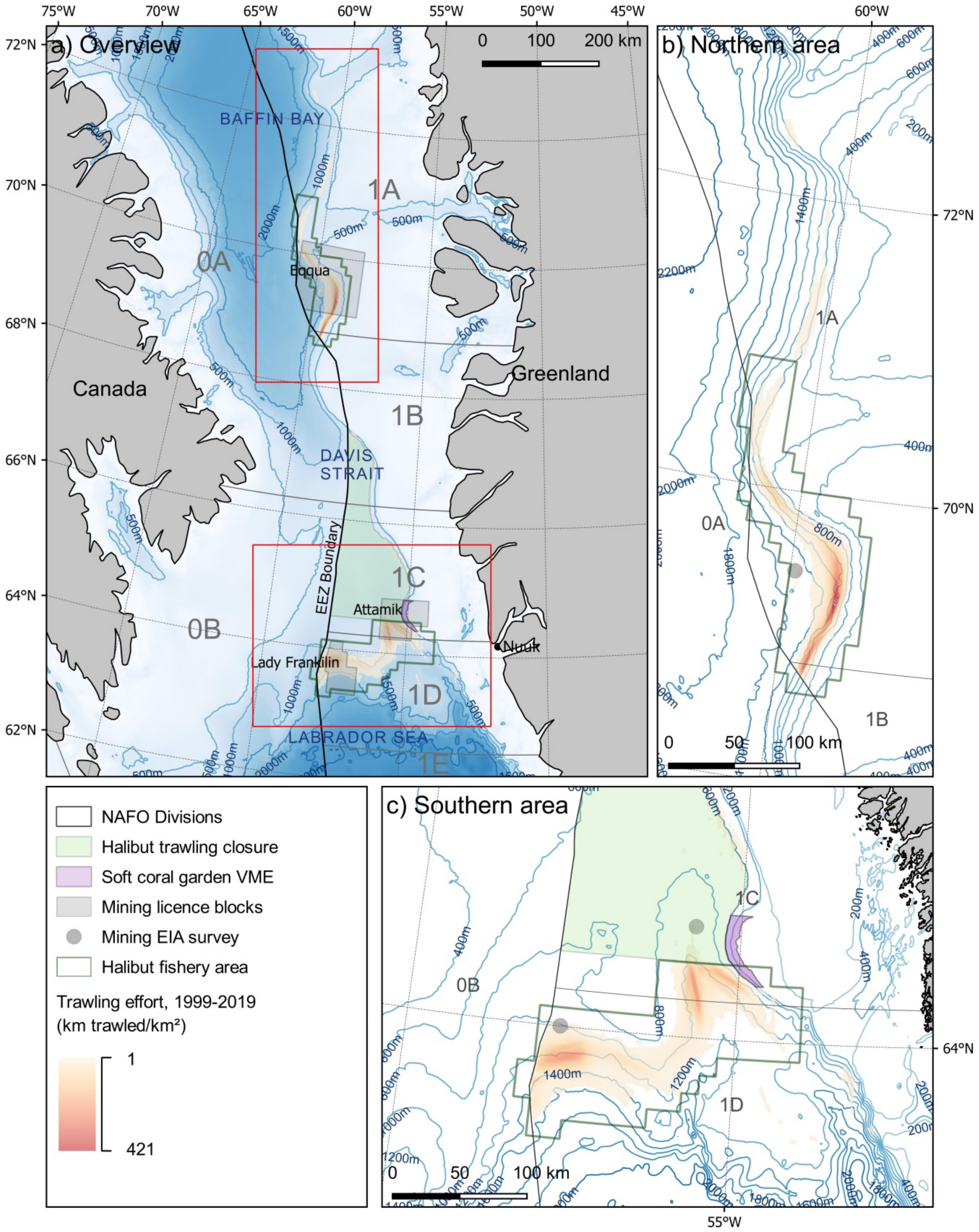


Figure 3.2 Map of the offshore Greenland halibut fishery, Davis Strait, west Greenland. Showing: a) an overview; b) the northern area of the fishery; and c) the southern area of the fishery Bathymetric contours are drawn at 500 m intervals in a) and 200 m intervals in b) and c), using the IBCAO Version 3, 500 m grid (Jakobsson et al., 2012). For clarity this bathymetric raster is included in a) but not b) and c). Halibut fishing activity is now 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 1999-2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.

The offshore halibut fishery is perhaps 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, despite a long history of exploitation. Commercial catches from the offshore stock 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).

At the outset of this study, and the fishery's entrance into the MSC certification process (see, 3.1 Emergence of MSC certification in Greenland), very little was known about the benthic habitats in this area and even less about the impacts of trawling. Some limited background information is available in environmental impact assessments (EIAs), which were undertaken for three spatially discrete mining exploration blocks that overlap the fishery (BSL, 2011a; BSL, 2011b; BSL, 2011c). These describe a seafloor consisting of unconsolidated sediments overlying soft clay (BSL, 2011c, BSL, 2011a, BSL, 2011b, Jørgensbye and Wegeberg, 2018), with occasional dropstones deposited by icebergs providing limited hard substrates (Gutt, 2002, Streuff *et al.*, 2017). Stock assessment survey bycatch data indicates several VME indicator taxa are known to be present, including Alcyonacea, Gorgonacea, Pennatulacea, Scleractinia, Antipatharia (Jørgensen et al., 2013; Blicher and Hammeken Arboe, 2021), though there are no existing comprehensive studies in the academic literature relating to the habitats, communities or impacts of trawling in this area of west Greenland.

4. Methodology

4.1. Ecological methods

A towed benthic video sled was used to survey deep-sea habitats in the offshore Greenland halibut fishery and adjacent areas in west Greenland. The imagery captured was used to describe the nature and distribution of benthic habitats (Chapters 5 and 6) and assess the impacts of trawling (Chapter 6). The study was fundamentally of the 'compare and contrast' type, comparing imagery from stations across a spectrum of fishing effort inside and outside the fishery's footprint.

Previous studies on deep-sea benthic habitats and trawling impacts in west Greenland have gathered imagery from depths of 61 to 725 m, using a drop camera to capture downward facing still images (Yesson *et al.*, 2015, Gougeon *et al.*, 2017, Yesson *et al.*, 2017). A limitation of this approach is that larger, more sparsely distributed fauna are not well represented in the imagery (Yesson *et al.*, 2017). This includes VME indicator species, which may be of the greatest conservation concern and management priority. For this reason a towed video sled was selected for the present research.

Towed video platforms are highly variable in their design and costs. The design of rigs determines the nature of the data gathered and the questions that can be addressed. In order to yield quantitative insights the area in the field of view needs to be estimated. There are three approaches: i) using a photogrammetric approach utilising stereo images from two cameras; ii) trigonometrically, using altitude and optical camera angles; iii) direct scaling using parallel lasers to produce a pattern of known dimensions in the imagery (Jones *et al.*, 2009). More complex towed systems with stereo-cameras allow not only areas to be determined, but also support size estimation of objects in the field of view (FOV) and three-dimensional reconstruction of surfaces, using photogrammetry. However, these systems are more costly and require careful, time-consuming calibration. In the interests of simplicity and cost this study uses a single camera set-up, with the area estimated trigonometrically. A key consideration is the camera orientation, which can either be vertical or obliquely angled, relative to the seabed. Bowden and Jones (2016) identify several advantages of oblique imagery: i) the area in the field of view is larger, giving a better impression of the habitat and increasing the likelihood of observing rare or sparse fauna; ii) the partially lateral view aids identification (compared with a vertical bird's eye view); iii) objects of interest have a longer transit time through the video frame, again aiding identification; iv) the oblique view is more visually appealing, which is helpful for communication and outreach. However, oblique imagery can be more difficult to interpret quantitatively because the spatial scales changes with distance from the bottom of the photograph (Wakefield and Genin, 1987) and the light attenuation of water means subjects at the top of the image can be poorly illuminated (Bowden and Jones, 2016). This study presents imagery collected using a custom built, low-cost benthic sled (total cost ~5,000 USD), which utilizes a single commercially available action camera (GoPro). The design of the rig, which is described below, was optimised during initial deployments prior to data collection.

4.1.1. The benthic video sled rig

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 outside of the fishery's footprint. On 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 45 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.

The towed benthic video sled featured an oblique angled centrally mounted video camera, lights, scaling lasers and an echo sounder unit (Figure 4.1). Illumination was provided by two Group-Binc Nautilux 1750 m LED torches arranged either side of the camera and angled inwards to achieve as close to even illumination as possible. A pair of green Z-Bolt lasers (wavelength=515 nm) in custom-made housings, were positioned 20 cm apart directly below the camera to provide an indication of scale. The position of the sled relative to the seafloor was monitored from the bridge using a Marport Trawl Eye Explorer (echo sounder unit) fixed to the top of the sled, which reported the depth (± 0.1 m), pitch and roll of the sled.

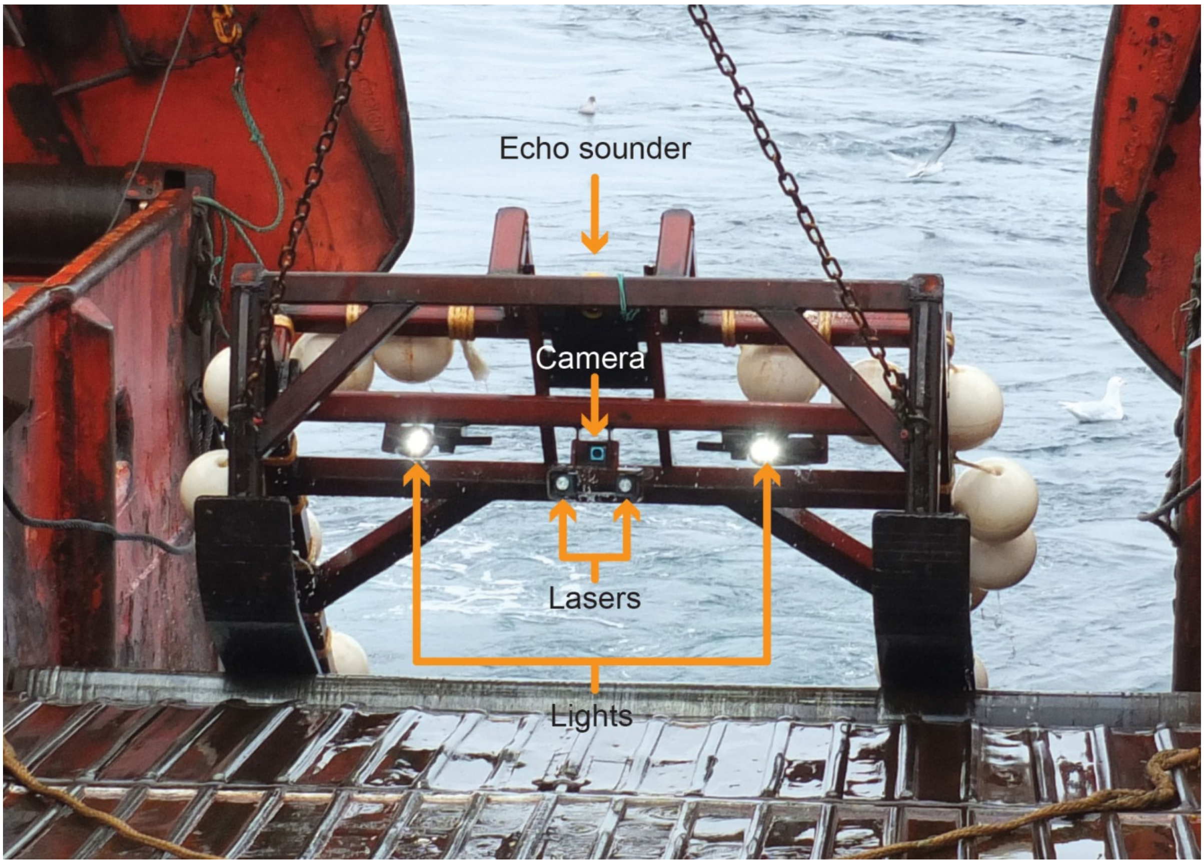


Figure 4.1 Picture of the benthic video sled rig. The position of the camera, lights, lasers and echo sounder unit are indicated (orange arrows). Picture taken as the rig is hauled back on to the trawl deck of the RV Paamiut.

Video was collected using a GoPro action camera in Group-Binc housings, which have a flat acrylic port. A GoPro4 recording 1920x1080 pixels at 48 frames per second (fps) was used in 2017, in a Group-Binc Scout housing. Subsequently, a GoPro5 was used, recording at the same aspect ratio (16x9) but higher resolution of 2704x1520 pixels at 60 fps, in a Group-Binc Benthic 3 housing.

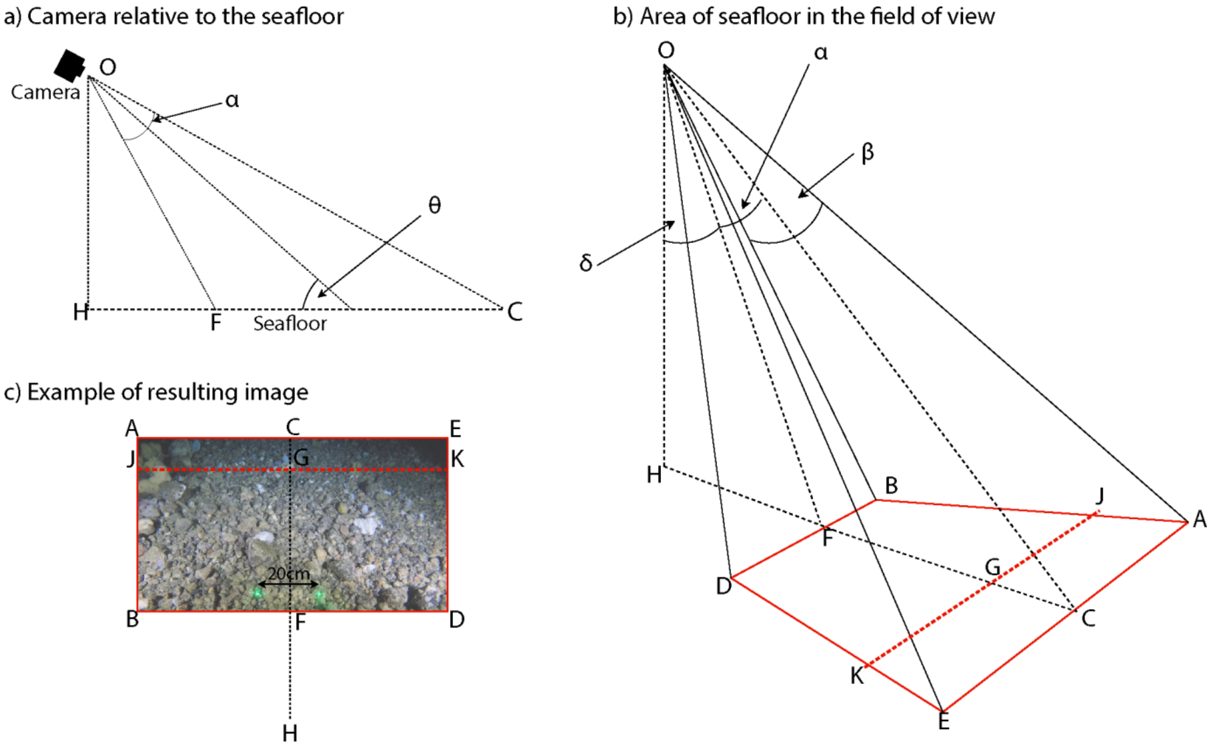
The 'Medium FOV' setting was used on both cameras. Per the manufacturer's specifications, this provides the same field of view (FOV), with vertical (α_{air}) and horizontal (β_{air}) aperture angles in air of 55˚ and 94.4˚ respectively. Guided by the discussion in Treibitz *et al.* (2011), these were corrected for refraction according to Snell's Law of refraction, which means it is necessary to correct for refraction by the bulk medium (seawater) but not the acrylic lens of the housing. This allows the vertical (α) and horizontal (β) aperture angles in seawater to be determined by Equations 1 and 2.

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

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

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

Due to the oblique angle, the very uppermost part of the image is difficult to interpret because of a lack of reflected light and taxa appearing smaller furthest from the camera. The distribution of all annotations made was reviewed and there were none in the top hundredth of the image. Excluding this unannotated area reduces the likelihood of artificially underestimating faunal density. Thus, the area of seafloor in the annotated FOV is calculated for *JBDK*, a subset of *ABDE,* where length JB is 0.99 of the length AB (Figure 4.2 Diagram of the towed benthic video sled camera set-up).


a) Camera relative to the seafloor

b) Area of seafloor in the field of view

c) Example of resulting image

Figure 4.2 Diagram of the towed benthic video sled camera set-up. Diagram supports the calculation of the area of the field of view (FOV). Where, a) shows the camera orientation relative to the seafloor. And, b) shows the camera position, aperture angles and area of seafloor (*ABDE*) in the camera's FOV (red line); with a cut-off line JK to exclude the portion of the image unsuitable for analysis (red dashed line). And, c) shows an example image of the seafloor, in relation to a) and b), for which the area *JBDK* is calculated and used in the estimation of fauna density. Adapted from: Nakajima *et al.* (2014).

The method described by Nakajima *et al.* (2014) is modified to allow the estimation of the area *JBDK* (Equations 3-8).

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

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

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

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

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

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

Where, *OH* the height of the camera was 0.55 m, θ the angle of incidence with the seafloor was 28.8° and the aperture angles (α and β) are determined as above (Equations 1 and 2). The area of seafloor analysed in each image (*JBDK*) was estimated to be 8.23 m^2, with a horizontal width of the FOV at the midline of 1.49 m. These values are used throughout for estimating densities of taxa.

4.1.2. Image processing

4.1.2.1. Image extraction

Quantitative analysis was conducted on still images extracted from videos. All footage was reviewed and useable video segments identified, excluding segments where: i) suspended sediment or other material obscured > 5% of the screen; ii) illumination was inadequate due to one or more torches being partially or wholly obscured; iii) the sled was not level and on the seabed; iv) the sled was stationary; or iv) the sled was moving too fast, which occurs at the end of a tow when the winch is being used to retrieve the sled. Stills were extracted at 15 second intervals from the useable segments. At each 15 second interval the frame with the sharpest focus within that second of video was selected, where one second of video was represented by 48 frames (GoPro4) or 60 frames (GoPro5).

The frame with sharpest focus was that with the highest value of standard deviation, based on the Laplacian Convolution Kernel of a greyscaled version of each frame, determined using the ‘convolve’ function of the R package ‘imager’ (R Core Team, 2013, Barthelmé, 2017). Convolution kernels are an established way of measuring the focus of an image within a range of similar images (Riaz *et al.*, 2008). The resulting stills were reviewed to ensure they met the criteria above and any exceptions were removed.

4.1.2.2. Image annotation platform

The images were then uploaded to a browser-based annotation platform, BioImage Indexing, Graphical Labelling and Exploration 2.0 (BIIGLE 2.0), (Ontrup et al., 2009; Langenkämper et al., 2017). The platform allows the creation of custom hierarchical label trees, which can be used to annotate features within images and/or be applied at the level of the image. A representative subset of the images was reviewed with the supervisory team to agree on a consistent approach to annotation. This was informed by previous experience of image and physical sampling surveys in the region. To ensure consistency the author made all primary annotations, for both fauna and substrate.

The nature of the imagery means not all fauna can be consistently seen and reliably identified. For example, small fauna closest to the camera (bottom of the image) may not necessarily be visible or identifiable at the back of the field of view (top of the image). Therefore, only taxa that could be consistently identified within and between images were selected for annotation and analysis. Only taxa where discrete individuals or colonies 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. When annotating each image, the section of video that it was obtained from was reviewed alongside the image. A moving perspective was found to be useful in aiding identification of taxa and distinguishing individuals or differentiating between separate colonies.

In Chapter 5, annotation was restricted to those taxa that form structurally significant/complex components of the habitats and thus are of relevance to criteria iv) of the FAO’s VME definition (FAO, 2009). To allow density estimation, only taxa where discrete individuals or discrete colonies (i.e. colonial organisms that form a discrete unit, e.g. a sea pen) could be identified were annotated. The taxa which met these conditions are shown with reference to whether they are considered VME indicator taxa by Northwest Atlantic Fisheries Organisation (NAFO) and NEAFC (Chapter 5, Table 5.2).

In Chapter 6, 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. 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 as they could not be consistently distinguished from other fauna present, especially small Ascidiacea.

4.1.2.3. Substrate annotation

Substrates were determined by annotation 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) for classifying substrates in imagery from west Greenland. For the purpose of this study this is further modified with clarified descriptions (A6.1.4 and A6.2.1) and four new subclasses (A6.1.5 and A6.2.2, A6.5.1, A6.5.2). Only those sub-classes used in this study are described here (Table 4.1, Figure 4.3). Additionally, to support the analysis in Chapter 6, 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.

Table 4.1 Substrate classes used to label images. Substrate classes are based on the revised EUNIS Habitat Classification (Davies *et al.*, 2004), as adapted by Gougeon *et al.* (2017) and further modified for this study. Only those sub-classes used in this study are described.

EUNIS	**Sub-class**	**Description**
A Marine habitats		
A6 Deep-sea bed		
A6.1 Deep sea bedrock and artificial hard substrate		
	A6.1.4 Coarse rocky ground (R)	Predominantly rocky material of varying sizes including gravel (<4 cm) and cobbles (4-20 cm).
	A6.1.5 Coarse rocky ground with boulders (Rb)	Rocky material of varying sizes including gravel (<4 cm) and cobbles (4-20 cm), with boulders (>20 cm) present.
A6.2 Deep-sea mixed substrata		
	A6.2.1 Gravelly mud (gM)	Mud with gravel (<4 cm).
	A6.2.2 Gravelly mud with boulders (gMb)	Mud with gravel (<4 cm), with boulders (>20 cm) present.
A6.5 Deep-sea mud		
	A6.5.1 Mud (M)	Mud
	A6.5.2 Mud with boulders (Mb)	Mud, with boulders (>20 cm) present.

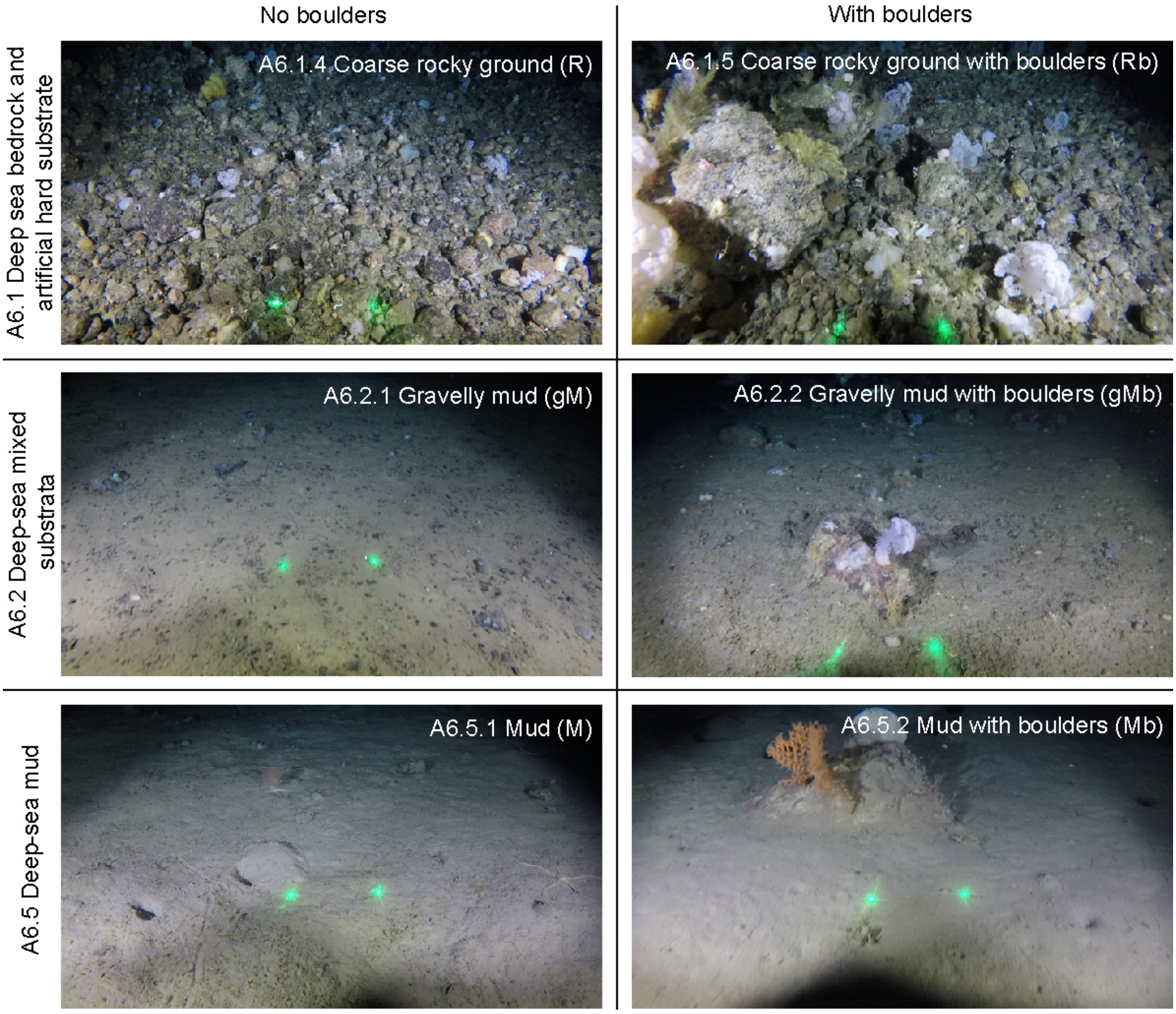


Figure 4.3 Example image of each type of substrate class used to label images. Substrate classes are based on the revised EUNIS Habitat Classification (Davies *et al.*, 2004), as adapted by Gougeon *et al.* (2017) and further modified here. Examples are taken from images used in the analysis. Where present laser dots (green) are 20 cm apart.

4.1.2.4. Video fauna counts

In Chapter 6, for selected fauna, generally those of conservation concern (e.g. VME indicators), counts were made from the video (in addition to image annotation). This more resource-intensive approach utilises all the available information in the video imagery. This provides the most accurate estimate of faunal density 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.

4.1.3. Station metadata

The sled position was inferred trigonometrically from the ship's position, direction, water depth and length of towing cable. 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 for each station was based on cross referencing survey positions with the effort raster (see, 4.1.4 Mapping), using a mean of all cells crossed by the sled's path.

4.1.4. Mapping

In Chapter 5, the BedMachine version 3, 150 m resolution bathymetry grid (Morlighem *et al.*, 2017) was used to produce bathymetric contours in figures and for describing the boundary of the proposed VME. In Chapter 6, the IBCAO Version 3, 500 m grid was used to provide bathymetric contours in figures (Jakobsson *et al.*, 2012).

Representation of fishing effort is based on haul-by-haul logbook data from all vessels deploying trawl gear between 1999 to 2019 inclusive, provided by Greenland Fishery Licence Control (GFLK). Raw data from GFLK was processed by GINR as follows. SAS statistical software (SAS Institute, 2019) was used to establish an annual data set with information on the target species, gear type, position, haul distance and speed. No information on gear width is available, so the transversal coverage of each haul is unknown. The data set was further processed using Safe FME Workbench software (SAFE Software, 2019) to establish line vectors from start and end haul positions, removing displaced positions and unrealistic long and fast hauls. The line vectors representing the hauls were interpolated with Python using the ESRI Spatial Analyst Line Density function (ESRI, 2013) with a 5 km search radius to a 1 km grid, and the result hereof further calculated against a mask of the proportion of sea and land. The resulting raster represents the distance trawled per unit area (km trawled km^{-2}).

4.1.5. Statistical approach

Data processing and analysis was performed in R (R Core Team, 2013).

4.1.5.1. Inter-taxa associations

In Chapter 5, a probabilistic approach was used to determine whether the taxa selected for annotation were positively, negatively or randomly associated with one another. The observed co-occurrence was compared to the expected co-occurrence, where the latter is the product of the two species' probability of occurrence multiplied by the number images (n = 1,239) (Veech, 2013). Associations were considered significant where the probability of the observed frequency of concurrence is <0.05, were the taxa distributed independently of one another. This was performed using the 'cooccur' package in R (Griffith *et al.*, 2016).

4.1.5.2. Benthic community analysis

In Chapter 6, non-metric multidimensional scaling (NMDS) was used to identify patterns in the benthic assemblage. 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, as 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 $p < 0.05$.

4.1.5.3. Taxa-specific modelling

In Chapter 6, the abundance of taxa was modelled as follows. There were only sufficient stations to support taxa-specific modelling in the southern area of the fishery ($n = 52$), using the video count data, which were normalised to the mean 'swept area' of 433.6 m^2 (standard deviation = 210.3), i.e. 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. 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. The count data for some taxa was zero inflated and/or over-dispersed, 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 linear models, 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 under- or over-fitting and compare models for goodness of fit. Validation of linear models 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).

4.2. Social science methods

Fisheries are highly complex systems, with ecological, social and economic components. Understanding and critically assessing the governance of any fishery is therefore an inherently complex undertaking. It requires the capture and synthesis of diverse evidence, from multiple actors and sources. Governance analyses are informed, either implicitly or explicitly, by some theoretical model of how the actors within the system interact (Jones and Long, 2020). Previous studies examining the role of the MSC certification in specific geographic contexts tend to employ an *ad hoc* framework and methodology, determined by the context, objectives of the study and practical constraints (e.g. Lajus *et al.*, 2018). Where possible, governance case studies should adopt a structured framework that is repeatable in both time and space. This facilitates both comparisons with case studies from elsewhere and future longitudinal studies.

4.2.1. The MPAG framework: theoretical basis

The Marine Protected Area Governance (MPAG) framework was developed to provide a structured, empirical approach for critically analysing the governance of Marine Protected Areas (MPAs) (Jones, 2014). The MPAG framework has subsequently been applied to 50 case studies, which has contributed to developing and refining an underlying theoretical concept that Jones and Long (2020) term 'coevolutionary governance'. In the absence of an equivalent tool and approach for assessing the governance of fisheries, this thesis sought to apply the MPAG framework to a fishery (the Greenland halibut fishery), rather than an MPA. This is premised on the fact that many fisheries, including this one, operate in discrete areas in which the marine resources are subject to management, in common with MPAs. This fundamental similarity allows the MPAG framework to be employed, now simply as a marine area governance framework. As a test case, Long *et al.* (2017) first applied the MPAG framework to the Ankobohobo small-scale crab fishery, Madagascar, an area without any formal MPA designation (Appendix I).

A recent paper by Jones and Long (2020) and the supplementary material therein, provides an extended discussion of different approaches to analysing the governance of marine resources, their underlying theoretical concepts and limitations. The coevolutionary governance model proposed, essentially builds on Elinor Ostrom's social-ecological systems (SES) framework (Ostrom, 2009), whilst addressing the limitations identified. The SES framework has been widely employed in environmental governance analyses, at its core it is a polycentric model, where *"decision-making centres take each other into account in competitive and cooperative relationships and are capable of resolving conflicts"* (Carlisle and Gruby, 2019), through deliberations and cooperation, both within and between places and actors. In summary, Jones and Long (2020) contend that the SES framework is somewhat idealistic, implicitly promoting a ‘bottom-up’ approach to natural resource management that is reliant on enabling conditions and a faith in linkages providing co-ordination between semi-autonomous places (and actors).

Conversely, the realist coevolutionary governance model recognises that some middle ground between decentralisation and state control is both a theoretical necessity for effective governance and a practical reality in most systems. This coevolutionary model adopts the political science concept of multi-level governance (Hooghe and Marks, 2003), where authority and influence is divested by the state to some extent among a network of state and non-state actors, with coordination being achieved through continuous negotiation among actors (Marks *et al.*, 1996). The model thus addresses a root problem of environmental governance identified by Dryzek (2013), as quoted by Jones (2014): “*problems of any complexity defy centralisation but decentralisation can undermine the integration required to strategically address wider-scale, interconnected challenges*”.

The coevolutionary governance model also adopts a synecology perspective from the ecological literature, where it is widely recognised that a diversity of species from different functional groups tends to promote the stability and resilience of ecosystems in response to perturbing forces (Polis, 1998). Similarly, relationships between different actors (and the incentives they employ) ‘coevolve’ over time, to produce a governance system linked via feedbacks with the ecosystem(s) under management. A recurring finding of MPAG case studies to date is that the resilience and effectiveness of marine resource governance is achieved through a diversity of actors and the incentives they collectively employ, with resilient governance systems being analogous to complex ecosystems (Jones, 2014, Jones and Long, 2020). Ultimately, as a methodology for critically analysing governance the MPAG framework’s underlying conceptual model is intended to adequately represent the realities across varied contexts, in order to be successful in yielding actionable insights.

4.2.2. Overview of the MPAG framework

The structure of the MPAG framework (Jones, 2014) is adopted in the case study presented in this thesis, with each element of the framework providing the headings in Chapter 7. An overview of the elements within the MPAG framework is outlined in Table 4.2. In both the test case and this study, only minor adaptation of the MPAG framework was required to address the governance of a fishery. Specifically, in the absence of formal MPA objectives, the objectives of the Greenlandic government and industry are considered (see, Chapter 7, 7.2 Objectives).

Table 4.2 Overview of the Marine Protected Area Governance (MPAG) framework. Adapted from: Jones (2014) and Jones and Long (2020).

MPAG framework element	Purpose	Sources
Context - National, regional and local context, including metrics: per capita GDP and growth rate, human development index (HDI), state capacity, population below poverty line and unemployment rate.	Provides an indication of the economic and development status for the country. State capacity provides an indication of the 'strength' of governance of the national government. The context supports comparison between studies.	Government statistics, literature, the Human Development Index (HDI) (UNDP, 2020) and state capacity indicator* (Kaufmann and Kraay, 2019).
Objectives - Social, economic and ecological objectives	Defines the objectives against which the effectiveness is evaluated.	Typically defined in management plans, policy documents or legislation. Other sources may indicate the objectives of different actors.
Drivers/Conflicts - Specific issues/activities/threats impacting the marine resources and undermining the realisation of objectives. These can be acting at different spatial and temporal scales.	Identifies the targets that management and governance need to address in order to achieve the objectives.	Often outlined in management plan or other policy documents; though these can emerge from various sources.
Governance framework/approach - Outline of the legal, policy and participative governance structure	Describes of the main approach by which the fishery is governed.	Detailed in management plans, policy documents and legislation.
Incentives – identify the incentives used and needed in governance framework and how they interact and are combined. From a possible 36 incentives (Appendix V Appendix) from 5 categories (Table 4.3).	Allows deconstruction of the governance approach to assess which incentives are used and which are priorities for strengthening or introducing. Describes how different incentives support and reinforce each other in a coevolutionary manner to create a 'web' of incentives.	Information sought in management plans, policy documents and legislation and also elucidated through interviews with actors.
Effectiveness - in achieving conservation objectives.	Provides an assessment of the degree to which the drivers and conflicts have been addressed to achieve the objectives, on a scale from 0 (ineffective) to 5 (wholly effective).	Should reflect information gathered from multiple sources including: management authority reports scientific literature and interviews with actors.
Cross-cutting issues	Discussion of themes that have arisen through the case study, these may be specific issues or common themes across governance case studies.	Informed by semi-structured interviews with actors and other data collected.

* The state capacity indicator is derived from the Worldwide Governance Indicators (WGI) project and is the mean of scores (−2.5 to +2.5) for six dimensions of governance (voice and accountability; political stability and absence of violence; government effectiveness; regulatory quality; rule of law; and control of corruption) calculated annually using an established methodology (Kaufmann *et al.*, 2011, Kaufmann and Kraay, 2019)

A key component of the MPAG framework is the use of empirical data to identify the incentives adopted within the area being governed. The MPAG framework described by Jones (2014) identifies 36 potential incentives (Appendix V) from five categories (Economic, Communication, Knowledge, Legal and Participation) (Table 4.3).

Table 4.3 Definitions of the 5 categories of 36 incentives in the MPAG framework. The 36 incentives are detailed in Appendix V. Adapted from: (Jones, 2014)

Category of incentives (Number of incentives)	**Definition**
Economic (10)	Using economic and property rights approaches to promote the fulfilment of objectives
Communication (3)	Promoting awareness of the marine resources, the related objectives for sustainably managing them and the approaches for achieving these objectives, and promoting support for related measures
Knowledge (3)	Respecting and promoting the use of different sources of knowledge (local-traditional and expert-scientific) to better inform management decisions
Legal (10)	Establishment and enforcement of relevant laws, regulations etc. as a source of ‘state steer’ to promote compliance with decisions and thereby the achievement of the obligations
Participative (10)	Providing for users, communities and other interest groups to participate in and influence decision-making that may potentially affect them, in order to promote their ‘ownership’ of the marine resources and thereby their potential to cooperate in the implementation of decisions

4.2.3. Social science data collection

The analysis was conducted using primary and secondary empirical data. Primary data was collected through semi-structured interviews and observation. Secondary data was obtained from reviews of publicly available documents related to MSC certification, peer-reviewed articles, grey literature and legislation. Prior ethical approval was obtained from the Zoological Society of London (ZSL) Ethics Committee (Ref: BME 728).

Semi-structured interviews were used to capture the perspectives of actors with knowledge and experience related to the fishery, the governance context and/or the MSC certification. Semi-structured interviews allow the interview to explore complex areas and are sufficiently unrestricted that important themes, not anticipated at the outset of the research, can emerge (Arksey and Knight, 1999, Valentine, 2005). Crucially, the flexibility avoids formulaic interactions, where the interviewee is presented with set questions that they have no relevant knowledge of, opinion on, or interest in. The semi-structured interviews were therefore intended to be “*a conversation with a [research] purpose*” (Eyles, 1988). The semi-structure devised (Appendix VI) was intended to gather information to populate the MPAG framework structure (4.2.2 Overview of the MPAG framework). It also served to ensure that, where appropriate, the same topics were explored with each interviewee to capture the full range of perspectives.

Qualitative interview data was collected, following the method employed by Jones (Jones, 2008). Interviewees were snowball sampled (Valentine, 2005) from initial informants from six broad categories of actors (Table 4.4). A total of 19 interviews were conducted in English, between October 2017 and March 2019, with a median duration of 79 minutes (range: 35 to 150 minutes). On two occasions, at the request of the interviewees, the interview was conducted with two people from the same organisation present. All interviews were recorded with prior permission and were anonymised in accordance with the study's ethics approval. Anonymity helps ensure interviewees feel that they can answer fully and in confidence, whilst being afforded protection (Jones and Long, 2020). A summary of each interview was prepared from a recording, which interviewees were given the opportunity to review and amend. The summaries include *verbatim* quotes, where that best captured the interviewee's knowledge or opinion.

Table 4.4 The number of interviews and interviewees by category. Categories of interviewees are, Scientist (SC), Fishing industry (FI), environmental non-government organisation (NGO), State actors, Conformity Assessment Body (CAB) and Marine Stewardship Council (MSC). The category 'CAB' includes permanent employees and assessors contracted by CABs. The category 'FI' includes individuals representing both commercial entities and Greenlandic fishers. Three of the interviewees (SC1, SC2 and SC3) categorised as 'SC' worked in a scientific capacity for a state funded research organisation and so had a dual perspective. Reference codes are used to attribute quotes.

Category	**Number of interviews**	**Number of interviewees**	**Reference codes**
Scientist (SC)	5	5	SC1 – SC5
Fishing industry (FI)	4	5	FI1 – FI4
eNGO (NGO)	2	2	NGO1 and NGO2
State actors (ST)	2	3	ST1 and ST2
CAB (CAB)	2	2	CAB1 and CAB2
MSC (MSC)	4	4	MSC1 – MSC4
ALL	**19**	**21**	

The author participated in the Greenland Institute of Natural Resources' (GINR) halibut and coldwater prawn stock assessment cruises between 2017 and 2019, inclusive. During these cruises, benthic habitats were also surveyed, including in the fishery and adjacent areas. Involvement in this research served as an opportunity to develop an understanding of the fishery and the stock assessment process, and also acted as gateway to actors. In August 2018, the author attended the first MSC surveillance audit of the West Greenland Offshore Greenland Halibut Fishery (WGOGHF) (Lassen and Chaudhury, 2018a), as both an observer and participant, at the invitation of the fishery client, Sustainable Fisheries Greenland (SFG). The author presented a preliminary report (Long *et al.*,

2018) on habitat surveys, on behalf of the Zoological Society of London (ZSL). The author's dual role was explicitly stated at the start of the meeting and the informed prior consent of all participants was deemed to have been gained.

The author's active engagement with benthic habitat research, collaboration with GINR, relationship with SFG and participation in the MSC assessment process are explicitly recognised. The perspective offered in this study is therefore that of both an observer and participant. Naturally, this positioning influences the analysis presented, but also resulted in insights and access that could not otherwise be obtained. Furthermore, the MPAG framework provides for a broad analysis of the governance of the Greenland halibut fishery, which helped avoid any perceptual biases arising from a single observer and analyst.

4.2.4. Interview analysis

The verified summaries were coded using NVivo (QSR International, 2019), a qualitative data analysis software package. Text was given an incentive specific code where it provided evidence pertaining to one of the 36 potential incentives. Additional codes were added as recurring issues or themes emerged. This allowed all evidence relating to particular incentives and topics to be reviewed collectively when preparing the analysis. In presenting the findings, *verbatim* quotes are included where illustrative, followed by the reference code to indicate the category of interviewee, their identity being anonymised (Table 4.4). Coded interview data, direct observations and secondary data were combined to elucidate the governance approach, identify emergent themes and highlight divergent perspectives.

5. Identification of a soft coral garden candidate vulnerable marine ecosystem (VME) using video imagery, Davis Strait, West Greenland

The results presented in this chapter were originally published in the paper below (Appendix II):

Long, S., Sparrow-Scinocca, B., Blicher, M.E., Hammeken Arboe, N., Fuhrmann, M., Kemp, K.M., Nygaard, R., Zinglersen, K. and Yesson, C. (2020). Identification of a Soft Coral Garden Candidate Vulnerable Marine Ecosystem (VME) Using Video Imagery, Davis Strait, West Greenland. *Frontiers in Marine Science* 7(460). doi: 10.3389/fmars.2020.00460.

5.1. Introduction

Since 2011, benthic camera surveys employing a drop camera have been used to map habitats and quantify trawling impacts in west Greenland, (Yesson *et al.*, 2015, Gougeon *et al.*, 2017, Yesson *et al.*, 2017). Drop camera images obtained from a single station on the slope of the Toqqusaq Bank appeared to show structurally complex habitats, with high densities of cauliflower corals (C. Yesson, pers. comm.). During the initial deployment and testing of the benthic video sled aboard the *RV Paamiut* in 2017, further imagery was obtained from this area that was previously identified as of interest. Subsequently, the benthic video sled was deployed during two *RV Sanna* research cruises in October 2018 and May 2019, dedicated to the Toqqusaq Bank area. Video imagery from these cruises and a smaller number of video stations obtained opportunistically on other cruises (*RV Paamiut* and *Helga Maria*) were reviewed. This highlighted that a subset of stations appeared to show structurally complex habitats with higher densities of cauliflower corals, VME indicator taxa and other structure forming taxa than had been observed elsewhere. Constraints prevent a comprehensive characterisation of all the habitats in this area using all available imagery. Instead the subset of stations (*n* = 18) identified in the review were selected for further analysis. The selected stations are at depths from 274 to 585 m, on the continental slope on the western edge of the Toqqusaq Bank, in Greenlandic waters (NAFO Areas 1C+D), immediately adjacent to the offshore Greenland halibut fishery (Figure 5.1). This chapter provides a quantitative description of these previously unknown habitats.

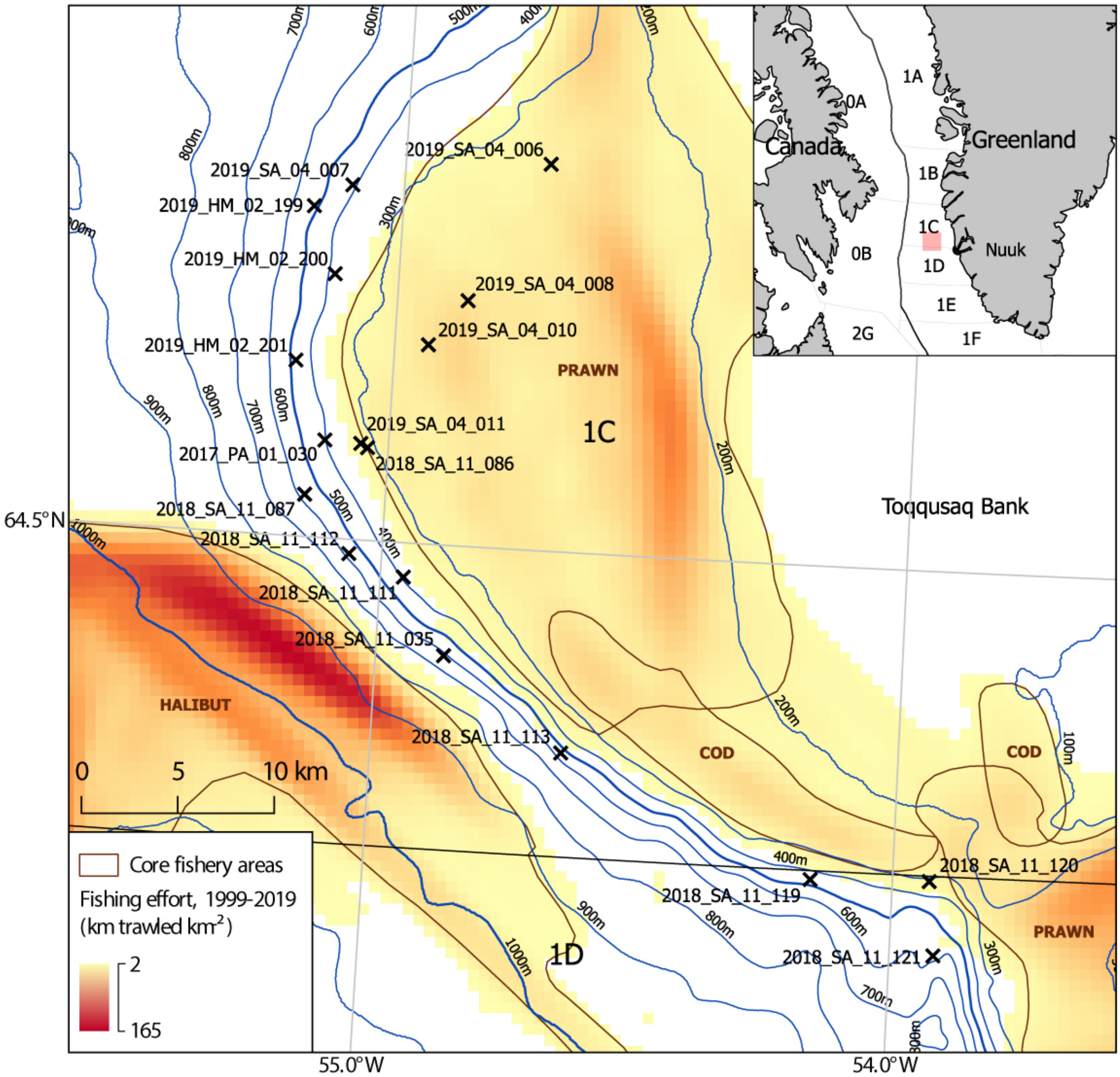


Figure 5.1 Map of study area, showing the continental slope of the Toqqusaq Bank, west Greenland. The locations of benthic video sled survey stations (n=18) are indicated. NAFO Divisions are drawn (black lines). Video sled stations (X) are drawn at the ship's position at the middle of each tow. The video sled station name indicates the year, vessel, cruise number and station number (Year_Ship_Leg_Station number). The two letter ship codes indicate the *RV Paamiut* (PA), *RV Sanna* (SA) or *MT Helga Maria* (HM). Fishing effort is based on haul by haul logbook data from 1999-2019, used to determine the distance trawled per unit area (km trawled km^2). The core target areas of halibut, prawn and cod trawling effort are annotated (brown), based on visual review of the effort dataset. This is intended to be indicative.

5.2. Study area

The study area lies on the west Greenland continental slope, where the shallower Davis Strait separates the deeper northern Labrador Sea and Baffin Bay basins. The continental shelf in west Greenland can extend over 100 km offshore, with numerous deep troughs and shallow banks (Jørgensen *et al.*, 2018). Historically, the banks in West Greenland have been important fishing grounds for cod and more recently for prawns. The areas trawled by the offshore halibut fishery are adjacent to the bottom of the slope descending from such banks. Monitoring studies suggest that hydrographic conditions can stimulate high pelagic primary production across the edge of these banks (Poulsen and Reuss, 2002, Juul-Pedersen *et al.*, 2015). Water mass characteristics are determined by the strength and mixing of two currents, the warm saline Irminger Current and colder, fresher East Greenland current (Myers *et al.*, 2007). Icebergs scour the seabed to maximum depth of 600 m and deposit terrigenous sediments and dropstones (Gutt, 2002, Streuff *et al.*, 2017). The diversity of topographic features and oceanographic influences results in diverse and heterogeneous benthic communities (Gougeon *et al.*, 2017).

The Toqqusaq Bank, adjacent to the southern area of the halibut fishery, is an example of one of these productive banks targeted by demersal trawling. Specifically, the top of Toqqusaq Bank is subject to trawling by the MSC certified West Greenland Coldwater Prawn Fishery, which targets areas on the continental shelf and slope (200 - 500 m) (Cappell *et al.*, 2018). There is also additional fishing pressure from an emerging cod (*Gadus morhua*) fishery. Following the collapse of the west Greenland offshore cod fishery in the early 1990s, a management plan introduced a closure in 2014 to allow recovery. This was overturned and a Total Allowable Catch (TAC) of 5,000 tonnes was set for 2015-2018, inclusive (ICES, 2019a). In 2018, 4,187 t was landed by trawlers (61%) and longliners (39%), half of which (2,666 t) was from NAFO 1C/D (ICES, 2019b), with the main fishing grounds being the Toqqusaq Bank, at the top of the slope (~200 - 300 m) centred on the NAFO 1C/D boundary (Figure 5.1) (ICES, 2019a). The slope itself has not been subject to trawling, whilst at the base of the slope lies the southern area of the halibut fishery, including the MSC certified Greenlandic and German components of the fleet, operating at 800 - 1,500 m (Cappell *et al.*, 2017, Cook *et al.*, 2019).

5.3. Results

A total of 18 video sled stations were selected, from which 1,239 images were extracted for annotation (Table 5.1). This represents a total area analysed of ~10,000 m^2

Table 5.1 Benthic video sled stations on the continental slope of the Toqqusaq Bank, west Greenland. The following are provided for each station: the position (ship's location at the midpoint of tow), mean depth (m), duration of tow (minutes), length of tow (m), number of images extracted from the video and total area of the extracted images (m^2). The duration of the tow (minutes) is provided along with the number of images extracted for analysis from the video. The station name indicates the year, vessel, cruise number and station number (Year_Ship_Leg_Station number). The two letter ship codes indicate the *RV Paamiut* (PA), *RV Sanna* (SA) or *MT Helga Maria* (HM).

Station	**Position**	**Mean depth (m)**	**Duration (mins)**	**Tow length (m)**	**Images**	**Area in images (m^2)**
2017_PA_01_030	64.580 °N, 55.122 °W	401	15	402	23	189
2018_SA_11_035	64.409 °N, 54.871 °W	446	15	415	44	362
2018_SA_11_086	64.576 °N, 55.040 °W	321	46	1,500	131	1,078
2018_SA_11_087	64.535 °N, 55.154 °W	585	48	1,835	133	1,095
2018_SA_11_111	64.472 °N, 54.956 °W	391	30	1,129	77	634
2018_SA_11_112	64.488 °N, 55.062 °W	579	30	978	81	667
2018_SA_11_113	64.335 °N, 54.638 °W	561	30	982	84	691
2018_SA_11_119	64.243 °N, 54.155 °W	415	30	975	110	905
2018_SA_11_120	64.246 °N, 53.930 °W	314	30	915	107	881
2018_SA_11_121	64.185 °N, 53.917 °W	557	15	481	37	305
2019_HM_02_199	64.771 °N, 55.171 °W	537	19	634	59	486
2019_HM_02_200	64.717 °N, 55.123 °W	368	15	416	39	321
2019_HM_02_201	64.644 °N, 55.187 °W	482	17	490	22	181
2019_SA_04_006	64.817 °N, 54.721 °W	274	17	561	60	494
2019_SA_04_007	64.790 °N, 55.100 °W	390	15	485	60	494
2019_SA_04_008	64.702 °N, 54.865 °W	287	15	539	63	518
2019_SA_04_010	64.663 °N, 54.936 °W	293	15	696	53	436
2019_SA_04_011	64.579 °N, 55.053 °W	315	15	488	56	461
Totals			417	13,921	1,239	10,198

5.3.1. Fauna observations

In this chapter, for practical reasons, annotation was restricted to those taxa that form structurally significant/complex components of the habitats and thus are of relevance to criteria iv) ('structural complexity) of the FAO's VME definition (FAO, 2009). The taxa selected for annotation are shown in Table 5.2. Genera of Nephtheidae (*sensu lato*) found in West Greenland are *Gersemia, Duva*, *Drifa*, and *Pseudodrifa* (Jørgensen *et al.*, 2013). The current taxonomy in the World Register of Marine Species (WoRMS) lists all these as belonging to the family Nephtheidae. Although the genus *Gersemia* is currently still formally placed in Nephtheidae, it is widely regarded as Alcyoniidae (McFadden *et al.*, 2006, Williams, 2013). These genera are hard to distinguish from imagery (Buhl-

Mortensen *et al.*, 2019) and so throughout this study have been treated as Nephtheidae (*sensu lato*) and collectively referred to as cauliflower corals.

Table 5.2 Taxa selected for image annotation. For each taxon NAFO (NAFO, 2012) and NEAFC (NEAFC, 2014) guidance was consulted to determine if the taxa is considered a VME indicator.

Common name(s)	**Phylum**	**Taxon/annotation label**	**VME indicator?**	
			NAFO	**NEAFC**
Bryozoans	Bryozoa	Alcyonidiidae* (*Alcyonidium gelatinosum*)	No	No
Anemones	Cnidaria	Actiniaria	No	No
Gorgonians	Cnidaria	Acanthogorgiidae	Yes	Yes
		Paragorgiidae	Yes	Yes
		Plexauridae	Yes	Yes
		Primnoidae	Yes	Yes
Soft corals	Cnidaria			
Mushroom soft corals		Alcyoniidae	No	No
Cauliflower corals		Nephtheidae	No	Yes
Feather stars	Echinodermata	Antedonidae	Yes†	Yes
Sponges	Porifera	Axinellidae	Yes	Yes
		Geodiidae	Yes	Yes
		Polymastiidae	Yes	Yes
		Rossellidae	Yes	Yes
		Porifera massive		
		Porifera branching		
		Porifera encrusting		

* It is thought that all annotations made using this label were of *Alcyonidium gelatinosum*

† Only *Trichometra cubensis* from the Antedonidae family

A total of 44,035 annotations of the selected fauna were made. The most numerous annotations were anemones (15,531) and cauliflower corals (11,633). The anemones appeared to be predominantly Hormathiidae. The least frequent were gorgonians, with just 250 annotations of Acanthogorgiidae, Paragorgiidae, Plexauridae and Primnoidae combined. The mean (Table 5.3), minimum and maximum (Table 5.4) densities of annotated taxa are shown for each station, aggregated to a parent label where appropriate. Cauliflower corals were the only coral present at all stations, with a maximum density of 9.36 m^{-2}. The maximum density of any coral taxa was mushroom soft corals 13.37 m^{-2}. The maximum density of any taxa was anemones 18.23 m^{-2}.

Table 5.3 Observed densities of taxa at each station. The mean (standard deviation) densities (individuals or colonies m^{-2}) are based on the number of annotations from all images for each station, adjusted for the area of the field of view in the images (8.23 m^{2}). A dash (-) indicates the taxon was not observed in the images extracted from the video obtained at that station. Gorgonians includes the annotation labels Acanthogorgiidae, Paragorgiidae, Plexauridae and Primnoidae. Sponges includes the annotation labels Axinellidae, Geodiidae, Polymastiidae, Rossellidae, Porifera massive, Porifera branching and Porifera encrusting.

Station	**Mean (standard deviation) density, individuals or colonies m^{-2}**						
	Bryozoan *(A. gelatinosum)*	Anemones	Gorgonians	Mushroom soft corals	Cauliflower corals	Feather stars	Sponges
2017_PA_01_030	0.11 (0.17)	0.64 (0.51)	0.01 (0.03)	-	2.92 (1.25)	0.08 (0.17)	1.91 (0.70)
2018_SA_11_035	0.06 (0.10)	0.03 (0.07)	0.25 (0.23)	0.00 (0.02)	1.74 (0.91)	0.01 (0.03)	0.72 (0.50)
2018_SA_11_086	0.14 (0.18)	8.92 (3.75)	0.00 (0.03)	-	0.65 (0.71)	0.00 (0.01)	0.42 (0.37)
2018_SA_11_087	0.04 (0.08)	0.18 (0.29)	0.03 (0.14)	0.89 (2.14)	2.41 (1.65)	1.69 (2.08)	0.70 (0.63)
2018_SA_11_111	0.06 (0.13)	0.21 (0.18)	0.05 (0.13)	-	2.30 (1.17)	0.02 (0.09)	1.06 (0.63)
2018_SA_11_112	-	0.07 (0.12)	0.05 (0.17)	0.88 (1.57)	0.67 (0.85)	1.42 (2.50)	0.41 (0.34)
2018_SA_11_113	0.01 (0.06)	0.05 (0.08)	0.04 (0.13)	0.03 (0.13)	0.20 (0.28)	0.09 (0.22)	0.78 (0.53)
2018_SA_11_119	0.00 (0.02)	0.01 (0.03)	0.00 (0.03)	0.01 (0.04)	0.28 (0.66)	0.05 (0.13)	1.60 (0.68)
2018_SA_11_120	2.26 (1.68)	0.01 (0.04)	0.00 (0.05)	-	2.18 (1.98)	0.00 (0.02)	0.77 (0.60)
2018_SA_11_121	-	0.00 (0.02)	0.03 (0.08)	0.02 (0.10)	0.06 (0.12)	0.54 (0.63)	0.88 (0.52)
2019_HM_02_199	0.01 (0.04)	0.14 (0.25)	-	0.01 (0.06)	0.04 (0.10)	0.35 (0.79)	0.48 (0.43)
2019_HM_02_200	0.01 (0.03)	0.39 (0.29)	0.02 (0.05)	-	2.30 (1.69)	0.01 (0.03)	1.10 (0.91)
2019_HM_02_201	-	0.03 (0.09)	0.01 (0.04)	-	0.96 (0.86)	0.53 (0.79)	0.75 (0.60)
2019_SA_04_006	-	0.01 (0.04)	-	-	0.10 (0.12)	-	1.45 (0.77)
2019_SA_04_007	0.02 (0.06)	0.23 (0.26)	-	-	2.31 (1.91)	0.02 (0.05)	0.98 (0.65)
2019_SA_04_008	1.50 (1.01)	0.01 (0.03)	-	-	0.03 (0.08)	-	0.86 (0.47)
2019_SA_04_010	0.00 (0.02)	0.00 (0.02)	-	-	0.24 (0.27)	-	0.70 (0.45)
2019_SA_04_011	-	10.94 (2.85)	-	-	1.37 (0.61)	0.00 (0.02)	0.37 (0.31)

Table 5.4 The minimum and maximum densities of taxa observed within a single image for each station. Minimum and maximum values (individuals or colonies m^{-2}) of taxa observed within a single image for each station, based on the number of annotations adjusted for the area of the field of view (8.23 m^2). A dash (-) indicates the taxon was not observed in the images at that station. Gorgonians includes the annotation labels Acanthogorgiidae, Paragorgiidae, Plexauridae and Primnoidae. Sponges includes the annotation labels Axinellidae, Geodiidae, Polymastiidae, Rossellidae, Porifera massive, Porifera branching and Porifera encrusting.

Station	**Minimum and maximum density within a single image, individuals or colonies m^{-2}**						
	Bryzoan *(A. gelatinosum)*	Anemones	Gorgonians	Mushroom soft corals	Cauliflower corals	Feather stars	Sponges
2017_PA_01_030	0.00-0.49	0.12-1.94	0.00-0.12	-	0.97-6.32	0.00-0.73	0.49-3.40
2018_SA_11_035	0.00-0.36	0.00-0.24	0.00-0.85	0.00-0.12	0.12-3.89	0.00-0.12	0.00-2.79
2018_SA_11_086	0.00-0.85	0.85-18.23	0.00-0.24	-	0.00-5.47	0.00-0.12	0.00-2.19
2018_SA_11_087	0.00-0.36	0.00-2.43	0.00-1.22	0.00-13.37	0.00-8.63	0.00-8.38	0.00-4.01
2018_SA_11_111	0.00-0.61	0.00-0.85	0.00-0.73	-	0.12-4.62	0.00-0.73	0.12-2.55
2018_SA_11_112	-	0.00-0.49	0.00-1.09	0.00-6.80	0.00-3.52	0.00-11.66	0.00-1.22
2018_SA_11_113	0.00-0.49	0.00-0.36	0.00-0.97	0.00-0.97	0.00-1.34	0.00-1.09	0.00-2.92
2018_SA_11_119	0.00-0.12	0.00-0.12	0.00-0.24	0.00-0.24	0.00-6.56	0.00-0.85	0.24-3.40
2018_SA_11_120	0.00-7.90	0.00-0.24	0.00-0.49	-	0.00-8.38	0.00-0.12	0.00-3.40
2018_SA_11_121	-	0.00-0.12	0.00-0.36	0.00-0.49	0.00-0.49	0.00-2.07	0.12-1.94
2019_HM_02_199	0.00-0.24	0.00-1.46	-	0.00-0.36	0.00-0.49	0.00-4.13	0.00-1.82
2019_HM_02_200	0.00-0.12	0.00-1.22	0.00-0.24	-	0.00-5.83	0.00-0.12	0.00-5.59
2019_HM_02_201	-	0.00-0.36	0.00-0.12	-	0.00-2.67	0.00-2.19	0.00-1.70
2019_SA_04_006	-	0.00-0.12	-	-	0.00-0.36	-	0.24-3.28
2019_SA_04_007	0.00-0.36	0.00-1.34	-	-	0.00-9.36	0.00-0.24	0.24-3.65
2019_SA_04_008	0.00-5.22	0.00-0.12	-	-	0.00-0.36	-	0.12-2.31
2019_SA_04_010	0.00-0.12	0.00-0.12	-	-	0.00-1.34	-	0.00-1.82
2019_SA_04_011	-	6.56-16.28	-	-	0.24-3.40	0.00-0.12	0.00-1.22

There were a number of different distinct assemblages, often characterised by a high density of one particular taxon. Examples of the differing assemblages showing high densities of particular taxa are shown (Figure 5.2). Assemblages dominated by cauliflower corals on rocky substrates, with and without boulders, up to a maximum density of 9.36 m^{-2} (Figure 5.2 A), were seen at multiple stations, with varying densities of feather stars, anemones and sponges also present. In some cases a similar assemblage was seen, in terms of species composition, but instead dominated by high densities of anemones (Figure 5.2 B), feather stars (Figure 5.2 C) and sponges (Figure 5.2 D). Patches dominated by mushroom soft corals, with other megafauna absent or occasional, were on observed rocky ground, where the substrate was largely homogenous gravel (<4 cm) (Figure 5.2 E). This assemblage was common in images from stations 2018_SA_11_087 and 2018_SA_11_112, with a maximum observed mushroom soft coral density of 13.37 m^{-2} (Table 5.4). Assemblages dominated by the bryozoan *Alcyonidium gelatinosum,* sometimes with sponges present, were seen on both rocky and muddy substrates to a maximum density of 7.90 *A. gelatinosum* m^{-2} (Figure 5.2 F).

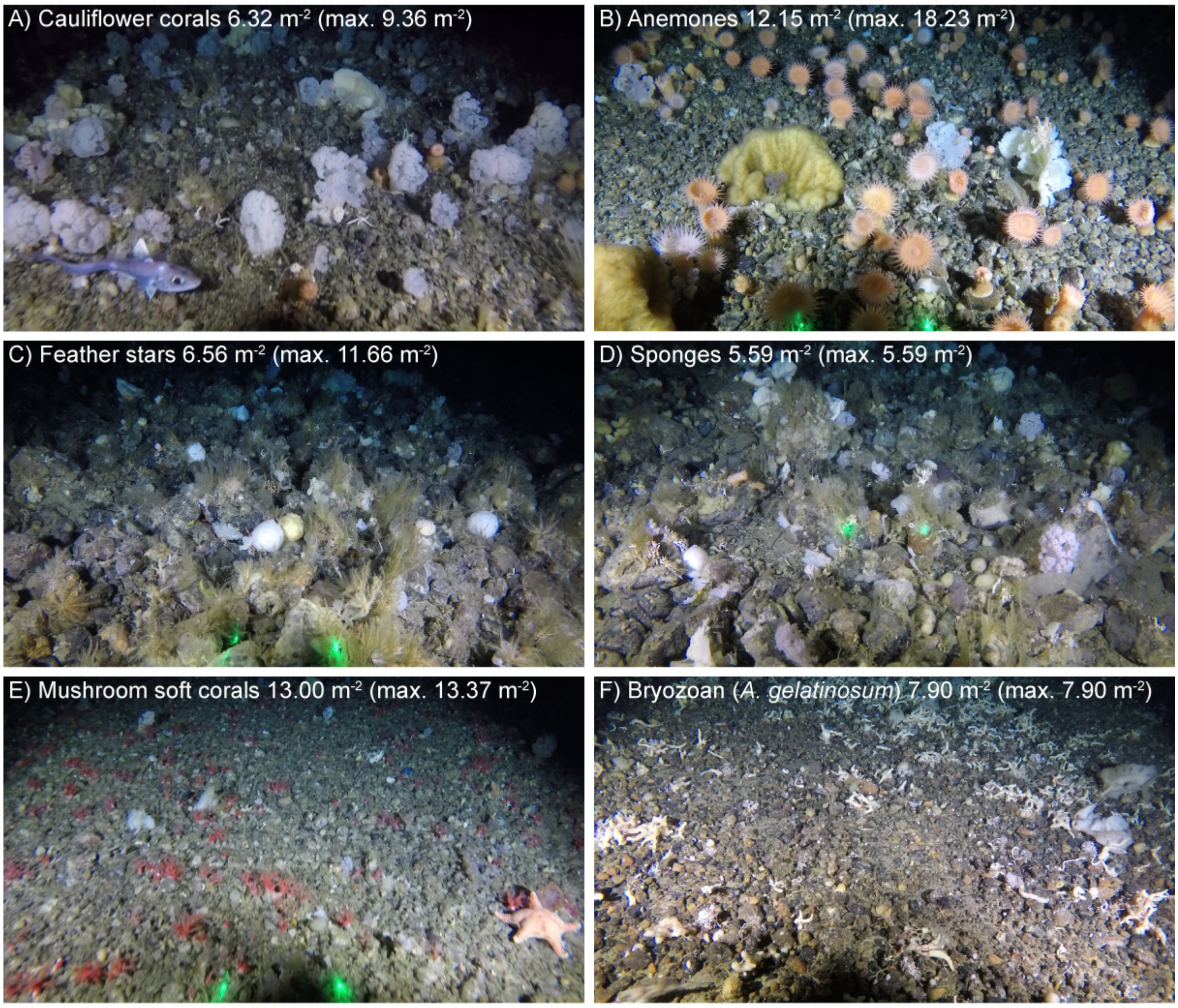


Figure 5.2 Examples of different benthic fauna assemblages, with high densities of specific taxa. Showing assemblages with high densities of: A) Cauliflower corals; B) Anemones; C) Feather stars; D) Sponges; E) Mushroom soft corals; and F) Bryozoan (*A. gelatinosum*). Images were selected for illustrative clarity. The density of the highlighted taxa within each image is reported (along with the maximum observed density in all images for reference). Where present, laser dots (green) are 20 cm apart.

There was considerable heterogeneity in the abundance and composition, both within and between stations (Table 5.3, Table 5.4, Figure 5.2, Figure 5.3). Cauliflower corals, anemones and sponges were present at all stations, whilst the bryozoan *A. gelatinosum*, gorgonians, feather stars and mushroom soft corals were not observed at all stations. Comparing those stations where taxa were present, the mean density varied by at least an order of magnitude in each taxon, with the exception of sponges, whose density was more evenly distributed (Table 5.3). There was also considerable variation in densities within stations, demonstrated by the range in minimum and maximum values (Table 5.4). This indicates an inherent patchiness, which is illustrated by visualising data from 2018_SA_11_087 (Figure 5.3). Areas where the assemblage is dominated by cauliflower corals, feather stars and sponges (Figure 5.3 A and C) are interspersed by patches of mushroom soft corals (Figure 5.3 B) where other taxa are absent.

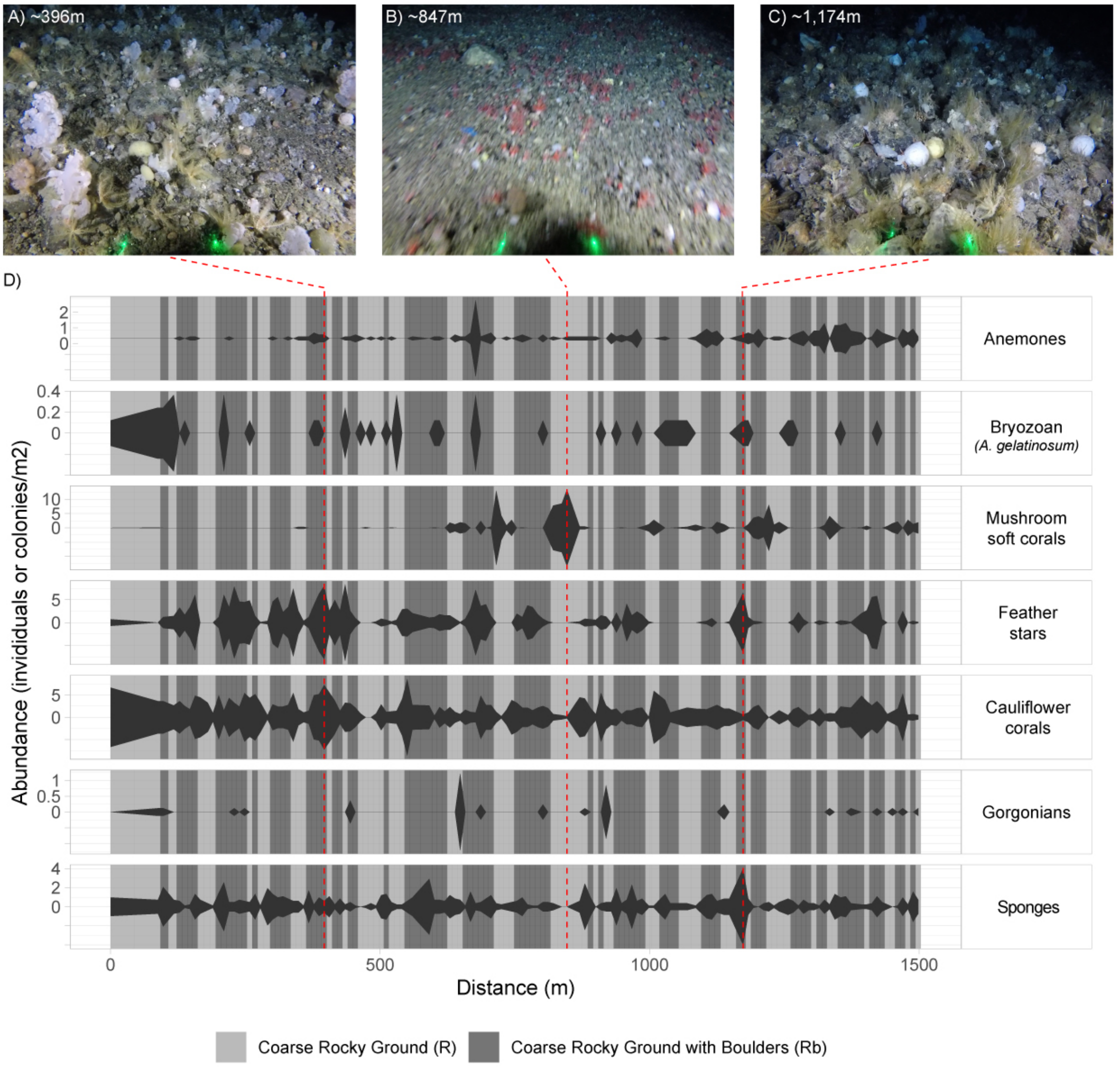


Figure 5.3 Kite diagram showing variation in faunal abundance and substrate across an example station. The variation in faunal abundance and substrate is shown for station 2018_SA_11_087, based on fauna and substrate annotations of images sampled from the video. The width of kite is determined by the observed abundance in the image sampled at that distance along the tow. Distance is based on the speed of the vessel and the time elapsed from touchdown. The background is shaded according to substrate observed in each image. Substrate type and faunal abundance is interpolated between images to produce an illustrative representation. The example images A), B) and C) are included to illustrate the variation across the station as described by D). The left and right extremities of example images have been cropped and thus do not display the full field of view (FOV). Laser dots (green) are 20 cm apart.

Significant positive and negative associations between pairs of taxa were observed (Figure 5.4). Cauliflower corals were positively associated with feather stars, gorgonians and anemones, which were more positive associations than any other taxa. Co-occurrence of cauliflower corals with feather stars and anemones was readily apparent in the imagery (Figure 5.2 A-D).

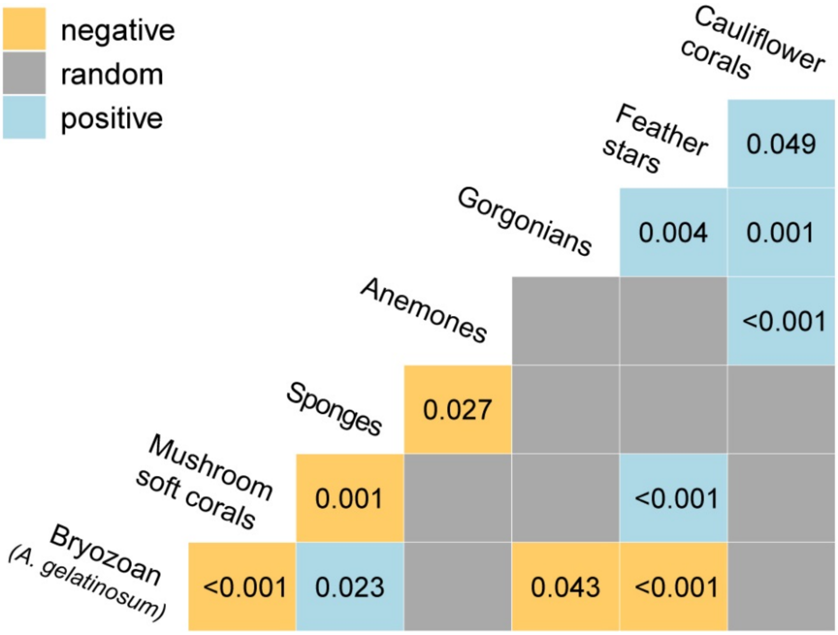


Figure 5.4 Heat map showing the positive and negative associations between taxa. Associations between taxa were determined by a probabilistic co-occurrence model (Veech, 2013). For each pair the observed frequency of co-occurrence within images (*n* = 1,239) is significantly large and greater than expected (positive association), significantly small and less than expected (negative association), or not significantly different and approximately equal to expected (random association). Associations are considered significant where the probability of the observed frequency of co-occurrence is <0.05 were the taxa distributed independently of one another. *P*-values are provided for significant associations.

There were other taxa, which could not be consistently identified and/or annotated in the imagery, but contributed to the structural diversity of the habitats. They can be observed in some sections of video and where abundant, clearly form a significant component of this habitat. Specifically this includes, calcified bryozoans, from the families Celleporidae, Flustridae, Horneridae, Myriaporidae and Phidoloporidae, as well as hydrozoans from the families Aglaopheniidae and Sertulariidae.

5.3.2. Substrate observations

The dominant substrates were coarse rocky ground, with and without boulders (Rb and R). These were the only substrates identified in 11 of the stations (*n* = 18) (Figure 5.5). Conversely, gravelly mud substrates, with and without boulders (GMb and GM) were the only substrates in just two of the stations. Boulders (b) were present at all the stations (Figure 5.5) and were typically observed intermittently during the course of a tow (Figure 5.3).

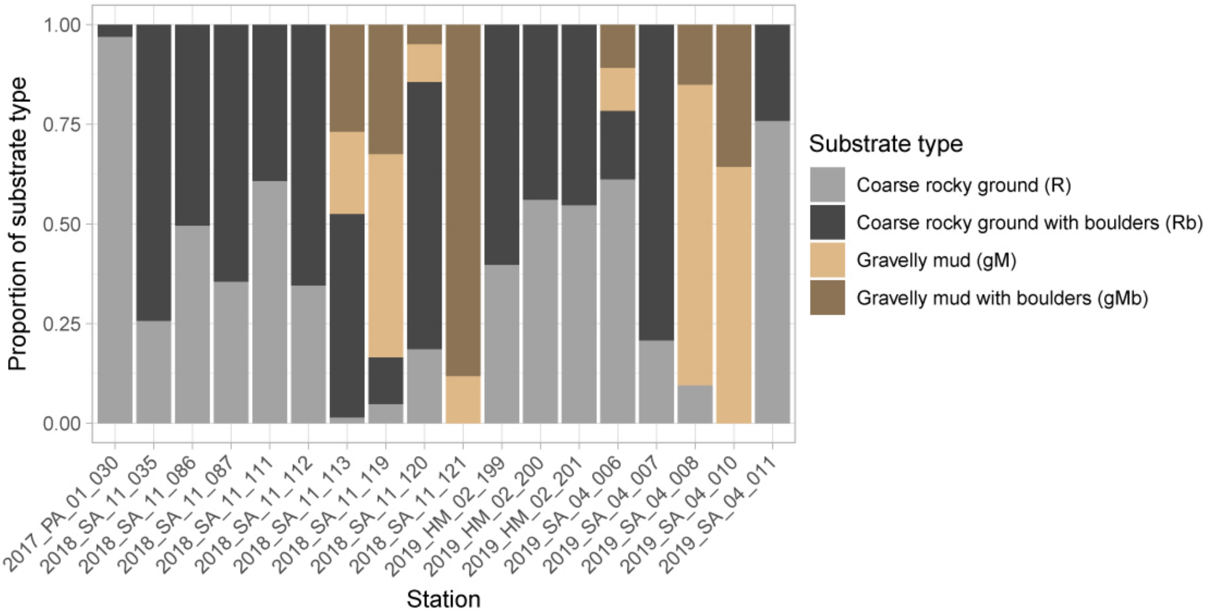


Figure 5.5 Proportion of each substrate type at stations. Substrate classes are based on the revised EUNIS Habitat Classification (Davies *et al.*, 2004), as adapted by Gougeon *et al.* (2017) and further modified for the purposes of this study.

The number of annotations of some taxa varied with substrate. Anemones, mushroom soft corals, feather stars and cauliflower corals were more prevalent on hard substrates (R and Rb) (Figure 5.6). Habitats dominated by cauliflower corals and or feather stars were typically found where there was a heterogeneity in size of the rocky material, with a combination of gravel, cobbles and boulders (Figure 5.2 A,C and D). Conversely, patches of mushroom soft corals appeared to only be found on more uniform gravel substrates (Figure 5.2 E). These differences in the size of rocky material were not quantified, with the exception of differentiating between the presence and absence of boulders.

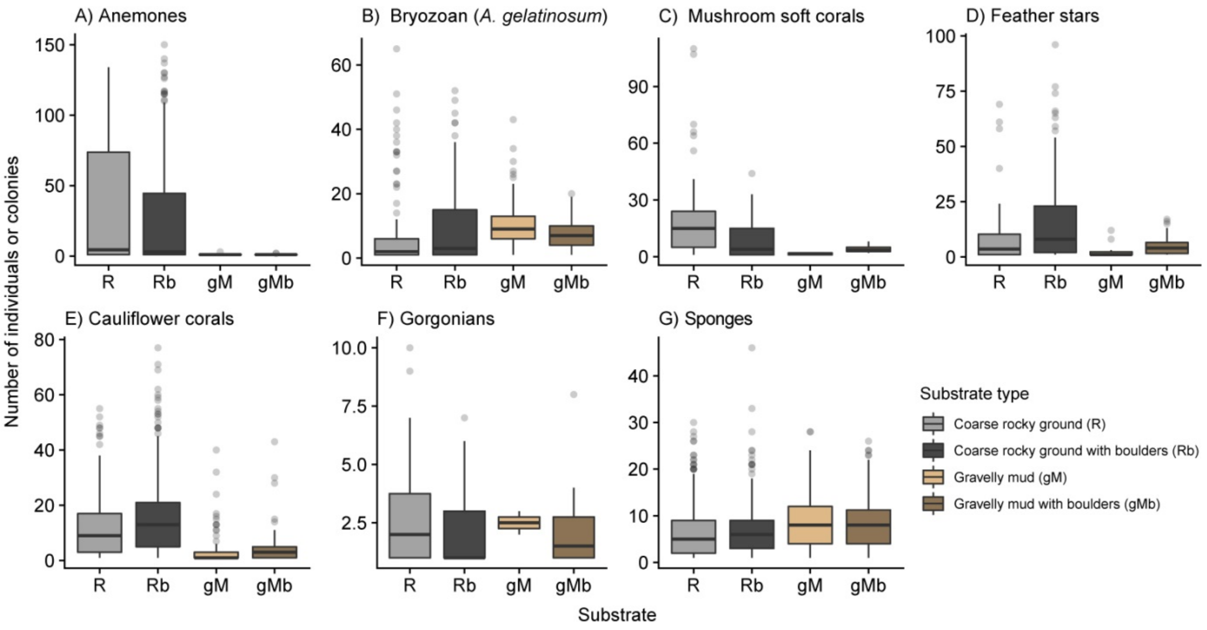


Figure 5.6 The number of taxa observations by substrate. Box-whisker plot showing the number of annotations of seven taxa (A-G) in images, which were annotated with one of four classes of substrate type. Substrate classes are based on the revised EUNIS Habitat Classification (Davies *et al.*, 2004), as adapted by Gougeon *et al.* (2017) and further modified for the purposes of this study.

5.4. Discussion

Analysis of the imagery from 18 stations showed heterogeneity in the substrates and communities on the slope of the Toqqusaq Bank. This patchiness was observed within stations, with notable variation across single video sled tows, as well as between stations. Several distinct assemblages were observed; in some cases the assemblage was dominated by a single taxa forming a patch of habitat, with anemone fields, mushroom soft coral beds and areas dominated by the bryozoan *A. gelatinosum*. The assemblages that appeared to be most structurally complex and diverse, were those characterised by high densities of cauliflower corals, feather stars and sponges. In such assemblages, the combined effect of observed densities is a habitat with considerable structural heterogeneity, found on coarse rocky substrates. Intuitively, substrate likely plays an important part in determining the assemblage present. Previously, Baker *et al.* (2012) found that substrate type had a clear influence on the occurrence and abundance of deep-sea corals in the Labrador Sea. They reported that the greatest diversity was seen in video transects with a mosaic of substrate types. Many of the taxa selected for annotation in this study are sessile and require a hard substrate for attachment; for example, it is known that most soft corals and gorgonians require hard substrates for larval settlement and growth (Pérez *et al.*, 2016). Some taxa (anemones, mushroom soft corals, feather stars and cauliflower corals) showed a clear preference for the coarse rocky substrates, whilst annotations of other taxa were more evenly distributed across the substrate classes.

5.4.1. Defining soft coral gardens

Habitat classification systems support conservation goals by providing universally understood definitions that can be used to describe and map the distribution of habitats, which is a necessary pre-requisite for spatial management (Howell *et al.*, 2010). The term 'coral garden' was first applied to dense aggregations of non-reef forming corals, dominated by gorgonians (Bullimore *et al.*, 2013). A formal definition offered by the Oslo and Paris Conventions (OSPAR) applies to a much wider range of cold-water corals on both hard and soft substrates (ICES, 2007, OSPAR Commission, 2010).

> *"The main characteristic of a coral garden is a relatively dense aggregation of colonies or individuals of one or more coral species. Coral gardens can occur on a wide range of soft and hard seabed substrata. For example, soft-bottom coral gardens may be dominated by solitary scleractinians, sea pens or certain types of bamboo corals, whereas hard-bottom coral gardens are often found to be dominated by gorgonians, stylasterids, and/or black corals."* (OSPAR Commission, 2010)

This definition captures a range of different habitats and does not therefore represent a single ecological unit (Bullimore *et al.*, 2013).

In their cold-water coral classification scheme, Davies *et al.* (2017) proposes a biotope consisting of cold-water Alcyoniina on hard/mixed substrate, specifically, Nephtheidae (cauliflower corals) and *Anthomastus* sp. (mushroom soft coral, family: Alcyoniidae). Whilst the proposed biotope refers to *Anthomastus* sp., it could be interpreted more broadly as mushroom soft corals, given: i) the known diversity of mushroom soft coral species in the North Atlantic (Molodtsova, 2013); ii) the taxonomic revision of genera in Alcyoniidae; and iii) the fact that close relatives have similar gross morphologies and likely occupy similar niches. In the present study, the imagery does not allow greater taxonomic resolution with regards to mushroom soft corals. The supplementary material in the Davies *et al.* (2017) classification scheme describes the cold-water Alcyoniina on hard/mixed substrate biotope as being known from depths of 600 m in Iceland and Norway (Guillaumont *et al.*, 2016) and provides an example image. The example image is comparable to the coral garden habitat described here. The NEAFC consider cauliflower corals to be a VME indicator taxa for a VME habitat type described as 'cauliflower coral fields', which is listed as a soft-bottom habitat (NEAFC, 2014).

There is no accepted quantitative definition of soft coral gardens or coral gardens more broadly. The definition suggested by Rogers *et al.* (2015) proposes that to qualify the density of coral garden species must exceed 10 times the background level:

> *"Coral communities formed by one or more of the coral groups Scleractinia, Octocorallia, Antipatharia or Stylasteridae where the density of colonies reaches >10 times background densities, is usually >0.1 colonies per m^2, and where there is an enhanced diversity of associated*

> *fauna or a distinct associated faunal community compared to the background benthic, epibenthic and epizoozoan fauna." (Rogers* et al.*, 2015)*

Practically, this relies on a good understanding of the background level, which is rarely the case, including in this context. Further, since coral gardens by their nature are comprised of multiple species, it is not clear whether densities should be considered individually or the combined density of the species present compared with combined background level. Thus, this study must rely on the application of 'expert' judgement to make a determination and in doing so provide a quantitative description that can be used to inform the development of revised definitions in the future. This judgement is guided by the indicative densities in the description of the broader coral garden habitat type (ICES, 2007, OSPAR Commission, 2010). Specifically, these suggest colony densities of 1-7 m^{-2} generally, 0.5-2 m^{-2} for small gorgonians (Acanthogorgiidae and Primnoidae) and 0.01-0.02 m^{-2} for larger gorgonians (Paragorgiidae). It has been suggested that these ranges can be used to differentiate between comparatively sparse and dense coral gardens (ICES, 2007). These indicative density thresholds are not accompanied by a requirement for the density to be present over a minimum area, which would be a useful additional guidance, pending consensus among the scientific community.

Cauliflower corals are the most abundant corals in the study area. They make a significant contribution to structural complexity and exhibited more positive associations than any other taxa. They are therefore an obvious candidate to serve as an indicator species for this soft coral garden habitat. A mean density threshold of 1 colony m^{-2} is applied to determine those stations where the soft coral garden habitat is present. The lower bound of the generic indicative density suggested by OSPAR is used, as it is recognised that the study area is inherently patchy. To use a higher threshold would potentially exclude stations with patches of cauliflower corals at significant densities, indicating areas of coral garden. Excluding these would not recognise their presence in an ecosystem displaying a mosaic nature, with patches of soft coral garden present among differing substrates and assemblages. Those 8 out of 18 stations which meet this threshold are highlighted (Figure 5.7).

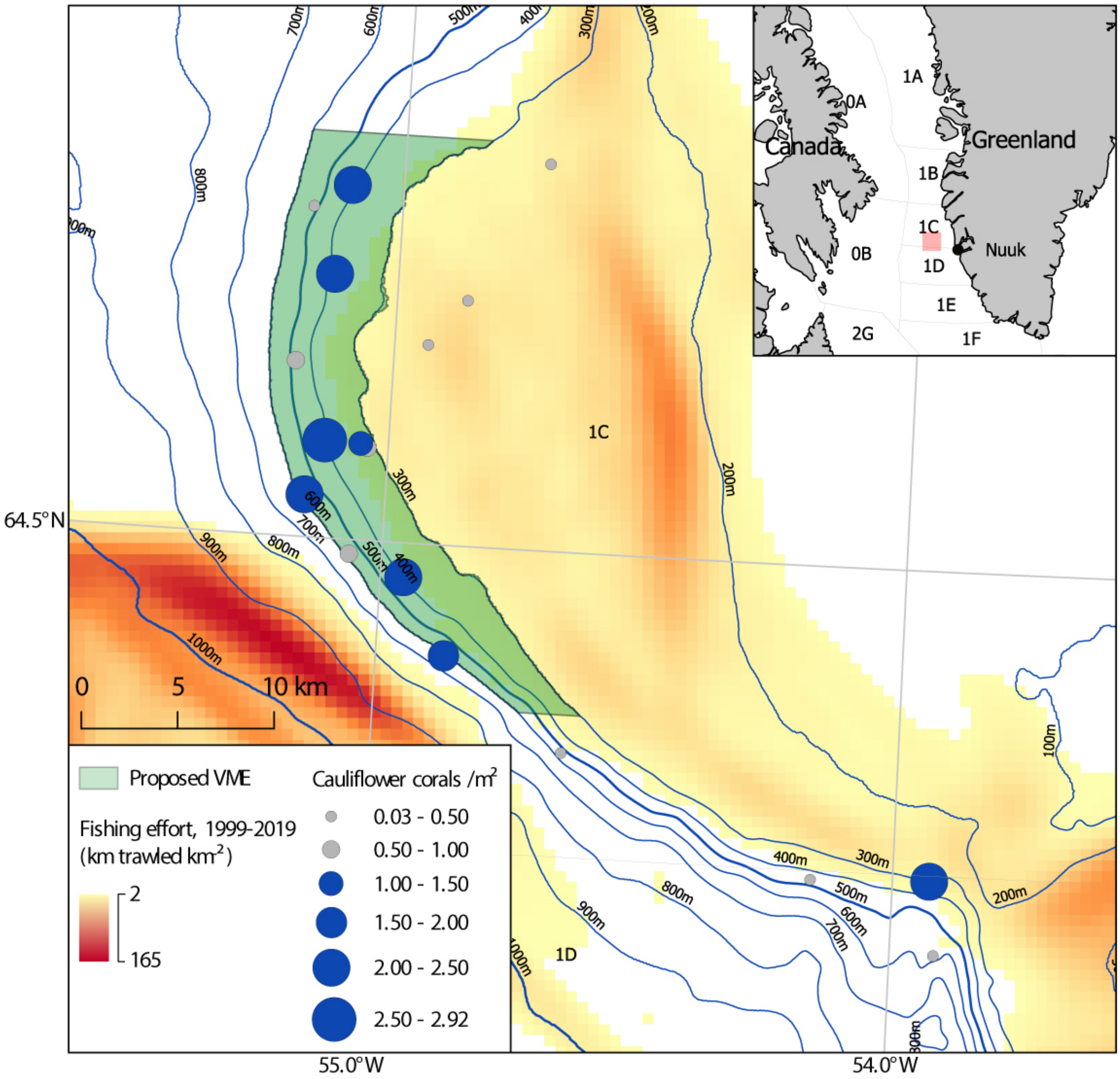


Figure 5.7 Map of the proposed soft coral garden vulnerable marine ecosystem (VME). Shows the proposed 486 km^2 soft coral garden vulnerable marine ecosystem (VME) (light green), on the continental slope of the Toqqusaq Bank, west Greenland. NAFO Divisions are indicated. The mean density of cauliflower coral colonies is shown (circles), with those stations exhibiting a density ≥1 m^2 highlighted in blue (<1 m^2 grey). Fishing effort is based on haul by haul logbook data from 1999-2019, used to determine the number of km trawled per km^2.

5.4.2. Does this soft coral garden constitute a Vulnerable Marine Ecosystem (VME)?

Soft coral gardens and cauliflower corals more generally are both recognised as VMEs and VME indicators respectively, by NEAFC, the RFMO for the Northeast Atlantic (NEAFC, 2014). Conversely, neither are considered a VME or indicator by NAFO, the RFMO for the Northwest Atlantic (NAFO, 2012). This apparent inconsistency could in theory reflect a fundamental difference in the nature of deep-sea benthic ecosystems in the Northwest Atlantic compared to those in the Northeast Atlantic, though no such rationale is provided by either RFMO. More likely, this is the product of differing interpretations of the VME definition by experts in separate RFMOs. This lack of coordination and harmonization between adjacent RFMOs has been noted by others (Bell *et al.*, 2019). Therefore here, direct reference is made to the underlying VME definition, with each criteria addressed in turn (FAO, 2009).

5.4.2.1. Uniqueness or rarity

There is no evidence to support recognition as a VME by virtue of the unique or rare criteria. The taxa observed have a wide distribution and are not known to be threatened globally. The rarity of the habitat is not known, but similar assemblages have been reported elsewhere in the North Atlantic. The true spatial extent within Greenlandic waters is not known, but it may well extend beyond the present study area along the continental slope.

5.4.2.2. Functional significance of the habitat

The soft coral garden habitat likely plays a functionally significant role, though this is not directly assessed here and only limited inferences can be made from the imagery. In general, more is known about gorgonians than cauliflower corals. Buhl-Mortensen and Mortensen (2005) reported finding 114 associated species and nearly 4,000 individuals on the 25 *Paragorgia arborea* and *Primnoa resedaeformis* colonies they sampled. Krieger and Wing (2002) observed 10 mega-faunal groups (rockfish, sea stars, nudibranchs, feather stars, basket stars, crabs, shrimps, snails, anemones, and sponges) associated with *Primnoa* spp., which was used to either prey on, suspension feed from, or provide protection. Cauliflower corals are known to host a variety of species. *Gersemia* spp. can be considered habitat-forming species, as the embryonic development of the basket stars (*Gorgonocephalus* spp.) may occur within the coral's tissues, with juveniles attached to the outside whilst feeding (Patent, 1970). As many as 118 small basket stars have been found on a single cauliflower colony (B. de Moura Neves, pers. comm.). Whilst not quantified, *Gorgonocephalus* spp. were observed on cauliflower corals in video and images in this study. The presence of cephalopods, decapods, Rajiformes and various fish were noted in images from this habitat. Grenadier fish (Macrouridae) and redfish (*Sebastes* spp.) were commonly encountered in videos and sampled images. Data from prawn stock assessment trawl and beam trawl surveys provides further insights into a rich community of benthic invertebrates associated with the observed soft coral garden habitat, see supplementary data in Long *et al.* (2020) (Appendix VII).

5.4.2.3. Fragility

The habitat should be considered fragile, as it is vulnerable to degradation by physical disturbance, especially trawling. The vulnerability of deep-sea gorgonians to trawling is well established (e.g. Freese *et al.*, 1999, Witherell and Coon, 2000). The largest and perhaps most vulnerable species present was *Paragorgia arborea*. The ability to retract and recover from acute local injury may render cauliflower corals less vulnerable to mechanical disturbance than other corals with rigid skeletons and unretractable colonies (Henry *et al.*, 2003). Nevertheless, these responses do not provide protection against removal. It has been noted that cauliflower corals are prone to incidental bycatch in emerging deep-sea fisheries (Devine *et al.*, 2019). Groundfish survey trawl data from the Grand Banks and Flemish Cap confirm that soft coral biomass was the largest component of bycatch and that abundance was significantly lower in previously trawled areas (Murillo *et al.*, 2010). In the Bering Sea, the biomass of *Gersemia* spp. has been found to be highest in untrawled areas (McConnaughey *et al.*, 2000). Similarly, Jørgensen *et al.* (2013) consider *Gersemia fruticosa , G. rubiformis, Drifa glomerata,* and *Duva florida* to be at 'high risk' from trawling and found the highest biomass outside trawled areas in the Barents Sea. In the imagery obtained here, the lowest densities of cauliflower corals were seen in those stations (2019_SA_006, 2019_SA_008 and 2019_SA_010) within the trawling footprint, with gorgonians and mushroom soft corals also being absent there. This supports the idea that the component taxa of this soft coral garden are vulnerable to trawling. It may be the case that this coral garden assemblage is only observed in the relatively narrow section of the continental slope that has not been subject to fishing pressure to date.

5.4.2.4. Life-history traits of component species that make recovery difficult

Slow growth and long-life are exhibited by component taxa of this habitat, rendering recovery slow. To date, studies on growth rates and longevity in deep-sea octocorals have focused on gorgonians (Pérez *et al.*, 2016), whereas cauliflower corals have received less attention, not least because of the challenges associated with measuring soft coral colonies. Sherwood and Edinger (2009) report gorgonian axial growth rates as little as 0.56 cm year^{-1} for *Paramuricea* spp., 1.62 cm year^{-1} for *Paragorgia arborea*, and 1.00 cm year^{-1} for *Primnoa resedaeformis*, with ages exceeding 100 years. Laboratory study of the larval and early growth of *G. fructicosa* and *D. florida* found post-settlement growth to be very slow, suggesting a 'sluggish recovery' following anthropogenic disturbance (Sun *et al.*, 2011). The authors note, however, that this may be partially offset by the small size at sexual maturity and the potential for disturbance to release planulae from fertile colonies that grow into viable offspring. A similar study with *Drifa* sp. and *D. glomerata* also suggested that early growth rates of primary polyps was extremely slow, with no budding of the primary polyps of *Drifa* sp. in 21 months (Sun *et al.*, 2010). Cordes *et al.* (2001) monitored *Heteropolypus ritteri* (mushroom soft coral; in the family Alcyoniidae; formerly in the genus *Anthomastus*) in the laboratory, finding slow initial growth became more rapid at intermediate size, before approaching an asymptote at 26 - 30 years. They observed that the slow growth and relative longevity was typical of other deep-sea organisms. Watling and Auster (2005) conclude that growth rates and patchy recruitment mean that recovery of alcyonacean communities following removal is likely to take a very long time.

5.4.2.5. Structural complexity

Perhaps the most compelling justification for consideration as a VME, provided by the imagery collected, is the structural complexity created by the biotic components of this habitat. The combined effect of all the taxa annotated, but especially cauliflower corals, feather stars, sponges and gorgonians, adds considerable structure at varying scales to the otherwise limited complexity of the coarse rocky substrates (Figure 5.8). Further structural complexity is added by the abundant bryozoans and hydrozoans that are present but were not quantified (Figure 5.8). As discussed above, these structures play a functional role in the ecosystems, for example by providing refugia and supporting filter feeding organisms, resulting in high diversity and abundance. These habitats are patchy in nature; denser areas of cauliflower corals are interspersed with other assemblages, for example, areas dominated by anemones (Figure 5.2 B) and mushroom soft corals (Figure 5.2 E). Similarly, substrates varied within and between stations, from coarse rocky ground to gravelly mud substrates. This mosaic nature and resulting variation in structural complexity on a larger spatial scale is likely to support greater diversity of species and functions.

Those highlighted stations (Figure 5.7) exhibiting the soft coral garden habitat, would appear to meet multiple criteria for a VME (FAO, 2009). Therefore it is proposed that this area be recognised as a VME.

Figure 5.8 Example image of the proposed soft coral garden vulnerable marine ecosystem (VME). From Station 2018_SA_11_087, at a depth of 585 m, on the continental slope of Toqqusaq Bank, west Greenland. Cauliflower corals, feather stars, gorgonians, sponges, anemones, brittle stars, hydrozoans and calcified bryozoans, are present. Laser dots (green) are 20 cm apart; the left hand dot is partially obscured.

5.4.3. Implications for management

It is widely recognised that spatial closures are the most effective method of avoiding serious adverse impacts on VMEs (Bell *et al.*, 2019). Executive Order No.4, 30 March 2017, Section 13, introduced by the Government of Greenland, makes provision for the closure of areas to bottom gears where VMEs are identified in Greenlandic waters (Government of Greenland, 2017). The soft coral garden habitat identified is immediately adjacent to the MSC certified cold-water prawn fishery (Cappell *et al.*, 2018) and Greenland halibut fishery (Cappell *et al.*, 2017, Cook *et al.*, 2019). This certification requires that measures are in place to ensure that fisheries do not cause serious or irreversible harm to VMEs (MSC, 2014). It should be acknowledged that the coarse rocky ground in the proposed VME area is not necessarily optimal for the prawn fishery and too shallow for the halibut fishery. Therefore, the most immediate threat maybe from the emerging cod fishery (ICES, 2019a), as the slope of the Toqqusaq Bank may be suitable ground for targeting cod. The soft coral garden habitat identified is also partially overlapped by a hydrocarbon exploration and exploitation licence, which is currently pending (Licence: No. 2019/02) (Government of Greenland, 2020).

A bounding polygon for this candidate VME is proposed, encompassing seven of the eight stations where the soft coral garden habitat was identified (Figure 5.7). These seven stations were spatially contiguous in the northern portion of the study area within a 60 km span of continental slope. In the southern portion of the study area, only one station (2018_SA_11_120) out of four exceeded the mean cauliflower corals density threshold (>1 m^2) used to determine the presence of the soft coral garden habitat. This suggests the soft coral garden habitat was not a dominant habitat there. On that basis, the southern portion of the study area was not included in the proposed VME area.

The depth range (314-585 m) of those eight stations where the soft coral garden habitat was found is used as the upper and lower boundary on the continental slope of the Toqqusaq Bank. For both pragmatic and precautionary reasons, this is rounded down to 300 m and up to 600 m. Bathymetric contours are used to form the eastern (300 m contour) and western (600 m contour) edges of the polygon. The latitudinal extent is determined by the latitude of the most northerly (2019_SA_04_007) and southerly (2018_SA_11_035) of these seven stations. A 5 km latitudinal buffer is added, rounded to the nearest minute (one nautical mile). The proposed VME area can be described as the area with depths of 300-600 m between 64˚50′ N and 64˚22′ N on the western edge of the Toqqusaq Bank. This 486 km^2 area spans ~60 km of the continental slope and is intended to be pragmatic from a spatial management perspective, whilst affording protection to known areas of this soft coral garden habitat.

The VME area proposed here is based on multiple, adjacent observations, which are sufficient to justify the introduction of spatial management measures. It is acknowledged that the data show that this soft coral garden habitat is also present towards the southern extremity of the study area at a single station. Thus patches of this habitat are present along at least 100 km^2 of continental slope. The true spatial range may well be greater, possibly extending a considerable distance along the continental slope of west Greenland. Management and future research should draw on other data, including unpublished GINR surveys (stock assessment trawl bycatch and beam trawls). Further research should address whether the VME area proposed in this study should be extended, especially in terms of its latitudinal extent. The role of fishing effort, substrate and other environmental variables should be subject to investigation, as one or more of these may explain the distribution of this habitat and abundance of its component species.

5.4.4. Limitations

A fundamental methodological decision in this Chapter was to annotate images sampled from stills rather than directly analyse videos. This was in part due to pragmatic constraints (time) but also provides greater scope for revision and further work on the images and annotations. However, it should be acknowledged that a considerable amount of data contained in the videos are therefore excluded. This impacts our understanding of the abundance of sparser (e.g. *Paragorgia arborea*) and mobile fauna, particularly fish, which are less likely to be sampled in images.

The nature of imagery means only certain taxa can be identified and limits the taxonomic resolution that can be obtained during annotation. A more complete taxa inventory based on unpublished beam trawl and stock assessment trawls from the proposed VME area is included for reference (Appendix VII). Efforts were made to annotate different sponge taxa and morphologies, but these were ultimately aggregated to achieve consistency. Aggregation of multiple taxa to a parent label, for example into ‘sponges’, results in a more general picture and does not allow more specific taxa associations with other taxa and substrates to be determined. The approach of annotating individuals or colonies means some taxa (e.g. hydrozoans) that formed significant components of the habitats were not quantified in this study. To do so would require a different annotation strategy and likely require considerably more investment of time, the latter being a familiar problem in the benthic imaging field.

The resolution within the substrate classes themselves limited their explanatory power. In the images gorgonians were only ever seen attached to hard substrates. It was anticipated that inclusion of a sub-class ‘with boulders’ into gravelly mud, would add explanatory power accounting for the presence of gorgonians in gravelly mud substrates. Clearly this was not adequate, with some gorgonians annotated on gravelly mud substrates (gM) (Figure 5.6). In such cases the gorgonians were attached to rocky material that did not exceed the 20 cm boulder threshold, thus the substrate in the image was classed as gravelly mud (gM) and not gravelly mud with boulders (gMb). The proportion and size of hard substrates for attachment varies considerably within classes and some images exhibit a range of substrates. A higher resolution approach to substrate annotation would enable further conclusions to be drawn regarding the relationship between substrates and the observed assemblage and abundance of taxa. This could be achieved by the introduction of additional substrate classes or sub-classes, or alternatively by applying substrate labels to discrete areas within the images. The optimum approach would depend on the question(s) being addressed.

5.5. Conclusion

Despite the limitations identified, the benthic video sled employed proved to be a low-cost effective tool to collect imagery suitable for identifying and providing a quantitative description of a proposed VME. This allowed the first description of this soft coral garden habitat, characterised by a high density of cauliflower corals, on the continental slope of the Toqqusaq Bank. This structurally complex habitat appears to meet the definition of a VME as provided by the FAO. The vulnerability and potential ecological value mean there is a need for effective spatial management measures, given the proximity of economically important halibut and prawn fisheries along with the emerging cod fishery. A candidate VME area of 486 km^2 is therefore proposed, from which activities liable to cause serious or irreversible harm, such as benthic trawling, should be excluded.

6. Deep-sea benthic habitats and trawling impacts in the offshore Greenland halibut fishery, Davis Strait, west Greenland

The results presented in this chapter were originally published in the paper below (Appendix IV):

> Long, S., Blicher, M.E., Hammeken Arboe, N., Fuhrmann, M., Kemp, K.M., Nygaard, R., Zinglersen, k., Yesson. C. (2021) Deep-sea benthic habitats and trawling impacts in the offshore Greenland halibut fishery, Davis Strait, west Greenland. *ICES Journal of Marine Science* 78(8), 274. doi: 10.1093/icesjms/fsab148

The overarching aim of the research presented in the following chapter was to use a towed benthic video sled to acquire new seafloor imagery, offering insights into poorly known deep-sea benthic habitats in and around the offshore Greenland halibut fishery, Davis Strait, west Greenland. The imagery was gathered across the full depth range of the fishery and across a spectrum of fishing effort, covering both the northern and southern area of the fishery, including untrawled areas. This sampling design was intended to address the following specific aims: i) determine the nature and distribution of epi-faunal communities; ii) identify any differences between the communities in the northern and southern area of the fishery; iii) describe the distribution of VME indicator species, identifying any potential VMEs; iv) model the role of environmental variables in determining the composition of communities; and v) model the impact of demersal trawling on communities and faunal abundance, with particular reference to VME indicator species.

6.1. Study area

In west Greenland a wide continental shelf extends upwards of 100 km from shore, beyond which the continental slope descends to depths of over 2000 m (Jørgensen *et al.*, 2018). The Davis Strait acts as a bathymetric bottleneck between the deeper Labrador Sea and Baffin Bay basins (Figure 6.1), 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 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 700 m, this cold deep water does not have direct access to the Labrador Sea to the south. Accordingly, there are significantly different oceanographic conditions between southern Baffin Bay and the Labrador Sea at the depth range of the offshore Greenland 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 3,000 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).

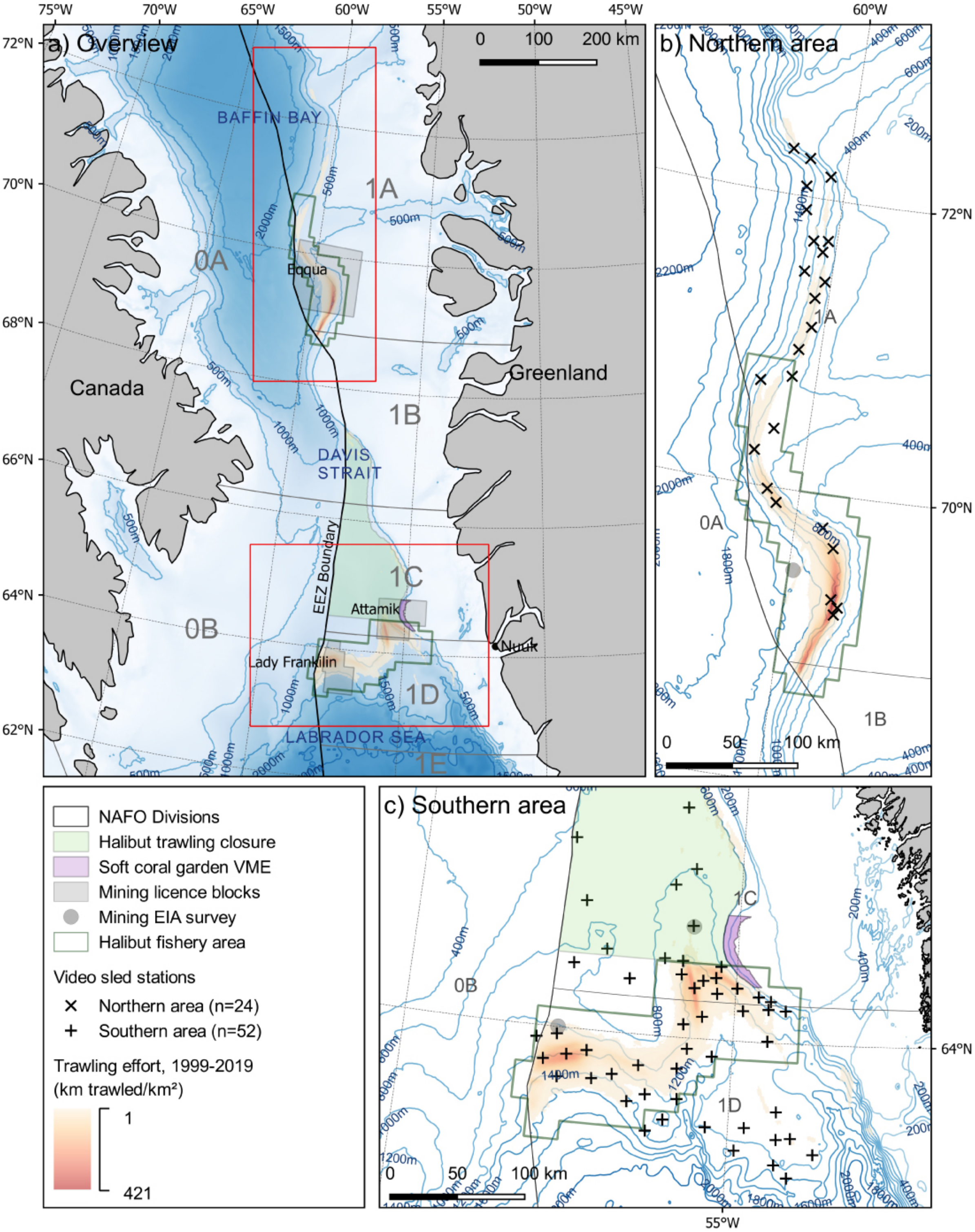


Figure 6.1 Location of video sled stations in the offshore Greenland halibut fishery and surrounding areas. Map shows a) an overview; b) the northern area of the fishery; and c) the southern area of the fishery. The position of video sled stations (*n* = 76) is shown in b) and c). Bathymetric contours are drawn at 500 m intervals in a) and 200m intervals in b) and c), using the IBCAO Version 3, 500 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 1999-2019, used to determine the distance trawled per unit area (km trawled/km²). Longline effort is not represented.

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 6.1) (BSL, 2011c, BSL, 2011a, BSL, 2011b). 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, 2011c, BSL, 2011a, BSL, 2011b, Jørgensbye and Wegeberg, 2018). Icebergs deposit terrigenous sediments and dropstones (Gutt, 2002, Streuff *et al.*, 2017), the latter providing 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 <1˚ (BSL, 2011c, BSL, 2011a, BSL, 2011b). Reportedly, steeper areas of the slope are associated with rockier ground and are not trawled (Cappell *et al.*, 2017). There are no previously identified VMEs in the area of the fishery within Greenland waters (Cappell *et al.*, 2017, Cook *et al.*, 2019), though bycatch data from stock assessment surveys indicates several VME indicator taxa are present, including: Alcyonacea, Gorgonacea, Pennatulacea, Scleractinia, Antipatharia (Jørgensen et al., 2013; Blicher and Hammeken Arboe, 2021).

In contrast to the limited knowledge within Greenlandic waters, 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 depths >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). 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).

6.2. Results

A total of 3,504 images covering 28,838 m² were obtained from 76 stations (Table 6.1). The depth range in the northern and southern stations was similar (Table 6.1). 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 6.1). 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 (Figure 6.20).

Table 6.1 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)	8,074	20,764	28,838
Number of fauna annotations	1,184	11,878	13,062
Annotations /m²	0.15	0.57	0.45
Depth (m)			
Minimum	653	649	649
Maximum	1,353	1,476	1,476
Mean (± sd)	923 (184)	1,058 (214)	1,015 (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 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

6.2.1. Trawl evidence

Evidence of trawling impact on the seabed was observed in the images (Figure 6.2), 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 6.2b); overturned sediments (Figure 6.2c); parallel grooves, caused by bobbins or rollers on rock hopper gear (Figure 6.2d); small regular grooves, perhaps from the bottom of the net, cod-end or roller clump (Figure 6.2e); and displaced, dragged or overturned rocks (Figure

6.2f). There was a strong correlation between the trawling evidence observed in images and the logbook fishing effort data (Figure 6.2a). 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 6.1).

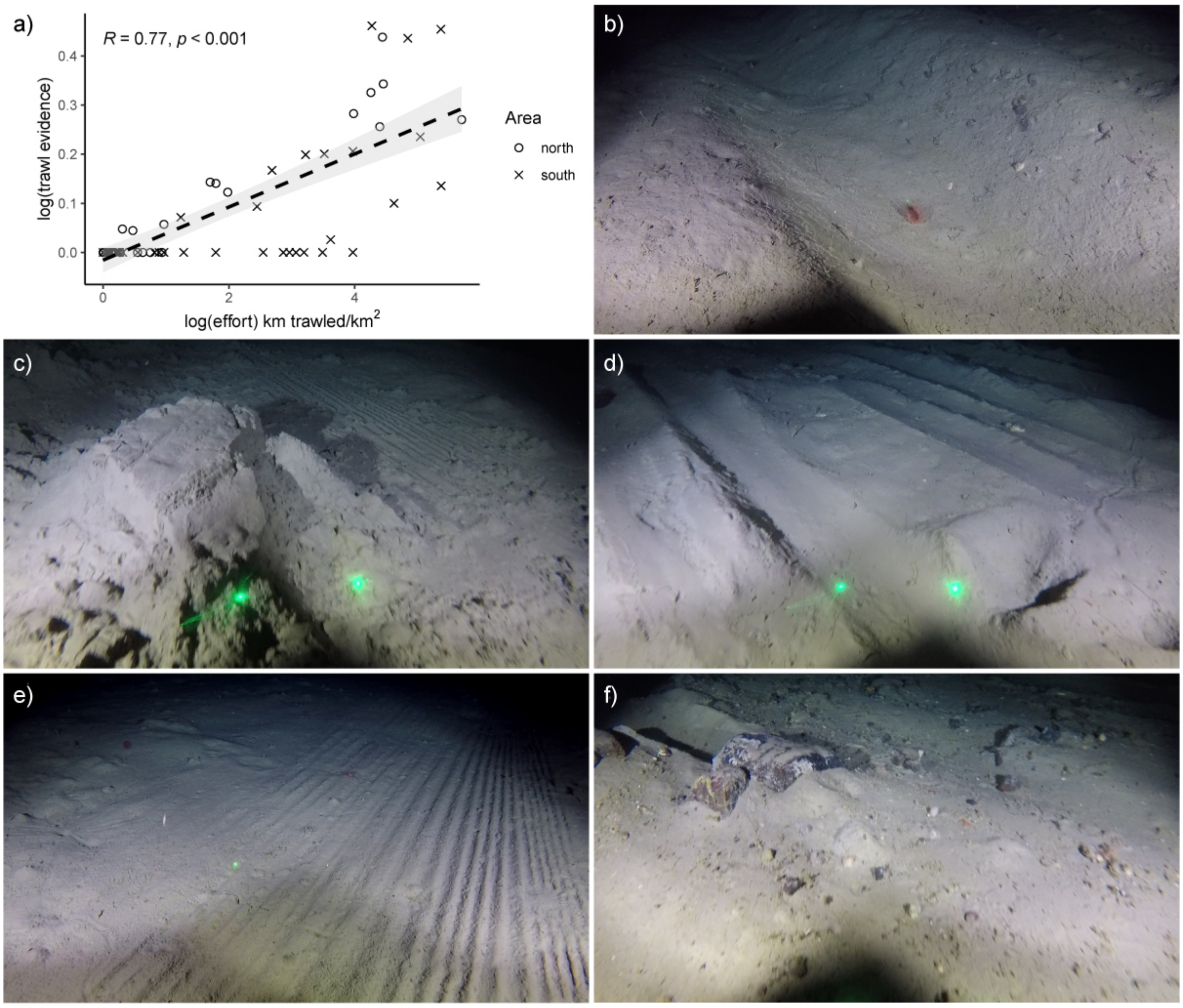


Figure 6.2 Physical evidence of trawling observed in images. Panel a) shows the relationship between the proportion of images observed with trawl evidence and effort at video sled stations, where, effort is determined by sampling along the sled path from a raster derived from logbook trawling effort data from 1999-2019. Panels b-f) show examples of the range of physical evidence of trawling observed in images. Where present, laser dots (green) are 20 cm apart.

6.2.2. Community composition

For the purposes of this study, 'community' refers 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 6.3). 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 6.3). 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 6.4). Figure 6.5 provides some examples of communities observed.

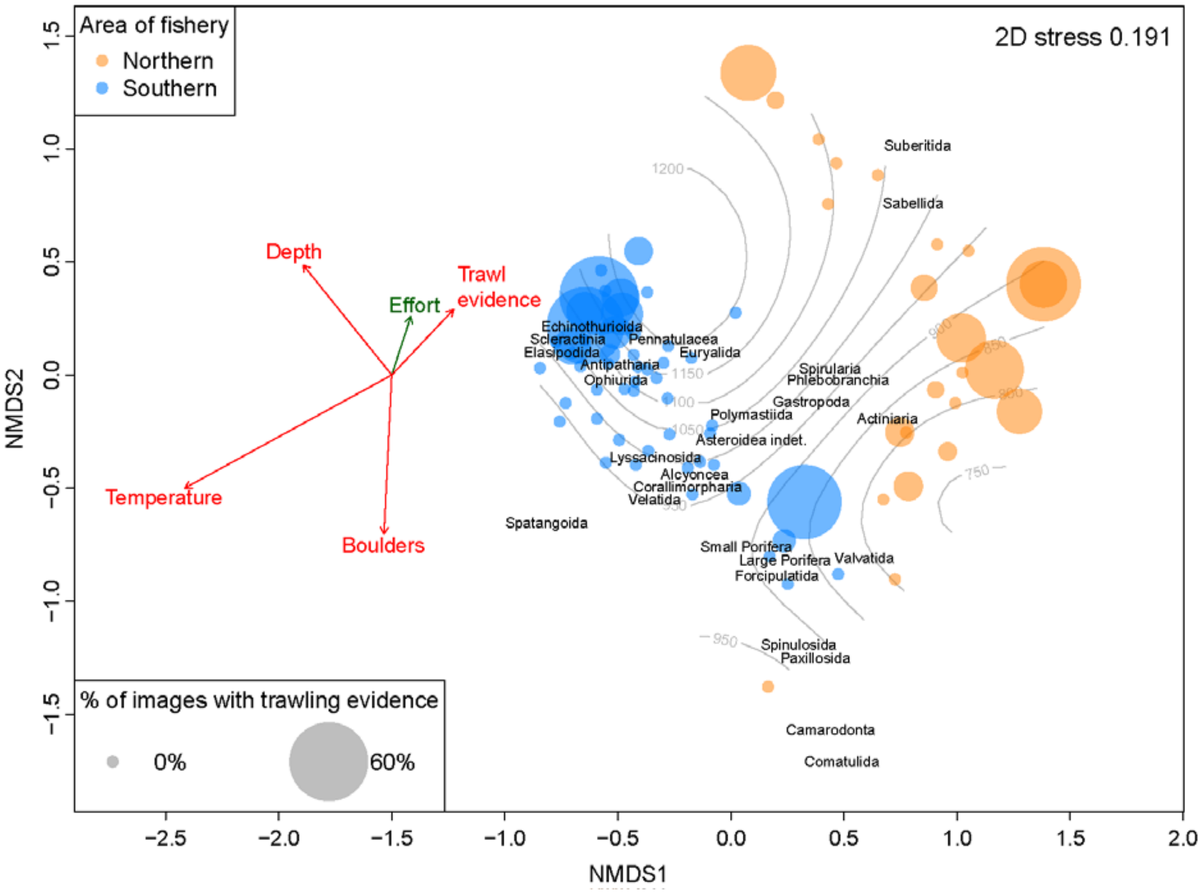


Figure 6.3 Non-metric multi-dimensional scaling (NMDS) ordination of the benthic fauna assemblage. Stations (filled circles, *n* = 76), from the northern (yellow, *n* = 24) and southern (blue, *n* = 52) areas are scaled by trawling evidence observed at each station. Fitted vectors of environmental variables are drawn in red (envfit, *p* <0.05) and green (envfit, *p* >0.05), offset from the origin for clarity. Effort is inferred from logbook data. Trawl evidence is the proportion of images from each station in which trawl evidence was observed. Boulders is the proportion of images at each station in which boulders were present. Depth fitted as a smooth surface, is indicated by 50 m contours (grey).

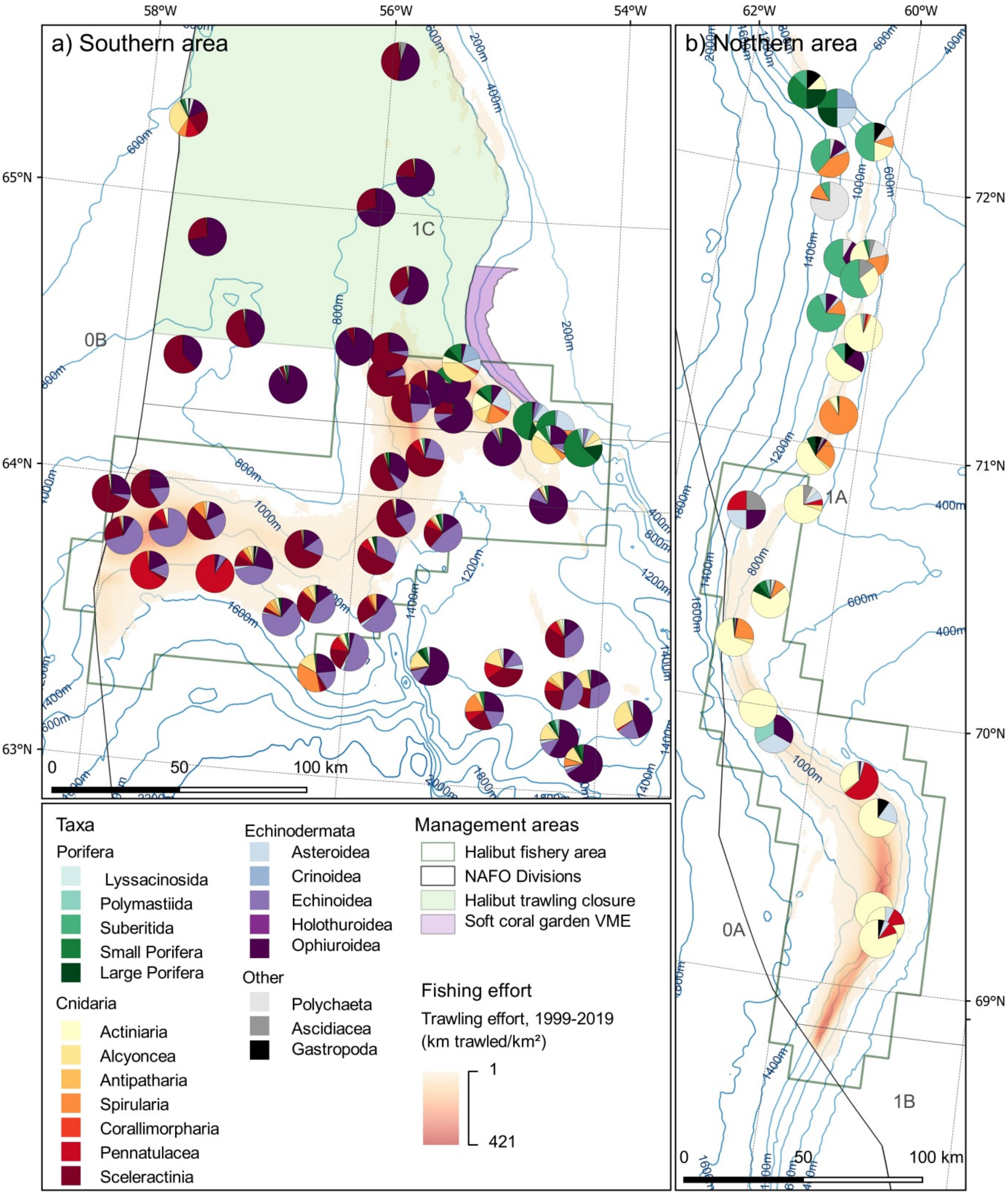


Figure 6.4 Map of community composition by station. Based on image annotation data. Classes containing VME indicator taxa are presented at the Order level, all other taxa are aggregated to the Class level.

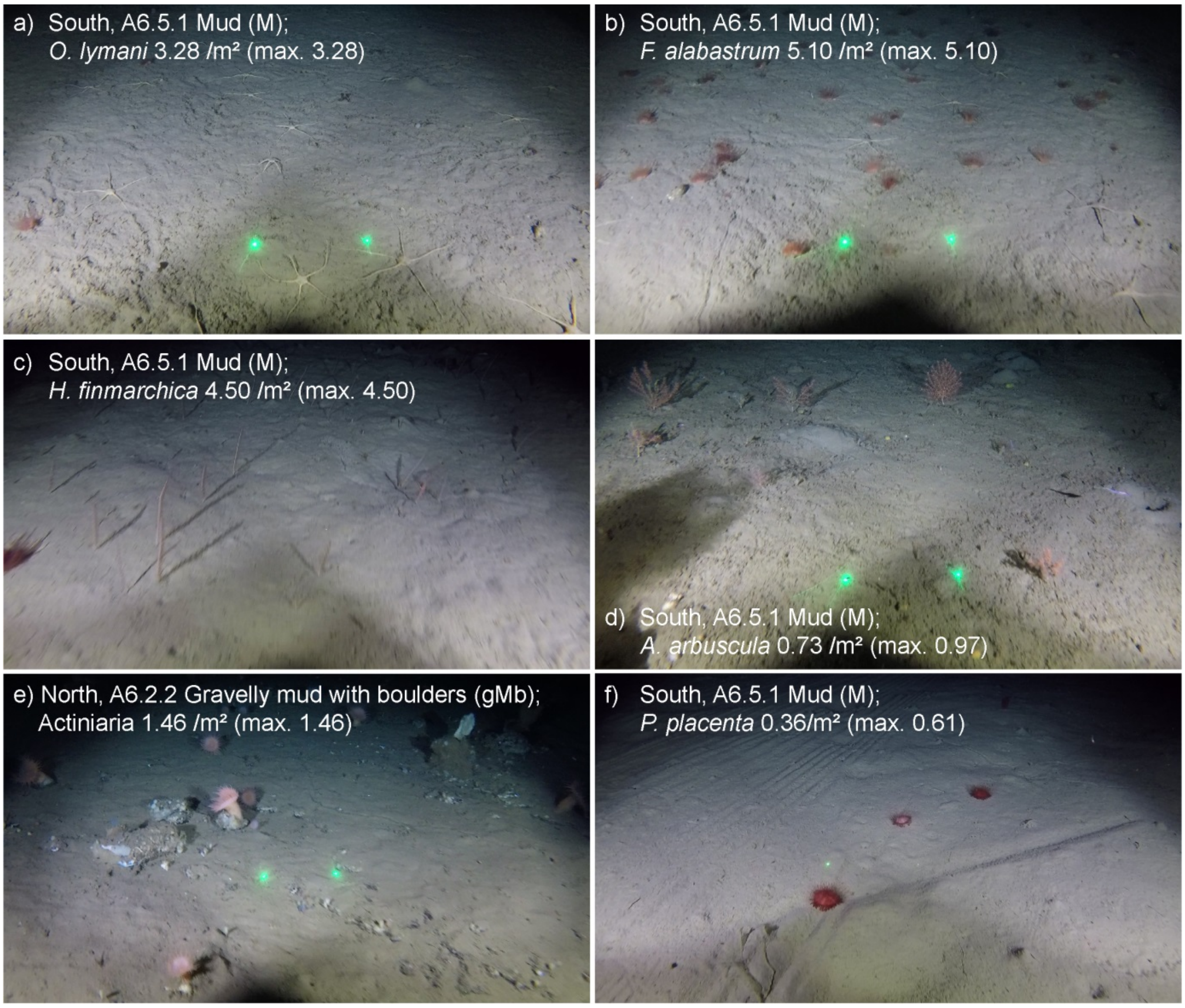


Figure 6.5 Example images of different communities. The area from which the image was obtained is indicated along with the substrate type. The density of dominant or notable taxa in each image is shown, followed, in parentheses, by the maximum density observed in any image for reference. Note, the presence of physical evidence of trawling in f).

6.2.3. Taxa observations

A total of 13,062 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 6.1). 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 6.2). 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 6.2), though this was not registered in the video annotation (Table 6.3). 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 37,088 observations of selected taxa were made in the videos (Table 6.3). 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 6.3). Locally, even higher densities of these taxa were seen within individual images, see examples in Figure 6.5a-c. The estimated density of individual taxa at each station based on image annotation data is shown in Figure 6.6 to Figure 6.20.

Table 6.2 Summary of image annotation data. Data derived from annotating images, showing the presence at stations, number of observations and maximum observed densities at the Order level for annotated fauna. 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.

Phylum			**VME Indicator?**		**Number of stations present at**			**Number of observations**			**Maximum observed density (taxa/m^2)**		
Class	**Order**	**Taxa**	NAFO	NEAFC	North (*n*=24)	South (*n*=52)	All (*n*=76)	North	South	All	Image level	Station level	Area
Porifera													
Hexactinellida	Lyssacinosida	*Asconema foliatum*	Yes	Yes	0	14	14	0	36	36	0.36	0.02	S
Demospongiae	Polymastiida	Polymastiidae	Yes	Yes	5	13	18	18	25	43	0.36	0.02	N
	Suberitida	*Stylocordyla borealis*	No	No	10	6	16	72	14	86	0.49	0.07	N
Size classes	Other small	5cm < Porifera ≤ 10cm	No*	No*	4	27	31	25	224	249	0.73	0.08	S
	Other large	Porifera > 10cm	Yes*	Yes*	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		?†	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

	Sceleractinia	*Flabellum alabastrum*	No	Yes	0	43	43	0	3566	3566	5.10	2.23	S
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	No	9	26	35	13	60	73	0.24	0.02	S
Crinoidea	Comatulida		?‡	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	5,450	5,451	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	5,452	5,470	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

* Inferred based on taxa listed as VME indicator species

† Tube dwelling anemones (Order: Spirularia) are included in NAFO VME indicators guidance but only *Pachycerianthus borealis* specifically is listed there.

‡ Crinoids (Order: Comatulida) are included in NAFO VME indicators guidance but only *Trichometra cubensis* specifically is listed there.

Table 6.3 Summary of video observations data. 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)**	
	Class	**Order**	**Taxa**	NAFO	NEAFC	North (*n*=24)	South (*n*=52)	All (*n*=76)	North	South	All	At the station level	Area
Porifera													
	Demospongiae	Polymastiida	Polymastiidae	Yes	Yes	7	24	31	32	93	125	0.03	N
		Large	All Porifera > 10cm	Yes*	Yes*	13	42	55	61	459	520	0.13	S
Cnidaria													
		Alcyonacea	*Acanella arbuscula*	Yes	Yes	0	44	44	0	1,300	1,300	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	2,015	2,015	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
		Sceleractinia	*Flabellum alabastrum*	No	Yes	0	44	44	0	11,764	11,764	4.64	S
Echinodermata													
	Echinoidea	Echinothurioida	*Phormosoma placenta*	No	No	0	48	48	0	2,558	2,558	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	18,029	18,029	4.11	S

* Inferred based on taxa listed as VME indicator species

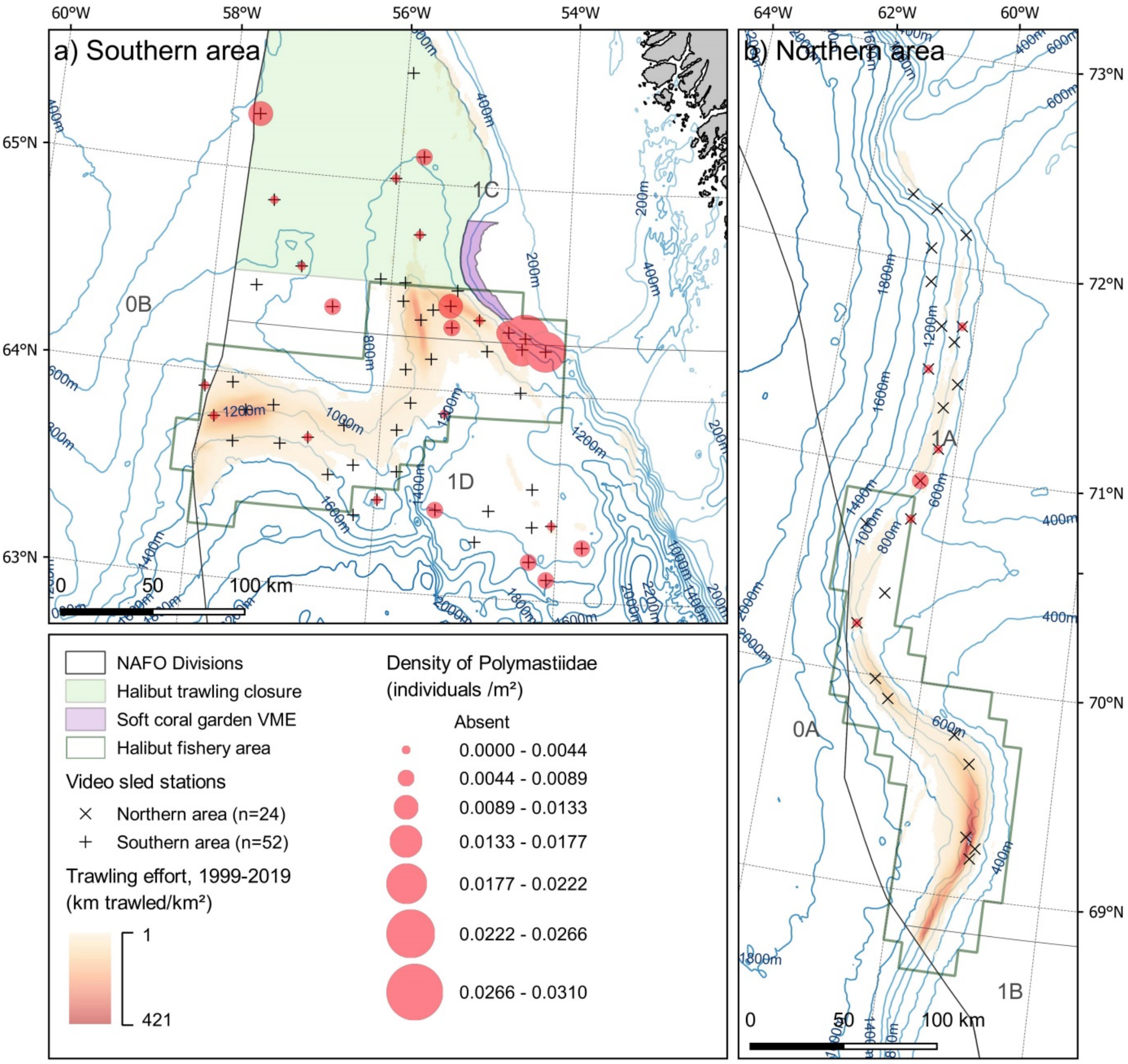


Figure 6.6 Map of the estimated density of Polymastiidae. Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

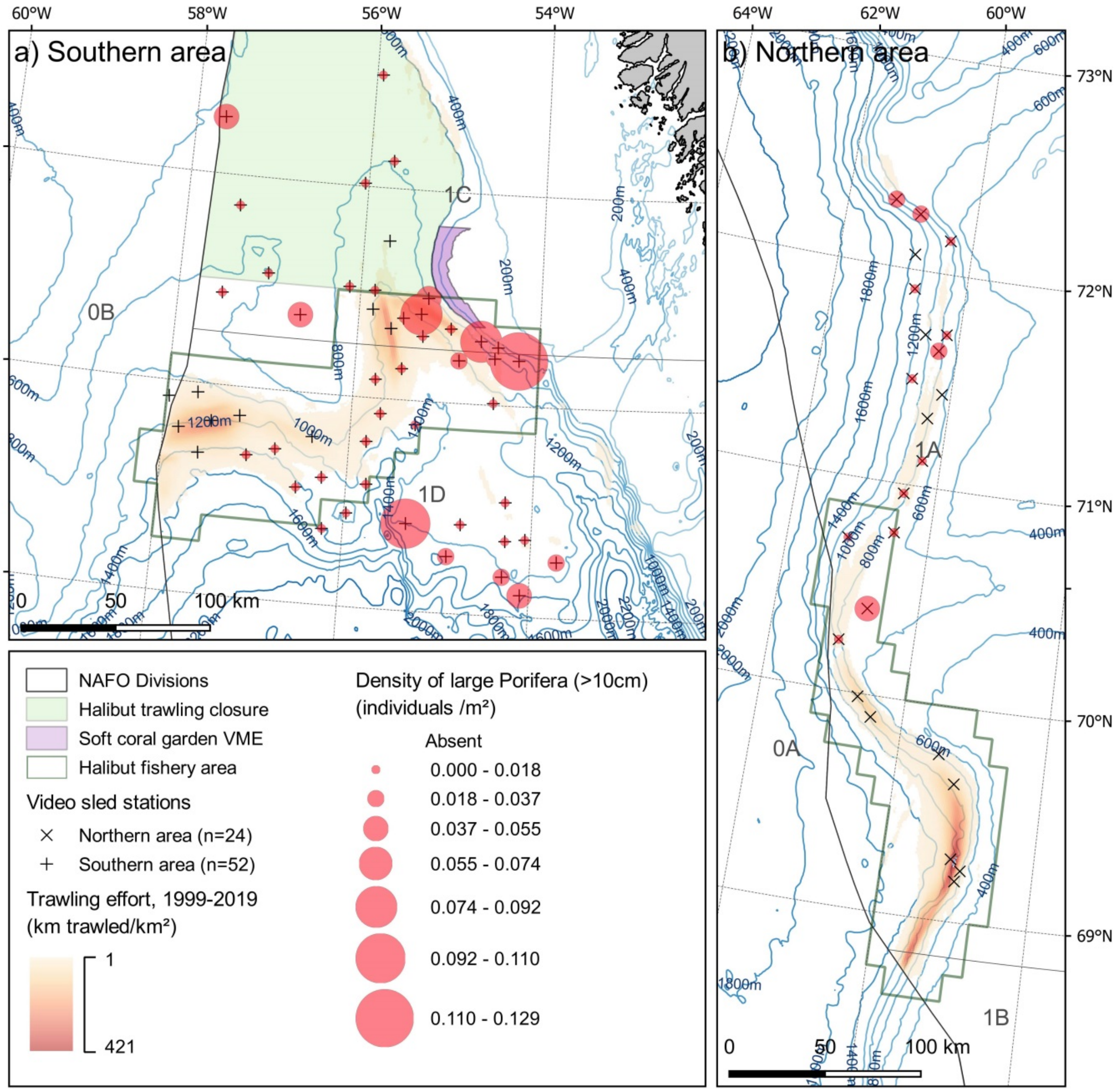


Figure 6.7 Map of the estimated density of large Porifera (>10cm). Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

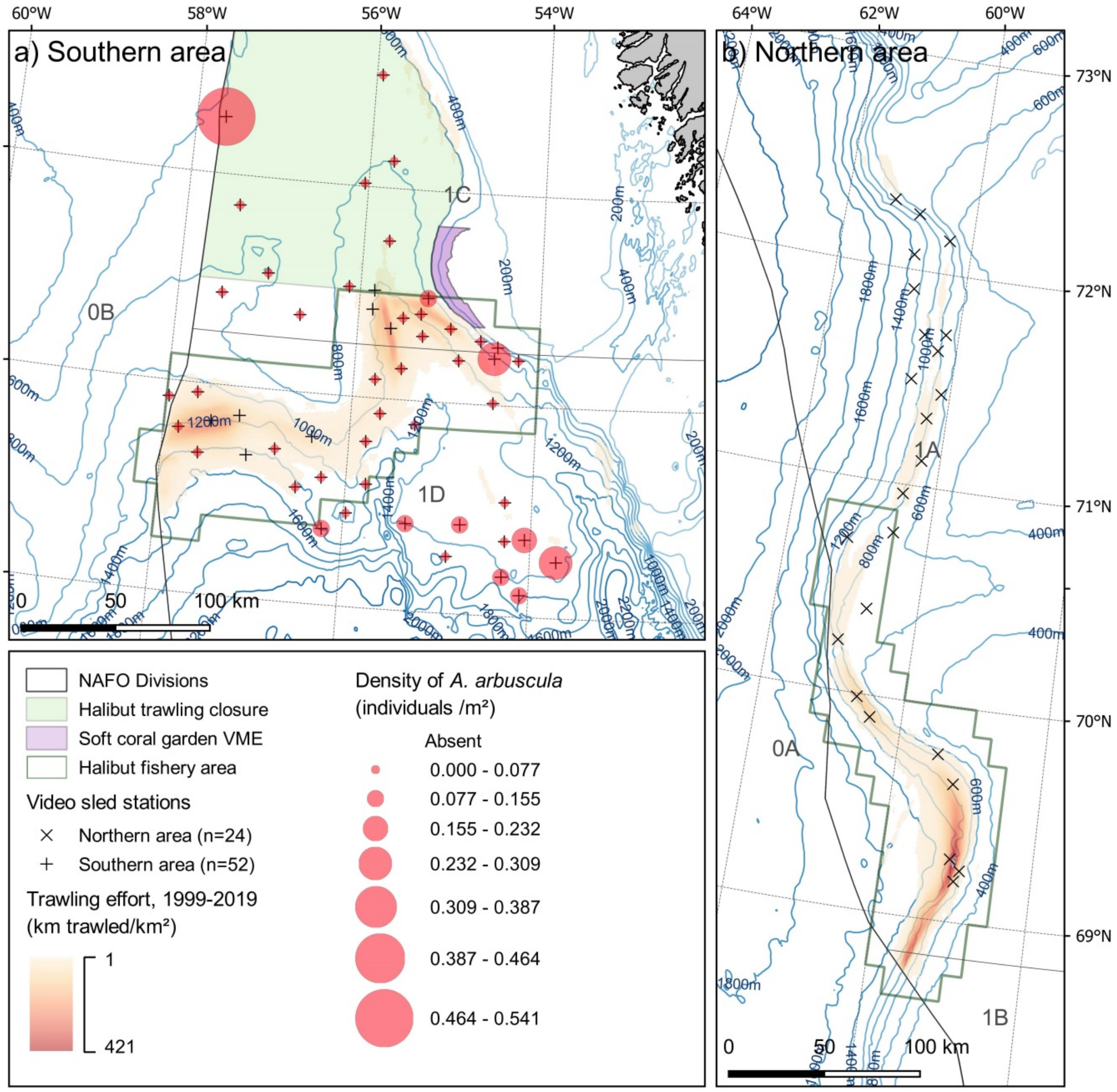


Figure 6.8 Map of the estimated density of *A. arbuscula*. Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

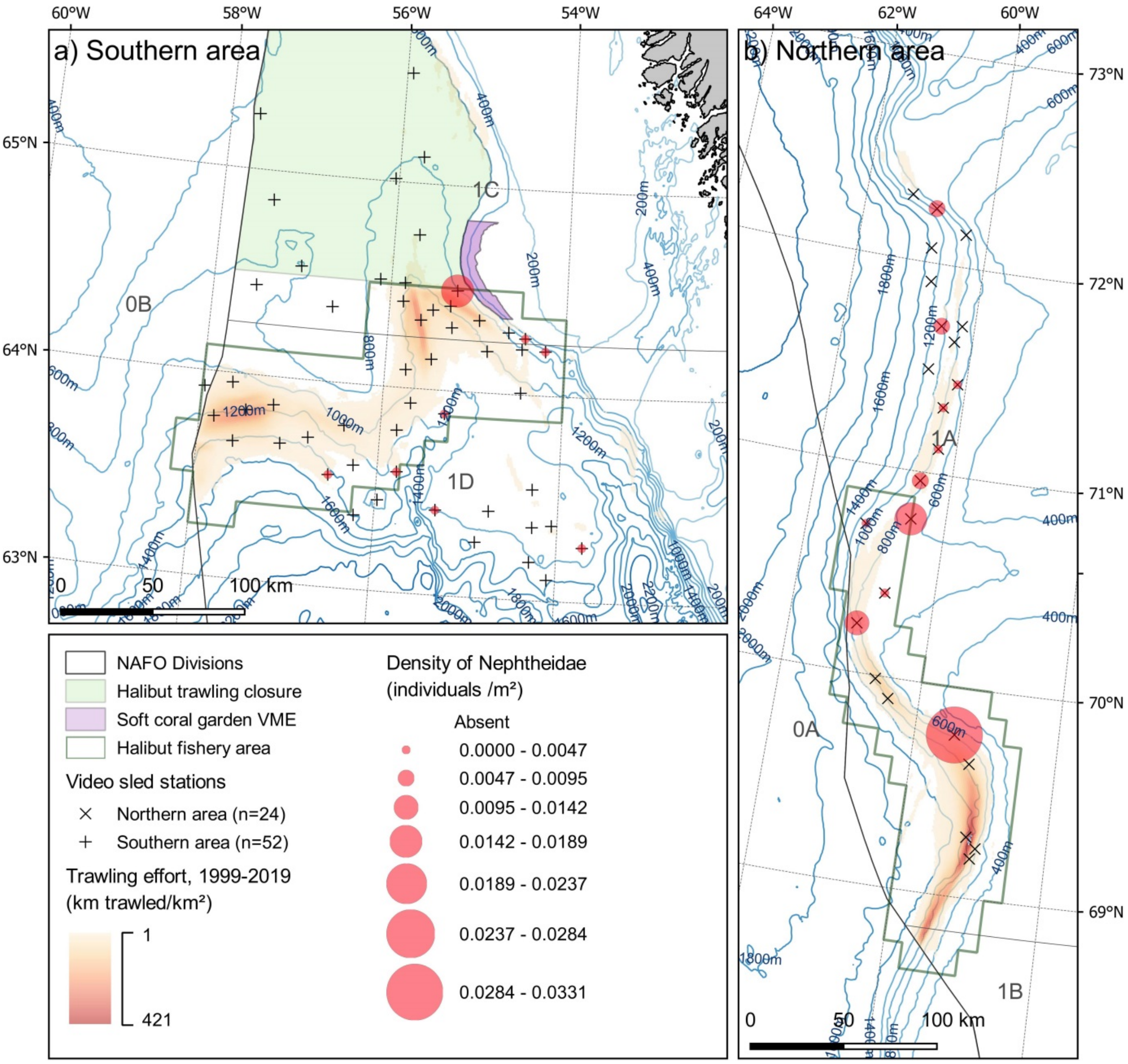


Figure 6.9 Map of the estimated density of Nephtheidae. Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

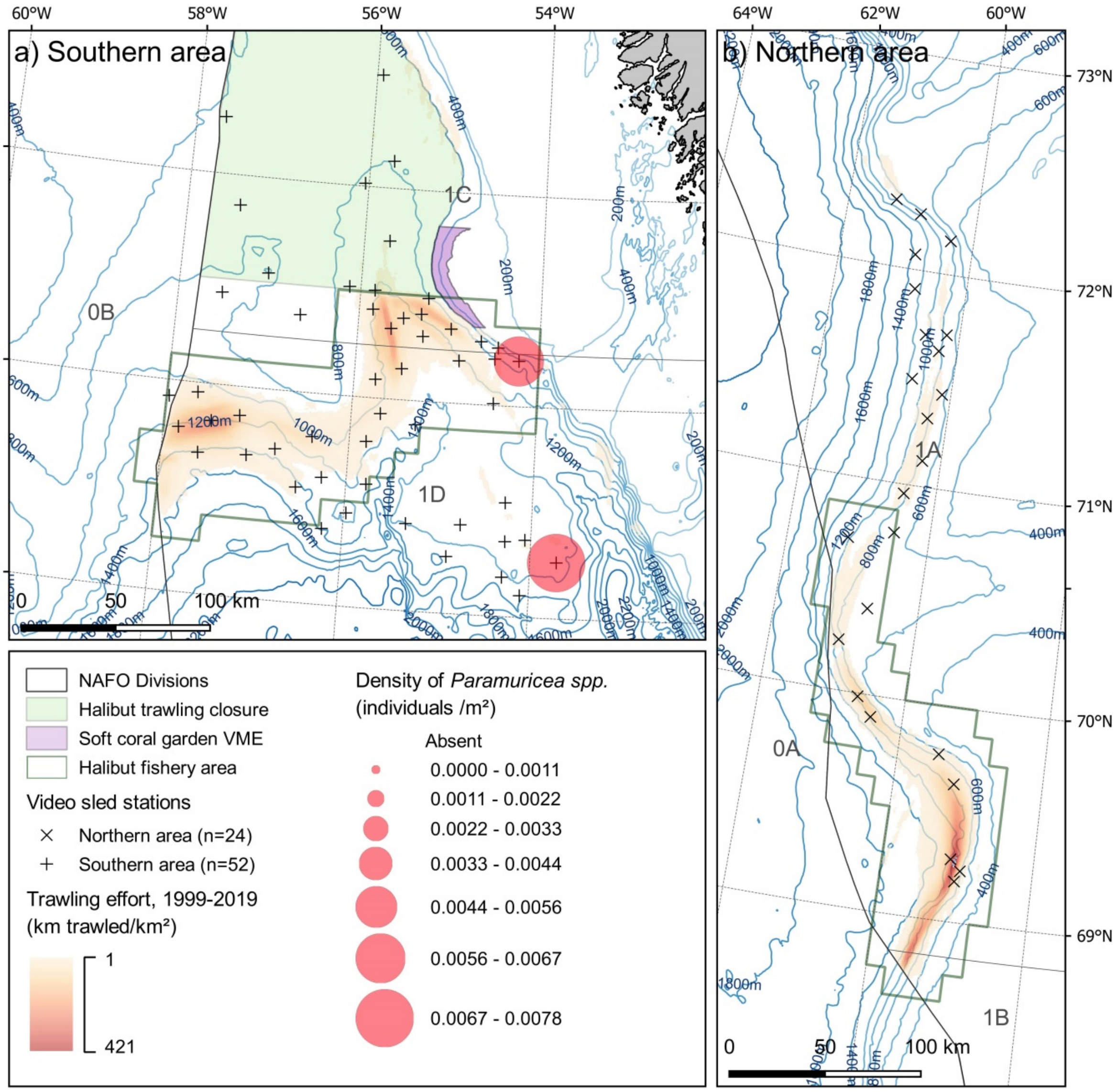


Figure 6.10 Map of the estimated density of *Paramuricea spp.* Based on video count data for a) the southern area (n = 52) and b) the northern area (n = 24).

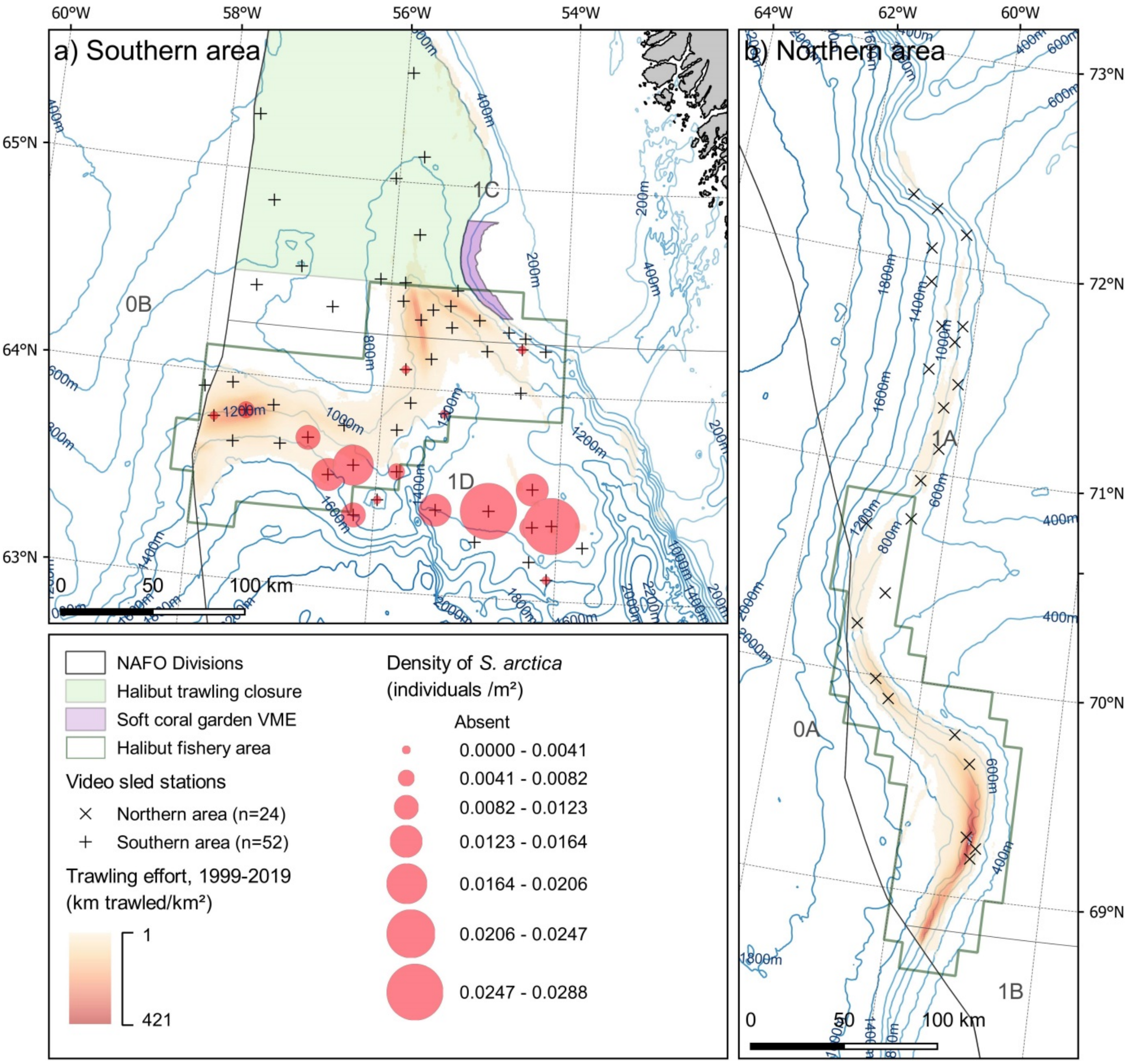


Figure 6.11 Map of the estimated density of *S. arctica.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

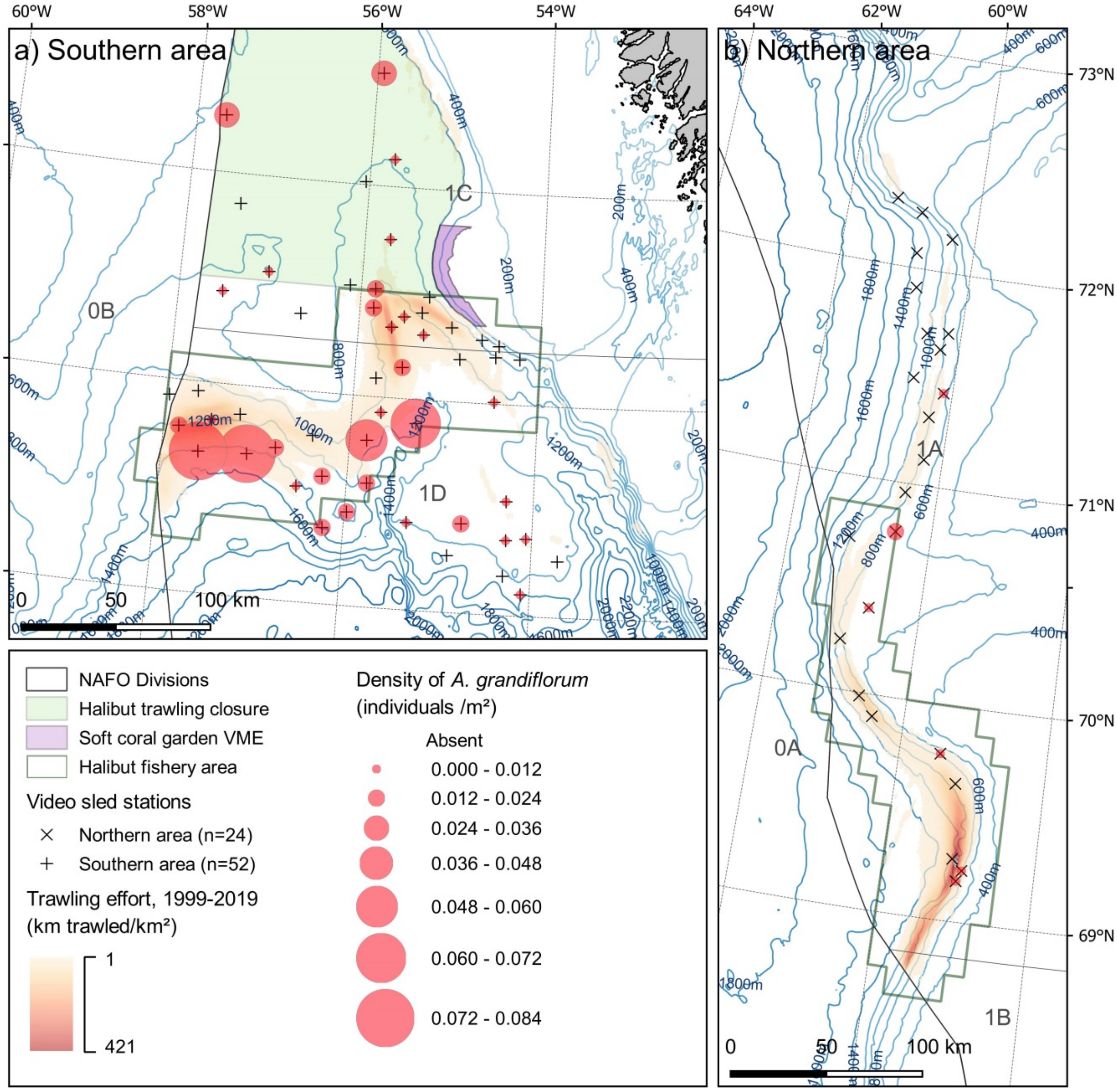


Figure 6.12 Map of the estimated density of *A. grandiflorum.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

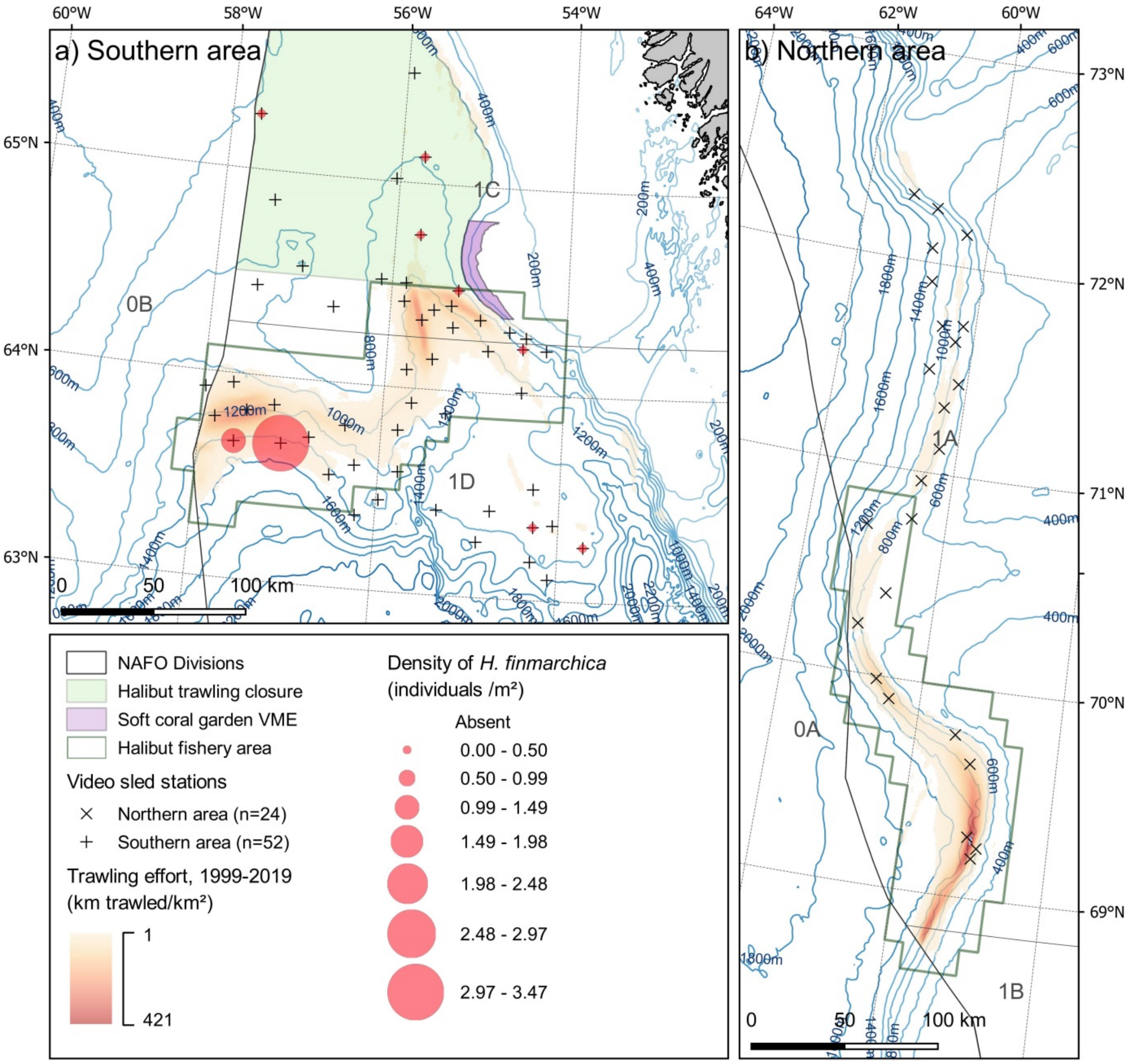


Figure 6.13 Map of the estimated density of *H. finmarchica.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

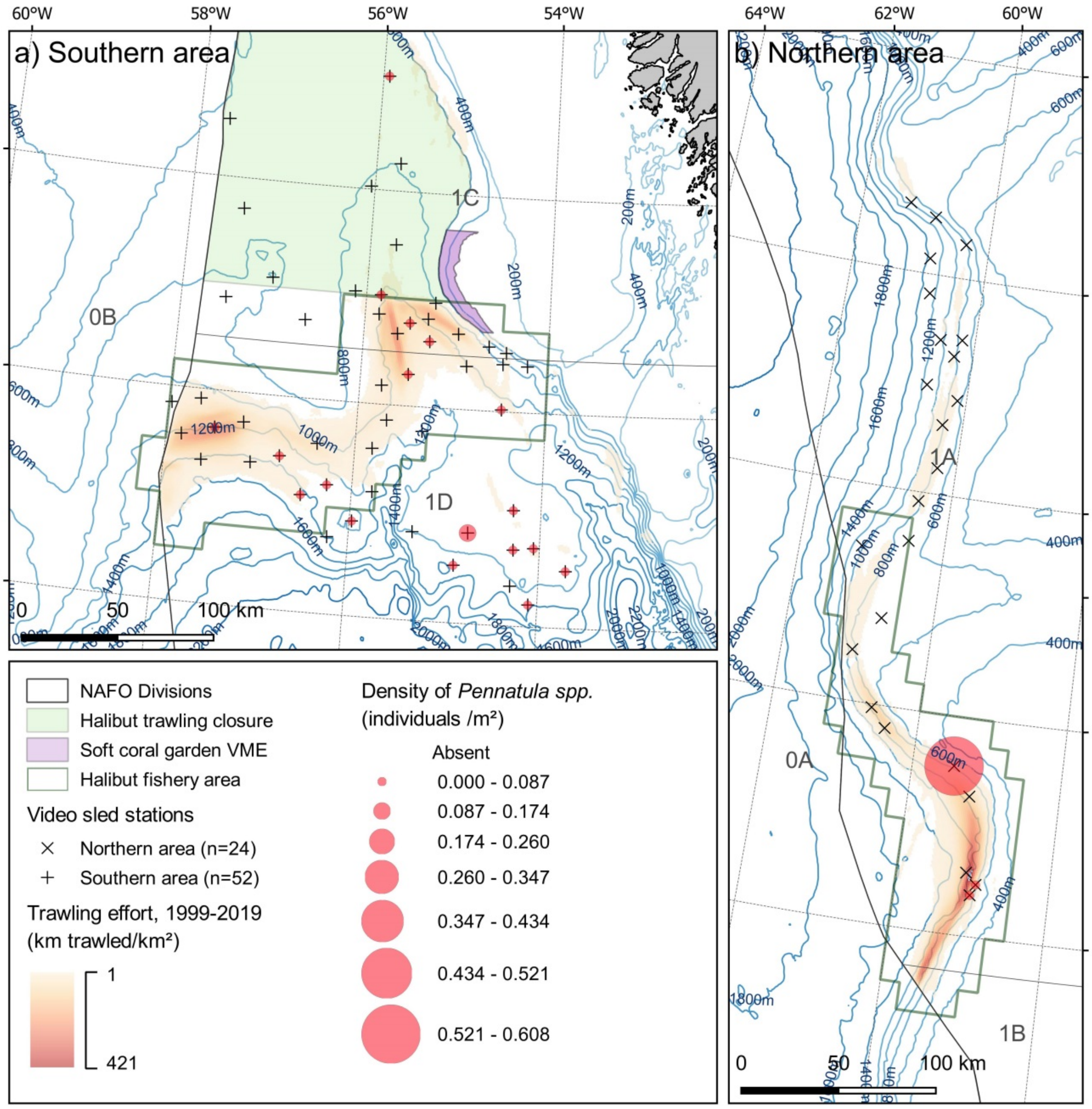


Figure 6.14 Map of the estimated density of *Pennatula spp.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

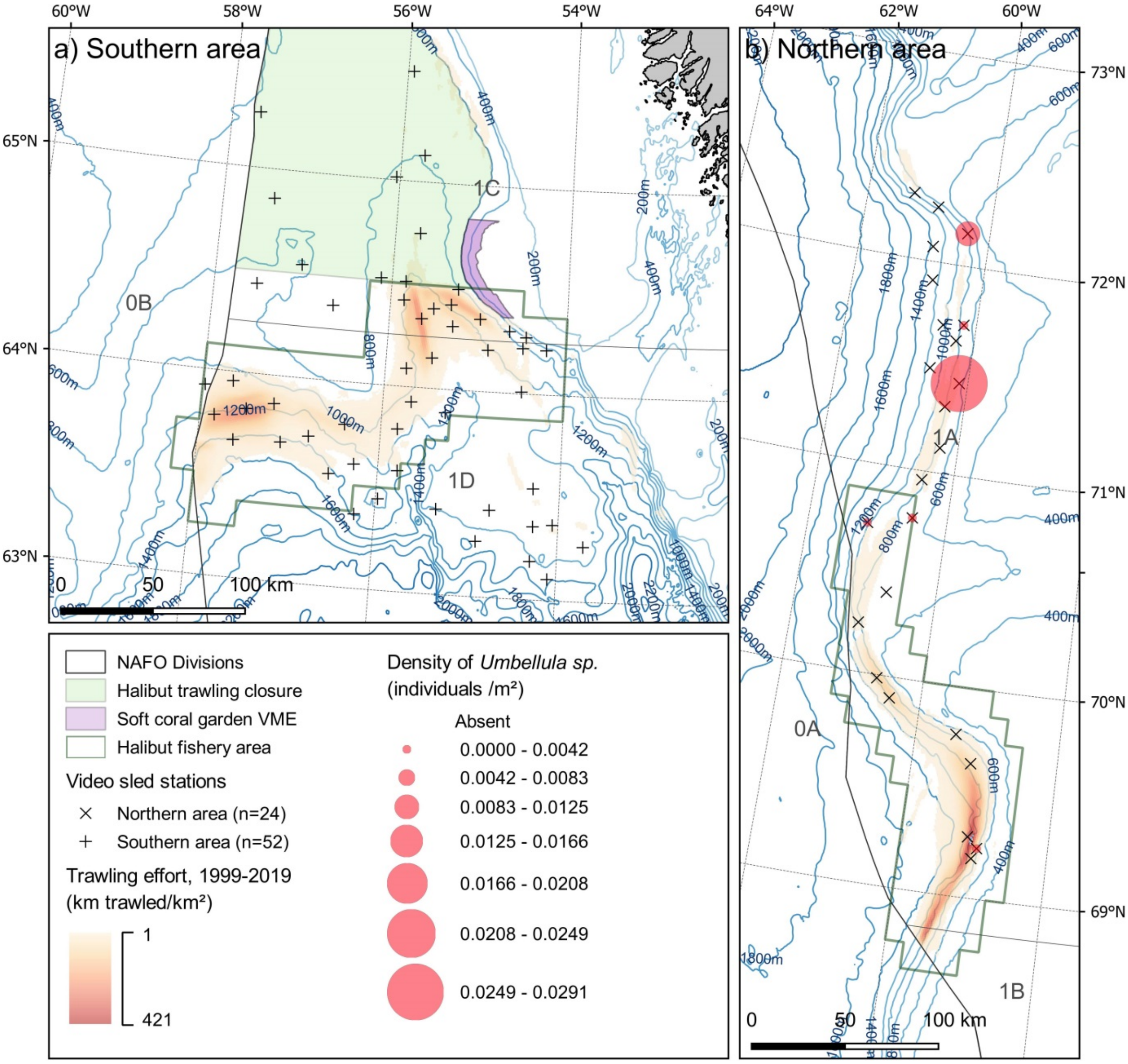


Figure 6.15 Map of the estimated density of *Umbellula sp.* Based on video count data for a) the southern area (n=52) and b) the northern area (n=24).

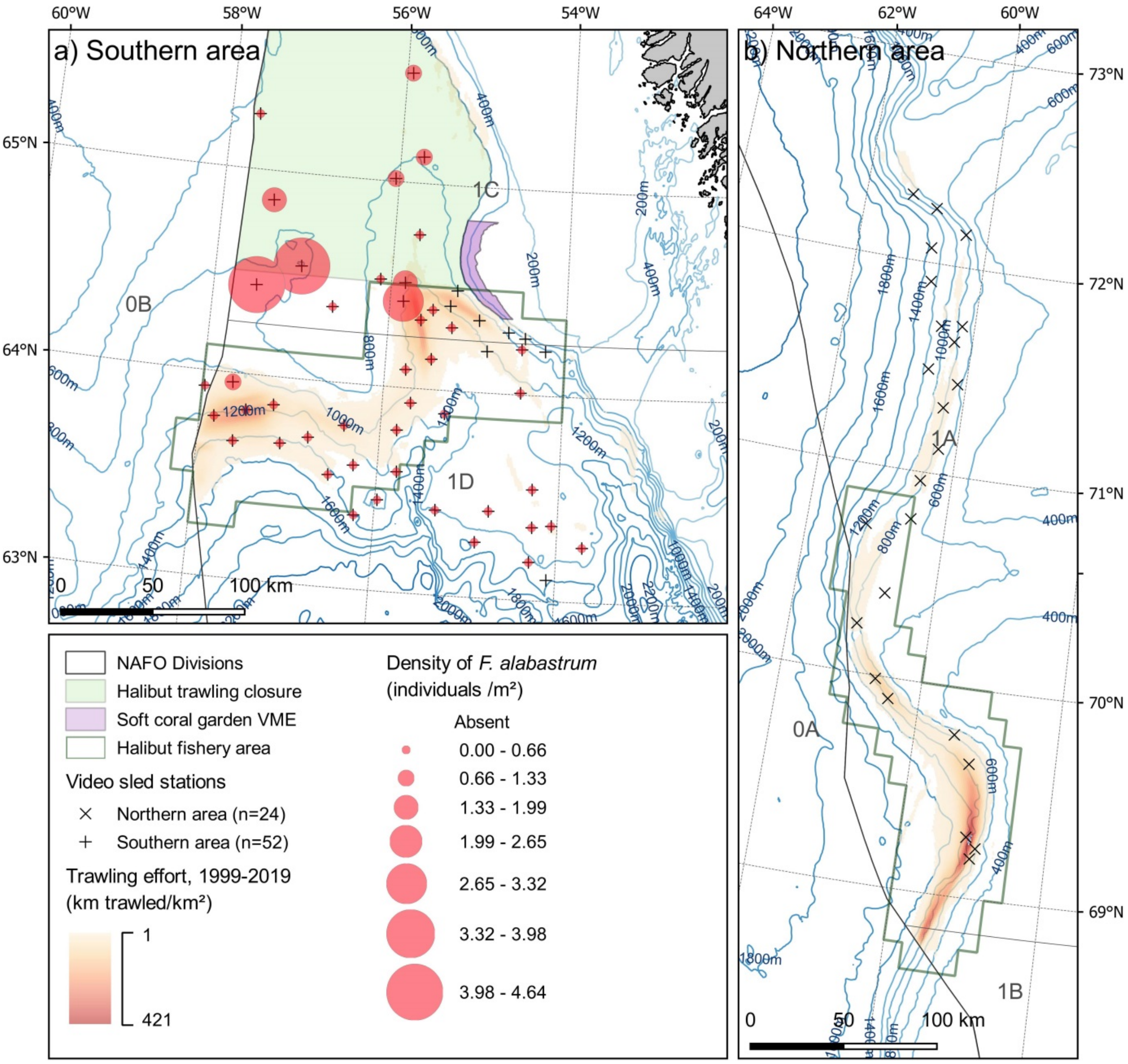


Figure 6.16 Map of the estimated density of *F. alabastrum.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

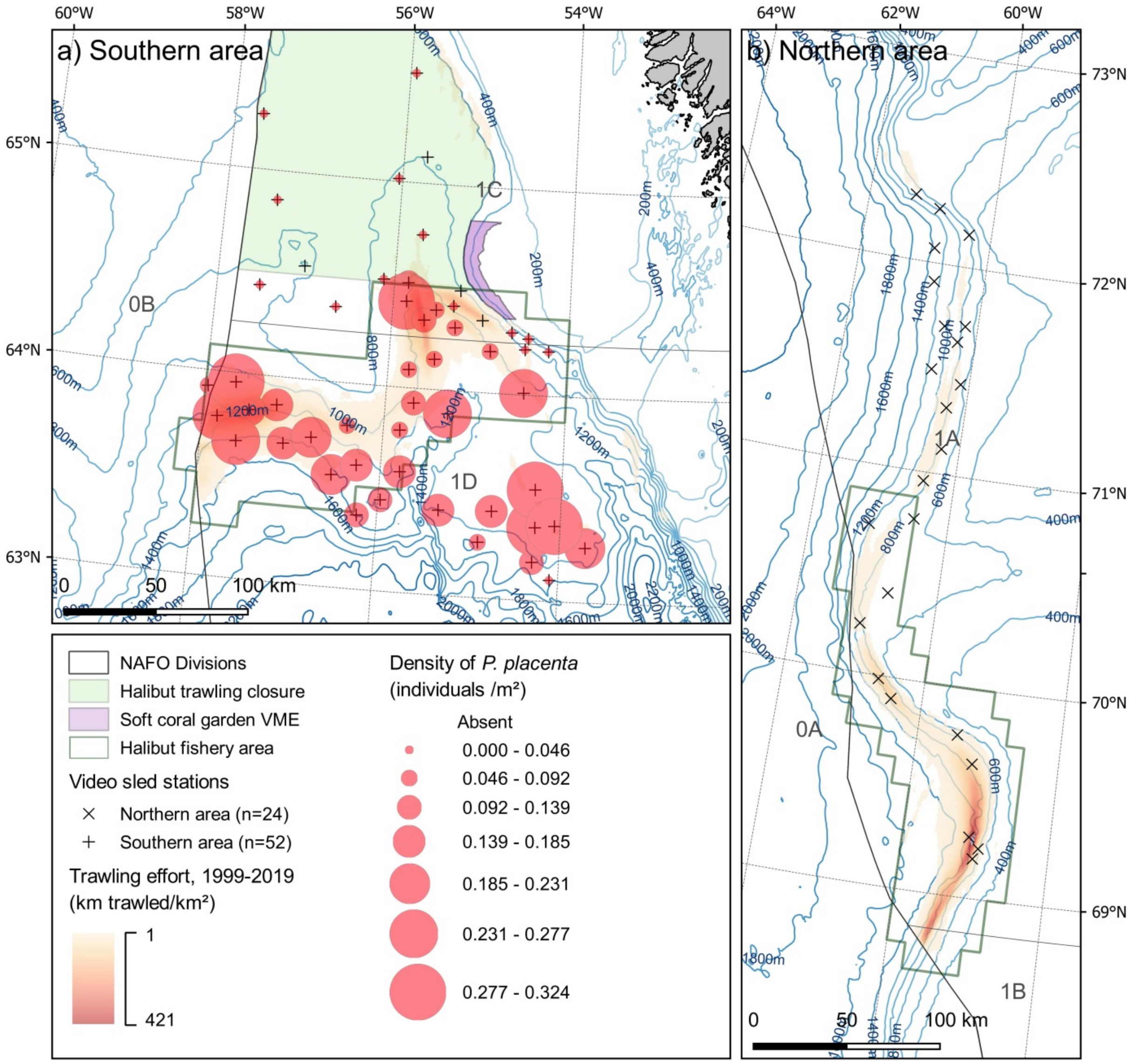


Figure 6.17 Map of the estimated density of *P. placenta.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

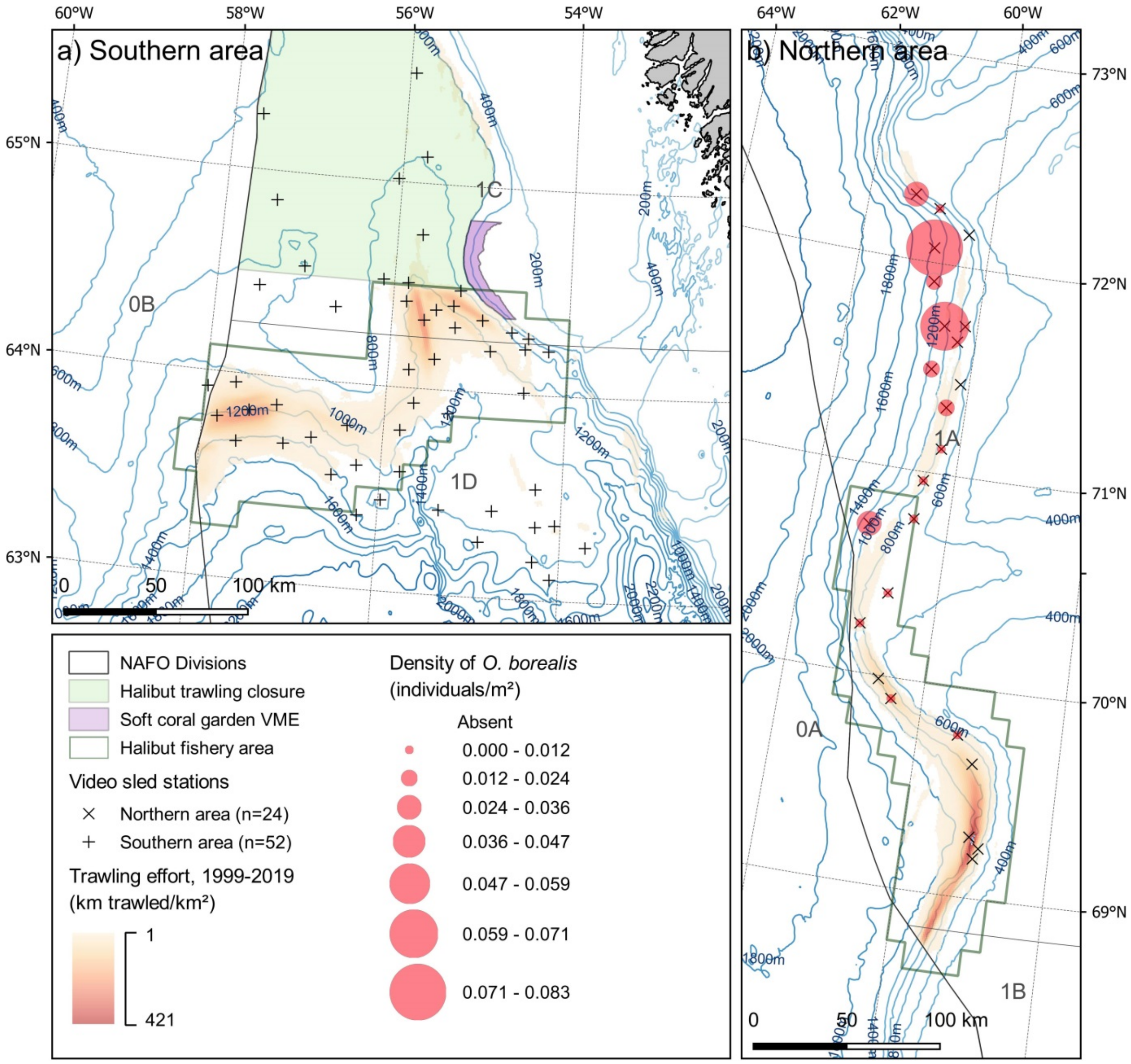


Figure 6.18 Map of the estimated density of *O. borealis.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

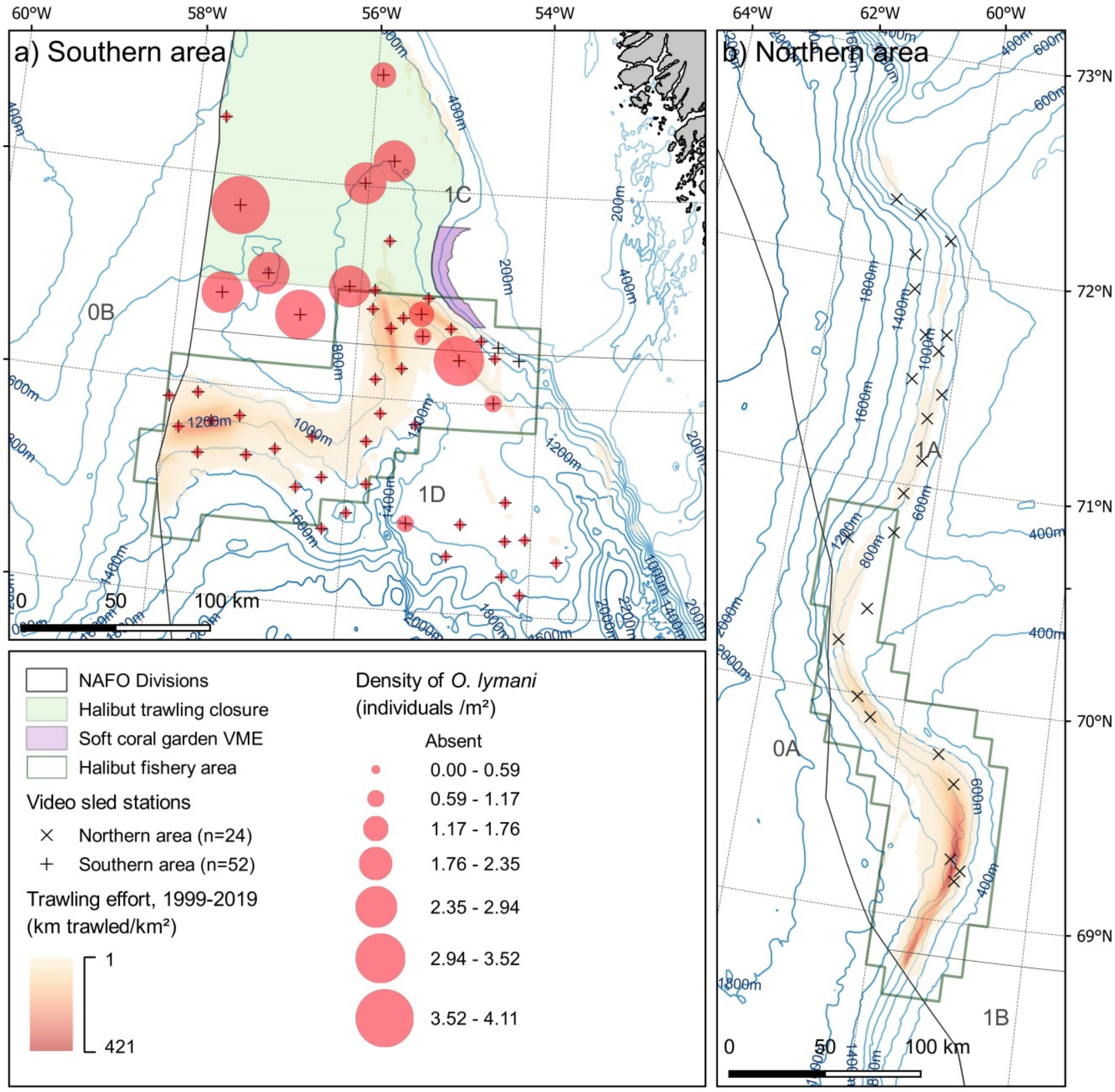


Figure 6.19 Map of the estimated density of *O. lymani.* Based on video count data for a) the southern area (*n* = 52) and b) the northern area (*n* = 24).

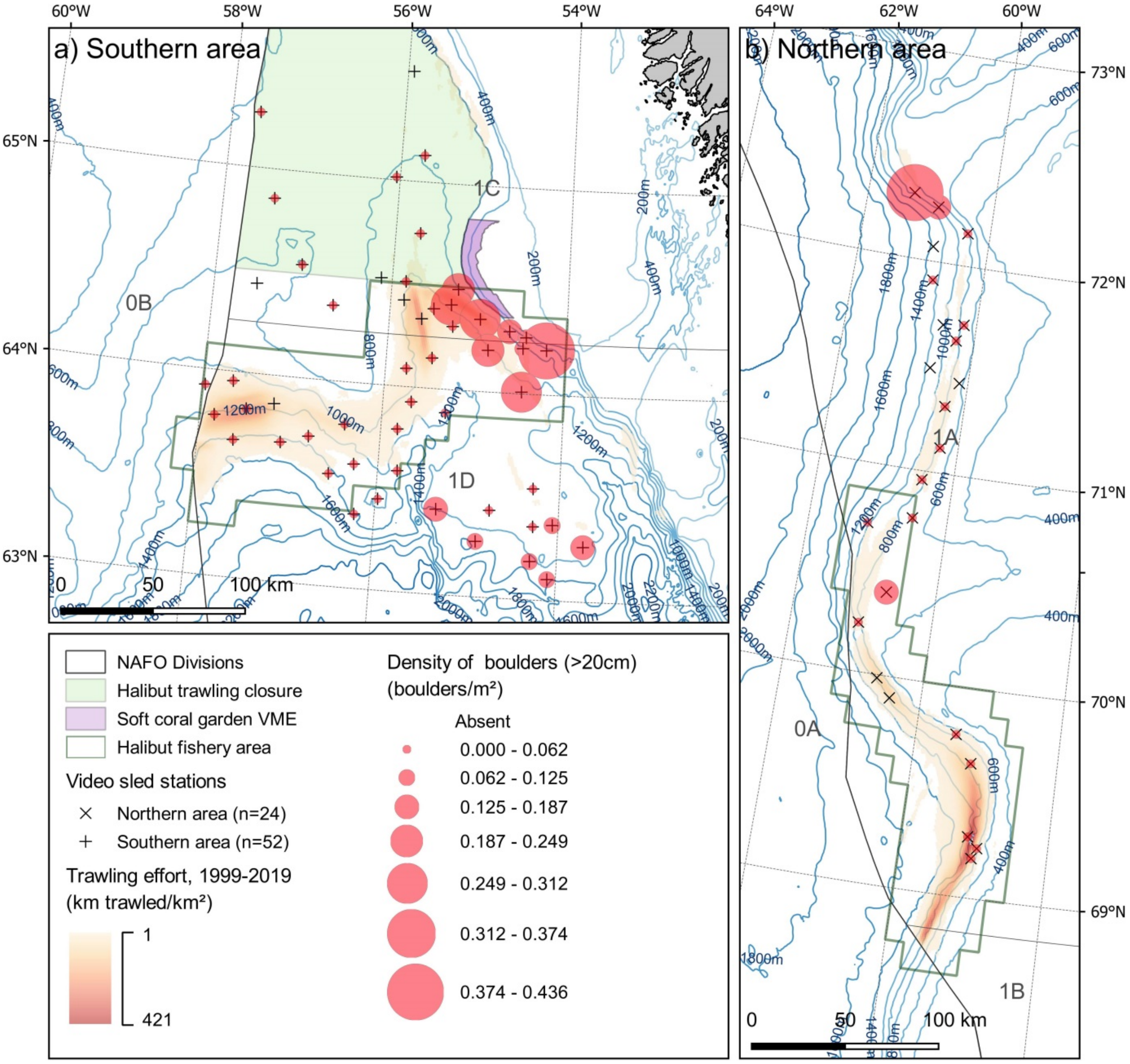


Figure 6.20 Map of the estimated density of boulders (>20cm). Based on video count data for a) the southern area (n = 52) and b) the northern area (n = 24).

6.2.4. Vulnerable marine ecosystems (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 were present in the north (Table 6.2 and Table 6.3). Maps of the observed densities of those 11 VME indicator taxa counted in the videos are provided (Figure 6.6 to Figure 6.16). 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 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 6.3), though typically at low abundance (Figure 6.21a). At the station level, a maximum density of 4.64 *F. alabastrum*/m^2 was seen, which was higher in individual images, with a maximum of 5.10 individuals/m^2. Conversely, *H. finmarchica* was absent from the majority of stations, being recorded at just nine. A maximum of 3.47 *H. finmarchica*/m^2 were observed at the station level, with the maximum within an image being 4.50 individuals/m^2. 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/m^2) (Figure 6.21b).

Excluding, *F. alabastrum* and *H. finmarchica,* which were both locally highly abundant, Figure 6.21c, 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.

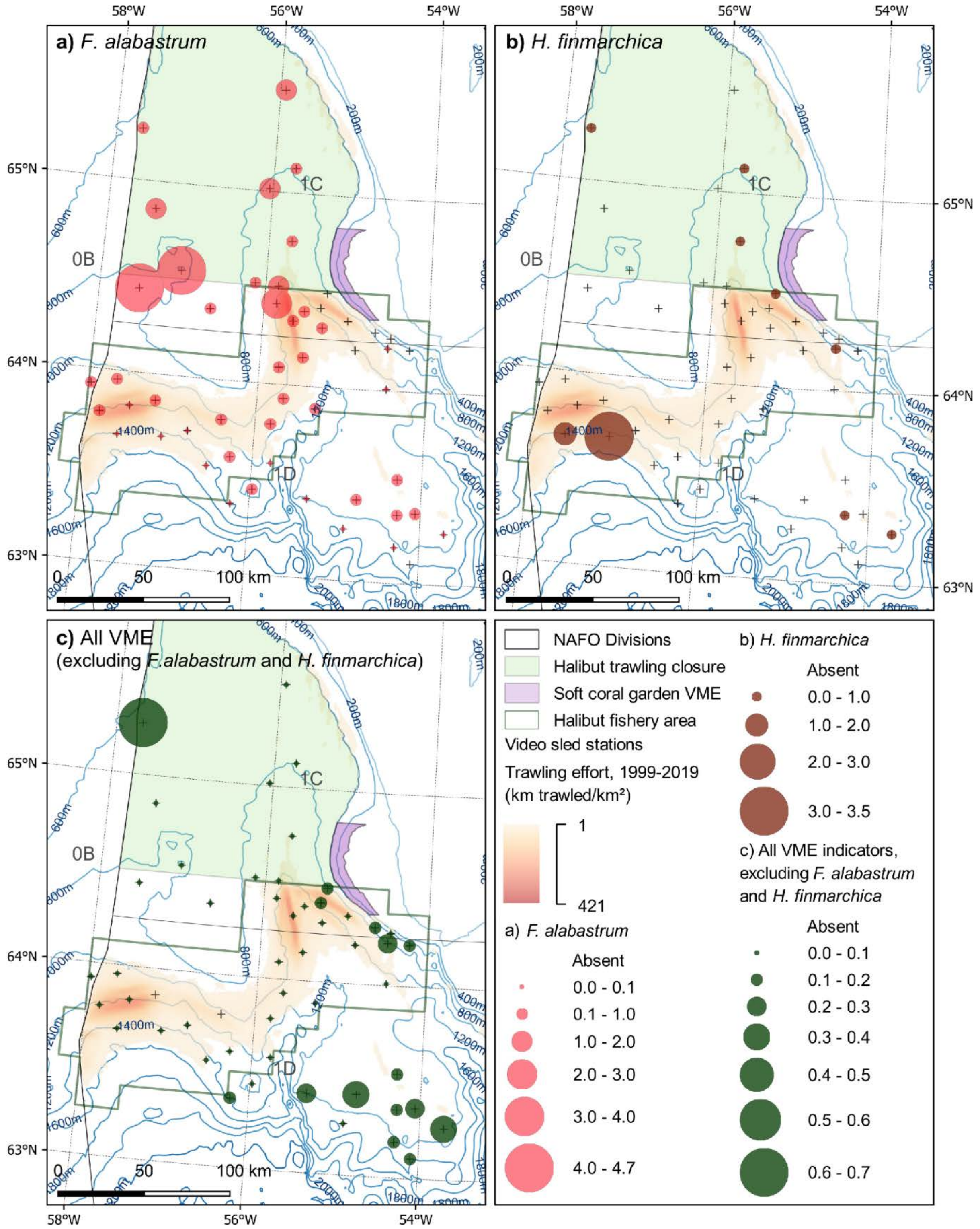


Figure 6.21 Map highlighting instances where the density of VME indicators taxa is notable. Shows the density (individuals or colonies /m^2) at stations in the southern area (n = 52) for: a) *F. alabastrum*; b) *H. finmarchica;* and c) all VME indicators (excluding *F. alabastrum* and *H. finmarchica*). The EEZ is drawn (solid black line).

6.2.5. 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 6.4). Depth, boulder prevalence and fishing effort were found to have significant associations with the abundance of some taxa (Table 6.4). 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 6.3 and Figure 6.12 to Figure 6.15). 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.

Table 6.4 Summary of taxa abundance models. Models use 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*	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*	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*	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†						
	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	$(X^2 = 4.19, df = 49, p = 0.041)$	

* Response variable log-transformed

† 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.

6.3. Discussion

6.3.1. 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. *Keratoisis spp.*

bamboo corals were not encountered, 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, 2011a), 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 with 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 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, 2011b). The absence of these taxa from the northern area 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. albastrum* to 3.7˚C, which overlaps with conditions in the southern but not northern area in this study. However, other processes and drivers such as oceanographic conditions 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, 2011a). 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, 2011a). 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.

6.3.2. Vulnerable marine ecosystems (VMEs)

The opinion of the author, based on these findings, is that there are three instances where the observed density of taxa warrant consideration as evidence of a potential VME. Each case is considered below, 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* in the following discussion.

6.3.2.1. *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 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 the 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, though the driver of this is not known. *F. alabastrum* have been observed to move slowly, it having been suggested that this movement is facilitated by expanding the polyp 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. Elsewhere, in the Barents Sea, Buhl-Mortensen *et al.* (2016) have also reported VME indicator taxa (*Geodia* and *Stetleta* sponges) being re-organised into lines filling the trenches left by trawl doors (Buhl-Mortensen et al., 2016).

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 showing 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 Northeast Atlantic, Lea-Anne and Roberts (2014) propose a threshold of 0.1 - 0.9 /m^2 (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/m^2; Table 3) is 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.

6.3.2.2. 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/m^2. Occasional *H. finmarchica* individuals were seen at 7 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 65-66°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 Northwest 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 6 species on *H. finmarchica* specimens of which 5 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. Firstly, 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 1999-2019. 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 (Figure 6.12).

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 pen 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.

6.3.2.3. 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 6.21c shows there to be a cluster of stations in the southeast 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 m 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 recognised 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 (Figure 6.20). 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 1,000 - 1,500 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.

6.3.3. 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, 2011b, BSL, 2011c). Imagery was not obtained from the EIA in the northern area (BSL, 2011a). 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 14,963 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 this 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 3.2, green outline) (MFHA, 2021). This new halibut fishery area (northern, 12,285 km^2; southern, 16,142 km^2; total, 28,247 km^2) encompasses, and significantly exceeds, the existing trawling footprint (northern, 5,780 km^2; southern, 9,323 km^2; total, 15,103 km^2) and so allows for a considerable expansion of fishing effort into previously unimpacted areas (Appendix VIII).

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.

6.4. Conclusion

The results presented in this chapter are 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 ~15,000 km^2 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.

7. Greenland's offshore Greenland halibut fishery and role of the Marine Stewardship Council certification: a governance case study

The results presented in this chapter were originally published in the paper below (Appendix III):

> Long, S. and Jones, P.J.S. (2021). Greenland's offshore Greenland halibut fishery and role of the Marine Stewardship Council certification: A governance case study. *Marine Policy* 127. doi: j.marpol.2020.104095.

The primary section headings in this chapter follow those of the Marine Protected Area Governance (MPAG) framework (Jones, 2014), which was developed to provide a structured, empirical approach for critically analysing the governance of marine protected areas (MPAs) (see, Chapter 4, Sections 4.2.1 and 4.2.2). As previously highlighted, there is a need for an equivalent tool and approach for assessing the governance of fisheries. This would allow case studies to be conducted in a replicable manner, facilitating comparisons within fisheries over time and between different fisheries. Therefore, this chapter has two mains aims: 1) to test the applicability of the MPAG framework to a fishery rather than a MPA; and in doing so 2) critically assess the governance of the offshore Greenland halibut fishery, with specific reference to the role of the Marine Stewardship Council (MSC) certification.

Throughout this chapter 'the fishery' refers to the offshore Greenland halibut (*Reinhardtius hippoglossoides*) fishery, west Greenland. In 2017, the Greenlandic portion of the fishery's fleet, consisting of six vessels known as the West Greenland Offshore Greenland Halibut Fishery (WGOGHF), was certified sustainable by the MSC (Cappell *et al.*, 2017). This was followed by two German vessels forming the Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF), which was first MSC certified in 2019 (Cook *et al.*, 2019). Thus, 'the fishery' refers to all offshore halibut fishing in the western Greenlandic EEZ, whilst WGOGHF and DSWGHF refer to the MSC certified Greenlandic and German components of the fishery, respectively. In March 2020, subsequent to the paper above (Appendix III), a scope extension was obtained for the WGOGHF MSC certificate, to incorporate a single long-line vessel (Chaudhury *et al.*, 2020). The text below reflects this development.

7.1. Context

Greenland, a constituent part of the Kingdom of Denmark, is the 12th largest country in the world but has a small population of ~56,000, which has been stable since the early 1990s (Andersen, 2015, Bendixen *et al.*, 2019). The Home Rule Act (1979) and Self-Rule Act (2009) transferred legislative and executive power to Greenland, granting the right to manage all natural resources in Greenland and its exclusive economic zone (EEZ) (Rosing *et al.*, 2014). The state capacity in 2018, calculated as a mean of scores (−2.5 to +2.5) for six dimensions of governance indicators, was 1.4 (Denmark: 1.6), with an average percentile ranking of 89.5% (Kaufmann *et al.*, 2011, Kaufmann and Kraay, 2019). This indicates a relatively high state capacity for governance.

Greenland left the European Union (EU) in 1985, principally to secure management of, and access to, fish stocks within its EEZ (Jacobsen and Raakjær, 2012, Andersen, 2015, Snyder *et al.*, 2017). Economically, Greenland remains dependent on Denmark, relying on an annual grant of 3.4 billion DKK (~500 million USD) set in 2009 and adjusted annually for inflation, which supports nearly half the public spending budget (Andersen, 2015). In 2016, this subsidy accounted for 20.3% of the GDP (Ministry of Finance, 2019). In 2015, GDP was 2.4 billion USD, since 2014 annual GDP growth has been positive, fluctuating between 0.3 and 7.7% (Ministry of Finance, 2019). Despite a relatively high GDP per capita of 41,800 USD (Purchasing Power Parity), some 16.2% of the population live below the poverty line (CIA, 2019). Around 10% of the workforce is unemployed (Bendixen *et al.*, 2019), with half the population (men 57%; women 42%) not having received education beyond primary school (Andersen, 2015). These challenges are exacerbated by the isolated nature of many Greenlandic communities.

7.1.1. Fishing in Greenland

Over the past century, Greenland has transitioned to an economy based on the public sector and commercial export fisheries (Bendixen *et al.*, 2019). Fishing remains central to the country's economic, political, social and cultural identify. Over 80% of the country's export income comes from fishing, principally for prawns (*Pandalus borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*) (Jacobsen and Raakjær, 2012, Rosen, 2016, Jacobsen, 2018). The industry is divided into the spatially discrete inshore and offshore sectors, which have distinct management and socio-economic contexts (Jacobsen, 2018).

The labour-intensive inshore fisheries employ small vessels with catches landed and processed locally. Conversely the high-capital, high productivity, offshore fisheries consists of factory trawlers (Christian Jervelund, 2013), which land the majority of catch overseas. The increasingly modernised industry employs a decreasing share of the population, with only 4.8% employed directly in fishing and a further 3% in the wider industry (Jacobsen and Raakjær, 2014, Rosen, 2016). Nevertheless, inshore fisheries are a vital income source, especially for the 8,000 people living in the smaller coastal settlements, many of whom directly or indirectly rely on fishing (Jacobsen and Raakjær, 2014). The offshore industry is dominated by two companies, Polar Seafood and Royal Greenland, the latter of which is 100% government-owned. These two companies share the vast majority of the offshore quota. Further, they own processing plants for handling catch, including from coastal fisheries, where they have invested in the inshore fleet. These separate but intertwined fishery sectors present complex issues around equity, productivity and sustainability, both economic and environmental, which are explored by Snyder *et al.* (2017). Bi-lateral agreements permit vessels from Norway, Russia, Faroe Islands and some EU member states to operate offshore in Greenland's EEZ (European Union, 2015, Cappell *et al.*, 2017, Cappell *et al.*, 2018, Ministry of Finance, 2019).

7.1.2. The offshore Greenland halibut fishery

As a high-value species, halibut is the second most important fishery target in Greenland (after prawns), accounting for 14% of the total catch by weight between 1990 and 2010 (Booth and Knip, 2014) and 20% of total export revenue in 2010 (prawns: 50%) (Andersen, 2015). The inshore fishery accounts for a greater proportion of the halibut catch (Pedersen and Zeller, 2001). In 2017, Greenlandic vessels landed 38,192 tonnes of halibut, of which 24,790 tonnes was from inshore (13,402 tonnes offshore) (Ministry of Finance, 2019).

The offshore Greenland halibut fishery operates in two spatially discrete northern (NAFO 1B) and southern (NAFO 1CD) areas (Figure 3.2) (Jørgensen *et al.*, 2014), at depths of 800-1,400 m, off west Greenland. Vessels >75 tonnes gross registered tonnage (GRT) must fish >3 nautical miles (nm) offshore and fishing for halibut is prohibited by Executive Order between 64°30'N and 68°00'N to protect juveniles (Government of Greenland, 2017). Reportedly, the fishery footprint (Fig. 1) has remained static (Cappell *et al.*, 2017, Cook *et al.*, 2019), primarily because these areas continue to be productive, with minimal risk of gear loss, rather than due to regulatory restrictions. In 2021, the Revised Halibut Fishery Management Plan introduced a spatial limit to the fishery, constraining it to two discrete areas (Figure 3.2, green outline), though this area is significantly larger than the existing trawling footprint. (MFHA, 2021) The fishery is conducted by vessels from Greenland, the Faroe Islands, Germany, Norway and Russia, principally employing bottom trawl gear. Bottom trawls use rock hopper gear, heavy (>2 tonnes) trawl doors (Cappell *et al.*, 2017) and must use a minimum of 100 mm mesh in the wings and 140mm mesh in the cod-end (Government of Greenland, 2017). Twin-rigged nets separated by a roller clump are used by some vessels. To date, there has been limited long-lining by Norwegian vessels (Jacobsen *et al.*, 2018). In March 2020, the West Greenland

Offshore Greenland Halibut Fishery (WGOGHF) obtained an extension to the scope of its MSC certification to include catch from a single longline vessel (Chaudhury *et al.*, 2020). Potentially, this may mean an increased footprint, as the long-liner targets new areas to avoid gear conflicts (Chaudhury *et al.*, 2019) and is able to fish areas that are not suitable for trawling.

The Greenlandic vessels form the WGOGHF, which obtained MSC certification in May 2017 (Cappell *et al.*, 2017). For the purposes of MSC certification, the Greenlandic industry, including those vessels forming the WGOGHF, is represented by Sustainable Fisheries Greenland (SFG). SFG is a tax-exempt organisation, formed for this purpose, whose members include: Royal Greenland; Polar Seafood; other smaller commercial entities; Grønlands Erhverv/Sulisitsisut (Greenland Business Association, GE) and Kalaallit Nunaanni Aalisartut Piniartullu Kattuffiat (the Fishers' and Hunters' Association of Greenland, KNAPK). The Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF) is formed of German vessels and was certified in June 2019 (Cook *et al.*, 2019), operating only in the southern area (NAFO 1C+D) (Figure 3.2).

7.1.2.1. Greenland halibut stock

The North Atlantic Fisheries Organisation (NAFO), which is the regional fisheries management organisation (RMFO), considers the halibut stock in NAFO 0+1 to be part of a larger population complex, distributed throughout the Northwest Atlantic (Treble and Nogueira, 2018). Uncertainties remain concerning the population structure, larval dispersion, migration and spawning (Pomilla *et al.*, 2008, Roy *et al.*, 2014). The prevailing assumption is that individuals that enter inshore fjords and coastal areas become resident, with limited subsequent emigration, particularly from Greenland's north western fjords (Boje, 2002). Hence, the inshore populations are currently considered 'dead-end stocks', although recent research is challenging the assumption of limited connectivity between inshore and offshore populations (Barkley *et al.*, 2018). Management of Greenland halibut stocks across the North Atlantic would benefit from an improved understanding of the species' life-history and population structure (Gundersen *et al.*, 2013). The stock is generally considered to be stable, which suggests that current levels of exploitation are not having an unsustainable impact on the offshore stock (Cappell *et al.*, 2017, Cook *et al.*, 2019).

7.1.2.2. Historic management (stock assessment, TAC and landings)

The commercial catches of halibut were first reported in the Davis Strait in the mid-1960s (Jacobsen *et al.*, 2018, Treble and Nogueira, 2018). Significant increases in catch began in the early 1970s, concurrent with the collapse of the cod (*Gadus morhua*) fishery and development of the prawn fishery (Pedersen and Zeller, 2001). Quota regulation was introduced in 1976 for NAFO Subareas 0+1, with a total allowable catch (TAC) of 20,000 tonnes (Treble and Nogueira, 2018). From 1987, catch reporting was disaggregated by NAFO Subareas (0 and 1) and Divisions (0A-B and 1A-F), in the Canadian (0A+B) and Greenlandic (1A-F) exclusive economic zones (EEZs) respectively. Comprehensive stock assessments led by NAFO were introduced in 1994, amid concerns about declining stocks, which saw the TAC lowered from 25,000 to 11,000 tonnes (Jacobsen *et al.*, 2018). Since then, offshore catches have followed the TAC in NAFO 0, 1A (offshore) and 1B-F, which has been increased in a step-wise fashion, with 34,661 tonnes landed in 2017 (Treble and Nogueira, 2018).

7.1.2.3. Current management (stock assessment, TAC and landings)

In NAFO Subareas 0 and 1, two separate stock assessment surveys are conducted by the Department of Fisheries and Oceans Canada (DFO) and GINR respectively. The NAFO Scientific Council advises on the TAC for NAFO 0+1, this is divided 50/50 between Greenland and Canada, based on a non-binding agreement (Table 7.1) (MFHA, 2016, Cappell *et al.*, 2017). Since 2002, this stock advice has been given separately for the northern area (0A and 1AB, excluding 1A inshore) and the southern area (0B and 1C-F). The Greenlandic Government then sets the TAC in consultation with the Fisheries Council (see, 7.4 Governance framework). The Greenlandic portion of the TAC is divided among the Greenlandic fleet and non-Greenlandic vessels according to bilateral agreements. Quotas for the Greenlandic fleet are distributed on the basis of historic fishing rights, capacity and through consultation with the Fisheries Council (MFHA, 2016).

A separate stock assessment is conducted for NAFO 1A inshore. This informs TAC advice produced by NAFO for each of the three inshore areas in NAFO 1A, namely Disko Bay, Uummannaq and Upernavik. In contrast to the offshore fishery, quotas routinely exceed advice and are often raised during the season in response to pressure from fishers (Jacobsen and Raakjær, 2012).

Table 7.1 NAFO Scientific Council Greenland halibut stock advice for NAFO Subdivisions 0+1, from 2010 to 2019. The Greenlandic share of this advice (50%, by bilateral agreement), Total Allowable Catch (set by the Greenlandic Government) and catch is provided for the northern and southern areas of the halibut fishery, west Greenland. Inshore fisheries are excluded for NAFO 1A but included for all other areas (NAFO 1B-F). Where information was not available in the public domain this is indicated (‘n/a’).

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
NAFO Scientific Council advice*										
0A + 1A (offshore) + 1B	13,000	27,000	13,000	13,000	16,000	16,000	16,000	17,150	17,150	- †
0B + 1C-F	14,000	27,000	14,000	14,000	14,000	14,000	14,000	15,150	15,150	- †
0 + 1A (offshore) + 1B-F	27,000	27,000	27,000	27,000	30,000	30,000	30,000	32,300	32,300	36,370
Greenlandic share (50%)										
Northern Area (Baffin Bay), 1A (offshore) + 1B										
Advised (tonnes) ‡	6,500	6,500	6,500	6,500	8,000	8,000	8,000	8,575	8,575	n/a
TAC (tonnes) §	6,500	6,500	6,500	6,500	8,000	8,000	8000	8,575	8,575	n/a
Catch (tonnes) |	6,462	6,472	6,459	6,513	7,985	8,016	8,335	8,655	n/a	-
Southern Area (Davis Strait), 1C-F										
Advised (tonnes) ‡	7,000	7,000	7,000	7,000	7,000	7,000	7,000	7,575	7,575	n/a
TAC (tonnes) §	7,000	7,000	7,000	7,000	7,000	7,000	7,000	7,575	7,575	n/a
Catch (tonnes) |	7,256	6,902	7,432	8,250	8,511	8,432	8,849	9,616	n/a	-

* NAFO Scientific Council stock advice available online (NAFO, 2019)

† From June 2018 the NAFO Scientific Council no longer provides separate advice for 0A+1A (offshore)+ 1B and 0B + 1C-F because ‘*there is no scientific basis with which to provide separate advice*’ (NAFO, 2018).

‡ The advised TAC is 50% of the NAFO advice by long-standing bi-lateral agreement between Greenland and Canada. The figures presented from 2014 to 2018 are provided by the Greenland Government (Government of Greenland, 2019). The figures presented from 2011 to 2013 are from the MSC assessment of the WGOGHF (Cappell *et al.*, 2017)

§ The TAC is set by the Greenlandic Government in consultation with the Fisheries Council. The figures presented from 2014 to 2018 are provided by the Greenland Government (Government of Greenland, 2019). The figures presented from 2011 to 2013 are from the MSC assessment of the WGOGHF (Cappell *et al.*, 2017).

| Data from NAFO Scientific Council 2018 stock assessment report (NAFO, 2018).

7.2. Objectives

The Fisheries Act 1996, explicitly states that its purpose *“is to ensure appropriate and biologically responsible use of fish stocks”* and that attention should be given to *“economic and employment considerations in the fishing industry, the processing industry and other related industries”* (Greenland Self-Government, 1996). This is closely aligned with the NAFO’s stated objective for the NAFO Convention Area, *“to ensure long term conservation and sustainable use of the fishery resources in the Convention Area and, in so doing, to safeguard the marine ecosystems in which these resources are found”* (NAFO, 1979), i.e. the explicit aim of the management authorities is to ensure the ecological and economic sustainability of the fishery.

7.2.1. Industry objectives

The primary objective of the industry in seeking MSC certification was to maintain access to markets. The MSC certification seeks to use market forces to promote sustainable fishing (Sutton, 1996, Cummins, 2004, Agnew et al., 2014), where certification costs are balanced by competitive advantages (Gulbrandsen, 2009), such as, price premiums and access to markets (Christian *et al.*, 2013). The latter has become increasingly important since the MSC helped mainstream fisheries sustainability and develop the market for sustainable seafood (Ponte, 2012). The clear consensus among interviewees was that, rather than seeking a price premium, the driver was to secure access to the lucrative European market, as previously reported by Jacobsen *et al.* (2018). CAB2 explained that “*if you want to sell your fish on the European market then you need MSC certification”* and therefore the industry’s response was “*OK if that’s the commercial conditions in which we have to operate then we’d better get the stamp*” (CAB2).

A secondary objective may be to achieve corporate social responsibility (CSR) goals, specifically concerning environmental sustainability. Sustainable sourcing is now well-established in the CSR strategies of global seafood industry actors (Bailey *et al.*, 2018). Indeed, Royal Greenland (WGOGHF), Polar Seafood (WGOGHF) and Parlevliet & Van der Plas, the parent company of Doggerbank Seefischerei (DSWGHF), all have CSR statements that make explicit reference to fishing sustainably. MSC3 reported “*one of the most important drivers for certification now is…the corporate social responsibility of the big retailers…they want to be seen to be being responsible, it’s something their shareholders will demand of them*”.

7.3. Drivers/conflicts

7.3.1. Economic dependence

In Greenland, fishing is important at the macro-economic level, accounting for 80% of exports (Jacobsen, 2018) and generating significant tax revenues. At the micro-economic level, it provides employment, household income and cash for subsistence hunters in isolated indigenous communities (Delaney *et al.*, 2012). Interviewees described how "*it is not a normal economic situation in Greenland*' (FI1), when you are dealing with fisheries in Greenland you are '*dealing with the economy [interviewee's emphasis]*" (CAB2). This economic dependence on fisheries and the resulting social and political ramifications cannot be overstated.

This dependence explains why, despite starting in 2003, efforts to reform the existing Fisheries Act have so far not reached a conclusion. Politicians have been unable to reach a consensus position that balances calls for a more equitable distribution of quotas, whilst maintaining an efficient and productive industry. It was reported that the revision is *"such a sensitive and controversial area"* (FI2) that progress has not been made and has become "*a never-ending story"* (NGO2).

7.3.2. Industry influence

Inevitably in a country dependent on fisheries, the industry exercises considerable influence. FI4 stated, *"when talking about offshore fishery I don't find any resistance, we get what we want*". This power and influence arises from several factors. Firstly, just two companies, Royal Greenland and Polar Seafood, account for the majority of production in the fisheries sector, reportedly 77% in 2011 (Christian Jervelund, 2013). Thus, to some extent, Royal Greenland and Polar Seafood exercise a duopoly. Secondly, the larger of these two, Royal Greenland, is 100% government-owned. Some have suggested that this presents an obvious conflict of interest for the government. Lastly, the industry has a dual positioning. On the one hand it sustains the national economy, generating revenue from the highly productive offshore fisheries for halibut and prawn. Simultaneously, the dominant industry players support inshore fisheries and communities by operating processing plants, which are of "*lifeline significance*" (Snyder *et al.*, 2017), making the industry actors indispensable mediators of coastal development (Jacobsen, 2018).

The industry is also able to exercise influence at a policy level. Jacobsen and Raakjær (2014) identified an influential "*grand reform network*", with the fishing industry and banks at the centre, lobbying for the introduction of individual transferable quotas (ITQs) in the prawn fishery. This successfully led to a paradigm shift in Greenlandic fishery governance, towards economic profitability and closer adherence to biological advice, associated with a new government in the period 2009-2012 (Jacobsen and Raakjær, 2012, Jacobsen and Delaney, 2014). This consolidated control and market share with quotas being held by a smaller number of entities, specifically Polar Seafood and Royal Greenland. Jacobsen and Delaney (2014) highlighted that this change was driven by the industrial fishery sector and not by the inshore fishers, processing workers or local communities. Interviewees also confirmed that the industry, *"share the rationality with the banks…and the Ministry of Finance"* (SC4), which collectively are a powerful lobby.

7.3.3. Unknown impacts on deep-sea habitats

A governance framework that allows for evidence-based management is desirable for the sustainable management of any natural resource. However, the paucity of knowledge on deep-sea ecosystems in terms or their nature, distribution and response to physical disturbance, presents significant challenges. As acknowledged by an interviewee from the MSC, "*in terms of having a quantitative basis and scientific basis to underpin any policy decisions, it is almost impossible for most of the deep-sea"* (MSC3). The halibut fishery and prawn fishery are not exceptions. At the point the industry in Greenland first engaged with the MSC certification, "*there had been no research at all about the seabed before that time*" (FI4). Another interviewee stated "*we did not have much knowledge about seabed…[and] impact on the seabed"* (ST1).

7.3.4. Inshore over-exploitation

Multiple interviewees noted that TACs routinely exceed scientific advice in inshore fisheries, for example "*generally the rule is that in the inshore areas the advice is not followed*" (SC1). This is driven by overcapacity in the inshore fleet and limited other employment opportunities, "*there are so many fishermen there and they all need enough [quota] to fish*" (MSC1). Accordingly, quotas are politically highly sensitive. Inshore fishers, referred to by multiple interviewees as the "*dinghy brigade*", are a key source of votes and thus hold considerable influence over politicians. This manifests in successful lobbying to raise TACs and exceed scientific advice (Jacobsen and Raakjær, 2012). This pressure and the impacts are most pronounced in Disko Bay, with negative impacts on stocks evidenced by declining catch per unit effort (CPUE) and size classes (Nygaard, 2019). FI3 described the inshore fishery as "*hopelessly overfished*". However, the current understanding of halibut stock dynamics suggests over-exploitation inshore will not negatively impact the offshore stocks.

Nevertheless, the inshore fishery is impacting the offshore fishery. The inshore Nuuk fjord halibut fishery, which recovered following previous collapses, was described as *"a brilliant example of bad management"* (NGO2). Catches were <500 tonnes prior to 2013. Subsequently, catches have increased varying between 1,000 and 2,000 tonnes, due primarily to increased effort (Treble and Nogueira, 2018). This inshore stock is not subject to assessment or quotas, with only a licence required to enter the fishery. Catches are recorded in the totals for NAFO 1C-F. Currently, the offshore fishery utilises the entire TAC for NAFO 1C-F. The combination of offshore and (unlimited) inshore catch has therefore resulted in the TAC being exceeded in NAFO 1C-D since 2013 (Table 7.1) (Cappell *et al.*, 2017). The certifications of both the WGOGHF and DSWGHF include specific conditions that require this situation to be addressed (see, 7.4.1 MSC certification) (Cappell *et al.*, 2017, Cook *et al.*, 2019). It is unclear how this will be resolved, the recent surveillance audit of the WGOGHF noted that progress to address this issue was behind schedule (Lassen and Chaudhury, 2019). Potential solutions proposed by interviewees included: i) increased management of the NAFO 1B-F inshore fishery; ii) introducing a TAC specifically for the inshore fishery; and iii) recording catches separately for this inshore area. Alternatively, offshore catches could be reduced to accommodate inshore catches without exceeding the TAC, though one industry interviewee observed *"for the offshore segment to cut 2000 tonnes of quota, that will mean a lot of money"* (FI2). The MSC certification is recognised as a pre-requisite for accessing the European market. If failure to address this condition results in withdrawal of the certification from either the WGOGHF, or the DSWGHF, then this would have significant financial impacts on the offshore industry. This is therefore a material threat to the offshore fishery.

7.3.5. Reliance on non-binding bilateral stock sharing agreement

The NAFO Scientific Council advises on the TAC for NAFO 0+1, based on a non-binding understanding that this is divided 50/50 between Greenland and Canada (Cappell et al., 2017, Ministry of Fisheries Hunting and Agriculture, 2016). The resilience of this arrangement has not (yet) been stress tested, as the advised TAC provided by NAFO has been steadily increasing over the past decade (Table 7.1). Were this to decrease, or other economic pressures to arise, it could potentially test the willingness of parties to honour this arrangement. In contrast, the combined Greenland-Canada prawn catch exceeds the NAFO advised TAC, the parties are unable to reach an agreement on a sharing arrangement and so set TACs separately. This has been subject to an outstanding condition in the MSC certification of the West Greenland Coldwater Prawn Fishery since initial certification in 2013, but has not yet been resolved (Lassen *et al.*, 2013b, Cappell *et al.*, 2018).

7.4. Governance framework

The fishery is governed by the state, supported by tri-lateral co-operation with Canada and Denmark (Figure 7.1). The legal framework for fisheries management is provided by the Fisheries Act, 1996 (Greenland Self-Government, 1996) and subsequent amendments. In addition, Executive Orders introduce further regulation relating to: gear requirements, spatial closures (Government of Greenland, 2017); bycatch (Government of Greenland, 2011); an observer programme (Government of Greenland, 2004); and reporting requirements for offshore vessels (Government of Greenland, 2010). Specific to the halibut fishery, a Greenland halibut management plan has been in place since July 2016 (MFHA, 2016).

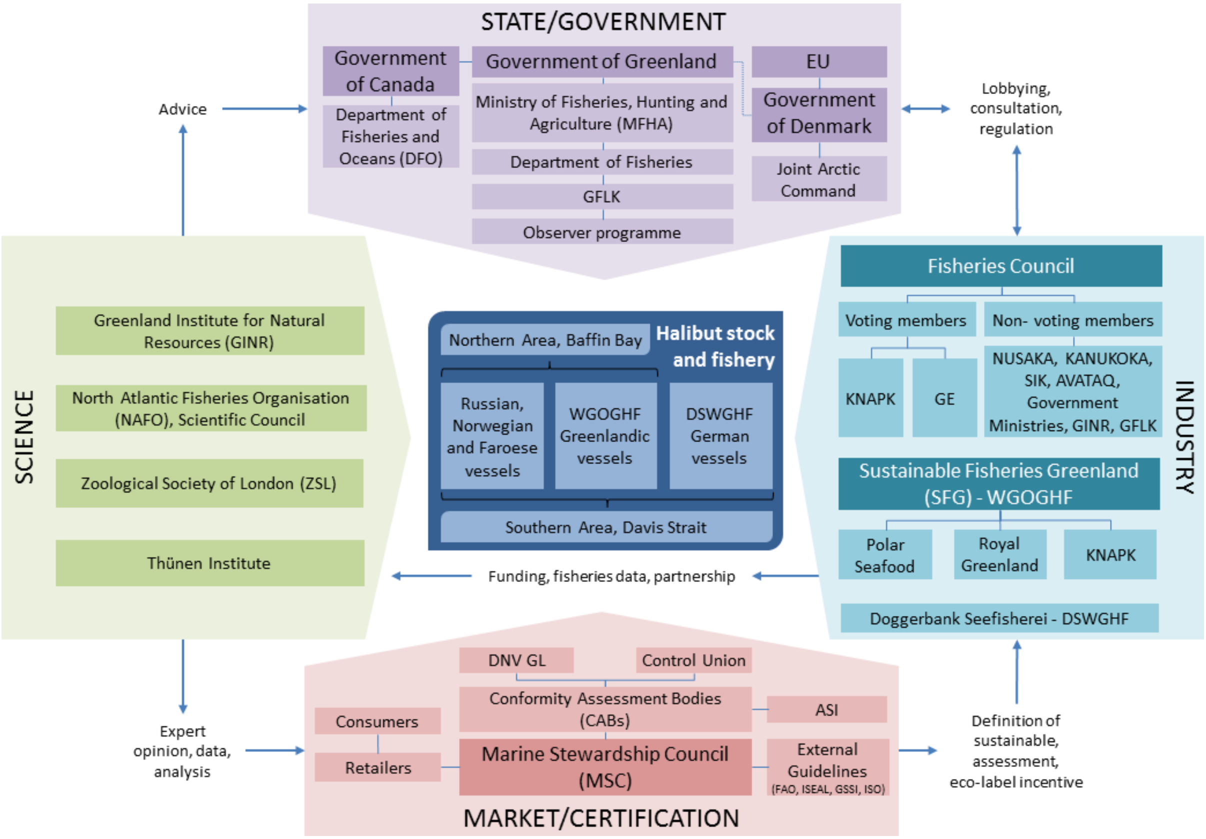


Figure 7.1 Governance framework for the offshore Greenland halibut fishery, west Greenland.

Fisheries management is the responsibility of the Department of Fisheries in the Ministry of Fisheries Hunting and Agriculture (MFHA). The Ministry of Environment and Nature *"has very little"* (ST2) involvement in the management of fisheries and their environmental impacts. Greenland Fisheries Licence Control (GFLK) is a subsidiary of the MFHA, responsible for: the issuing of licences, recording catch statistics, inspecting landings, reviewing and managing logbook data, and overseeing observer programmes. GFLK also contribute to the development and implementation of new regulations. Interviewees agreed that whilst GFLK nominally sits within the MFHA, it is *"rather autonomous"* (SC2) and an *"entity of their own"* (SC4). Whilst the governance approach is legally state-led, the MSC certification, industry and scientific actors play significant roles in the governance structure, formally and otherwise (Figure 7.1).

7.4.1. MSC certification

The MSC Standard complies with the UN FAO's Code of Conduct for Responsible Fishing, Global Sustainable Seafood Initiative (GSSI) guidance, ISEAL codes and relevant International Standards Organisation (ISO) standards. The Standard consists of three principles: sustainable target stocks (P1), environmental impact (P2) and effective management (P3) (MSC, 2014). The three principles are assessed by 28 performance indicators (PIs), for which a score between 0 and 100 is given. Scoring below 60 for any PI results in failure, whilst scores from 60-79 attract a condition requiring a specified improvement within a set timeframe. The average of PIs for each principle must exceed 80 for a fishery to be certified. Following initial certification, an annual surveillance audit is conducted, followed by a full re-assessment after five years.

Assessments, annual audits and re-assessments are conducted by Conformity Assessment Bodies (CABs), who are responsible for assembling a team of assessors with the required background, training and experience. Draft assessments are subject to peer review, technical oversight by the MSC and stakeholder comments. CABs are contracted by the fishery client and subject to oversight by Assurance Services International (ASI). The fishery client represents the components of the fishery seeking certification. In this fishery these are SFG (WGOGHF) and Doggerbank Seefischerei (DSWGHF).

The Standard requires that where there is overlap between an existing certified fishery and a fishery under assessment, the CAB is responsible for harmonising the new assessment to ensure the consistency of outcomes between fisheries. This was the case for the DSWGHF, which was assessed subsequent to the certification of the WGOGHF. Conditions are summarised for the WGOGHF and DSWGHF (Table 7.2).

Table 7.2 Summary of MSC certification conditions in the offshore halibut fishery, west Greenland. The principle (P), performance indicator (PI), condition and timeline for resolution are summarised based on the MSC public certification reports (PCRs).

Principle	PI	Summary of condition	Timeframe
West Greenland offshore Greenland halibut fishery (WGOGHF), certified 2017 [21]			
P1 - Stock	1.2.2	Ensure the TAC advised for Greenland halibut for NAFO stock in SA 0A, 1a (offshore) and 1B-1F (including inshore catches) is not exceeded.	2020
P2 - Ecosystem	2.4.1	Ensure commonly encountered habitats are highly unlikely to reduce structure and function to a point where there would be serious or irreversible harm.	2021
P2 - Ecosystem	2.4.2	Introduce management provisions to ensure footprint of the fishery is such that habitat outcome score is maintained.	2020
P2 - Ecosystem	2.4.3	Improve information on nature, distribution, vulnerability and impact of the fishery on main habitats.	2021
Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF), certified 2019 [22]			
P1 - Stock	1.2.2	Tools in use are appropriate and effective in achieving the exploitation levels required under the harvest control rules (HCR).	2023
P2 - Ecosystem	2.4.2	Management should include provisions for managing the extent of the fishery interactions with commonly encountered habitats. The fishery should encourage and help improve the knowledge base on the distribution of VME indicator species, and encourage protection where they occur in concentrations.	2023
P2 - Ecosystem	2.4.3	Improve understanding as to the vulnerability of the main habitats, with regards to the gears used and recovery times. Implement appropriate habitat sampling in the area where the fishery operates, which allows the possibility of trends to be determined.	2022

7.4.2. Industry

The Fisheries Act established the Fisheries Council, which the government is obliged to consult on matters of fisheries policy, including the setting of TACs (Greenland Self-Government, 1996, Jacobsen and Raakjær, 2012). The Fisheries Council has two voting members, GE and KNAPK, representing the industry and fishers respectively. Additionally, representatives from the following contribute to discussions but do not hold a vote: MFHA, Ministry of Finance, Ministry of Nature and Environment, GINR, GFLK, Association of Municipalities (KANUKOKA), Employees' Union (SIK), Employers' Association (NUSA) and the Nature Protection Association (Avataq), an environmental NGO. The Fisheries Council meets regularly, but does not necessarily always formally assemble, instead members can be consulted by email (Jacobsen and Raakjær, 2012, Cappell *et al.*, 2017).

Polar Seafood and Royal Greenland are able to liaise directly with the MFHA and apply their considerable influence. For example, several interviewees agreed that the process of formulating and introducing management plans in the halibut (and prawn) fishery was very much driven by the industry, in response to the requirements of the MSC Standard. Industry actors in the WGOGHF and DSWGHF are actively seeking to address the issue of TACs being exceeded in NAFO 1B-F (Table 7.1), per the MSC certification conditions (Table 7.2). In the case of WGOGHF actors, this is through direct consultation with the MFHA (Lassen and Chaudhury, 2019), whilst DSWGHF have formally approached relevant ministries in Germany to raise the issue during EU-Greenland fishery consultations (Cook *et al.*, 2019).

The industry has promoted benthic research to improve knowledge of the nature and distribution of habitats and the impacts of trawling. SFG have engaged ZSL, including research that forms part of this thesis, whilst Doggerbank Seefischerei has engaged the Thünen Institute (see, 7.4.3 Scientific advice). These actions by industry were directly attributable responses to the requirements of the MSC Standard.

7.4.3. Scientific advice

Scientists at GINR are responsible for undertaking stock assessments and serve as experts in the NAFO Scientific Council. Subject to an annual request for advice, a working group within the Scientific Council of NAFO is responsible for conducting halibut stock assessments and delivering TAC advice to Greenland and Canada. This advice is based on both stock assessment surveys and fishery data from the respective EEZs.

GINR advises the government directly and through participation in the Fisheries Council. GINR has also developed a programme of benthic research, combining stock assessment bycatch data, beam trawl sampling and seafloor imagery. The latter is collected by means of a towed benthic video sled in partnership with ZSL. To address knowledge gaps that represented a potential barrier to certification, SFG engaged ZSL to conduct photographic survey work. Initially in the prawn fishery using a drop camera (Yesson *et al.*, 2015, Gougeon *et al.*, 2017, Yesson *et al.*, 2017), this was subsequently extended to the halibut fishery, employing a benthic video sled (see Chapters 5 and 6) (Long *et al.*, 2020, Long *et al.*, 2021). ZSL was directly funded by SFG, with additional funding for an IUCN BEST 2.0 project in which SFG acted as partners and co-funders. The survey work is undertaken in collaboration with GINR during annual stock surveys cruises. To support the certification of the DSWGHF, Doggerbank Seefischerei engaged the Thünen Institute to analyse bycatch data from German vessels in the fishery on an ongoing basis (Cook *et al.*, 2019). SFG also funded PhD research into vulnerable marine ecosystems (VMEs) in Greenland (Jørgensbye, 2017).

7.5. Incentives

Drawing on the MPAG framework's taxonomy of 36 incentives, empirical evidence was used to determine those incentives employed in the governance of the halibut fishery (Table 7.3). A total of 25 incentives were identified, of which seven are important priorities for strengthening, with no incentives identified as important priorities for introduction.

Table 7.3 Description of the incentives employed in the fishery. Incentives are from one of five categories of incentive: a) economic, b) communication, c) knowledge, d) legal and e) participation. Those incentives in need of strengthening are identified (Y= used; Y*= Used, in particular need of strengthening). Selected from the 36 incentives (I-1 to I-36) in five categories identified by Jones (Jones, 2014).

a) Economic incentives		
Incentive (I)	**Used**	**How/why?**
I-3. Reducing the leakage of benefits	Y*	Greenlandic vessels must land and process 25% of offshore halibut catch in Greenland (Cappell *et al.*, 2017). By law 60% of officers on Greenlandic vessels must have residency status (lived and paid tax in Greenland for at least the past 2 years). Corporate tax and specific fishery duties, transfers fisheries' revenue to the public purse, *"a third of all tax income is from fisheries"* (ST1). ST1 described the introduction of "*a new system to tax the utilisation of the resource…this year [2018] we are counting on having an income of 400 million DKK* (~60 million USD)*"*. There are growing calls for a revised Fisheries Act to ensure revenue from fisheries is more equitably distributed, employment is maximised and reliance on social security is reduced.
I-4. Promoting profitable and sustainable fisheries and tourism	Y*	The explicit aim of the management plans and Fisheries Act is to ensure exploitation is sustainable and gain MSC certification accordingly. SFG has been granted tax exempt status, presumably to support the industry's pursuit of sustainability. Executive Orders introduce management measures, e.g. prohibition on halibut fishing between 64°30'N and 68°N to protect juveniles (Government of Greenland, 2017). Profitability in the inshore halibut fishery is marginal for some fishers, with over-capacity issues and political pressure to set TAC which routinely exceeds scientific advice. This has implications for the offshore fishery.
I-5. Promoting green marketing	Y	The Greenlandic and German components of the offshore halibut fishery have obtained MSC certification. This eco-label is a form of green marketing and critical to access the European market. Within Greenland there is limited understanding and awareness of the MSC certification among inshore fishers and wider the society.
I-8. Investing fishery income/funding in facilities for local communities	Y	The fishery is a significant contributor to the public purse through tax and duties (The Economic Council, 2017), so contributes to funding public facilities.
I-9. Provision of state funding	Y	GINR is funded by the state and conducts stock assessment surveys. A new state-funded research vessel is currently under construction. SFG is also tax exempt.
I-10. Provision of NGO, private sector and user fee funding	Y	SFG is a private sector entity that has directly contributed to the funding of a programme of benthic research led by ZSL. This has also been supported by the IUCN BEST 2.0 Grant programme. Licensing of vessels generates

		revenue for the state.

b) Communication incentives		
Incentive (I)	**Used**	**How/why?**
I-11. Raising awareness	Y	The use of an eco-label promotes awareness of sustainability issues among consumers. FI3's opinion is that "*the best way to introduce new practices is to inform*", accordingly "*news from MSC and SFG have been introduced as a regular part of agendas for all internal company conferences for officers of the fishing fleet [in the WGOGHF]"*. Scientific research has been shared by ZSL with diverse audiences in Greenland from fishers to school children. For example, research was exhibited at the PolarFish Trade Fair in Sisimiut 2017, allowing dialogue between researchers, fishers and other industry stakeholders. An online game, 'Tricky Trawling', teaches children about sustainable fishing and benthic habitats in Greenland, drawing on ongoing research (ZSL, 2018).
I-12. Promoting recognition of benefits	Y*	There was initially some scepticism and reluctance to engage with the MSC certification among industry and government. This was reduced as awareness grew of the need for certification to compete in European markets. However, there remains limited awareness about eco-labelling and sustainability in general among inshore fishers, *"the local fishermen with their dinghies don't really understand what MSC is and they don't really care about it"* (FI2).
I-13. Promoting recognition of regulations and restrictions	Y	GFLK are responsible for communicating the regulations. The observer programme provides a point of contact on some vessels.

c) Knowledge incentives		
Incentive (I)	**Used**	**How/why?**
I-14. Promoting collective learning	Y*	Stock assessments are conducted by Greenland (GINR) and Canada (DFO). The NAFO Scientific Council conducts the analysis and provides TAC advice, which is in the public domain (Treble and Nogueira, 2018). The SFG-ZSL and Doggerbank Seefisherei-Thünen Institute partnerships promote collective learning by industry and scientific actors. Bycatch logbooks are completed on-board fishing vessels and submitted to GFLK, who share the data with GINR. German vessels have implemented a self-sampling programme, providing data to the Thünen Institute (Cook *et al.*, 2019). Pictorial guides to benthic fauna focussing on VME species are produced by NAFO and made available to the fleet (Kenchington *et al.*, 2009, Best *et al.*, 2010). However, accurate monitoring of invertebrate bycatch remains a challenge, pictures provided often do not resemble the damaged or fragmented bycatch on deck. When trawls "*pull up some fauna…it's very difficult when they place it on the deck to distinguish what it is*" (ST1). Crew and observers lack the technical knowledge, so identification of *"sponges, corals and sea*

		pens…it is a hopeless task" (ST2). For example, in the assessment of the DSWGHF, observer reports of 21.5kg of Scleractinian bycatch from 22 hauls are considered *"highly likely"* to be "*calcareous rock*" which has been misidentified (Cook *et al.*, 2019). Both certification assessments place emphasis on the collection of benthic bycatch data and sharing of these data with scientific institutes (Cappell *et al.*, 2017, Cook *et al.*, 2019). However, effective collective learning must clearly be based on data collectors having adequate knowledge, skills and training, which is currently lacking.
I-15. Agreeing approaches for addressing uncertainty	Y	Recognising that stock assessments are estimates with inherent uncertainty, the halibut management plan stipulates that TAC should be based on the advice received but can only deviate from the prior year TAC by a maximum of 15% (up or down). This addresses uncertainty by providing a clear approach if there is significant variation in stock assessment and gives the industry stability.
I-16. Independent advice and arbitration	Y*	Independent scientific advice is provided by NAFO, GINR, DFO, Thünen Institute and ZSL. CABs act as an arbiter, determining whether a fishery meets the MSC Standard. The MSC's aim is that the "*the process is reliable, robust and evidence based",* but ultimately CABs are trusted to operate with a "*degree of scientific integrity"* (MSC3). CABs are subject to oversight by ASI (Fig. 2), which has the power to impose sanctions. Formal objections to an assessment are resolved by an Independent Adjudicator, appointed by the MSC. The independence of CABs has been repeatedly questioned in the wider literature (Jacquet *et al.*, 2010, Christian *et al.*, 2013, House of Commons Environmental Audit Committee, 2019). The relationship between CABs and fishery clients observed in this study would be better characterised as a consultant-client relationship, rather than an independent assessor-subject relationship. It has also been highlighted that the objection process is narrowly constrained and objections are rarely upheld (Christian *et al.*, 2013). Note, to date there have been no objections to the WGOGHF or DSWGHF. The MSC assessment process is heavily reliant on the assessment and expert judgement of the CAB. This can be challenged by third party stakeholders and the MSC Technical Oversight Team at the Public Comment Draft Report stage. It is the CAB who is then the ultimate arbiter of whether amendments are necessary and sufficient. Similarly, for formal objections the Independent Adjudicator is instructed to defer to the expert judgement of the CAB where there is disagreement. Given the inherent uncertainties around deep-sea habitats and fishing impacts, there is necessarily a reliance on expert judgement. However, expert opinions are not equally weighted, instead the final decision always lies with an entity (the CAB) paid by the fishery client. Thus, some interviewees felt strongly that the independence of CABs needs to be addressed.

d) Legal incentives		
Incentive (I)	**Used**	**How/why?**
I-17. Hierarchical obligations	Y	The United Nations General Assembly (UNGA) Resolution 61/105 called upon States to take action to protect vulnerable marine ecosystems (VMEs) in high seas (UNGA, 2006). This definition has been incorporated into the MSC Standard (MSC, 2014). Assessments of WGOGHF and DSWGHF include discussions of VME habitats and impacts, which are poorly known and accordingly have attracted conditions, with remedial action ongoing (Cappell *et al.*, 2017, Cook *et al.*, 2019, Lassen and Chaudhury, 2019). The MSC Standard is aligned with UN FAO guidance (Figure 7.1), specifically the Code of Conduct for Responsible Fishing and Guidelines for the Ecolabelling of Fish and Fishery Products from Marine Capture Fisheries. Non-Greenlandic vessels are subject to fisheries regulations of their home states in addition to relevant Greenlandic regulation. As Germany is a member state of the European Union, the DSWGHF vessels are subject to the Common Fisheries Policy (CFP), which is reflected in German law and applies to the activities of EU vessels operating outside of EU waters (Cook *et al.*, 2019).
I-18. Capacity for enforcement	Y*	Policing and enforcement is the responsibility of Joint Arctic Command (a naval component of the Danish armed forces), in cooperation with the Greenland Police. Joint Arctic Command conducts at-sea and Port State Control (PSC) inspections. One interviewee reported that prosecutions are few because of limited capacity, with only one vessel to patrol all the offshore waters. In German ports, all halibut landings are inspected (Cook *et al.*, 2019). An observer programme is operated by GFLK (Government of Greenland, 2004), which applies to all vessels. Additionally, German vessels have observers from the Thünen Institute, in accordance with EU requirements, though coverage is "*infrequent*" (Cook *et al.*, 2019). The MSC Technical Oversight for the DSWGHF repeatedly indicates that observer coverage is too low without adequate justification, the CAB's response consistently being that the scoring of this PI remains unchanged (Cook *et al.*, 2019). In the assessment of the WGOGHF it is reported that "*observer coverage…is variable and has recently been reduced*", coverage is inconsistently reported to be "*22 per cent of all hauls in the fishery*" and elsewhere in the same report to '*cover around 5 per cent of fishing*' (Cappell *et al.*, 2017). ST2 explained that budgetary constraints had reduced the number of observers to 15 (in 2018) to cover all large trawlers in all fisheries. Consequently, deployment is on a risk-basis and coverage in the offshore halibut fishery is "*very low"*. Given the frequency with which conclusions in the assessment of WGOGHF and DSWGHF are supported by the presence of observer programmes and data they provide, improved coverage would give greater assurance and capacity for enforcement. This lack of capacity is not considered critically in either MSC assessment.
I-19. Penalties for deterrence	Y	The Fisheries Act details sanctions and fines for infringements. One interviewee's opinion was that fines imposed on industry are relatively small *"peanuts"*, compared to the potential gains of illegal fishing (SC3).
I-20. Protection from	Y	Quotas and licenses are strictly controlled, foreign flag vessels are only

incoming users		permitted through bilateral agreements. There is no evidence of illegal, unregulated or unreported fishing in the offshore fishery.
I-21. Attaching conditions to use, property rights, decentralisation, etc.	Y	MSC certification includes explicit conditions with specified timeframes. These are monitored through annual surveillance audits. This appears to be an effective incentive. FI2 reported the industry is "*doing some things that maybe you [the industry] would rather have not*", such as promoting benthic research, in order to meet the conditions attached to a certificate.
I-22. Cross-jurisdictional coordination	Y*	There are bilateral fisheries agreements with the European Union, Norway, the Faroe Islands and Russia. All foreign vessels operate outside of a 12 nautical mile limit and are subject to the same regulation and licensing system as the offshore Greenlandic fleet. There is a need to strengthen the non-binding basis on which the TAC is split between Greenland and Canada.
I-23. Clear and consistent legal definitions	Y	The Fisheries Act, 1996, subsequent amendments and Executive Orders provide a clear and consistent legal basis (Greenland Self-Government, 1996).
I-25. Legal adjudication platforms	Y	The Fisheries Council is established by the Fisheries Act (Greenland Self-Government, 1996). The MFHA participates in the Council acting as secretariat. The Chairmanship alternates yearly between an appointee from GE and KNAPK. The Chairman is responsible for calling meetings which happen three or four times each year. There are procedural rules, which ensure it functions well. The Fisheries Council considers matters relating to fisheries such as management plans, new Executive Orders and quota setting. Industry actors are all members of the Fisheries Council.
I-26. Transparency, accountability and fairness	Y	Stock assessment reports are made publicly available by NAFO. There are calls for a revised Fisheries Act to make the distribution of quotas more equitable, but this is not focused on the offshore halibut fishery itself. The MSC assessment process provides some opportunity for stakeholders to engage. The MSC Standard and assessment documentation are publicly available.

e) Participation incentives		
Incentive (I)	**Used**	**How/why?**
I-28. Establishing collaborative platforms	Y	The Fisheries Council, established by the Fisheries Act, 1996 (Greenland Self-Government, 1996), serves as a collaborative platform. It was described as an *"important institution"* and part of a *"special political model where you make sure to have the actors are represented in the decision making"* (SC4). It serves as a stakeholder consultation platform for the regular decision-making cycle (e.g. TAC) and longer-term policy initiatives. SFG is a collaborative platform. One interviewee recalled that initially companies had considered MSC certification, but progress was only made by coordinated action following the formation SFG. The NAFO Scientific Council consists of experts from multiple states working together to conduct stock assessments. TAC advice is considered at the NAFO annual meeting, which serves as a collaborative platform attended by members of the Scientific Council; the NAFO Commission; the NAFO Secretariat and delegates from the 12 NAFO Contracting Parties.
I-33. Building trust and	Y	SFG was established as a consortium of industry actors to pursue MSC

the capacity for cooperation		certification of Greenlandic vessels in multiple fisheries. Although Royal Greenland and Polar Seafood are direct competitors, this has worked effectively as a cooperative platform. Collaboration through SFG has also *"contributed to an improved and more productive relationship"* between KNAPK and Royal Greenland, *"in the past both parties have adopted a more hostile stance"* to each other (FI1).
I-34. Building linkages between relevant authorities and user representatives	Y	The Fisheries Council provides a linkage between stakeholders and the MFHA. Interviewees described the Fisheries Council positively as an effective participatory approach to stakeholder consultation.
I-36. Potential to influence higher institutional levels	Y	The Fisheries Council provides a formal mechanism to influence higher institutional levels, e.g. the MFHA (Figure 7.1). The economic dependence of Greenland on fisheries means that both the offshore industry and inshore fishers are able to influence higher institutional levels, though this is not necessarily always a positive outcome from a sustainability perspective.

7.6. Effectiveness

The MPAG framework's effectiveness scale, from 0 (ineffective) to 5 (wholly effective), indicates the extent to which the governance framework addresses the potential impacts, conflicts and drivers identified (Jones, 2014). Here a score of 4 '*most impacts addressed but some not completely*' is assigned.

Many deep-sea fisheries have exhibited a 'boom and bust' cycle and examples of long-standing sustainably exploited target stocks are rare (Koslow *et al.*, 2000, Norse *et al.*, 2012). This halibut fishery is perhaps a notable exception, with a comparatively long history of exploitation (>40 years). Stock assessments since 1994 show relative stability, accordingly the advised TAC has been incrementally increased (Cappell *et al.*, 2017, Treble and Nogueira, 2018). The apparent resilience of this deep-sea stock to exploitation may perhaps be related to its life-history characteristics, though this is not assessed here.

The state-led system of governance is complemented by input from scientific, market-based certification and industry actors. This includes the Fisheries Council, an apparently effective participatory mechanism for consultation, which is important in a context where fisheries are integral to the economy and Greenlandic life. The MSC has acted as an external agency, setting a sustainability agenda and directing the industry's considerable influence, with positive impacts on the governance framework and tangible outcomes. These include the introduction of a management plan and a programme of research to address the paucity of knowledge on benthic habitats and trawling impacts. This has undoubtedly improved the effectiveness of governance, *'once we have management plans in place…it was easier to persuade the politicians [to follow scientific advice]… you have to apply the management plan otherwise you lose the MSC [certification]'* ST1.

However, challenges remain, including the management of the related and politically sensitive inshore halibut fishery, which shows signs of over-exploitation. The trajectory of inshore fishery governance in the halibut and other fisheries remains uncertain. In 2018, a Fisheries Improvement Project (FIP) was established for the inshore halibut fishery, with the long-term goal of achieving MSC certification (Royal Greenland, 2019, SFG, 2020). Critics have repeatedly highlighted that the MSC certification is less applicable and accessible to small-scale fisheries (Jacquet and Pauly, 2008, Foley and McCay, 2014). It remains to be seen whether certification can contribute to the governance of inshore fisheries in this context, with potentially positive impacts throughout Greenland's fishing sector.

Although components of the fishery are 'certified sustainable' and the target stock appears stable, the impacts of trawling on the benthic habitats were not known at the point of certification. This limitation of the certification was recognised by CAB1, "*the difficulty with the habitats outcome part is it is not as strongly evidenced based as you would like, there is a lot of expert judgement going on*". Critics of the MSC have often highlighted that fact that certification does not necessarily result in the changes on the water (e.g. Arnold and Roebuck, 2017). This applies to this fishery, where the majority of changes have been off the water. This was acknowledged by FI2, *"nothing has changed in the Greenland halibut fishery [on the water] as a result of the MSC certification. They fish according to the same rules, they use the same gear and they fish in the same area".* Certification has not limited the use of heavy demersal trawling gear over a large area, which likely has significant impacts on deep-sea benthic habitats. The footprint, whilst reportedly stable, was not currently constrained at the point of certification. The recent certification of a Greenlandic the longline vessel, may mean the total footprint increases, though this gear likely has different and lesser impacts. The MSC rebut the 'lack of change on the water' criticism, citing that the certification seeks to promote a much wider programme of change on and off the water (MSC, 2017). Ultimately, the question of whether the governance framework succeeds in ensuring the environmental objectives (see, 7.2 Objectives) are met, with respect to the benthic impacts, remains somewhat open. The following chapter (Chapter 8), considers this utilising the findings here and the data presented in Chapters 5 and 6.

7.7. Cross cutting issues

7.7.1. The role of the Ministry of Fisheries, Hunting and Agriculture

Governing the largest industry in an undiversified economy is inherently challenging. The political sensitivity of fishery governance is demonstrated by the long-running but unsuccessful efforts to revise the existing Fisheries Act. Challenges are compounded by a high ministerial turnover, *"we have had eight Ministers of Fisheries within the last four, five years"* (ST2). One interviewee described how some people have been critical of the limited formal education of former Ministers of Fisheries, Hunting and Agriculture but balanced this with the observation that "*in a country like Greenland, isn't it an advantage to have someone who knows the fishery as a fisher?"* (SC4). Some interviewees were highly critical of the capacity of the MFHA, in terms of the number of people and their skills. SC3 described how there is "*very weak management in Greenland…the department [MFHA, Fisheries Department] who should be managers doesn't have the knowledge to manage*". They continued, "*there are not the skills needed for making sound management and there's no will to get the skills"* (SC3). Jacobsen and Raakjær (2012) reported the opinion of one person from GINR who had observed fisheries governance in Greenland for a long time who felt that "*the FD [MFHA Fisheries Department] was kept to a weak and politically controlled function".*

Civil servants were supportive of engagement with the MSC and "*spent a lot of resources trying to convince our politicians that MSC is a good idea"* (ST1). The MSC certification process represented a significant workload for the MFHA, *"it's a lot of work from our part [MFHA] but also for the companies [SFG] and it entails cooperation and working groups, numerous meetings, numerous hearings - we spend a lot of resources…[and] a lot of time in the administration attempting to facilitate"* (ST1). SFG and CABs requested *"an incredible amount of data",* creating a significant amount of work for GFLK, which at times was *"a show-stopper"* (ST2).

The implementation of management plans, attributed to engagement with the MSC certification, has had positive impacts for MFHA. Without management plans, stocks are *"under pressure all the time"*, as fishers and/or the industry lobby to increase quotas or access new areas, *"the pressure is taken off by the MSC"* (NGO2). Several interviewees described how the strict adoption of scientific advice by MFHA has become routine in certified fisheries. Following the implementation of management plans, "*the discussion about setting the quota…is a simple administrative process…we [management] just open the book [management plan] and we can see what we have to do"* (ST2). ST1 described how *"once we have management plans in place…it was easier to persuade the politicians [to follow scientific advice]…you have to apply the management plan otherwise you lose the MSC".* One interviewee reported a spill-over effect influencing how politicians acted with respect to non-certified fisheries, "*the MSC has the impact that politicians, at least some, have tried to be more strict with not raising the quota"* (SC4).

7.7.2. Is the industry driving governance?

Previous studies have recognised the significant influence of the Greenlandic fishing industry, describing a "*grand reform network"* with considerable power to lobby for the interests of industrial fisheries (Jacobsen and Raakjær, 2014, Jacobsen, 2018). Pursuit of MSC certification provided an opportunity to see how the industry exercises this influence. There was little doubt among interviewees representing the breadth of actors that the administrative changes required were driven by the industry.

> *"Basically the industry came to the fishery Ministry and said you need to make a management plan for this fishery if we are going to have it MSC certified".* During this process *"the civil servants saw themselves as facilitators of [the development of] these management plans".* Specifically, the civil servants felt their responsibility was only to *"arrange a meeting between biologists [GINR] on the one side and the industry on the other, and then they should agree" (SC4).*
>
> *"[SFG] are pretty much running the MSC process and the administration is just running after the industry. In practice the industry is doing all the work and the administration is just trying to keep up. It is never coming from the politicians, it is coming from the industry" (NGO2).*
>
> *"SFG had to write three of the existing management plans because the Ministry of Fisheries didn't have any employees who knew how to do it and it didn't have the time to" (FI2).*
>
> *"[With regards the MSC certification] the industry is driving the management"* (SC3).

Interviewees' descriptions of the extent to which SFG were involved in the actual preparation of the management plan varied. SFG clearly had a hands-on role, which, depending on the account, ranged from drafting the document to being consultees. Whilst there was agreement that outcomes such as the introduction of a management plan were positive, some questioned the legitimacy of the process.

> *"People at the GINR wondered, is it enough for the managers just to be facilitators or should they take a more leading role?" (SC4).*
>
> *"That this is not how things should be, it should be the manager who writes the management plans… [rather than] adopt a management plan that it didn't write itself".* They stressed that the introduction of a management plan *"is a good thing, it's just the wrong way round, it should come from the Government itself" (FI2).*

Evidently, the industry is able to exert considerable control in the governance of the fishery, whilst some are concerned by this, others "*don't see it as a problem*" (CAB2). Those of the latter opinion see it as an important and appropriate for the key industry in the economy to be able to present its interests. The MSC has incentivised the industry to use its influence to drive governance towards alignment with the requirements of the certification, which is in accordance with the MSC theory of change. "*It's not the MSC that makes changes happen, it's our partners and the MSC acts as a catalyst or facilitator, the programme helps accelerate change, but it's really the work of the fisheries and the other actors in the space, governments and NGOs, that make the change*" (MSC4). Whilst the MSC's Theory of Change (Figure 2.1) describes a cyclical feedback loop, the empirical evidence here suggests a more linear model has driven changes in the governance of the fishery. The MSC's influence on the market has created demand for certified seafood, as described by Ponte (2012). Responding to this demand, the industry, principally Polar Seafood and Royal Greenland, have steered the state actors, dictating developments in the management and governance of the fishery (Figure 7.2). The critical question is 'does this result in a more sustainable fishery'? The answer depends on the adequacy of the MSC definition of sustainable and the process of assessment.

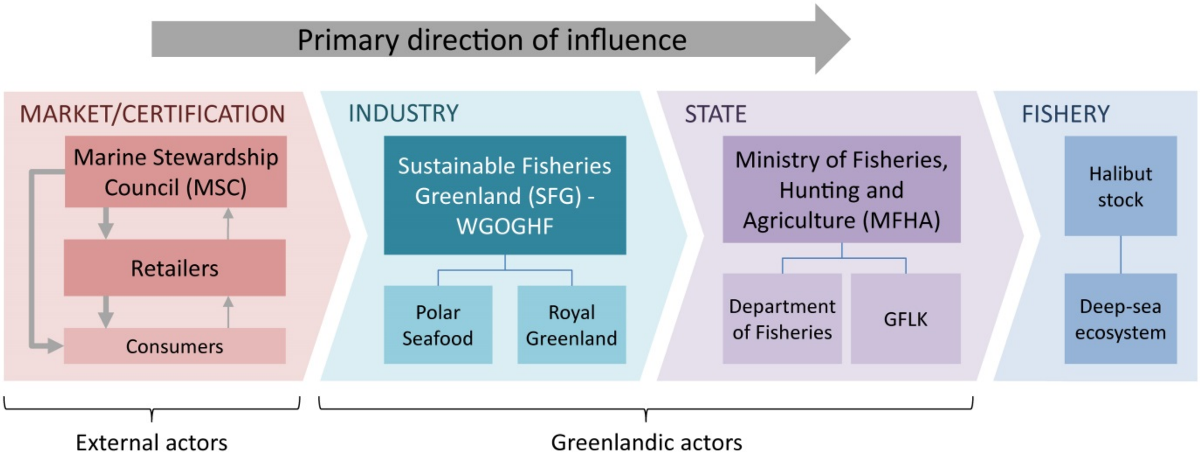


Figure 7.2 Representation of the influence of actors in steering the governance of the fishery. Shows key Greenlandic and external actors. Grey arrows indicate the direction of influence/steer, scaled to suggest relative strength.

7.7.3. MSC certification: defining and assessing sustainability

The MSC's Standard codifies the MSC's definition of sustainable, which is intended to be as "*reputable and scientifically based as possible"* (MSC3). "*The Standard is defined linguistically"* and is written like a "*legal text*" (CAB2). Although there are quantitative elements, it is fundamentally qualitative and requires the exercise of judgement by CABs, a process informed by the MSC guidance and interpretations log. The Standard is not stationary but iteratively revised through the MSC's Fisheries Standard Review (FSR) every five years. Thus, it is "*always going to be a moving paradigm relating to public and stakeholder appetite…and where the scientific community judges that bar to be*" (MSC2). If the bar is too high and it runs the risk of disenfranchising the fishing industry, "*why should we even bother trying to live up to this?"* (FI2). This would undermine the MSC's theory of change, "*if you were to raise the bar dramatically higher from there, then no fishery would be able to meet that bar, would you [the MSC] have the impacts you want?"* (MSC1). Too low and it does not offer the consumer the assurance that the certification seeks to provide or incentivise fisheries to operate sustainably.

There have been high profile criticisms from established NGOs and academics. Some of these critics were supporters of the MSC at the outset and fundamentally believe in the role of eco-labelling as a tool to promote sustainable behaviour. Nevertheless, they warn that the Standard's credibility is seriously comprised, *"they have got to change and if they don't change they will be yesterday's organisation…they either reform or die"* (SC5). NGO1's opinion was that the Standard is "*so weak"* and *"vague"* it renders assessments open to interpretation and *"leaves room for CABs to make money"*. An interesting observation is that, to date, significant criticisms have not emerged from consumers or retailers. These stakeholders are core to the MSC's financial model and theory of change, "*we would see significant trouble…if the retailers stopped trusting the MSC"* (MSC4).

Many interviewees, including from the MSC, noted the disparity between the consumers' understanding of sustainability and the MSC's Standard, *"the science of sustainability is different from the public perception of sustainability"* (MSC1). This arises because consumers are rarely familiar with the realities of commercial fishing, for example the high impact heavy gear employed in deep-sea halibut trawling. There is an important distinction to be made between impactful and sustainable. The Standard allows for the certification of fisheries that can have significant impacts, including at large spatial scales, providing they meet the Standard's definition of sustainable. "*I think the MSC know that of course if you have been trawling…you have been destroying a lot of areas"* (SC3), but despite this retailers rely on the eco-label to provide assurance that the fishery has the *"low impact the consumer wants to see*" (SC5). Thus, because consumers are unfamiliar with the technical details of the Standard, they "*do not necessarily understand the difference between what is sustainable and what is impactful"* (MSC3). Others put this point more unequivocally, "*fundamentally, they [consumers] don't have a clue"* (CAB2). Some interviewees accuse the MSC of being *"disingenuous and misleading to consumers"* in allowing this disparity to persist (SC5). This issue is best summed in written evidence to the United Kingdom Parliament's Environmental Audit Select Committee that examined the effectiveness of the MSC certification (House of Commons Environmental Audit Committee, 2019). Here, Roberts (2018) questions whether elements of the Standard and process would "*pass the person on the street test, would the average person think a policy is right or wrong?*".

There are existing technical criticisms of the Standard and process, a number of which are pertinent to this fishery and emerged as issues in the empirical evidence gathered. These are the independence of CABs, the inconsistency of harmonisation and the assessment of benthic habitat impacts. Interviewees representing CABs and the MSC dismissed criticisms around independence, citing the safeguards in place, such as oversight by ASI. Conversely, others questioned whether CABs *"as judge and jury and have too much control over the outcome, this leads to risks that they will favour the client…because they are being paid by them"* (SC5). The relationship between CABs and fishery clients observed in this study would be better characterised as a consultant-client relationship, rather than an independent assessor-subject relationship.

Whether issues around the independence of CABs are real or perceived, there are simple measures that the MSC could take to address these concerns, and strengthen the incentives described here (Table 7.3e, I-30). Currently, it can be argued that CABs are incentivised to certify a fishery as this offers the potential of future business in the form of annual audits and re-assessment. In the WGOGHF, the initial assessment, two subsequent surveillance audits and scope extension were all conducted by the same CAB, DNV GL (Cappell *et al.*, 2017, Lassen and Chaudhury, 2018a, Lassen and Chaudhury, 2018b). Fishery clients could be required to instruct new CABs (and or assessors) for re-assessments or surveillance audits, which would be simple to implement and have little or no cost implications. This may have the added benefit of promoting a greater number of CABs and assessors, in what has been described by others as a small pool (Auld, 2018).

Another modification would be to the process by which stakeholder, MSC technical oversight and peer review comments are handled. By design, the process of producing the assessment report is similar to the publishing of academic papers. The author submits the draft manuscript for comment from peers and is required to address these. A critical difference is that the CAB acts as both the author and editor, they are responsible for determining if their response to comments is sufficient and deciding to publish the final report, termed the Public Certification Report (PCR). There are multiple examples in the certification of the DSWGHF and WGOGHF where the CAB's response is not to change the scoring, which would have implications in terms of the number of conditions (Cappell *et al.*, 2017, Cook *et al.*, 2019). There is an obvious risk of abuse in a system where the roles of author and editor are played by a single entity that is employed by the fishery being assessed. This could readily be addressed by assigning the editor's decision to a neutral third party, perhaps another CAB or the MSC's peer review college.

Harmonisation is an inbuilt test of the certification process, asking whether the system is adequately designed to ensure that outcomes are consistent. Vessels in the DSWGHF operate within a subset of the area exploited by the previously certified WGOGHF, employing the same gear and subject to the same Greenlandic regulations. Thus, some components of the assessment required harmonisation, including P2 (Cook *et al.*, 2019). Two stakeholders, SFG and ZSL, made written submissions questioning the consistency of the assessments and whether they had been harmonised properly.

SFG details the rationale for believing that the conditions for the DSWGHF are not harmonised with those for the WGOGHF. The CAB's (Control Union) response is that *"there is no material difference in* *the conditions"* for the WGOGHF and DSWGHF (Cook *et al.*, 2019). This is demonstrably not the case given there was one less P2 condition imposed on the DSWGHF fishery (Table 3). This difference is not trivial as conditions are core to the MSC's Theory of Change (Figure 2.1), a key mechanism by which the certification drives fishery improvements. The submission by ZSL is considered in the following section (7.7.4 Benthic habitats).

7.7.4. Benthic habitats

It is undoubtedly challenging to produce a definition of sustainability that can be universally applied to the wide range of fisheries and habitats that enter certification. MSC2 acknowledged that this was evident in earlier versions of the Standard, where "*Principal 2 was scored really inconsistently, it had quite open language, which meant that assessment outcomes were quite inconsistent*". This challenge is perhaps greater in deep seas, where relatively little is known about the nature of the habitats and the impacts of fishing gears.

Interviewees shared their understanding of trawling impacts within the halibut fishery. For example, "*when you have a [deep-sea] trawl fishery there is only very little left of the original fauna*" (SC1). ST2 stated that within the halibut fishery there are *"certainly not any corals because if there has been corals out there, the seabed has been flattened [by trawling] many years ago"*. NGO2 described how "*[the industry has] trawled the same areas for the last ten, fifteen, twenty years both for shrimp and Greenlandic halibut… there is nothing left there*". FI3 explained that the gear used to target halibut is very heavy, *"it is rigged in a way that it takes the top off the seafloor"*.

Given the widely accepted vulnerability of deep-sea benthic habitats and slow speed of recovery, spatial management is often cited as the most appropriate tool for managing deep-sea exploitation (Clark and Dunn, 2012). This is implicitly recognised within the MSC's Standard, which requires that fisheries do not cause serious or irreversible harm to the structure or function of habitats, where serious or irreversible harm is defined as: "*the reduction in habitat structure, biological diversity, abundance and function such that the habitat would be unable to recover to at least 80% of its unimpacted structure, biological diversity and function within 5-20 years, if fishing were to cease entirely*" (MSC, 2014). The implication of this in contexts where recovery is slow (i.e. >20 years), is that habitat within the footprint of fishery can be wholly and irreversible altered provided that 80% of the total area of habitat remains unimpacted. This is effectively a quantitatively defined ratio for spatial management. It is on this basis that the WGOGHF was found to be sustainable with respect to benthic impacts (P2.4.1) (Cappell *et al.*, 2017).

The WGOGHF assessment reports that the total area trawled in a three year period by the Greenlandic halibut fleet was reported to be 14,963 km^2 and that this footprint is stationary (Cappell *et al.*, 2017). The impacted area is compared with 270,000 km^2, the total area >500m in west Greenland, from which it is concluded that 94.5% of the habitat remains unimpacted. Assuming all areas within the western half of Greenland's EEZ >500m represent equivalent habitat represents a gross simplification. At the very least this should be constrained to the depth range (800 to 1,400m) within which trawling occurs, as conditions hundreds or even thousands of meters deeper will be different, dictating the habitats and communities present. The fishery operates in two discrete areas of the comparatively shallow Davis Strait, which acts as a bathymetric bottleneck between deeper Labrador Sea and Baffin Bay basins. This distinct topography uniquely shapes the hydrographic conditions within this region. A more nuanced consideration of habitat would therefore consider abiotic factors, including temperature, salinity, current and slope characteristics within the fishery and to what extent they are replicated elsewhere. Indeed, the findings of Chapters 5 and 6 now confirm that, in terms of benthic habitats, the two areas of the fishery are demonstrably different. MSC2 agreed that *"they [the CAB] haven't defined the [spatial extent of the] habitats effectively"*, and explained that *"as evidenced by the technical oversight that we [the MSC] raised…we weren't particularly satisfied with the rationale presented"*, but noted that *"[the MSC] are a stakeholder in the process, they [the CAB] are not mandated to change their information, we're not replacing their expert knowledge"*. Ultimately the fishery was certified on the basis of this simplistic, somewhat cursory analysis of the spatial extent of benthic impacts, relative to unimpacted 'equivalent' areas.

Subsequently and conversely, the DSWGHF assessment found the recovery of habitats impacted within the footprint is likely to be sufficiently fast to ensure recovery to at least 80% of structure and function within 20 years (Cook *et al.*, 2019). This was subject to a lengthy stakeholder submission by ZSL, which outlined their extensive experience surveying benthic habitats in this fishery. The principle concern was that the CAB's assessment found that recovery from trawling impacts was likely to be relatively quick based on a global analysis of trawl impacts by Hiddink *et al.* (2017). The analysis of Hiddink *et al.* (2017) was based on shallow shelf fisheries predominantly at depths <50m, with only one 'deep' fishery at just 400m. Thus, ZSL's opinion was that this was not applicable to the DSWGHF, citing literature that demonstrates the recovery of benthic habitats is far slower in deep-sea environments compared with shallow shelf habitats.

Clearly the rationale employed in each assessment is questionable in terms of the scientific rigour employed, though some may dismiss this as differences in expert option. However, critically the fundamental basis on which two overlapping fisheries employing the same gear were found to be sustainable in terms of ecosystem impacts (P2, PI 2.4.1) was wholly different and contradictory. This is not trivial, two CABs applied the same Standard employing contradictory arguments to find the habitat impacts to be sustainable. In this case, the harmonisation, or lack thereof, demonstrates serious failings in the consistency and robustness of the MSC assessment process.

7.7.5. Vulnerable marine ecosystems (VMEs)

VMEs are now explicitly incorporated into the MSC Standard, which extends the definition from exclusively deep seas to be irrespective of depth (MSC, 2014). States and RMFOs have not yet adopted consistent approaches for identifying and protecting VMEs, and knowledge gaps remain (Ardron *et al.*, 2014, Morato *et al.*, 2018), including in the northwest Atlantic. MSC2 notes that for MSC assessments, "a *perennial issue has been the identification and understanding of management frameworks around vulnerable marine ecosystems (VMEs)*".

In the halibut fishery, move-on rules are in place to protect VMEs. Specifically, vessels must cease fishing, move a minimum of 2 nm and inform GFLK in the event that 300 kg of live sponges or 60 kg of live corals are taken in one trawl (Government of Greenland, 2017). The inadequacy of move-on rules in general has been discussed elsewhere (Auster *et al.*, 2010). In the halibut fishery, the large mesh (140mm cod-end) employed means many VME indicator species can be impacted but without forming a significant component of the landed bycatch. There are no reports of move-on rules having been triggered in the halibut fishery. This may indicate that VMEs are absent from this area. Conversely, VMEs may be present and subject to damage but not sufficiently represented in the bycatch landed on vessels. Challenges discussed above around the identification of benthic bycatch (Table 7.3c, I-14) potentially compound this. Alternatively, VMEs originally present may have been removed long before the introduction of the VME concept. A better management approach would employ spatial exclusion informed by an improved understanding of VME indicator distribution and abundance.

The engagement with the MSC has resulted in the promotion and funding of research by the industry, which is ongoing. This is providing new information on the nature and distribution of VME indicator species, the impacts of trawling and the presence of VMEs. To date, this research has resulted in the identification of a candidate soft coral VME immediately adjacent to the southern portion of the halibut fishery in shallower water (300 to 600 m), spanning 60 km of continental slope (Chapter 5) (Long *et al.*, 2020). Within the depth range of the fishery, Chapter 6 identifies three potential VMEs: i) a *Flabellum alabastrum* cup coral meadow; ii) areas exhibiting a high combined density of corals, sea pens and sponges; and iii) a *Halipteris finmarchica* sea-pen field. The latter is of immediate conservation concern, as the *H. finmarchica* sea-pen field is within the fringes of the existing fishing footprint and appears to be locally if not regionally rare. The response of the government and industry to this new research will serve as a test of the governance framework and its capacity for adaptive management.

7.7.6. Role of NGOs

Despite having an economy dependent on natural resource exploitation, environmental NGOs (eNGOs) in Greenland are conspicuous by their absence. WWF is the only international eNGO with a permanent presence, maintaining an office in Nuuk staffed by one person. This is partly because of a long-standing antipathy towards eNGOs arising from past campaigns against marine mammal hunting. *"In Greenland we have had very bad experiences about NGOs especially Greenpeace…which we still believe has devastated our seal hunting…[people] are very sceptical about NGOs"* (ST2). This perhaps explains initial reservations about the MSC in Greenland. *"In the beginning we were very reserved, reluctant…we saw guys from MSC, from abroad, coming in…we thought, what are they doing, why should they tell us how we should do our business?"* (FI1).

A key component of the MSC model is stakeholder engagement, including from eNGOs. "*It benefits fishery assessments when there is engagement from NGOs…in areas where there is less presence [of NGOs], you are going to have less scrutiny, it's obvious"* (MSC2). There is very little input from NGOs in either assessment compared with other MSC certifications of trawl fisheries in the North Atlantic. MSC3 conceded that the halibut fishery assessment would have "*undoubtedly*" received more scrutiny in other contexts. The robustness of the MSC assessments and the governance framework in general would likely be improved by more eNGO engagement, providing a much needed critical perspective.

7.8. MPAG case study conclusions

The MPAG framework served as an effective tool to critically assess the governance of this fishery and the role of the MSC certification. It is clear that the framework could readily be applied to other fisheries. The study found an effective state-led system of governance supported by scientific, certification and industry actors. Previous MPAG studies have shown that effective governance requires a diversity of actors and related incentives (Jones *et al.*, 2013), as is the case here, with a wide range of actors from within and beyond Greenland. Collectively, they operate a diversity of interacting and mutually supportive incentives from all five categories, including the collaborative role of the Fisheries Council (I-28), a participatory incentive that enjoys widespread support and could be replicated elsewhere.

The MSC certification provides a strong market steer for the industry's considerable influence. Engagement with the MSC led to a new paradigm, from which there emerged "*an interesting dynamic between the companies and the Government because the companies come and ask to be regulated, which is otherwise very rare*" (ST1). Outcomes include the introduction of a halibut management plan and a program of benthic research delivered through new partnerships between industry and scientific actors. Whilst certification has undoubtedly strengthened the governance of the fishery with tangible changes, significant issues remain. It is uncertain how challenges in the inshore fishery will impact the offshore fishery and whether the MSC certification can achieve similar results in this contested small-scale fishery.

However, the study provides specific examples of existing criticisms of the MSC certification. The assessment of habitat impacts is weak and over-reliant on the expert and definitive judgement of CABs, whose independence has reasonably been questioned. In this context, the issue is compounded by the limited input from third party stakeholders to provide a critical voice. The most serious concern is the lack of harmonisation between the two MSC assessments of overlapping fisheries. Greenlandic and German vessels employing the same gear in the same area were found to be sustainable with respect to benthic impacts by CABs which employed fundamentally different and conflicting logic. This represents a serious failing of the assessment process, compromising one of the MSC three principles of sustainability.

8. Conclusion

It is commonly accepted that the deep seas are the largest and least explored biome on earth but this is changing. Since the start of this PhD research, the first manned descents have been made to the bottom of each the earth’s five oceans, including the deepest manned dive to 10,925 m in the Mariana Trench’s Challenger Deep, Pacific Ocean (Stewart and Jamieson, 2019). Industry preparations for commercial scale deep-sea mining are in an advanced state, with the demand for metals and depletion of terrestrial reserves driving the exploration of this frontier and the development of new mining technologies (Kung *et al.*, 2021). Meanwhile, the commercial exploitation of deep-sea fish stocks continues around the world.

Globalisation has resulted in increasingly complex international supply chains where the extraction, processing, distribution, sale and consumption of goods is separated in both time and space (Meixell and Gargeya, 2005). Fisheries, especially those operating offshore and in deep-seas, are an excellent example of this growing gap between natural resource and end-consumer. It is into this gap that the MSC certification steps, offering, at least in theory, a connection between fishers and consumers that promotes sustainability.

This thesis has presented new insights into the deep-sea benthic habitats in a poorly known region of the Northwest Atlantic, in which the offshore Greenland halibut fishery is found. The governance of this fishery has been critically analysed yielding new insights into the role of the MSC certification. This concluding chapter summarises the key findings, highlights areas for future research and considers what can be said about the sustainability of this fishery in light of the new social and ecological data acquired. The final section offers some reflection on the process of undertaking this project and preparing the thesis, identifying limitations and weaknesses of the research presented.

8.1. Deep-sea benthic habitats in the Davis Strait

Whilst the deep-seas of the North Atlantic are comparatively well known, Greenlandic waters in the Northwest Atlantic have received less attention. This includes the seafloor in and around the west Greenland offshore Greenland halibut fishery, with a paucity of knowledge about the nature and distribution of benthic habitats. This knowledge gap has been highlighted by: NAFO, the regional fishery management organisation (NAFO, 2019); Marine Stewardship Council (MSC) fishery assessments (Cappell *et al.*, 2017, Cook *et al.*, 2019); and scientists (Morato *et al.*, 2021). The latter identified the southern Davis Strait as being an area where there is a significant risk of fisheries having serious adverse impacts on vulnerable marine ecosystems (VMEs), supported by VME data from Canadian waters (Morato *et al.*, 2021). This thesis has sought to begin to address this knowledge gap.

The thesis has presented data from 94 towed video sled stations from 274-1,476 m in the Davis Strait, west Greenland, with the majority of these stations (76 stations, Chapter 6) being from the approximate depth range of the halibut fishery. The 4,743 images extracted from these videos cover ~40,000 m^2 of seabed, from which over 57,000 individual fauna annotations have been made, along with substrate annotations at the image level. Additionally, over 37,000 individual fauna and more than 1,700 boulders (rock >20cm) were counted in videos from the 76 stations analysed in Chapter 6. These data represent a significant new source of information. The only pre-existing imagery was low resolution and confined to two proposed well head locations in the southern area of the halibut fishery (BSL, 2011b, BSL, 2011c). The low-cost, purpose-built, video sled proved to be an effective tool for this research, the information rich imagery obtained was adequate to address the aims. This is, in itself, an important finding. The increasingly advanced technologies available to explore the deep sea allow precision measurement, targeted sampling and in-situ experiments; however, low-cost approaches are required to tackle a challenge on this spatial scale, gather basic data and democratise deep-sea research.

There was relatively little variation in the substrates encountered. At the depth range of the fishery, soft sediments dominated, with occasional hard substrates in the form of boulders and smaller rocks, which were more commonly encountered close to the continental slope. Mixed and rocky substrates were found in shallower waters on the slope of the Toqqusaq Bank. The taxa observed were consistent with those known from the wider region. The communities encountered were varied, despite the relative homogeneity of substrates. The northern and southern area of the fishery were markedly different, with considerably less diversity and abundance observed in the north. Temperature would appear to be a key factor in explaining the differences between the colder northern waters and warmer southern ones, with the topography of the Davis Strait acting as a bathymetric bottleneck directing currents and resulting in separate water masses in these discrete areas of the fishery. This is an important finding from a management perspective, with the previous MSC assessment of the WGOGHF being premised on the assumption that the benthic habitats in these areas were equivalent (Cappell *et al.*, 2017). Within these separate areas, the data suggest that depth and the availability of hard substrates make a contribution to driving the differentiation of communities. The most diverse, abundant and structurally complex habitats encountered were the soft coral gardens on the slope of the Toqqusaq Bank between 300 and 600 m.

The imagery gathered confirmed the presence of a variety of VME indicator taxa, including: sponges (Porifera), soft corals (Alcyonacea), hard corals (Antipatharians, Sceleractinia), sea pens (Pennatulacea) and feather stars (Crinoidea). Four candidate VMEs were identified: i) the soft coral garden on rocky substrates in shallower waters adjacent to the southern area of the fishery; ii) *Flabellum alabastrum* cup coral meadows; iii) a *Halipteris finmarchica* sea pen field; and iv) areas exhibiting mixed assemblages of coral and sponge VME indicators.

These are valuable findings in terms of understanding the distribution of VMEs in this region and informing management. Further, this makes an important contribution to the wider discourse on VMEs and their management globally. There remain significant challenges in adopting universally consistent and objective approaches for identifying VMEs (Auster *et al.*, 2010, Watling and Auster, 2020), which is a critical step in the sustainable management of deep-sea resources. In the authors' experience, these challenges arise from two sources. Firstly, there is still a lot to be discovered about the nature and distribution of VMEs (and VME indicator taxa) in the deep-sea. For example, the limited spatial extent of exploration to date means it can be difficult to assess the comparative ecological importance of findings in any given location: i.e. 'is this a unique and rare habitat, or is it that we simply haven't looked enough elsewhere?'.

Secondly, the existing FAO definition of a VME lacks specificity. This is perhaps out of necessity: it is hard to offer a comprehensive definition based on only limited knowledge. Accordingly, there are no universally accepted density thresholds for indicator taxa. Nor is there agreement on what spatial extent constitutes an ecosystem (i.e. 'what makes the 'e' of VME?') (Watling and Auster, 2020). It is also worth recognising that not all VMEs are born equal. Their relative ecological importance, sensitivity to anthropogenic disturbance and ability to recover will vary (Morato *et al.*, 2018). The approach adopted in Chapters 5 and 6 was to provide as extensive a description of the candidate VMEs as the data allowed. The findings were then reviewed with specific reference to each of the criteria in the FAO's VME definition. The intention is that this approach is the best way for these new data to contribute to the revision, interpretation and application of the VME definition elsewhere. For example, soft coral gardens are a very broad category of VME, which can include a diverse range of substrates and communities. In the existing literature, there is no comprehensive description of a similar soft coral garden on mixed rocky substrates, with abundant cauliflower corals, as described in Chapter 5. This is therefore a valuable account of this ecosystem with quantitative descriptions, including the densities of key VME indicator taxa and an indication of the minimum spatial extent of the mosaic of habitats forming this ecosystem. Thus, the findings here will provide helpful reference points against which to benchmark future discoveries.

8.2. The impacts of trawling on benthic ecosystems

The collective weight of the gear employed in the fishery likely exceeds 10 tonnes. Unsurprisingly, the physical impacts of demersal trawling on the seafloor were readily apparent in imagery from the core of the fishing footprint. Visual evidence of the interaction of trawling gear with substrates included: large, deep single furrows or scars; overturned sediments; regular parallel grooves; and displaced, dragged or overturned rocks. There was a strong correlation between the trawling evidence observed in images and the logbook fishing effort data, with any differences between these likely being related to the disparity of resolution between the two datasets. In the area of greatest trawling effort, the processed logbook data suggested that individual kilometre squared areas of seabed had been subjected to over 400 km of trawling in the period 1999-2019. In some videos from high effort areas, it was possible to distinguish multiple trawl paths crossing each other. Interviewees, including those from the fishing industry, were candid about their expectations of the impacts. FI3 explained the gear for targeting halibut was "*rigged in a way that it takes the top off the seafloor*". Given the 15,103 km^2 trawling footprint of the fishery (Appendix VIII), this represents an extensive area of seafloor that has been subject to physical modification. This modification can reasonably be likened to ploughing, as others have elsewhere (Puig *et al.*, 2012).

Determining the magnitude, longevity and significance of the impacts of trawling on communities is challenging. Firstly, this study does not have an experimental design, so causality can only be inferred in any observed relationships. Secondly, there is considerable underlying ecological variation in the study area. For example, the northern and southern areas of the fishery are demonstrably different, within each of these areas habitats are patchy and the study area spans a considerable depth and latitudinal range. Further, some of the taxa of interest are sparely distributed and therefore rarely encountered. Lastly, sampling in the deep sea is inherently costly, both in terms of time and money, and so sample sizes are small as a result. Nevertheless, the analysis of the data did provide evidence to support the hypothesis that trawling has impacted the benthic ecosystem. Ordination of community data using non-metric multidimensional scaling (NMDS) showed there to be a significant relationship between the community composition and the evidence of trawling observed in the imagery. Modelling showed there to be a significant negative relationship between trawling effort and the abundance of some of the VME indicator taxa for which modelling was possible.

Given the available data and the wider literature, it is highly likely that multiple decades of trawling have resulted in a significantly altered benthic ecosystem, from which populations of vulnerable fauna have been removed or greatly reduced. The chronic and intensive trawling have likely resulted in reduced biodiversity and impaired ecosystem functioning (Pusceddu *et al.*, 2014). There is no temporal component to this study, so inferences about recovery rates must be based on the wider literature. Many of the species encountered in the study area, for example the erect corals, have growth rates measured in millimetre annual increments (e.g. Sherwood and Edinger, 2009). The recovery time of this benthic ecosystem to an unimpacted state would therefore be expected to be of the order of decades or longer.

A priority for management is to ensure that trawling does not have serious or irreversible impacts on VMEs. This is reflected in Greenlandic law, which makes provision for the closure of areas to bottom gears where VMEs are identified in Greenlandic waters (Government of Greenland, 2017). Not all of the potential VMEs identified appear to be at significant risk. The *F. alabastrum* cup coral meadows, for example, are widely distributed in the southern area. Whilst the highest densities of *F. alabastrum* (up to 5.1 individuals m^{-2}) were observed outside the fishery footprint, they were still relatively abundant within trawled areas. Two of the potential VMEs identified should be considered urgent priorities for further research and management inventions, specifically the soft coral garden and the *H. finmarchica* fields. In both cases, a key aim of further research should be to determine the spatial extent of the habitats described here. This will inform spatial management measures and help to determine their relative ecological importance. The most pragmatic and precautionary management measure would be the introduction of spatial exclusions to afford protection to these in the interim. Currently, the two stations with the highest densities of *H. finmarchica* are on the fringes of the existing trawling footprint and well within the newly defined halibut fishery area (MFHA, 2021), and so may be subject to trawling. Whilst, *H. finmarchica* were present at a limited number of other stations this was only at much lower density and did not exhibit a 'field' like habitat. Thus trawling could result in the removal of the only known example of this *H. finmarchica* field habitat type in Greenlandic waters. This may potentially constitute the fishery causing serious and irreversible harm to a VME, which if this were the case would require withdrawal of the MSC certification per the MSC Fishery Standard. The soft coral garden is unlikely to be subject to trawling for halibut, being in shallower water on unsuitable ground. Nevertheless, there are no spatial restrictions on fishing there and potentially the recovering cod fishery or other fisheries could expand into this area. Given the lack of trawling here to date, the introduction of measures to protect the candidate soft coral garden VME would seem to be 'low hanging fruit' for management authorities.

8.3. The governance of the offshore Greenland halibut fishery

The adaptation of the Marine Protected Area Governance (MPAG) framework to examine the halibut fishery provided an effective means to critically assess the governance of the fishery. The study found an effective state-led system of governance with significant contributions from scientific, certification and industry actors, who collectively impose a diversity of mutually supporting incentives. The results here concur with those from other MPAG case studies, where a diversity of incentives has been found to be key to effective and resilient governance (Jones and Long, 2020). One notable aspect of the governance framework in this fishery is the role of the Fisheries Council. The Fisheries Council is a collaborative, participatory platform, which gives a voice to stakeholders, allowing them to actively participate in the decision-making cycle. The inclusive nature of the Fisheries Council means that it is seen as fair and transparent, one interviewee describing it as a *"special political model where you make sure to have the actors represented in the decision making"* (SC4). This kind of participatory incentive could be readily adapted and applied elsewhere. Another, recent but now central component in the governance framework, is the role of green marketing in the form of the MSC eco-label, discussed further below.

8.4. The MSC in Greenland

The central role of fisheries in Greenland, including socially and economically, make this a unique context in which to study fisheries and their governance. Elsewhere in the North Atlantic, whilst fisheries are politically sensitive, especially in coastal communities, their economic importance is often marginal at the national level. In contrast, in Greenland, as one interviewee observed, fisheries are "*<u>the</u> economy [interviewee's emphasis*]" (CAB2). Nevertheless, despite this unique context, insights gained here can be applied more widely. The country serves as a microcosm case study for fisheries globally and the role of the MSC certification. Within Greenland there is the full spectrum of artisanal, small-scale and commercial fisheries, with their overlapping ecological, social and economic issues. Since the initial engagement with the MSC certification in 2008, the industrial component of the sector has pursued certification of several fisheries, including the offshore halibut fishery. A large and growing proportion of the country's fishery exports are now MSC certified. Indeed, the author speculates whether there are any other countries with a higher proportion of their GDP MSC certified? However, in common with existing criticisms in the literature (e.g. Bailey *et al.*, 2016, Stratoudakis *et al.*, 2016), the MSC certification does not appear to be as relevant, accessible or attractive to Greenland's small-scale fishery sector.

The data gathered clearly demonstrate that engagement with the MSC certification has had significant impacts on the governance of the halibut and other fisheries in Greenland. The industry, principally represented by Royal Greenland and Polar Seafood, are clearly an exceptionally powerful lobby in Greenland and have long been able to exercise considerable influence over the state (Jacobsen and Raakjær, 2014). Into this context, the MSC entered as a new external actor. This development was driven by the industry itself, which sought to maintain access to European markets, where MSC certification was increasingly becoming a pre-requisite. The result was the industry began to exercise its influence to alter fishery management in Greenland to align with the requirements of the MSC's Fishery Standard.

Arguably the scale and pace of this disruption would be hard to imagine beforehand, especially in a country where many are vehemently opposed to environmental NGOs; a legacy of anti-hunting campaigns in recent decades. In a relatively short space of time, an industry with a long history of lobbying for bigger quotas was actively seeking more restrictive management of fisheries. A civil servant reported how in this new paradigm, there emerged *"an interesting dynamic between the companies and the Government because the companies come and ask to be regulated"* (ST1). Civil servants were at times overwhelmed by the volume of work associated with pursuing MSC certification. In a short space of time there were tangible outcomes, which are directly attributable to the MSC certification. In the offshore halibut fishery and others, management plans have been introduced for the first time, with new spatial restrictions and limits on the amounts by which Total Allowable Catch can be increased. Additionally, associated with the pursuit of MSC certification, new research into deep-sea benthic ecosystems has been initiated. Despite the halibut and prawn fisheries being high-impact, demersal trawl fisheries, the MSC sees the Greenland story as a textbook demonstration of its model. MSC1 reported *"the MSC theory is in practice in Greenland"*. Certainly there have been improvements in the governance and management of the halibut fishery, but is the fishery sustainable? In particular, are the significant and extensive benthic impacts sustainable and does the MSC certification offer assurance of this?

8.4.1. Reviewing the MSC assessment of the offshore Greenland halibut fishery

When considering the MSC certification in relation to this, or any other fishery two questions frequently emerge. 1) Is the MSC's definition of sustainable adequate? And, 2) is the process by which fisheries are assessed sufficiently robust?

The first question is beyond the scope of this thesis. Objectively, it can be acknowledged that the Fishery Standard is a definition of sustainable. The definition combines qualitative and quantitative elements, which is probably necessary and appropriate in assessing social-ecological systems as complex as fisheries. The MSC, in its self-assigned role as a standard setter, sets the bar where it deems fit. Inevitably, this divides stakeholders into those that see it as too low and those that see it as too high. Arguably, the MSC have got this about right, judging from the widespread adoption by industry on the one hand and demand from the market and consumers for what is currently perceived as a credible eco-label. The commercial success and market-share of the MSC certification support this.

The second question can be answered by considering the halibut fishery and the data presented in this thesis. The MPAG analysis in Chapter 7 provided case study examples of some the existing criticisms of the MSC certification. As noted in the methodology (see, 4.2.3 Social science data collection), the insights gained were in-depth, as the author occupied a privileged position able to participate in the MSC surveillance audit process as both an observer and a scientific contributor.

The Conformity Assessment Bodies (CABs) responsible for conducting assessments cannot be legitimately described as wholly independent. A direct financial relationship exists between them and the fishery under assessment. Even in MSC parlance the fishery is referred to as the '*fishery client [emphasis added]*', which perhaps unintentionally captures the essence of the relationship between industry and assessor. Where this research has identified shortcomings, or cursory assessments, it cannot be discounted that these may in part arise from the CAB(s) being incentivised to maximise the potential of their client's fishery being certified. It is perverse that the MSC simultaneously models elements of the assessment on the peer-review process in academic literature, whilst also assigning CABs dual roles as authors and editors. Some have reasonably suggested this is a case of marking one's own homework. Chapter 7 discusses simple, pragmatic and low-cost options open to the MSC to mitigate this issue, reducing the over-reliance on the definitive 'expert' judgement of CABs.

Serious shortcomings were identified in the assessment of ecosystem impacts (MSC Fishery Standard, Principle 2) in both the certification of the WGOGHF and the DSWGHF. In simple terms, the Fishery Standard defines impacts to be sustainable if they do not cause serious or irreversible harm. This can be; either, because habitats can recover 80% of their structure and function within 20 years; or, at least 80% of each habitat remains unimpacted. Both assessments found the fishery to meet this definition of sustainable, though the rationale provided is not robust in either case.

In the WGOGHF assessment, it is concluded that whilst impacts within the footprint are likely to be significant, 94.5% of the habitat remains unimpacted. This is on the basis the footprint was 14,963 km^2 and the total area in west Greenland >500m was 269,282 km^2 (Cappell *et al.*, 2017). This gross simplification, assuming equivalence of all deep-sea habitats in the region, would surely not have passed peer-review in any reputable scientific journal?

The data presented in Chapter 6 clearly show that the habitats within the northern and southern areas are not equivalent, let alone all west Greenland waters below 500 m. It should be acknowledged that the assessment predated these new findings. However, at the time of the assessment, good oceanographic information was available that shows the currents, water masses and temperatures vary across the western Greenlandic EEZ, including significantly between the two areas of the fishery. This alone is sufficient to discount the logic employed. Furthermore, the deepest areas within NAFO 1A-E are >3,000 m. Any brief review of the deep-sea literature would highlight the fallacy of expecting to encounter the same habitats at 500 m or 3,000 m (Ramirez-Llodra *et al.*, 2010), compared to those at depths of the fishery, specifically 800-1,400 m. Our knowledge of areas deeper than 1,500 m in Greenland is very limited, as this is beyond the depth at which regular stock assessment surveys are conducted and beyond the range of the camera equipment employed in this study. However, we do know that the deeper limit of Greenland halibut depth preference is around 1,500 m (Vihtakari *et al.*, 2021) and depth zonation has been observed in numerous deep-sea studies (e.g. Brandt *et al.*, 2019), including evidence of ecological boundaries at c.1,500 m (Wei *et al.*, 2010). Thus, it is difficult to justify the unsupported assumption that habitats significantly deeper than 1,500m are equivalent to those in the fishery's depth range. In the simplest terms, would any ecologist, terrestrial or marine, be willing to assume that habitats were equivalent across thousands of meters of altitude spanning more than 15 degrees of latitude?

A simple and more defensible approach would be to compare the size of the fishery with the total area of 'equivalent' habitat; where this was constrained by the depth range of the fishery allowing for a buffer, rather than all areas deeper than 500 m. This simple recalculation is presented in Appendix VIII and the areas compared are shown below (Figure 8.1). In NAFO 1A-E (approximately the area considered by the WGOGHF assessment) the total area at depths between 700-1,500 m is 83,596 km^2; compared with 269,282 km^2, the area in west Greenland <500m per Cappell *et al.* (2017). The trawling footprint, according to the logbook data presented here, occupies some 18.1% of this depth constrained area, whilst the fishery area (defined by the Revised Halibut Fishery Management Plan) occupies 34.0% of this. Notably, these values straddle the 20% threshold defined by the MSC Fishery Standard (80% of the habitat remaining unimpacted, where the fished area is unlikely to recover within 5 to 20 years).

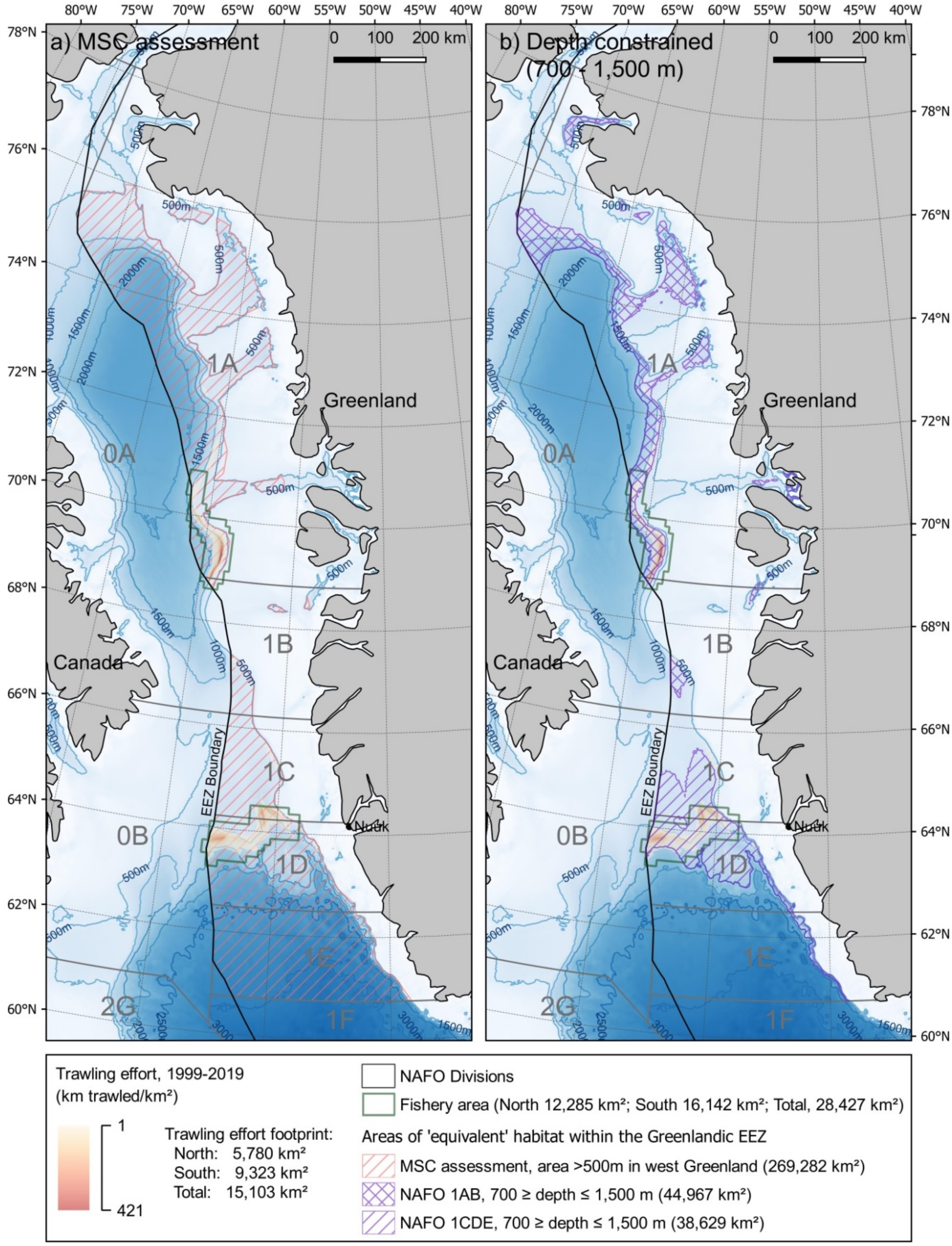


Figure 8.1 Comparison of the fishery size with the total area of 'equivalent' habitat. Panel a) represents the calculation presented in the MSC assessment of the WGOGHF (Cappell *et al.*, 2017). Panel b) represents a revised calculation where the depth is constrained to that of the fishery, allowing a buffer (700-1,500 m). In b) the areas within the constrained depth range are calculated separately for the northern area (NAFO 1AB) and southern area (NAFO 1CDE) of the fishery. The area of the trawling footprint and that of the fishery area in which trawling is permitted per the Revised Halibut Fishery Management Plan (MFHA, 2021) are shown in the legend.

This can, and should be, further refined by considering the northern and southern areas separately, recognising the distinct nature of the benthic habitats in these discrete areas as detailed in Chapter 6. In the northern area (NAFO 1AB) the percentage of the total area of 'equivalent' habitat occupied by the trawling footprint is 12.9%, with 27.3% occupied by the fishery area (Appendix VIII). In the southern area (NAFO 1AB) the percentage of the total area of 'equivalent' habitat occupied by the trawling footprint is 24.1%, with 41.8% occupied by the fishery area (Appendix VIII).

The simple recalculation outlined above and detailed in Appendix VIII and Figure 8.1, shows the area impacted relative to the total area of 'equivalent' habitat is grossly under estimated in the WGOGHF assessment. It should be recognised that the choice of depth range to constrain this recalculation is somewhat arbitrary. The reported depth range of the fishery was used, with a 100 m buffer, based on the simplistic assumption that areas at the same depth range of the fishery are most likely to contain similar habitats. Many of the species encountered are known to occur at a greater range of depths so there is scope to further revise this. However, as Chapter 5 demonstrates very different habitats are found in immediately adjacent shallower waters at 300-600 m, with some of this area (>500m) inappropriately included in the WGOGHF MSC assessment calculation. Thus, the brief recalculation presented here, whilst no means comprehensive, is sufficient to demonstrate that the basis of the ecosystem impact assessment (MSC Principle 2) requires revision if the WGOGHF MSC assessment is to be considered credible. This is not least because the revised management plan introduced in 2021, now defines a fishery area (28,427 km²), in which trawling may occur, that is nearly double the size of the existing trawling footprint (15,103 km²). Were the assessment to be re-performed on the basis outlined above, following the MSC Fishery Standard and applying a more justifiable ecological rationale, the WGOGHF would not necessarily meet the threshold defined by the Standard.

The subsequent assessment of the DSWGHF arrived at a completely different conclusion to justify the finding that benthic impacts are sustainable. Contrary to the previous WGOGHF assessment, it found that impacts within the footprint were unlikely to be significant and that, were fishing to cease, recovery would be sufficiently fast to ensure at least 80% of structure and function was recovered within 20 years (Cook *et al.*, 2019). The justification for this was a global analysis of trawl fisheries (Hiddink *et al.*, 2017) that contained no data from fisheries operating even remotely close to the depth range of the halibut fishery. The reported depth of the deepest fishery in that study being just 420m with the majority being shallower than 100 m. The combination of the evidence here and in the wider deep-sea literature (see, 2.2.1 Benthic impacts of deep-sea demersal fisheries) would not support the assumption made in the DSWGHF assessment that recovery in this context can occur within 20 years. For example many of the VME indicator species present have lifespans significantly exceeding 20 years, are vulnerable to trawling by removal or in-situ damage and so expecting recovery to a mature habitat within 20 years is unrealistic.

The most serious failing here is the lack of standardisation between these two assessments, something that should be ensured through what the MSC terms ‘harmonisation’. Chapter 7 demonstrates that clearly this has failed in this case, indicating that the assessment process is not robust or reproducible. The questionable logic of both assessments and the failure of harmonisation has subsequently been highlighted by participants and stakeholders at surveillance audits for both fisheries, but has not resulted in any revisions (e.g. Hoare and Seip-Markensteijn, 2021). In the author’s opinion, the inescapable conclusion is that with respect to the benthic habitats in this fishery, the MSC assessment is not wholly credible and does not offer assurance that the impacts of trawling are sustainable as defined by the Fishery Standard.

8.5. Is this a sustainable deep-sea fishery?

In general, assessing the sustainability of exploitation from a stock perspective is comparatively straightforward, in that it requires estimation of the current and future size of a single population (rather than multiple components of an ecosystem). Such stock estimates and projections can be made in a reproducible way with a fair degree of confidence. Sustainability can be defined in a quantitative manner, for example in relation to the estimated maximum sustainable yield, which is an approach adopted in Principle 1 of the MSC Fishery Standard (MSC, 2014).

The only conditions relating to stock (Principle 1) in both certifications are concerned with the non-binding nature of the stock sharing agreement between Greenland and Canada and issues with the partitioning of catch between the inshore (NAFO 1C+D) and offshore fishery in Greenland (Table 7.2). These are to some extent administrative, though nonetheless important, issues. As the stock straddles Canadian and Greenlandic waters, Total Allowable Catch is set based on advice from NAFO, informed by annual stock assessment surveys conducted by both countries. Seemingly, this is a well-managed stock, which beginning in the 1960s, has supported a relatively long-history of continuous exploitation and is currently stable (noting the related but separate issues in the inshore fishery). From a stock perspective, it therefore appears to be a rare counter example to the ‘boom and bust’ norm of deep-sea fisheries.

However, the answer is less clear from a benthic ecosystem perspective, which is one of the most controversial aspects of deep-sea demersal trawl fisheries. Clearly trawling has significant impacts and recovery from those impacts will take decades or more. Whether this is sustainable depends on how sustainable is defined. Whilst the MSC offers a definition, the existing assessments against this are not credible. The new research presented here should be useful in informing the management authorities, scientists and future MSC (re-)assessments in this fishery. However, the knowledge gap is not closed, more information is needed. Specifically, a greater understanding of the spatial extent of the candidate VMEs and a broader understanding of the nature of ecosystems regionally to inform the assessment of the ecological importance of those habitats described here. These knowledge gaps must be closed before this fishery can be conclusively considered to be sustainable. In the interim precautionary management is advised, specifically the introduction of spatial management measures to afford protection to those candidate VMEs identified as being priorities. Without the introduction of precautionary spatial management measures, there remains a real risk of serious or irreversible harm being caused to VMEs.

Ultimately, this is a comparatively well managed fishery and is perhaps an exceptional example of a deep-sea fishery that may be sustainable. The MSC certification makes an important contribution to the governance of this fishery and has led to a new paradigm in Greenland, where the industry is working with the state to strengthen fishery management. However, this will not persist if it becomes apparent to industry actors that assessments are cursory and that conditions and their attached milestones are flexible. Critics perhaps expect too much from the MSC, in part fuelled by the MSC promising more than in can realistically deliver. The author agrees with Hønneland (2020), *"the MSC certification is no panacea, but it seems to have found a niche as a supplement to national legislation and international agreements"*. Certainly, in Greenland, the result of the MSC certification occupying this niche has had positive and transformative effects. At little more than 20 years old, the MSC certification is still evolving in a 'learning-by-doing' process. The onus is therefore on scientists and NGOs to facilitate this, through constructive criticism, to which the MSC must remain receptive and responsive.

To date the MSC has succeeded in developing a growing appetite for sustainable seafood among consumers (Ponte, 2012). However, if consumers become more discerning, paying greater attention to how seafood is produced and what assurance eco-labels offer, they may find that MSC certified seafood leaves a bad taste in the mouth. The MSC has the opportunity to address these issues highlighted here and elsewhere (Various, 2018b, Various, 2018a), before they become a problem in the marketplace. Robust, credible eco-labels have the potential to play an important role in the future as effective market-based mechanisms to promote the sustainable exploitation of marine resources.

8.6. Self-reflection

I have thoroughly enjoyed my PhD and found it a rewarding process. The subject and the interdisciplinary approach proved to be a good fit for me, maintaining and growing my interest throughout. Beyond the research itself, the PhD has provided lots of related opportunities, particularly in terms of science communication. I greatly enjoyed the fieldwork components of the research, both ecological and social. In terms of ecological fieldwork, going to sea on research vessels was a new and exciting experience, during which I learnt a great deal in a short space of time, from practical skills to taxonomic knowledge. With a background in ecology, I was less familiar with conducting social research and specifically semi-structured interviews. However, I found these to be fascinating, with interviewees being more willing, candid and open than I had expected. The result was a series of free-flowing and informative conversations, the majority of which lasted over an hour.

I am conscious that I was very fortunate in having the support of various, institutions, partners and collaborators (see, Acknowledgements), who facilitated my research in areas that would otherwise be inaccessible. Here, I am referring to both the physical environment and the commercial fishery, along with its various stakeholders. Naturally, offshore deep-sea environments in Arctic and sub-Arctic waters are inherently inaccessible, in this context the barriers were removed by GINR and the previous experience of my supervisors. However, it is also worth noting that I was given rare access and insights into the commercial fishery. Without exception, individuals and organisations that I approached were willing to support my research to a degree I had not anticipated and would not necessarily expect in other fisheries. This access made an invaluable contribution to my research, supporting critical insights that could not otherwise have been gained.

I particularly enjoyed the somewhat open-ended nature of the PhD process, which afforded me the latitude to explore different avenues, not all of which are evident in the final thesis. For example, I was able to spend some time looking into the practicalities of using stereo-camera rigs to open up photogrammetry and structure from motion techniques, which would have allowed the production of three-dimensional images of the seabed. Another example was the possibility of using artificial intelligence (AI) to annotate imagery. In both cases, it was clear to me that these would be worthwhile additions but in the interests of keeping the breadth and scope of the project manageable, I elected not to pursue them further. Nevertheless, such explorations sufficiently developed my awareness and familiarity with the techniques to give me the confidence to go down these routes in future. I also took the opportunity to develop practical skills that I had not expected to gain from my PhD. For example, time spent at UCL's Institute of Making, learning how to precisely machine aluminium, to produce cost-effective deep-sea housings for scaling lasers.

Perhaps the most ambitious element of my PhD was the interdisciplinary approach. There is an obvious value in being able to synthesise research from different disciplines to produce insights that are greater than the sum of their parts. However, this is far easier said than done. It is necessary to become a jack-of-all-trades, without compromising on the detail and depth of understanding in any one area. Throughout the research process and in writing the thesis, I have endeavoured to ensure that the social and ecological work are linked and mutually supporting, rather than being related exercises conducted in isolation. Ultimately, I am pleased with the end result and feel that I was reasonably successful in this respect, which I hope will be most evident to readers in this concluding chapter.

A key methodological decision in this research was the use of the benthic video-sled. Employed for the first time at the beginning of the project, the sled proved to be a valuable tool, gathering information-rich imagery. A challenge was then to develop a robust, replicable and efficient means of gathering data for analysis from the imagery. There is scope to further improve this process, for example, (semi-)automating the time-consuming annotation process using AI, or introducing more systematic approaches to quality assurance. When using the data gathered by the sled it was important to be mindful of its limitations, ensuring inferences were restricted to what can be reliably determined from the imagery. Whilst highly mobile taxa (e.g. fish) are seen, it is not possible to obtain robust estimates of their densities, as the responses to the sled (i.e. flight or avoidance behaviours) of different mobile taxa are not known. Hence, highly mobile taxa were deliberately not explored in this research. Another key consideration was being realistic about the level of taxonomic certainty that could be consistently achieved across the image set. Using the sled therefore necessitates a trade-off between taxonomic resolution and the reliability of the annotation data. Whilst the ecological fieldwork was a major undertaking, in terms of both time and costs, it is important to bear in mind that the resulting 94 video sled stations presented in the thesis are spread over a very large area, spanning a depth range of >1,000 m and thus offer only a tiny snapshot. A complementary approach would be to use modelling (e.g. species distribution modelling) to extrapolate beyond the limited data gathered. Alternatively or addition, other data sources, such as fishery-dependent bycatch data could be used to address the inherent weakness of the video sled's limited spatial coverage.

In reality, only a limited amount of the information contained within the video imagery was used in this thesis, so there are opportunities to gain further insights using the imagery already obtained.

For example, careful examination of the sediment in the videos reveals the presence of various *lebensspuren*. *Lebensspuren*, a German word meaning life traces, are the structures, burrows and physical imprints left by fauna. The presence, absence and abundance of different forms of *lebensspuren* in imagery could be determined with a similar annotation methodology. Such data would serve as a proxy for levels of bioturbation and offer insights into the abundance and diversity of infauna, which were not assessed in the work conducted to date.

Fundamentally, undertaking a PhD is a learning-by-doing process, gaining experience, knowledge and skills along the way. Naturally, one would expect there to be areas for improvement and mistakes, without which there would be no opportunities for learning and development. Chapters 5 and 6 were produced chronologically and provide a good example of this, in the different approaches taken to analysing community composition. In Chapter 5, Figure 5.4 shows the positive and negative association between different pairs of taxa. The purpose of this analysis was to attempt to characterise the assemblage that makes up the soft coral garden community. It shows for example, that cauliflower corals were positively associated with three other taxa. This finding informed the use of cauliflower corals as an indicator taxa for the soft coral garden habitat. Subsequently, in Chapter 6, non-metric multi-dimensional scaling (NMDS) was used to produce an ordination plot of the benthic fauna assemblage, with fitted vectors showing the effect of different environmental variables (Figure 6.3). To me, this was a new and very useful statistical approach that I learnt during the analysis of the data in this chapter. With the benefit of hindsight and new knowledge gained through the learning-by-doing process, the NMDS approach may have been a more sophisticated and informative option to have employed in Chapter 5. This is just one of many examples through the course of my PhD journey, which have contributed to my development as a research scientist.

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Appendix

Appendix I

Paper I

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Governance analysis of a community managed small-scale crab fishery in Madagascar: novel use of an empirical framework

Stephen Long [a,b,*], Peter J.S. Jones [b], Zoavina Randriana [c], Jeneen Hadj-Hammou [d,e]

[a] Institute of Zoology, Zoological Society of London, UK
[b] Department of Geography, University College London, UK
[c] VetClinic, Antananarivo, Madagascar
[d] School of Geography and the Environment, University of Oxford, UK
[e] Lancaster Environment Centre, Lancaster University, UK

A R T I C L E I N F O

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A B S T R A C T

The Marine Protected Area Governance (MPAG) framework was developed to offer a structured, empirical approach for analysing governance and has been applied to marine prottabected areas (MPAs) around the world. This study sees the novel application of the MPAG framework to a small-scale mangrove crab fishery in northwest Madagascar. The country typifies developing country environmental governance challenges, due to its poverty, political instability and lack of state capacity, with bottom-up approaches often identified as a potential solution. In this context, small-scale fisheries (SSF) play a vital role in food security and poverty alleviation but are vulnerable to over-exploitation. The case study examines community-based management, including the role of three nascent fishing association managing portions of the fishery, within a mangrove ecosystem. Despite issues with underrepresentation of fishers in local resource management organizations that have partial responsibility for the mangrove habitats, some management measures and incentives have been applied, including the replantation of mangroves and fishery-wide gear restrictions. However, the analysis highlights market forces and migration are drivers with negative synergistic effects that cannot be controlled by bottom-up management. Incentives identified as needed or in need or strengthening require the support of external actors, the state, industry and or NGO(s). Thus, governance approaches should seek integration and move away from polarised solutions (top-down vs- bottom-up). As shown by other MPAG case studies, effective governance is dependent on achieving 'resilience through diversity', in terms of the diversity of both the actors and the incentives they are able to collectively employ.

1. Introduction

The Marine Protected Area Governance (MPAG) framework was developed to offer a structured, replicable approach to empirically assessing the governance of marine resources in protected areas [1] and recently this framework has been applied to several new case studies in this issue. Assessing marine resource management outside of protected areas, including in fisheries, requires comparable approaches to assess governance. Small-scale fisheries (SSFs), which account for an estimated 23% of global catch [2] and employ 500 million people worldwide [3], present particular governance challenges, due to their complexity, diversity and geographically dispersed nature [4]. In developing countries, they play an important role in food security and poverty alleviation [3,5]. Therefore, identifying effective approaches to SSF governance is vital for the maintenance of marine biodiversity and the ecosystem services, on which human well-being is dependent.

Madagascar typifies the challenges of natural resource management in developing countries, with low gross domestic product (GDP), limited state capacity and rapid population growth [6]. The country has been identified as a terrestrial biodiversity hotspot, simultaneously noted for its high degree of endemism and rate of habitat loss [7,8]. Since the late 1980s there has been an influx of funding, linked to protecting biodiversity, to support integrated conservation and development projects (ICDPs), community-based natural resource management (CBNRM) and payments for ecosystems services (PES) [9]. Despite having a coastline of 5500 km, marine resource management efforts have lagged behind

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* Corresponding author at: Institute of Zoology, Zoological Society of London, UK.
E-mail address: stephen.long.16@ucl.ac.uk (S. Long).

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terrestrial efforts [10,11]. Consequently, legislation designed to support CBNRM, as with other environmental policy, has often been focussed on the terrestrial realm [12]. However, in the past decade, owing to the biodiversity value of marine habitats such coral reefs and mangroves and their socio-economic importance, there have been increasing efforts to promote marine resource management at the community level [10].

Madagascar's SSF sector plays an important role in nutrition and income generation [10,13,14]. Data show SSF catches account for a greater proportion of catch from Madagascar's exclusive economic zone (EEZ) than industrial fisheries [15]. However, whilst effort is increasing, SSF landings may have peaked, with many in decline [6,13]. One response to increasing pressure and limited state capacity for marine resource management has been the promotion of bottom-up management, including the development of locally managed marine areas (LMMAs) [16]. In the last decade over 100 LMMAs have been created, now covering 12,000 km^2 (~1% of the exclusive economic zone), represented by *MItantana HArena sy Ranomasina avy eny Ifotony* (MIHARI - Marine resource management at the local level) [17]. The infancy of Madagascar's LMMAs and proliferation of community-based fishery management means the efficacy of these governance approaches, both ecological and socio-economically, requires critical assessment [18].

Mangrove ecosystems are known to support high levels of floral and faunal biodiversity [19], providing ecosystem services to local communities [20,21]. At a global scale they play an important role in carbon sequestration, with exceptionally high below ground carbon stocks [22,23]. Recent decades have seen widespread, significant degradation and clearance of mangroves, with principal drivers including coastal development, over-exploitation and conversion for agri- and aquaculture [24,25]. Annual global mangrove loss has been estimated to be 1–2% [26]. Madagascar's extensive mangrove systems are the fourth largest in Africa and account for 2% of the global distribution [27,28]. However, the rate of mangrove deforestation is concerning, with an estimated net nationwide loss of 21% between 1990 and 2010 [28]. These mangroves are important from a SSFs perspective, acting as nursery areas for many exploited marine species [19] and being home to commercially important fisheries. In particular, the mangrove crab (*Scylla serrata*) is targeted commercially and for subsistence [29,30]. Recently there has been increased interest in mangrove crab from foreign buyers [30], with a national catch of 3087 t in 2014, 75–80% of which was exported, principally to China [13,31,32].

In a context where bottom-up or participatory management of natural resources has often been identified as the solution to lack of state capacity for environmental governance [32,33], this study makes novel use of the MPAG framework to critically assess the governance of a locally managed crab fishery, which serves as a LMMA initiative. The study site is located within Boeny region, which is part of the (former) province of Mahajanga, the centre of the country's crab export, where SSFs employ 27% of the workforce [29]. The crab fishery of the Ankobohobo wetlands is chosen as a typical SSF, contributing to the regional export fishery and operating within a mangrove wetland system known for its biodiversity. A crucial distinction is that where many studies of SSF management in Madagascar have focussed on fisheries that have been the direct focus of NGO projects [18,34], this is not the case for the study fishery. However, there are significant interactions with NGO(s) operating in the area, which are considered. The principal aims are to describe the fishery and expand the scope of the MPAG framework, allowing an empirical and critical assessment of the fishery's governance. Findings will have direct application to SSF managers in Madagascar and the Western Indian Ocean, and enable comparisons to be drawn with findings from other case studies of MPAs and LMMAs analysed using the MPAG framework. This will contribute to a more holistic understanding of marine resource governance, identifying convergent themes with global applications.

2. Methods

The MPAG framework [1] was originally designed to empirically assess the governance of marine protected areas (MPAs). Here, it is employed in a novel context to analyse the governance of a SSF. Some areas of mangroves featured in this study are considered part of Madagascar's LMMA network, known as MIHARI [35]. LMMAs may be considered as an International Union for Conservation of Nature (IUCN) Category VI Protected Area (sustainable use of natural resources), depending on the objectives of the spatially defined area, in accordance with the guidelines on applying the categories in marine contexts [36,37]. It is not assumed from the outset that the study area can be classified as a MPA (in the form of an LMMA) or by some other term. The focus here is on the novel application of the MPAG framework to the crab fishery and by extension the mangrove habitat, enabling an empirical assessment of the governance of these marine resources. To apply the MPAG framework to the study fishery, minor adaptions were made. The context section was expanded to briefly describe local ecosystem context and fishery operations. The objectives section differs from previous MPAG cases studies of MPAs, in that the crab fishery has no formally defined objectives, which is discussed.

Primary data were collected in June and July 2016 with an additional site visit in 2017 providing an opportunity to seek clarifications and verification. Semi-structured interviews (n = 7, 5 male and 2 female) lasting 15–40 min were conducted with key informants representing fishers, collectors, officials and NGOs (Table 1).

Initial key informant interviews informed the design of a questionnaire, which was a mixture of numeric, categorical and open questions. Questionnaire participants (n = 48, 5 female and 43 male) were selected by an initial purposive sample of fishers from each village (Table 2). Subsequently, snowball sampling was used, a method commonly employed to gain access to dispersed demographics [38]. Responses to open questions were coded in relation to the MPAG framework, to identify common themes. Focus groups were conducted in three communities with the largest number of crab fishers (Table 2). Focus groups consisted of five individuals, who were always a mixture of questionnaire participants and non-participants. Emergent themes are illustrated with representative quotes from interviews, questionnaires and focus groups. These were conducted in Malagasy with a translator who was experienced working with researchers in rural Madagascar, and able to translate for functional equivalence. The purpose of the study was outlined prior to data collection

Table 1
Key informants and their roles in the Ankobohobo small-scale crab fishery, northwest Madagascar.

Key Informant (reference code)	**Role**
Informant 1 (I-1)	Fisher and local guide with extensive knowledge of the Ankobohobo wetlands, member of VOI Tanteraka, member of the Anjiamandroro Fishers' Association. Works with Development, Biodiversity, and Conservation Action Madagascar (DBCAM) and Operation Wallacea, NGOs which undertake an annual research field season.
Informant 2 (I-2)	Bekobany *Chef Secteur* (state official representing the village of Bekobany)
Informant 3 (I-3)	Deputy *Chef Commune* (deputy to the mayor of the Mariarano Commune) and former Antsena *Chef Secteur*
Informant 4 (I-4)	Coordinator of DBCAM, responsible for facilitating an annual six week research field season as part of a long-term ecological monitoring programme, whose focus is the dry forest and mangroves.
Informant 5 (I-5)	Head of Transfers of Management and Natural Resources (TGRN) at the Deutsche Gesellschaft für Technische Zusammenarbeit (GIZ).
Informant 6 (I-6)	Crab collector operating in the community of Mariarano.
Informant 7 (I-7)	Crab collector operating in the community of Bekobany.

Table 2
Crab fishing communities by *fokontany* with number of fishers, questionnaires and focus groups in each. The number of crab fishers was estimated by triangulating information from local officials, association documents and key informants.

Village	*Fokontany*	Crab fishers	Questionnaire participants		Focus groups	
				(Reference code)		(Reference code)
Bekobany	Mariarano	43	7	(Q-B)	1	(FG-B)
Mariarano	Mariarano	8	7	(Q-M)	–	
Antsena	Mariarano	90	10	(Q-ANTS)	1	(FG-ANTS)
Anjiamandroro	Marosakoa	50	12	(Q-ANJ)	1	(FG-ANJI)
Antafiamahagandra	Mariarano	30	9	(Q-ANTA)	–	
Antafiameva[a]	Mariarano	5	3	(Q-AMEVA)	–	
Total	**2**	**226**	**48**		**3**	

[a] Questionnaires were conducted at two household compounds which self-identified as Ampanolorana and Antafiabe. These were in the immediate vicinity of the larger village of Antafiameva and were included as such.

and verbal consent was obtained. Questionnaire and focus group responses were anonymised to the community level (Table 2). Key informants are not named but as they are identifiable by their role, verbal consent was explicitly obtained to proceed on this basis. The design of the study was informed by marine management monitoring guidelines specific to the Western Indian Ocean [39].

Documents obtained and reviewed include: the Commune's environmental action plan [40], the Commune's socio-economic development plan [41]; documents relating to the transfer of natural resource management responsibility to local user groups [42,43]; and paperwork from fishers' associations, including meeting minutes and articles of association.

3. Context

Madagascar is one of the world's poorest countries, in 2015 GDP per capita was just US$ 402 [44], with 77.8% of the population below the poverty line and ranking 158th out of 188 countries in Human Development Index [45]. Growth in GDP was estimated be 4.1% in 2016, compared with an average of 2.6% over the preceding 5 years [46]. This is balanced against rapid population growth of 2.8% [6], which is higher in coastal areas [13]. Political crises have disrupted growth since independence in 1960, with the last political coup in 2009 having devastating economic and social impacts [6]. The state capacity calculated for 2015 as a mean of scores (−2.5 to +2.5) for six dimensions of governance indicators was just −0.72, lower than the average of −0.68 for sub-Saharan Africa [47,48].

3.1. Study site

Located on the Mahamavo peninsula, the study site is approximately equidistant between the larger Mahajanga Bay (Betsiboka estuary) and Mahajamba Bay (Sofia estuary) mangrove delta systems (Fig. 1).

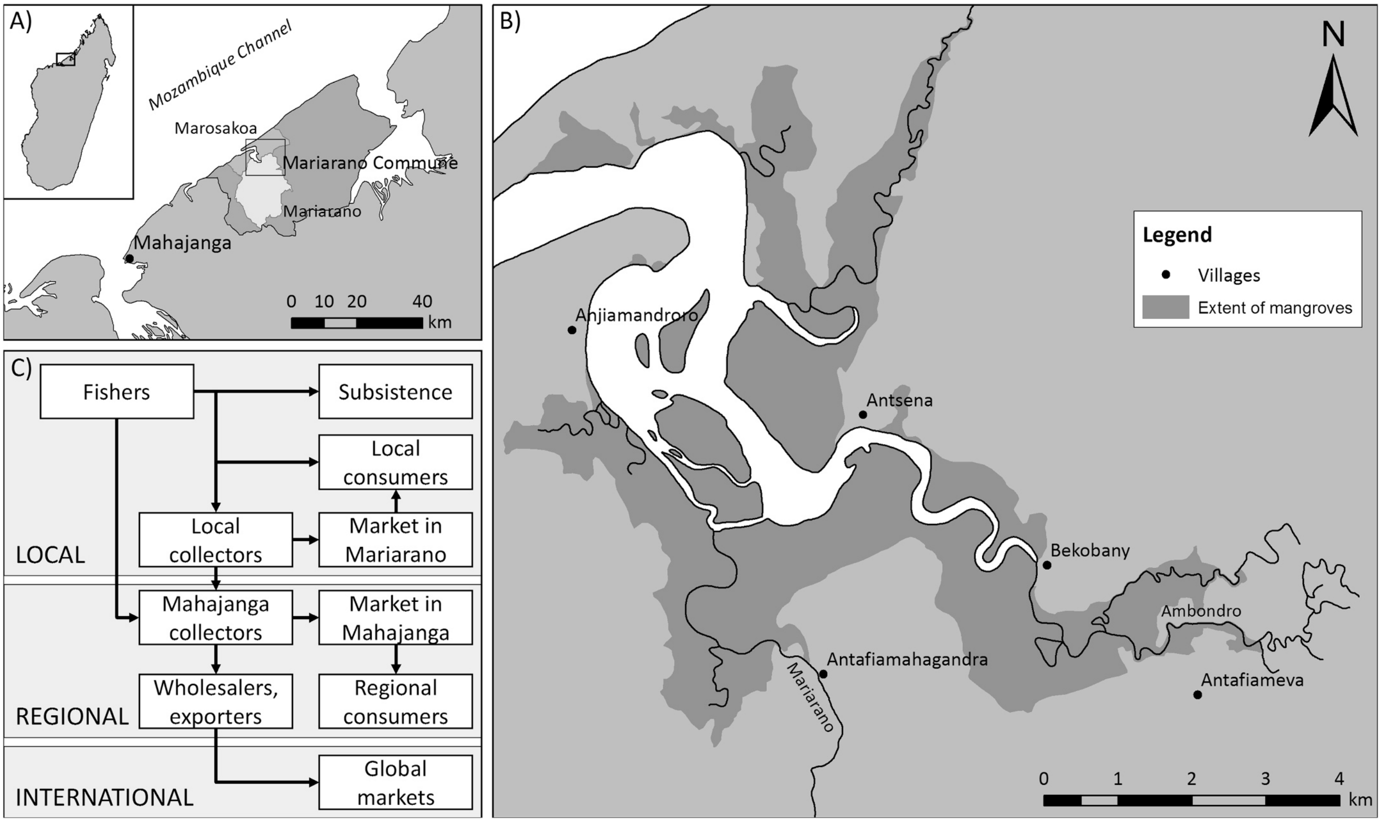

Fig. 1. Location (A and B) and value chain (C) of the Ankobohobo small-scale crab fishery, northwest Madagascar. The fishery, northwest of Mahajanga, is in the *fokontanys* of Mariarano and Marosakoa, which are part of the Mariarano Commune (B). The crab fishery operates within the current extent of the mangroves on the Mariarano and Ambondro rivers and their tributaries (B). Mangrove extent was determined by inspection of 5 m RapidEye satellite data acquired on 06/10/15, granule 3832022_2015-10-06_RE5_3A_944153 provided courtesy of the European Space Agency [51], combined with and opportunistic ground truthing. Value chain schematic, identifies actors at the local regional and international level, based on key informant interviews.

Approximately 50 km north-east of the regional population centre of Mahajanga, the wetlands are found within the Mariarano Commune, whose population was 9488 in 2009 [41]. The commune is subdivided into eleven *fokontany*, the smallest administrative district in Madagascar. The Mariarano *fokontany* is the administrative centre of the commune to which it gives its name [49]. The fishery and wetlands are found within the *fokontanys* of Mariarano and Marosakoa (populations 2412 and 796 respectively [41]). The study site is situated in a mosaic landscape of dry forest (the Ankatsabe and Analabe forest fragments); endemic palm dominated savannah; seasonally dry lakes; small-scale agriculture and the Ankobohobo mangrove wetlands. As is typical in rural Madagascar, the majority of livelihoods are in the primary sector with agriculture (principally rice and manioc), pastoralism (cattle, known locally as *zebu*) and fishing dominating (Fig. 2) [49,50]. Mariarano is accessible from Mahajanga by sea or an unmade road, impassable for several months a year during the wet season.

The wetlands include mangrove stands estimated to cover 2330 ha in 2010, the 19th largest area in Madagascar [28]. During this study six mangrove tree species were observed: *Avecinnia marina*, *Ceriops tagal*, *Rhizophora mucronata*, *Lumnitzara racemosa*, *Heritera littoralis* and *Bruguiera gymnorhiza*. Additionally, the tree species *Xylocarpus granatum* has been reported to be present, along with the mangrove fern *Acrostichum aureum* [52], which is prevalent in the upper less saline reaches of the mangrove system. The mangroves and wetlands have a total area of 3750 ha and are an Important Bird Area (IBA) [53,54]. The wetlands have been identified as a potential Ramsar site, by virtue of meeting Criterion 2 '…*should be considered internationally important if it supports vulnerable, endangered, or critically endangered species*' [53,55], as the critically endangered Madagascar fish-eagle (*Haliaeetus vociferoides*) is known to nest here [55,56]. Other fauna of interest found in the mangroves include endangered species of lemur, Coquerel's sifaka (*Propithecus coquereli*) and the golden-brown mouse lemur (*Microcebus ravelobensis*) [57].

The fishery targets mangrove crab known locally as *drakaka* [41]. Crab fishers are predominantly from the communities of Antafiamahagandra, Anjiamandroro, Antsena, Mariarano, Bekobany and Antafiameva (Fig. 1), with landing sites dispersed throughout the river system. Fishers navigate the mangroves and river system on foot or in *pirogues* (small wooden boats stabilised by an outrigger). Fishers described a total of five gear types (Table 3; Supplementary material, Fig. 1). Gears are baited with fish, *zebu* or crocodile (*Crocodylus niloticus*), the latter of which is hunted locally (R. Gandola, pers. comm.).

Gear use varies considerably between communities, with the *garigary* most frequently used (58% of participants) (Fig. 3). The *fingovitra* was predominantly used in Mariarano and Antafiamahagandra, where the river is shallow and navigable by foot during the dry season. Baited lines were reportedly only used by women. Only participants from Antafiamahagandra and Antsena reported using the *treko* (Fig. 3).

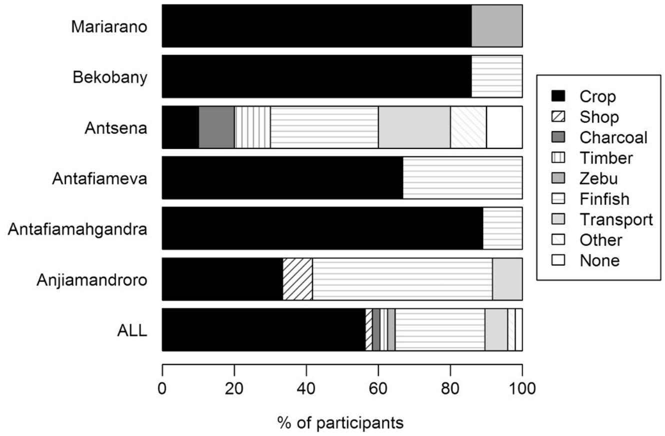

Fig. 2. Main source of livelihood, other than crab fishing, identified by questionnaire participants (n = 48) from the Ankobohobo small-scale crab fishery, northwest Madagascar.

There is a national closed season (1st July to 31st October inclusive) [32], which restricts commercial fishing, though subsistence fishing appears to continue year round. The majority of crabs are bought by collectors for ~3000 MGA kg^{-1} (US$ 1), who transport catch to wholesalers in Mahajanga from where it is exported (Fig. 1). Collectors receive 5000 to 9000 MGA kg^{-1} (US$ 1.60–2.94), depending on the size of crabs (I-6, I-7). Fishers with access to larger boats are able to bypass local collectors by transporting their catch to Mahajanga to attain a higher price (Q-ANTS). Additionally, crabs are sold locally for ~1500 MGA kg^{-1} (US$ 0.50) by fishers and through a weekly market held in Mariarano.

4. Objectives

In applying the MPAG framework to this novel context it is necessary to draw a key distinction between MPAs and fisheries. An MPA is established at a discrete point in time by a group of actors who in the process of forming the MPA agree, formally or informally and to a greater or lesser extent, a set of shared objectives [1]. In contrast a fishery is a subsistence and or commercial activity which emerges over time, typically without explicitly defined or collectively agreed objectives. Nevertheless, it can be presumed that the implicit objective of any fishery, including the study fishery, is to catch the target species and to sustain this activity through time.

5. Drivers/Conflicts

5.1. Migration, population growth and market demand increases effort

Madagascar has a population growth rate of 2.8% [6], which is even higher in coastal regions [13], partly due to migration. The population of the Commune of Mariarano increased from 6140 in 2001 [59] to 9488 in 2009 [41], an annual growth rate of approximately 5.6%. Although data are not available, this trend has likely continued over recent years. Key informants, questionnaire participants and focus groups all identified the influx of migrants as being responsible for increasing fishing effort. The spatial distribution of fishing effort is continuous, throughout the mangrove extent, rather than being discretely organised around individual villages [60].

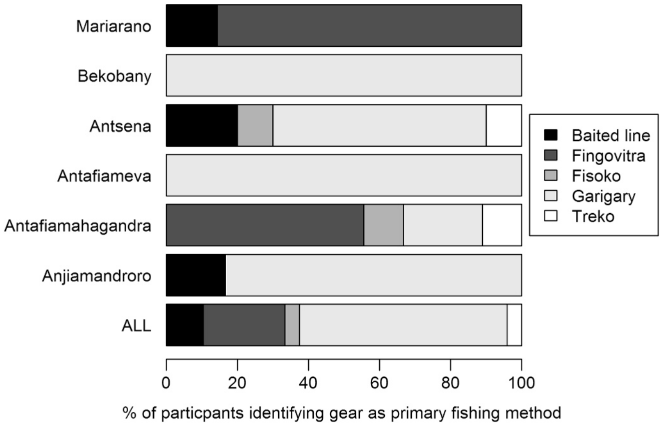

Fig. 3. Gear preference by community, where fishers (n = 48) indicated the primary method they use in the Ankobohobo mangrove crab fishery, northwest Madagascar.

Table 3
Fishing gears types used in the Ankobohobo small-scale crab fishery, northwest Madagascar.

Gear	Type	Description	References
Treko	Passive trap	Conical trap made of women palm/vines (100 × 40 cm, with 10 cm opening and 6 cm mesh). Deployed and collected at low tide, secured by a stick.	(Supplementary material, Fig. 1A)
Garigary	Passive trap	A baited, circular lift net (diameter ~60 cm, mesh size ~3 cm). They are deployed beneath a marker (empty bottle) and left for 10 min to 2 h. Fishers operate 1–20 traps spaced 5–20 m apart.	(Supplementary material, Fig. 1B) [31]
Baited line	Active	A baited line, weighted with a stone, shell and/or a piece of lead.	(Supplementary material, Fig. 1E)
Fingovitra	Active	Long wooden stick (~1–1.5 m) with carved hook end. Used at low tide to remove crabs from exposed burrows.	(Supplementary material, Fig. 1C) [30,58]
Fisoko	Handling aid	Often used in conjunction with other gear to handle crab. Consists of a handle with a mesh held by a frame, similar to a small net.	(Supplementary material, Fig. 1D) [30]

The increased effort and pressure on the crab stock is attributed to a growth in demand from Chinese exporters, which led to increased prices (I-6, I-7). As articulated in a focus group, "*crabs were not that pricey before, but now with the Chinese, you can get a lot of money for the crabs. It is the main income for us. That's why lots of people are migrating here and becoming fishers*" (FG-ANTS). The majority of questionnaire participants (54%, n = 48) self-identified as being a migrant, whose family had been resident in the area for less than one generation. Similar circumstances have been reported in the Toliara region, south-west Madagascar, where crab fishing was traditionally a subsistence activity. Foreign merchants, principally Chinese, starting buying significant quantities of live crab for export, resulting in price increases of as much as 500% [32]. This is associated with increased effort and catches, leading to concerns about over-exploitation [30]. This cycle has been described as a threat to mangroves in Madagascar, with migration leading to over-fishing and decreased mangrove productivity, migrants then often being forced to turn to the exploitation of mangrove wood [29].

5.2. Habitat loss

Using data presented by Jones et al. [28], it is estimated that there was a net loss of 5.7% in mangrove extent, between 1990 and 2010 (Table 4). Visual surveys on foot and by boat in 2016 and 2017 revealed numerous sites within the wetlands with evidence of mangrove clearance, for timber and charcoal production (Fig. 4). Extensive degradation of mangroves in Mariarano and Marosakoa is highlighted in the Commune's environmental action plan [40], whilst a previous study notes extensive degradation of mangroves within an area of management transfer (see, Governance Framework/Approach and Fig. 4) [61].

Mangroves are nursery and adult habitat for the crabs, which form burrows in sediments stabilised by the mangrove root system, so loss of this habitat can seriously impact crab populations [19,62]. Habitat loss was identified as negatively impacting the fishery in an interview with the deputy Chef Commune, '[mangrove exploitation] *is one of the biggest threats facing the crab fishery*' (I-3), and in all three focus groups, '*the reason for the decrease in crabs is the degradation of the mangroves*' (FG-B).

Whilst mangrove wood is used locally for fuel and timber, the primary driver is to meet regional demand from Mahajanga. The relative proximity to Mahajanga and accessibility via maritime routes results in mangrove exploitation for the production of timber and charcoal, to meet regional demand rather than local needs [40,41]. The exploitation of mangrove wood is prohibited by national law and local management rules (see Governance Framework/Approach), producing charcoal is perceived as an illicit activity by the local community in Mariarano [49]. Nearly all questionnaire participants (98%, n = 48) supplement crab fishing income with other livelihood activities (Fig. 2), though only 2% volunteered that this included the production of timber and charcoal. However, it was apparent that this was a common last resort to generate income, '*during the closed season, crab fishermen chop mangroves because they aren't allowed to do the only real job they have… they know that it is not good, but if they don't have anything to eat, they will cut them down anyway'* (FG-ANJ), this being reinforced by the comments of questionnaire participants (Q-ANTS; Q-ANJ).

There is thus a potential synergy between the driving forces, leading to a downward spiral of positive feedbacks, with higher external market demand for crab stimulating inward migration of fishers and increased effort, including to feed a growing local population, and thereby crab stock declines, leading to increased harvesting of mangroves as an alternative livelihood, which indirectly leads to further declines in crab stocks (Fig. 5). This downward spiral represents a typical case of synergies between driving forces [1], leading to an unsustainable trajectory of resource overexploitation.

6. Governance framework/approach

In terms of the governance approaches described by the MPAG framework the fishery is governed primarily by local communities. Fishery management is '*…on a bottom-up basis by local users, often through local organizations, with most implementation and decision-making remaining delegated to local users/organizations, but often requiring some degree of state support for enforcement and therefore also involving some influence by central governments*' [1]. The mechanisms by which the fishery is managed by the state and the local community are described below.

Table 4
Mangrove area extent (hectares) in 1990, 2000 and 2010 for Mariarano, with mangrove areas to the north (Mahajamba Bay), south (Mahajanga Bay) and Madagascar for reference. Net change between 1990 and 2010 is calculated and presented as an area and percentage.

Mangrove area	Mangrove extent by year (ha)			Net change 1990–2010	
	1990	2000	2010	(ha)	(%)
Mariarano	2472	2412	2330	−142	−5.7
Mahajamba Bay	27,778	27,577	26,677	−1101	−4.0
Mahajanga Bay	12,375	11,814	9574	−2801	−22.6
Madagascar total	253,765	220,792	200,492	−53,273	−21.0

Source:Adapted from [28], who partitioned USGS mangrove cover map derived from Landsat imagery [27], into areas within Madagascar.

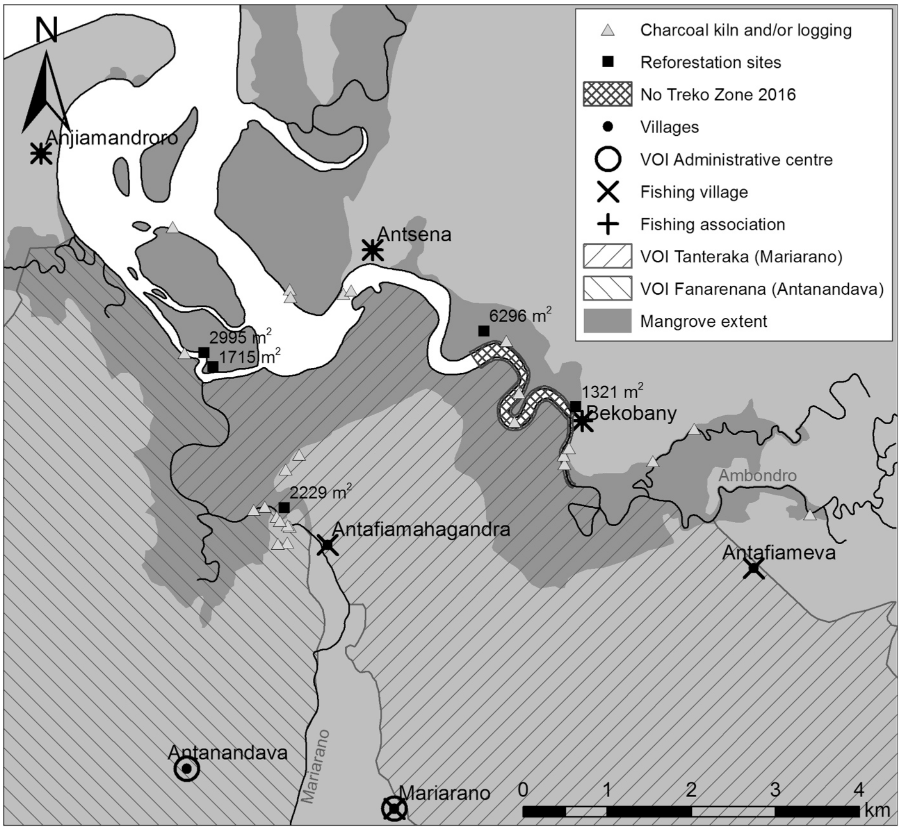

Fig. 4. Exploitation and management of the Ankobohobo wetlands, northwest Madagascar. Mangrove exploitation evidenced by observed active logging and/or the presence of charcoal kilns in June and July of 2016 and 2017 is indicated. The *Vondron'Olona Ifotony* (VOI) Tanteraka and VOI Fanarenana areas of management responsibility are indicated as determined from georeferenced management transfer documents. Mangrove reforestation sites are identified and labelled with their area (m^2) determined by use of a GPS unit. The location of the No *Treko* Zone, which operated in 2016, is shown. Villages (black circle) are overlaid to indicate if they: contain fishers subject to the study (black X); have a fishing association (black cross); and/or are the administrative centre of a VOI (black circle).

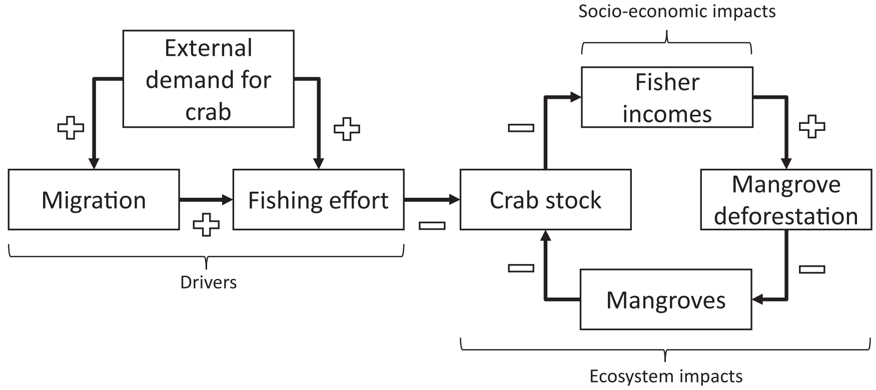

Fig. 5. Schematic illustrating the synergistic effect of drivers on the socio-economic and ecological system, in the Ankobohobo mangrove crab fishery, northwest Madagascar.

6.1. State

State governance of the fisheries sector is the principal responsibility of the Ministère des Ressources Halieutiques et de la Pêche (MPRH, Ministry of Fisheries and Aquatic Resources), which is comprised of over 40 subsidiary entities, including 22 Directions Régionales des Ressources Halieutiques et de la Pêche (DRRHP, Regional Fisheries Authorities). The DRRHP's are responsible for raising awareness of fishery regulations, maintaining statistics and issuing licences to fishers, collectors and exporters. The crab fishery is within the jurisdiction of the Mahajanga DRRHP. The Centre de Surveillance des Pêches de Madagascar (CSP, Fisheries Surveillance Centre) is responsible for the enforcement of fishery regulations and prevention of illegal fishing.

The following national legislation was identified as being of direct relevance to the fishery. Since 1997 all fishers require a licence or permit to target marine species (Arrêté 10404/97), though in practice this has never been applied [11]. The national closed season for crab fishing runs from 1st July to 31st October inclusive (I-1; MIHARI, pers. comm.) [32]. In 2014 a national minimum landing size (MLS) of 11 cm carapace width was introduced by MPRH (Arrêté No. 32101/14) [30], though elsewhere this is reported to be 10 cm [31]. Since 2014 the extraction, transportation and sale of mangrove wood is prohibited by law (Arrêté Interrministériel No. 32100/2014) [63].

6.2. Local

Introduced in 1996, to support CBNRM of forests, the *Gestion Locale Securiseé* (GELOSE) legislation provides a legal mechanism for transferring management rights from the state to local communities [64]. This is achieved through a contract between the state and the local community, the latter of which is represented by a *Communauté Locale de Base* (COBA) or *Vondron'Olona Ifotony* (VOI) - an institution formed of local users created for this purpose. GELOSE was first applied in a marine context in 1999, when a community in Toliara were given management rights over a mangrove ecosystem [65]. A *dina*, a long-standing customary Malagasy system of law, can be described as a code of conduct, which is developed and enforced by communities [66]. Recognised in national law since 1996, *dina* have been divided into three categories by Rakotoson and Tanner [67]: i) one that is unwritten; ii) one that is aligned with national laws, and iii) one that is created via a legal institution. *Dina*, either legally ratified or not, are often the mechanism through which GELOSE contracts and VOIs establish rules to protect natural resources [68].

There are two local VOIs (Tanteraka and Fanarenana) with a legal mandate to manage the dry forest and some parts of the mangrove system. The Deutsche Gesellschaft für Technische Zusammenarbeit (GIZ), a German state aid organisation, which operates across Madagascar, was responsible for initiating the management transfers, providing technical assistance and capacity building for the VOIs. Established in 2001, VOI Tanteraka, based in the community of Mariarano, is responsible for the Ankatsabe forest and 713 ha of mangrove south of the Antsena river (Fig. 4) [42]. The VOI Fanarenana, based in the community of Antanandava and established in 2013, has management responsibility for 390 ha of mangrove which is also south of the Antsena river (Fig. 1) [43]. The management transfers and *dina* for both VOIs prohibit commercial exploitation of wood. Local subsistence use is permitted, specifically large trees may be felled with prior permission and upon payment of a fee, but the felling of small trees is prohibited, whilst charcoal can only be produced from dead wood [42,50,61]. VOI Fanarenana conducts patrols to identify illegal activity but these do not include the mangroves, where it is known there is a greater level of illicit activity [61]. VOI Tanteraka's management transfer includes a rule which prohibits crab fishing in areas of degraded mangrove [42], though neither questionnaire respondents nor key informants demonstrated any awareness of this.

Three fishing associations operate in Bekobany, Antsena and Anjiamandroro (Fig. 4). Formal, legal status had been achieved by the Bekobany and Antsena associations, confirmed by paperwork endorsed by state officials. The most established of these is the Bekobany Fishers' Association, which in 2016 had reportedly been in operation for over a year. New members are required to pay a fee (20,000 MGA, US$ 6.50) to join the association. Benefits include a form of social security, where the association and members are committed to paying costs when other members require medical treatment. In terms of fishery management, the association had introduced a ban on using *treko* within an area of the fishery (Fig. 4), which was communicated to Antsena via a letter addressed to the *Chef* Antsena (head of the village). Further the Bekobany Fishers' Association had undertaken mangrove replantation (Fig. 4 and see Effectiveness). Collectors are required to register with the association in order to purchase crabs from members at a set price, presumably to control price fluctuations and ensure fairness. The Antsena Fishers' Association had only been formally established for two weeks in June 2016, its stated aim being to alleviate poverty through the management of the fishery using *dina*. Membership is verified through a membership card which confers access rights, though it was not clear how this would be enforced and the cards had not yet been distributed (FG-A). No management measures introduced or enforced by the Antsena Fisher's Association were identified. The association in Anjiamandroro was waiting on paperwork to formalise its status and identified being eligible for government aid as the main reason for its establishment (FG-A).

6.3. Incentives used

The incentives identified as currently being used in the governance of the Ankobohobo crab fishery are described (Table 5), based on the MPAG framework taxonomy of governance incentives [1].

7. Effectiveness

The MPAG framework, assesses governance effectiveness on a scale of zero to five, with zero being wholly ineffective '*no impacts addressed*' and five being fully effective, '*all impacts…completely addressed*' [1]. Here an effectiveness score of one, '*some impacts beginning to be slightly addressed*', is assigned.

State and local management has limited efficacy in addressing threats to the fishery. There is limited awareness and compliance with national legislation. Not all fishers knew when the national closed season was, with only 29 participants (60%, n = 48) being able to recall the dates of fishery closure. Only 19 questionnaire participants (40%, n = 48) stated they were aware of a MLS. This may be explained by the state's limited capacity for enforcement. It has previously been reported that in practice both DRRHP and CSP lack the resources to carry out their mandates, most DRRHPs have just one or two agents and the CSP has just three boats to patrol an exclusive economic zone (EEZ) of 1 million km^2 [11]. Neither the state, nor local community has addressed the impact of population growth, through both reproduction and migration, increasing fishing effort and pressure on the mangroves, a situation reported in other rural areas on Madagascar's coast [70]. The introduction of membership cards by at least one fishing association (FG-A) may be the beginning of efforts to restrict or control access.

Conversely, the loss of mangrove habitat has been at least partially addressed, as evidenced by the presence of reforestation sites. A total of five were found with a combined area of 14,556 m^2 (Fig. 4). There may be more sites, which were not identified, either: due to accessibility (two were discussed but could not be reached to verify or measure); difficulty of distinguishing mature plantations from natural habitat; or, because informants were unaware of them. The commune's environmental action plan, developed with technical assistance from GIZ, includes provision to fund mangrove replantation of 5 ha/year in Marosakoa and 5 ha/year in Mariarano between 2012 and 2016 at a total cost of 10,000,000 MGA (US$ 3260) per *fokontany* [40]. The management transfer zoning map for VOI Tanteraka includes an area designated for replanting mangroves [42].

It was difficult to determine which entities were responsible for the existing replantation sites in terms of funding, planning and execution. It was also difficult to ascertain to what extent this was in accordance with the commune's environmental plan and the VOI Tanteraka's management transfer. Fishers reported being paid ~2000 MGA (US$ 0.65) per day for reforestation efforts in Antsena (FG-ANTS), Bekobany (FG-B) and Antafiamahagandra (I-1) though they were not always sure whether this was from the state, an NGO or the VOI. Payments may have been made by the state via the VOI. Two key informants stated the official standing of the VOI was the reason for receiving government funding for mangrove restoration projects (I-3; I-4). In Antsena, government funding went specifically to the Women's Association, who adopted mangrove conservation as a group mission and undertook replantation (F-ANTS). The Bekobany Fishers' Association undertook replantation in collaboration '*with the mayor*' (FG-B), replanting a total area of 0.76 ha across two sites (Fig. 4). One key informant highlighted two replantation sites (Fig. 4) which he stated were undertaken as a personal initiative, his evident knowledge and enthusiasm making this plausible (I-1). This latter example appears to have occurred organically and without monetary incentives.

8. Incentives in need of strengthening or introduction

The empirical analysis highlighted the need for the strengthening and introduction of a number of incentives in order to improve the effectiveness of the fishery's governance (Table 6).

Table 5
Incentives used in the governance of the Ankobohobo small-scale crab fishery, northwest Madagascar.

Category	Incentive	How the incentive is applied
Economic	Assigning property rights	Management transfers from state to VOIs assign property rights to local resource users, promoting stewardship and sustainable exploitation of the mangroves.
	Reducing the leakage of benefits	Unsuccessful attempts to fix prices and manipulate the value chain, post-harvest actors hold disproportionate power and receive a greater proportion of economic benefits than the fishers.
	Promoting alternative livelihoods	Bee-keeping and ecotourism have been promoted as an alternative livelihood by GIZ. The Operation Wallacea and DBCAM research field season is associated with employment opportunities, including guiding, portering, and other services.
	Provision of NGO, private sector and user fee funding	The VOIs collect an entrance fee from visitors (2,000 – 14,300 MGA, US$ 0.65 – 4.66) and charge for the use of campsites (2,200 – 6,600 MGA per tent per week, US$ 0.72 – 2.15) (I-4). Funding from GIZ has supported the VOI to build management infrastructure including campsites and local offices.
Interpretative	Raising awareness	Operation Wallacea present research findings annually to the VOI, but the focus is on dry forest and to a lesser extent mangrove without any explicit mention of crab fishery.
	Promoting recognition of regulations and restrictions	The DRRHP announces the national closed season via local radio, which was confirmed by several participants. The Bekobany Fishers' Association informed other fishers of the ban on using *treko* verbally and with a letter sent to another community (FG-B).
Knowledge	Promoting collective learning	There is a history of limited knowledge sharing between local people and scientists associated with Operation Wallacea and DBCAM [56,69]. This includes in the mangrove system, though the research focus has been on wetland bird and the crocodile populations.
Legal	Penalties for deterrence	The VOIs have developed *dina* which includes penalties for unauthorized collection of wood from mangroves and forest.
	Attaching conditions to use, property rights, decentralisation, etc.	The GELOSE management transfer contract imposes conditions upon the VOI related to the management of the area. The contract stipulates the timeframe for review of the management transfer contract, post review options are renewal, amendment or cessation
	Cross-jurisdictional coordination	There is some limited coordination between NGOs (DBCAM, Operation Wallacea and GIZ) and between VOIs.
Participative	Rules for participation	All members of the local community, over the age of 18, who use natural resources within the area of management transfer, are eligible for VOI membership. Participation levels are known for the VOI Tanteraka, where around half of eligible people in Mariarano are members [50]. In Antanandava, the centre of VOI Fanarenana, 63% of people in surveyed households were members [61]. Membership of fishers' associations is limited to those living within the respective communities.
	Establishing collaborative platforms	Although not evident on the ground, the area is listed as a member of the MIHARI network of LMMAs, a nationwide collaborative platform.
	Decentralising responsibilities	The VOI is the legal mechanism through which management responsibility for local resources has been devolved to local users. This has been facilitated by GIZ who provide technical expertise, capacity building and financial support.
	Peer enforcement	*Dina* are a customary system of law, long established in Madagascar which rely on peer enforcement. The fishing associations rely on peer enforcement of their management measures
	Building on local customs	The use of *dina*, to achieve community recognition of VOI management measures is an example of building on local customs.

9. Cross cutting issues

9.1. Participation

Despite widespread adoption of GELOSE management transfers, with 453 in operation by 2004 [71], there have been a number of criticisms [64], some of which apply here. For VOIs to operate as intended they must be representative of local resource users, but not all users may be willing or able to participate. It has been demonstrated that in Mariarano richer and more educated people are more likely to be VOI members [50]. This so called 'tyranny of localism' results in the capture of governance processes by local elites and marginalises the less advantaged [1,72]. Some individuals may not be able to commit the time required to be active members of the VOI, attending meetings and undertaking actions, thus reducing representation. Non-participation in CBNRM can also result in a 'free rider' effect where individuals receive the benefits without the costs [73]. Eligible non-members of both local VOIs cited not being able to commit the time as a reason [50,61]. VOIs are based in Mariarano and Antanandava, which would be a round trip of several hours for some fishers that operate in the areas of mangrove within this VOIs' jurisdiction. Key informant interviews highlighted that fishers were underrepresented in the VOIs and that this was resulting in limited attention to the mangrove habitat (I-4 and I-5). Another common criticism is that due to the complexity of GELOSE, contracts are always facilitated by NGOs, who seek to formalise resource management and introduce regulation preventing extractive resource use, accordingly there is often a suspicion of external actors [74]. The introduction of a new institution alters community dynamics, moving customary power of *fokonolona* (community) leaders to control access to land and resources to others, who are typically younger, more educated and often recent migrants [64,75].

9.2. Ownership of fishery management

Absence of effective state management of the crab fishery and mangrove habitat leaves a vacuum to be filled by CBNRM. This was emphasised by the deputy Chef Secteur, who volunteered that the mayor's office did not have any management responsibility for the fishery (I-3), suggesting there was neither the legal mandate nor the appetite for involvement in management. Management transfers represent a nationally and locally recognised mechanism by which a portion of the mangrove habitat, but not the fishery, is managed by the VOI. However, Cinner et al. [12] point out there is an uneasy application of the GELOSE law to the aquatic environment due to the law being transposed from a terrestrial context, with contracts authorised by the Ministry of Environment but not recognised by the Ministry of Fisheries. Le Manach et al. [11] suggest that this source of tension and confusion stems from the principle that marine resources should belong to all Malagasy people and not just the communities dependent on the natural resources who gain the management rights. A further problem is that the VOIs do not operate at the scale of the fishery, covering only a portion of the mangroves, a problem noted at other sites where VOIs manage marine resources in Madagascar [76]. The fishers' associations, although in their infancy, have taken ownership of the management of the fishery. However, the lack of inter-association coordination and coordination between associations and VOIs is clearly limiting their efficacy. The current *status quo* means that management ownership is divided among local actors and is not synergistic. The resources are not being managed at an appropriate spatial scale, in terms of the mangrove extent, crab population or spatial distribution of fishing effort.

Table 6
Incentives that require strengthening (strengthen) or introduction (needed) to improve the governance of the Ankobohobo small-scale crab fishery, northwest Madagascar.

Category	Incentive	Strengthen or Needed?	How/why?
Economic	Assigning property rights	Strengthen	Fishers are poorly represented in VOIs which are focussed on terrestrial resources (dry forest), and have no responsibility for fisheries (I-5). Fishing effort is overlapping (between communities) [60] but associations are discrete, so management is not aligned with *de facto* access.
	Reducing the leakage of benefits	Strengthen	Unsuccessful attempts to fix prices and manipulate the value chain (I-2), post-harvest actors holding disproportionate power and receiving a greater proportion of management benefits than the users who implement them [32].
	Promoting profitable and sustainable fisheries	Needed	Periodic no take zones (NTZs) have proved a socio-economically viable model elsewhere in Madagascar [18,34]. Has the potential to protect habitat and target stock.
	Promoting alternative livelihoods	Strengthen	Existing livelihoods (Fig. 2) do not provide sufficient opportunities, resulting in high fishing effort and mangrove exploitation particularly in the closed season (FG-ANTS).
Interpretative	Raising awareness	Strengthen	Operation Wallacea present research findings annually to the VOI, but the focus is on dry forest and to a lesser extent mangroves without any explicit mention of crab fishery.
	Promoting recognition of regulations and restrictions	Strengthen	Limited awareness of national legislation, association management measures and their spatial coverage. Radio is an important communication mechanism for state regulation e.g., national closed season.
Knowledge	Promoting collective learning	Strengthen	There has been limited knowledge sharing between local people and scientists. In the mangroves, the focus has been on wetland bird and crocodile populations. Participatory monitoring of crab fishery is needed.
	Independent advice and arbitration	Needed	Crab fishery management advice to inform evidence-based decision making and introduce design participatory monitoring [32].
Legal	Capacity for enforcement	Needed	Successful peer enforcement of the dina requires state support, where authorities can support where peer enforcement is challenged.
	Penalties for deterrence	Strengthen	More effective use of ratified *dina* to get state enforcement of regulation designed at a local level – as seen in other LMMAs in Madagascar [18].
	Protection from incoming users	Needed	Currently no barriers to entry, though one fishing association is in the process of introducing membership cards conferring access rights (FG-A). The study site is close to regional population centre (Mahajanga) which is a source of demand for natural resources and a source of migrants.
	Cross-jurisdictional coordination	Strengthen	Coordination required between terrestrial conservation/management efforts and the fishery, between fishers' associations and with VOIs.
Participative	Rules for Participation	Strengthen	Better representation of fisher interests in VOIs is required.
	Establishing collaborative platforms	Strengthen	Better coordination between communities. Potential to unite the fishers' associations under one structure. There is potential to share experiences with other fishing communities through MIHARI. Despite being listed as members of the MIHARI LMMA network, no evidence of this was found; it was not mentioned in any interview, questionnaire or focus group.
	Peer enforcement	Strengthen	The fishing associations and VOIs rely on peer enforcement, this could be strengthened, including provision of back-up state enforcement capacity.
	Building linkages between relevant authorities and user representatives	Needed	Fishers are disconnected from regional and national fishery management authorities, with limited awareness of state legislation. Potential to link fishers' associations with DRRHP, which has been achieved elsewhere [18].

9.3. Role of NGOs

There are three key NGOs which have been operating in the area for multiple years. GIZ have had a presence since at least 1999 when efforts began to facilitate the first GELOSE management transfer, establishing VOI Tanteraka and subsequently VOI Fanarenana as part of their Programme d'Appui à la Gestion de l'Environnement (PAGE). NGOs have their own agenda, as the organisation responsible for both facilitating the management transfers and ongoing VOI capacity building, GIZ have significant influence on the focus and priorities of CBNRM. The interview with the head of management transfers at GIZ highlighted that whilst the mangroves were included in the management transfer, a lack of membership of fishers in the VOI means the bulk of the organisation's conservation activities are directed at the dry forest (I-5). This may likely reflect GIZ aims rather than a greater local appetite for forest management. Since 2010, Operation Wallacea and DBCAM have been conducting a landscape-scale long-term ecological monitoring project. The project aims to identify spatial and temporal trends in biodiversity, monitor the condition of the forest habitat, generate revenue in the local communities and use research results to leverage funding for environmental projects [56]. Again, the focus is on the dry forests rather than the mangroves. To date the project has not fulfilled its aim to secure additional funding for environmental projects. A shared goal of DBCAM, Operation Wallacea, GIZ and the VOIs is to promote ecotourism, particularly through paying volunteers facilitated by NGOs [50]. The long-term ecological monitoring field season, six weeks in June and July, brings a large number of visitors to the area and is a source of revenue for some local households. However, beneficiaries are predominantly in Mariarano, with little or no benefits reaching communities more dependent on the crab fishery and mangroves. The relative inaccessibility of the area means that outside of this field season there are few visitors, making ecotourism only a seasonal opportunity. A closer strategic working relationship between Operation Wallacea, DBCAM, GIZ and the local community (represented by the VOI) could seek to design conservation or developments projects that provide year-round benefits across a wider area. This could potentially address threats to the fishery and mangrove habitat if fishers' interests were adequately and equitably represented. However, there is currently limited information sharing between these actors, and indications of mistrust between DBCAM and the VOIs [77].

9.4. Conflict, coordination and cooperation

The spatial distribution of fishing effort is continuous, rather that restricted to discrete areas, meaning that fishers from different communities overlap. This appears to be a source of conflict as management decisions are made at the village level, but this occurs in the absence of any spatial delineation of access or management responsibility. Focus group participants in Antsena reported an unsuccessful attempt to limit access to areas immediately adjacent to the community '*we sent a letter to*

Anjiamandroro to ask them to stop fishing here, but…they can fish anywhere they like' (FG-ANTS). This conflict between communities was highlighted by efforts to restrict certain gears. Some participants identified the *treko* as a threat to the fishery as it is a non-selective gear which catches undersized crabs (<MLS, 11 cm). In response to this perceived threat the Bekobany Fishers' Association established a 'No Treko Zone', an area where the use of this gear was banned (I-2, Fig. 4). '*The association forbids the treko. We shouldn't use it because it takes small crabs*' (FG-B). However multiple *treko* were observed deployed or awaiting deployment in the 'No Treko Zone' in 2016. Members of the Bekobany Fishers Association were keenly aware that forfeiting the use of this gear put them at a disadvantage (F-B). The Anjiamandroro group expressed similar frustrations, articulating the desire for a system that would allow them to penalize fishers from other villages when they were caught using *treko* (F-ANJI). In 2017 a key informant (I-1) explained that in the current season fishers from all communities had agreed to a universal ban on the use of *treko*, which was being observed. In contrast to the previous year no evidence of *treko* deployed or awaiting deployment was seen throughout the fishery during 2017 field visit.

The relationship between fishers and collectors (Fig. 1) was also highlighted as an area that was impacted by the lack of coordination between villages. Throughout the mangrove crab fisheries of Madagascar's west coast it is noted that post-harvest actors hold a disproportionate amount of negotiating power [32]. The practices of collectors were identified as a '*social*' threat to the fishery (I-3). According to the Deputy Mayor, some villages allowed collectors from anywhere to buy crabs from the fishers. This competition resulted in variations in the price that fishers were getting for their crabs and created '*social tension*' (I-3). The Bekobany Fishers' Association's documents showed that there was an attempt made to fix the price of the crab, but according to the interview with the Chef Secteur, this never came to fruition, because the villages could not coordinate the action, and just applying the rule solely in Bekobany would put them at a disadvantage (I-2).

The need for a co-ordinated approach between communities was repeatedly identified, though many were resigned to the fact that this would not happen, as the governance framework does not allow management measures to be designed and enforced at the scale of the whole fishery. This is best summarised by comments from the focus group held in Anjiamandroro 'i*t is good if you have the same opinion and values, but that will never happen here. What would be good is if the villages could discipline each other, or apply some sort of penalty when rules are broken*' (FG-ANJIA). Nevertheless, the apparent cooperation between communities in apparently successfully banning *treko* gear in the 2017 season, as evidenced by the comments from a key informer and empirical observations, is a positive indicator of the potential for an effective local governance framework at the ecosystem and fishery wide scale. There remain challenges in terms of a lack of integration between management units at the community scale and a lack of capacity to enforce restrictions, particularly between communities and in the face of synergistic driving forces.

10. Conclusion

The study demonstrates the value the novel application of the MPAG framework to a fishery, yielding critical governance insights. The readiness with which the framework could be applied is a result of the fundamental similarity between fisheries and MPAs, in that they are both spatially defined areas in which management aims to achieve the collective sustainable use objectives of the actors. Indeed, it could be argued that the study site can legitimately be simultaneously described as a SSF, a LMMA and an IUCN Category VI MPA.

The study site is an example of genuine community-based, locally-led, fishery management that has developed organically. Significant challenges to this local approach remain. Specifically the VOIs, the community based natural resources management institutions, are focussed on terrestrial resources, with fishers being underrepresented. This is a product of the underlying GELOSE legislation and its application, which was developed from the long-standing focus on the conservation and management of terrestrial ecosystems in Madagascar. A result of this is the development of three nascent fisher associations, which will need to co-ordinate their efforts as seen in the seemingly successful implementation of a fishery wide ban of a gear, the *treko*, in 2017. This local management has resulted in measures such as replanting of mangroves being undertaken, at least in some cases by fishers without external funding or support.

However, the analysis shows that the main threats to the fishery are external drivers, namely migration and demand for charcoal, timber and crab, the latter fuelled by crab merchants supplying Asian markets. These drivers have synergistic effects negatively impacting the mangrove habitat on which the fishery is dependent and are beyond the control of local management. This accounts for the limited efficacy of this bottom-up approach. The majority of the incentives identified as needed or in need or strengthening require the support of external actors, the state, industry and or NGO(s). This highlights the need to move away from polarised governance solutions, often characterised as top-down vs- bottom-up, and seek integrated approaches. It is key the full range of actors contribute to governance systems to ensure 'resilience through diversity', both in terms of the governance actors and the incentives they are able to collectively employ. This theme has repeatedly been identified as critical in numerous previous MPAG case studies [1, 78]. This case study again emphasises the need to focus on the co-evolution of a diversity of incentives in the building of a governance framework. This is especially evident where an ecosystem-scale fishery is divided between relatively autonomous communities, amongst which mutual cooperation and reciprocal enforcement of restrictions needs to be ensured and supported by the state, in the face of synergistic driving forces that have the potential to perturb the social-ecological system. Only a combined approach to governance through the co-evolution of a diversity of incentives can address such challenges.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2017.11.022.

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Glossary

CBNRM: community based natural resource management

Chef Commune: elected official, mayor of the *commune*

Chef Fokontany: mayor of the fokontany

Chef Secteur: representative at the sub-fokontany level, appointed by the *Chef Fokontany*

COBA: Communauté Local De Base institution formed of local natural resource users, with management responsibility transferred from the state through GELOSE legislation. See also VOI

Commune: administrative district comprised of multiple *fokontany*

DBCAM: Development, Biodiversity, Conservation Action Madagascar, a Malagasy NGO

dina: customary form of law acting as a social contract, recognised in national law since 1996

DRRHP: Directions Régionales des Ressources Halieutiques et de la Pêche, regional fisheries authorities, which are subsidiaries of MPRH

fokonolona: community

fokontany: smallest administrative district in Madagascar

fingovitra: fishing gear, a wooden stick with a hooked end used to remove crabs from burrows

fisoko: fishing gear, a small hand net, used for handling crab

garigary: fishing gear, a circular lift net which is baited and used to catch crabs

GELOSE: Gestion Locale Securiseé, legal mechanism for the transfer of management responsibility of natural resources to local communities represented by a COBA/VOI

GIZ: Deutsche Gesellschaft für Technische Zusammenarbeit (German society for technical collaboration), a German state aid organisation

LMMA: Locally managed marine area

MIHARI: MItantana HArena and Ranomasina avy eny Ifotony, Marine resources management at the local level, Madagascar's LMMA network

MLS: minimum landing size

MPRH: Ministère des Ressources Halieutiques et de la Pèche, the Ministry of Fisheries and Aquatic Resources

NGO: non-governmental organisation

Operation Wallacea: a UK NGO

pirogue: traditional wooden fishing vessel, powered by sail or oars, usually incorporating an outrigger for stability

treko: fishing gear, a baited crab trap made of women palm/vines

VOI: Vondron'Olona Ifotony institution formed of local natural resource users, with management responsibility transferred from the state through GELOSE legislation. See also COBA

Appendix II

Paper II

The results presented in the following paper are detailed in Chapter 5, whilst the methodology is described in Chapter 4.

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Identification of a Soft Coral Garden Candidate Vulnerable Marine Ecosystem (VME) Using Video Imagery, Davis Strait, West Greenland

Stephen Long[1,2]*, Bridget Sparrow-Scinocca[3], Martin E. Blicher[4], Nanette Hammeken Arboe[4], Mona Fuhrmann[2], Kirsty M. Kemp[2], Rasmus Nygaard[4], Karl Zinglersen[4] and Chris Yesson[2]

[1] Department of Geography, University College London, London, United Kingdom, [2] Institute of Zoology, Zoological Society of London, London, United Kingdom, [3] Department of Life Sciences, Imperial College London, London, United Kingdom, [4] Greenland Institute of Natural Resources, Nuuk, Greenland

Edited by:
Christopher Kim Pham,
University of the Azores, Portugal

Reviewed by:
Travis William Washburn,
University of Hawai'i at Mānoa,
United States
Tina Molodtsova,
P. P. Shirshov Institute of Oceanology
(RAS), Russia

***Correspondence:**
Stephen Long
Stephen.long.16@ucl.ac.uk

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The term vulnerable marine ecosystem (VME) was introduced to facilitate the spatial management of deep-seas, identifying those habitats vulnerable to anthropogenic disturbance, such as trawling. Consistent interpretation of the VME definition has been hampered by an underlying paucity of knowledge about the nature and distribution of deep-sea habitats. Photographic and video platforms yield data rich, quantifiable imagery to address these knowledge gaps. A low-cost towed benthic video sled has been used to investigate deep-sea habitats and trawling impacts in west Greenland. A review of imagery from multiple cruises highlighted an area where benthic megafauna contributes to notable structural complexity on the continental slope of the Toqqusaq Bank. Quantitative analysis of imagery from this area provides the first description of a soft coral garden habitat and other communities. The coral garden and observed densities are considered in relation to the VME guidelines (FAO, 2009) and wider literature. The study proposes a 486 km^2 area spanning ~60 km of continental slope as a VME. This has direct implications for the management of economically important deep-sea trawl fisheries, which are immediately adjacent. This furthers our knowledge and understanding of VMEs in North Atlantic, in a previously understudied region and demonstrates the utility of a low-cost video sled for identifying and describing VMEs.

Keywords: deep-sea, coral garden, spatial management, fishery management, towed video sled, cauliflower corals, benthic habitats

INTRODUCTION

The deep-sea (> 200 m) is the world's largest habitat covering ~65% of the earth's surface (Danovaro et al., 2017) and is increasingly subject to anthropogenic disturbance from fishing (Morato et al., 2006). Typically, deep-sea species are characterized by traits, including slow growth, late-maturity, and longevity, which can render populations, communities and habitats vulnerable to exploitation and disturbance (Ramirez-Llodra et al., 2010). Recognizing this, the

United Nations General Assembly (UNGA) Resolution 61/105 called upon States to take action to protect vulnerable marine ecosystems (VMEs) (UNGA, 2006). Following a period of consultation, the Food and Agriculture Organization (FAO) defined VMEs as exhibiting 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 (Gjerde et al., 2008; FAO, 2009).

The term VME has subsequently been applied to a wide variety of deep-sea habitats in both areas beyond national jurisdiction (ABNJ) and within exclusive economic zones (EEZs) around the world. States and regional fisheries management organizations (RFMOs) have adopted differing approaches for both identifying VMEs (Ardron et al., 2014) and implementing measures to protect them (Rogers and Gianni, 2011), which includes bycatch thresholds and move-on rules (Auster et al., 2010). Frequently, identification of VMEs has been based on the occurrence of VME indicator species, such as cold-water coral or sponges, at significant concentrations, which is a matter of expert judgment in the absence of explicit thresholds in the FAO guidance (Auster et al., 2010). This has led efforts to establish more consistent, quantitative and systematic approaches for identifying VMEs (Ardron et al., 2014; Morato et al., 2018). Fundamentally, adoption of a consistent systematic approach requires a sound understanding of the underlying nature and distribution of VMEs and indicator species globally. Currently, biases in survey effort mean that regions such as the Northeast Atlantic have received considerable attention (e.g., Muñoz and Sayago-Gil, 2011; Buhl-Mortensen et al., 2015; Huvenne et al., 2016), whilst others remain comparatively poorly known.

Survey approaches which yield quantifiable seafloor imagery by employing remote operated vehicles (ROVs), manned submersibles or towed cameras are among the preferred approaches for identifying VMEs. Morato et al. (2018) observe that the cost of obtaining and deploying equipment capable of imaging deep-sea environments has limited the identification of VMEs, with only a minute fraction of the deep-sea floor having been surveyed to date. Nevertheless, they predict that the rapid advance in technologies will reduce costs and increase coverage.

Despite having an EEZ of over 2.2 million km^2, Greenland has few Marine Protected Areas (MPAs). These are exclusively in inshore waters totalling ~4.5% of the EEZ (UNEP-WCMC, 2019), with none designated to protect known VMEs. A number of "Technical Conservation Measures" introduced by Executive Orders have been used to limit the use of bottom-contact fishing gears in some areas, of these only two are associated with the presence of VME indicator species. Specifically, there is a ~6.5 km^2 area in southwest Greenland bounding a single observation of *Desmophyllum pertusum* (Government of Greenland, 2017; Kenchington et al., 2017) and 11 discrete areas within the offshore region of Melville Bay closed to bottom trawling "*based on significant observations of sea pens*" (*Umbellula* sp.). (Cappell et al., 2018; Government of Greenland, 2018). This paucity of spatial management measures to protect VMEs is principally due to a lack of knowledge about the nature and distribution of VMEs within the Greenlandic EEZ, representing a knowledge gap in the North Atlantic.

Greenland is economically dependent on fisheries which account for 80–95% of the country's export income (Mortensen, 2014; The Economic Council, 2017; Jacobsen, 2018). The majority of this income is from deep-sea fisheries for prawns (*Pandalus borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*) in west Greenland, though there is a growing contribution from pelagic fisheries in east Greenland. Since 2011, a program of benthic surveys using a drop camera (Yesson et al., 2015, 2017; Gougeon et al., 2017) and more recently a benthic video sled, has been working to quantify the impacts of trawling on benthic habitats by sampling across a spectrum of fishing effort. A series of stations from the western slope of the Toqqusaq Bank between 274 and 585 m, appear to show varied communities, with notable concentrations of cauliflower corals (Nephtheidae) and other VME indicator species, on rocky and mixed substrates.

Coral gardens are characterized by aggregations of one or more species (typically of non-reef forming coral), on a wide range of hard and soft substrates, supporting diverse benthic and epi-benthic fauna (ICES, 2007; OSPAR Commission, 2010). There is considerable diversity among coral garden communities, which may be dominated by soft corals (Alcyonacea), sea pens (Pennatulacea), black corals (Antipatharia), and stony corals (Scleractinia), often with sponges (Porifera) abundant but not dominant. Coral gardens dominated by cauliflower corals from four genera (*Gersemia, Duva*, *Drifa,* and *Pseudodrifa*), found on hard and mixed substrates are sometimes referred to as "cauliflower coral gardens" (Davies et al., 2017; Buhl-Mortensen et al., 2019). These have previously been observed in northwest and southeast Iceland (J. Burgos, pers. comm.; Buhl-Mortensen et al., 2019), Norway (Guillaumont et al., 2016) and eastern Canada (B. de Moura Neves, pers. comm.). Recognizing the vulnerability of cauliflower corals to physical disturbance, especially trawling (Devine et al., 2019), these cauliflower coral gardens have been considered VMEs by some including the North East Atlantic Fisheries Commission (NEAFC) (NEAFC, 2014; Buhl-Mortensen et al., 2019).

This study presents imagery collected using a custom built, low-cost benthic sled (total cost ~5,000 USD), which utilizes a commercially available action camera (GoPro). Imagery is used to produce a quantitative description of soft coral garden habitat in west Greenland, in the Northwest Atlantic. The findings are used to propose an area of continental slope as a soft coral garden VME, with reference to the FAO guidance and the wider literature.

MATERIALS AND METHODS

Study Site

The study site lies on the west Greenland continental slope, where the shallower Davis Strait separates the deeper northern Labrador Sea and Baffin Bay basins. The continental shelf in west Greenland can extend > 100 km offshore with numerous deep troughs and shallow banks (Jørgensen et al., 2018). Historically, the banks in west Greenland have been important fishing grounds for cod and more presently for prawns. Monitoring studies suggest that hydrographic conditions can stimulate high pelagic primary production across the edge of these banks (Poulsen and Reuss, 2002; Juul-Pedersen et al., 2015). Water mass characteristics are determined by the strength and mixing of two currents, the warm saline Irminger Current and colder, fresher East Greenland current (Myers et al., 2007). Icebergs scour the seabed to maximum depth of 600 m and deposit terrigenous sediments and dropstones (Gutt, 2002; Streuff et al., 2017). The diversity of topographic features and oceanographic influences results in diversity and heterogeneity of benthic communities (Gougeon et al., 2017).

Since 2011, benthic camera surveys (∼30–1,500 m) have been used to map habitats and quantify trawling impacts in west Greenland, employing a drop camera (Yesson et al., 2015, 2017; Gougeon et al., 2017) and benthic video sled from 2017. The benthic video sled was deployed during two *RV Sanna* research cruises in October 2018 and May 2019, dedicated to the Toqqusaq Bank area. Video imagery from these cruises and a smaller number of video stations obtained opportunistically on other cruises were reviewed. This highlighted that a subset of stations appeared to show structurally complex habitats with higher densities of cauliflower corals, VME indicator taxa and other structure forming taxa than had been observed elsewhere. Constraints prevent a comprehensive characterization of all the habitats in this area using all available imagery. Instead the focus is on producing a quantitative description of the habitats in a subset of stations where the review highlighted notable structural complexity created by benthic macrofauna. This subset of stations selected during the review (n = 18), are at depths from 274 to 585 m, on the continental slope on the western edge of the Toqqusaq Bank, in Greenlandic waters (NAFO Areas 1C + D) (**Figure 1**).

The study area sits directly between two Marine Stewardship Council (MSC) certified deep-sea trawl fisheries. Namely, the West Greenland Offshore Greenland Halibut Fishery (800–1,500 m) (Cappell et al., 2017) and the West Greenland Coldwater Prawn Fishery, which targets areas on the continental shelf and slope (200–500 m) (Cappell et al., 2018; **Figure 1**). In the southern part of the study area there has been additional fishing pressure from an emerging cod (*Gadus morhua*) fishery. Following collapse of the west Greenland offshore cod fishery in the early 1990s, a management plan introduced a closure in 2014 to allow recovery. This was overturned and a Total Allowable Catch (TAC) of 5,000 tonnes was set for 2015–2018, inclusive (ICES, 2019b). In 2018, 4,187 t was landed by trawlers (61%) and longliners (39%), half of which (2,666 t) was from NAFO 1C/D (ICES, 2019a), with the main fishing grounds being the Toqqusaq Bank, at the top of the slope (∼200–300 m) centered on the NAFO 1C/D boundary (**Figure 1**; ICES, 2019b).

Benthic Video Sled

Imagery from 14 stations sampled with *RV Sanna* (SA, 2018–2019) was supplemented with a single station from *RV Paamiut* (PA, 2017) and three stations from *MT Helga Maria* (HM, 2019). All stations were sampled between May and October. Imagery was collected using a towed benthic video sled with an oblique angled centrally mounted video camera, lights, scaling lasers and an echo sounder unit. Illumination was provided by two Group-Binc Nautilux 1,750 m LED torches arranged either side of the camera and angled inwards to achieve as close to even illumination as possible. A pair of green Z-Bolt lasers (wavelength = 515 nm) in custom-made housings, were positioned 20 cm apart directly below the camera to provide an indication of scale. The position of the sled relative to the seafloor was monitored from the bridge using a Marport Trawl Eye Explorer (echo sounder unit) fixed to the top of the sled, which reported the depth (± 0.1 m), pitch and roll of the sled. Once the sled had made bottom contact it was towed at a target speed of 0.8–1 knots for a minimum of 15 min and up to 45 min. Longer tow times were used where time allowed, or to ensure adequate footage was obtained when there were potential issues (e.g. rough sea) during deployment.

Video was collected using a GoPro action camera in Group-Binc housings, which have a flat acrylic port. A GoPro4 recording 1,920 × 1,080 pixels at 48 frames per second (fps) was used in 2017, in a Group-Binc Scout housing. Subsequently, a GoPro5 was used, recording at the same aspect ratio (16 × 9) but higher resolution of 2,704 × 1,520 pixels at 60 fps, in a Group-Binc Benthic 3 housing.

The "Medium FOV" setting was used on both cameras. Per the manufacturer's specifications this provides the same field of view (FOV), with vertical (α_{air}) and horizontal (β_{air}) aperture angles in air of 55 and 94.4°, respectively. Guided by the discussion in Treibitz et al. (2011), these were corrected for refraction according to Snell's Law of refraction, which means it is necessary to correct for refraction by the bulk medium (seawater) but not the acrylic lens of the housing. This allows the vertical (α) and horizontal (β) aperture angles in seawater to be determined (Eqs. 1 and 2).

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

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

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

Due to the oblique angle the very uppermost part of the image is difficult to interpret due to a lack of reflected light and taxa appearing smaller furthest from the camera. The distribution of all annotations made was reviewed, there were none in the top hundredth of the image. Excluding this unannotated area reduces the likelihood of artificially underestimating faunal density. Thus the area of seafloor in the annotated FOV is calculated for *JBDK*, a subset of *ABDE,* where length JB is 0.99 of the length AB (**Figure 2**).

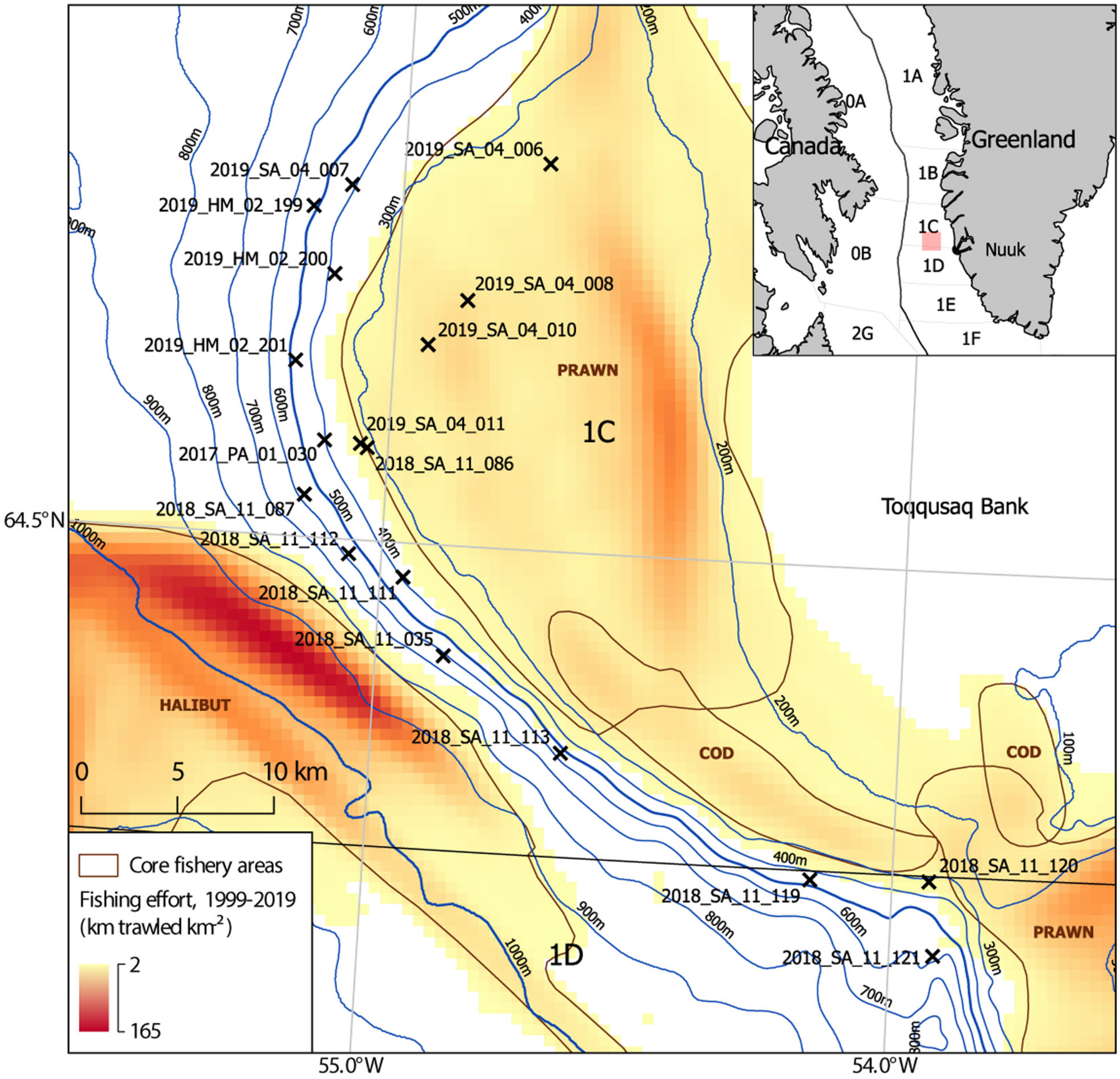

FIGURE 1 | Map of study site showing the location of benthic video sled survey stations (*n* = 18), on the continental slope of the Toqqusaq Bank, west Greenland. NAFO Divisions are indicated. Video sled stations (X) are drawn at the ship's position at the middle of each tow. The video sled station name indicates the year, vessel, cruise number, and station number (Year_Ship_Leg_Station number). The two letter ship codes indicate the *RV Paamiut* (PA), *RV Sanna* (SA), or *MT Helga Maria* (HM). Fishing effort 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}). The core target areas of halibut, prawn and cod trawling effort are annotated (brown), based on visual review of the effort dataset. This is intended to be indicative.

The method described by Nakajima et al. (2014) is modified to allow the estimation of the area *JBDK* (Eqs. 3–8).

$$\delta = \pi - (\frac{\pi}{2} + \theta + \alpha) \tag{3}$$

$$\gamma = 0.99\alpha \tag{4}$$

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

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

$$GF = OH(\tan(\delta + \gamma) - \tan(\delta)) \tag{7}$$

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

Where, *OH* the height of the camera was 0.55 m, θ the angle of incidence with the seafloor was 28.8° and the aperture angles (α and β) are determined as above (Eqs. 1 and 2). The area of seafloor analyzed in each image (*JBDK*) was estimated to be 8.23 m^2. This value is used throughout for estimating densities of taxa.

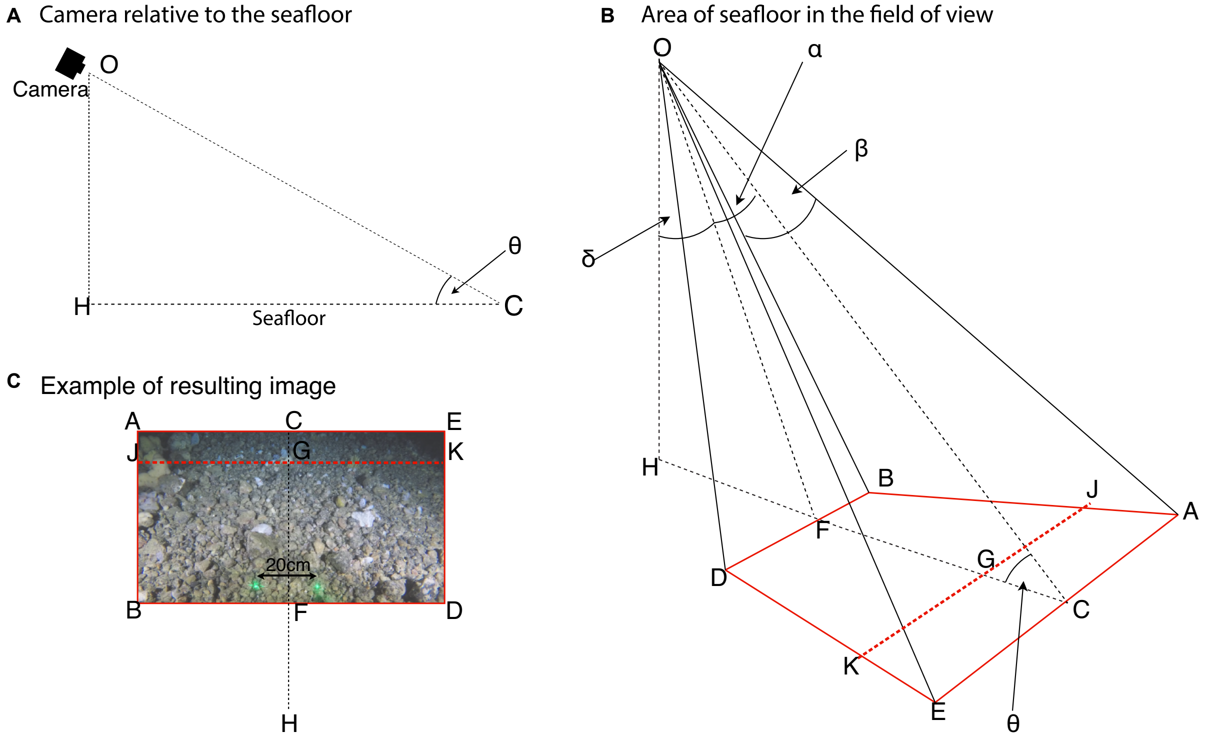

FIGURE 2 | Diagrammatic representation of the benthic video sled camera for determining the area of the field of view. **(A)** Shows the camera orientation relative to the seafloor. **(B)** Shows the camera position, aperture angles and area of seafloor (*ABDE*) in the camera's FOV (red line); with a cut-off line JK to exclude the portion of the image unsuitable for analysis (red dashed line). **(C)** Shows an example image of the seafloor, in relation to **(A,B)**, for which the area *JBDK* is calculated and used in the estimation of fauna density. Adapted from: Nakajima et al. (2014).

Image Processing

Extraction of Images

Quantitative analysis was conducted on still images extracted from videos. All footage was reviewed and useable video segments identified, excluding segments where: (i) suspended sediment or other material obscured > 5% of the screen; (ii) illumination was inadequate due to one or more torches being partially or wholly obscured; (iii) the sled was not level and on the seabed; (iv) the sled was stationary; or (iv) the sled was moving too fast, which occurs at the end of tow when the winch is being used to retrieve the sled. Stills were extracted at 15 s intervals, from the useable segments. At each 15 s interval the frame with the sharpest focus within that second of video was selected, where 1 s of video was represented by 48 frames (GoPro4) or 60 frames (GoPro5).

The frame with sharpest focus was that with the highest value of standard deviation based on the Laplacian Convolution Kernal of a grayscaled version of each frame, determined using the "convolve" function of the R package "imager" (R Core Team, 2013; Barthelmé, 2017). Convolution kernels are an established way of measuring the focus of an image within a range of similar images (Riaz et al., 2008). The resulting stills were reviewed to ensure they met the criteria above, any exceptions were removed.

Processing of Images

The images were then uploaded to a browser based annotation platform, BioImage Indexing, Graphical Labeling and Exploration 2.0 (BIIGLE 2.0) (Ontrup et al., 2009; Langenkämper et al., 2017). The platform allows the creation of custom hierarchical label trees, which can be used to annotate features within images and/or be applied at the level of the image. A representative subset of the images was reviewed by the team to agree on a consistent approach to annotation. This was informed by previous experience of image and physical sampling surveys in the region. To ensure consistency a single member of the team made all primary annotations, for both fauna and substrate.

Fauna annotation

The nature of the imagery means not all fauna can be consistently seen and reliably identified. For example, small fauna closest to the camera (bottom of the image) may not necessarily be visible or identifiable at the back of the field of view (top of the image). Therefore, only taxa that could be consistently identified within and between images were selected for annotation and analysis. Additionally, annotation was restricted to those taxa that form structurally significant/complex components of the habitats and thus are of relevance to criteria (iv) of the FAO's VME definition (FAO, 2009). To allow density estimation only taxa where discrete individuals or colonies could be identified were annotated. The taxa which met these conditions, are shown with reference to whether they are considered VME indicator taxa by Northwest Atlantic Fisheries Organization (NAFO) and NEAFC (**Table 1**).

When annotating each image the section of video that it was obtained from was reviewed alongside the image. A moving perspective was found to be useful in aiding identification of taxa and distinguishing individuals or differentiating between separate colonies.

Genera of Nephtheidae (*sensu lato*) found in west Greenland are *Gersemia, Duva*, *Drifa*, and *Pseudodrifa* (Jørgensen et al., 2013). The current taxonomy in the World Register of Marine Species (WoRMS) lists all these as belonging to the family Nephtheidae. Although the genus *Gersemia* is currently still formally placed in Nephtheidae, it is widely regarded as Alcyoniidae (McFadden et al., 2006; Williams, 2013). These genera are hard to distinguish from imagery (Buhl-Mortensen et al., 2019) and so throughout this study have been treated as Nephtheidae (*sensu lato*) and collectively referred to a cauliflower corals.

Substrate annotation

Substrates were determined by annotation 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) for classifying substrates in imagery from west Greenland. For the purpose of this study this is further modified with clarified descriptions (A6.1.4 and A6.2.1) and two new subclasses (A6.1.5 and A6.2.2). Only those sub-classes used in this study are described here (**Table 2** and **Figure 3**).

TABLE 1 | Taxa selected for annotation in images. For each taxon NAFO (NAFO, 2012) and NEAFC (2014) guidance was consulted to determine if the taxa is considered a VME indicator.

Common name(s)	Phylum	Taxon/ annotation label	VME indicator?	
			NAFO	NEAFC
Bryozoans	Bryozoa	Alcyonidiidae* (*Alcyonidium gelatinosum*)	No	No
Anemones	Cnidaria	Actiniaria	No	No
Gorgonians	Cnidaria	Acanthogorgiidae	Yes	Yes
		Paragorgiidae	Yes	Yes
		Plexauridae	Yes	Yes
		Primnoidae	Yes	Yes
Soft corals	Cnidaria			
Mushroom soft corals		Alcyoniidae	No	No
Cauliflower corals		Nephtheidae	No	Yes
Feather stars	Echinodermata	Antedonidae	Yes†	Yes
Sponges	Porifera	Axinellidae	Yes	Yes
		Geodiidae	Yes	Yes
		Polymastiidae	Yes	Yes
		Rossellidae	Yes	Yes
		Porifera massive		
		Porifera branching		
		Porifera encrusting		

**It is thought that all annotations made using this label were of Alcyonidium gelatinosum. †Only Trichometra cubensis from the Antedonidae family.*

Modeling

Data processing and analysis was performed in R (R Core Team, 2013). A probabilistic approach was used to determine whether the taxa selected for annotation were positively, negatively, or randomly associated with one another. The observed co-occurrence was compared to the expected co-occurrence where the latter is the product of the two species' probability of occurrence multiplied by the number images (n = 1,239) (Veech, 2013). Associations were considered significant where the probability of the observed frequency of concurrence is < 0.05, were the taxa distributed independently of one another. This was performed using the "co-occur" package in R (Griffith et al., 2016).

Mapping

The BedMachine version 3, 150 m resolution bathymetry grid (Morlighem et al., 2017) was used to produce bathymetric contours in figures and for describing the boundary of the proposed VME.

Representation of fishing effort is based on haul-by-haul logbook data from the Greenland Fishery Licence Control (GFLK) from fisheries employing demersal trawl gear from 1999 to 2019, all species and vessels inclusive. Raw data from GFLK was processed and recalculated in SAS statistical software (SAS Institute, 2019) to establish an annual data set with information on the target species, gear type, position, haul distance, and speed. No information on gear width is available, so the transversal coverage of each haul is unknown. The data set was further processed using Safe FME Workbench software (Safe Software, 2019) to establish line vectors from start and end haul positions, removing displaced positions and unrealistic long and fast hauls. The line vectors representing the hauls were interpolated with Python using the ESRI Spatial Analyst Line Density function (ESRI, 2013) with a 5 km search radius to a 1 km grid, and the result hereof further calculated against a mask of the proportion of sea and land. The resulting raster represents the distance trawled per unit area (km trawled km^{-2}).

RESULTS

Station Data

A total of 18 video sled stations were selected from which 1,239 images were extracted for annotation (**Table 3**). This represents a total area analyzed of ~10,000 m^2.

Fauna Observations

A total of 44,035 annotations of the selected fauna were made. The most numerous annotations were anemones (15,531) and cauliflower corals (11,633). The anemones appeared to be predominantly Hormathiidae. The least frequent were gorgonians, with just 250 annotations of Acanthogorgiidae,

TABLE 2 | Substrate classes used to label images sampled from videos. Substrate classes are based on the revised EUNIS Habitat Classification (Davies et al., 2004), as adapted by Gougeon et al. (2017) and further modified here.

EUNIS	Sub-class	Description
A Marine habitats		
A6 Deep-sea bed		
A6.1 Deep sea bedrock and artificial hard substrate		
	A6.1.4 Coarse rocky ground (R)	Predominantly rocky material of varying sizes including gravel (< 4 cm) and cobbles (4–20 cm).
	A6.1.5 Coarse rocky ground with boulders (Rb)	Rocky material of varying sizes including gravel (< 4 cm) and cobbles (4–20 cm), with boulders (> 20 cm) present.
A6.2 Deep-sea mixed substrata		
	A6.2.1 Gravelly mud (M)	Mud with gravel (< 4 cm).
	A6.2.2 Gravelly mud with boulders (Mb)	Mud with gravel (< 4 cm), with boulders (> 20 cm) present.

Only those sub-classes used in this study are described.

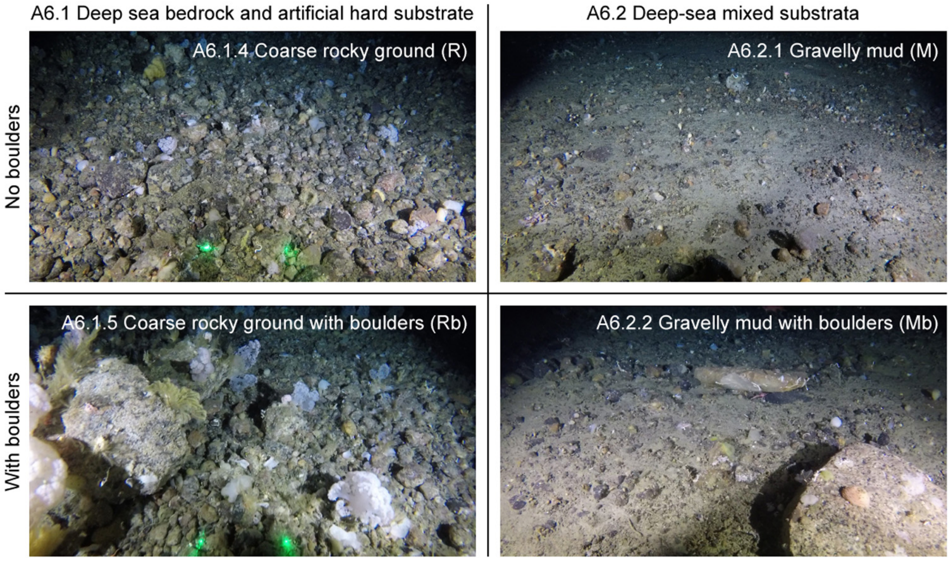

FIGURE 3 | Example image of each type of substrate class used to label images sampled from videos. Substrate classes are based on the revised EUNIS Habitat Classification (Davies et al., 2004), as adapted by Gougeon et al. (2017) and further modified here. Examples are taken from images used in the analysis. Where present laser dots (green) are 20 cm apart.

Paragorgiidae, Plexauridae, and Primnoidae combined. The mean (**Table 4**), minimum and maximum (**Table 5**) densities of annotated taxa are shown for each station, aggregated to a parent label where appropriate. Cauliflower corals were the only coral present at all stations, with a maximum density of 9.36 m^{-2}. The maximum density of any coral taxa was mushroom soft corals 13.37 m^{-2}. The maximum density of any taxa was anemones 18.23 m^{-2}.

There were a number of different distinct assemblages, often characterized by a high density of one particular taxon. Examples of the differing assemblages showing high densities of particular taxa are shown (**Figure 4**). Assemblages dominated by cauliflower corals on rocky substrates, with and without boulders, up to a maximum density of 9.36 m^{-2} (**Figure 4A**), were seen at multiple stations, with varying densities of feather stars, anemones and sponges also present. In some cases a similar assemblage was seen, in terms of species composition but instead dominated by high densities of anemones (**Figure 4B**), feather stars (**Figure 4C**), and sponges (**Figure 4D**). Patches dominated by mushroom soft corals, with other megafauna absent or occasional, were observed on rocky ground, where the substrate was largely homogenous gravel (< 4 cm) (**Figure 4E**). This assemblage was common in images from stations 2018_SA_11_087 and 2018_SA_11_112, with a maximum observed mushroom soft coral density of 13.37 m^{-2} (**Table 5**). Assemblages dominated by the bryozoan *Alcyonidium gelatinosum,* sometimes with sponges present were seen on both rocky and muddy substrates to a maximum density of 7.90 *A. gelatinosum* m^{-2} (**Figure 4F**).

There was considerable heterogeneity in the abundance and composition both within and between stations (**Tables 4**, **5** and **Figure 5**). Cauliflower corals, anemones, and sponges were present at all stations, whilst the bryozoan *A. gelatinosum*, gorgonians, feather stars and mushroom soft corals were not observed at all stations. Comparing those stations where taxa were present, the mean density varied by at least an order of magnitude in each taxon, with the exception of sponges whose

TABLE 3 | List of stations where the benthic video sled was deployed on the continental slope of the Toqqusaq Bank, west Greenland.

Station	Position	Mean depth (m)	Duration (mins)	Tow length (m)	Images	Area in images (m^2)
2017_PA_01_030	64.580°N, 55.122°W	401	15	402	23	189
2018_SA_11_035	64.409°N, 54.871°W	446	15	415	44	362
2018_SA_11_086	64.576°N, 55.040°W	321	46	1,500	131	1,078
2018_SA_11_087	64.535°N, 55.154°W	585	48	1,835	133	1,095
2018_SA_11_111	64.472°N, 54.956°W	391	30	1,129	77	634
2018_SA_11_112	64.488°N, 55.062°W	579	30	978	81	667
2018_SA_11_113	64.335°N, 54.638°W	561	30	982	84	691
2018_SA_11_119	64.243°N, 54.155°W	415	30	975	110	905
2018_SA_11_120	64.246°N, 53.930°W	314	30	915	107	881
2018_SA_11_121	64.185°N, 53.917°W	557	15	481	37	305
2019_HM_02_199	64.771°N, 55.171°W	537	19	634	59	486
2019_HM_02_200	64.717°N, 55.123°W	368	15	416	39	321
2019_HM_02_201	64.644°N, 55.187°W	482	17	490	22	181
2019_SA_04_006	64.817°N, 54.721°W	274	17	561	60	494
2019_SA_04_007	64.790°N, 55.100°W	390	15	485	60	494
2019_SA_04_008	64.702°N, 54.865°W	287	15	539	63	518
2019_SA_04_010	64.663°N, 54.936°W	293	15	696	53	436
2019_SA_04_011	64.579°N, 55.053°W	315	15	488	56	461
Totals			**417**	**13,921**	**1,239**	**10,198**

The following are provided for each station: the position (ship's location at the midpoint of tow), mean depth (m), duration of tow (minutes), length of tow (m), number of images extracted from the video and total area of the extracted images (m^2). The duration of the tow (minutes) is provided along with the number of images extracted for analysis from the video. The Station name indicates the year, vessel, cruise number and station number (Year_Ship_Leg_Station number). The two letter ship codes indicate the RV Paamiut (PA), RV Sanna (SA), or MT Helga Maria (HM).

TABLE 4 | Observed mean (standard deviation) densities (individuals or colonies m^{-2}) of taxa at each station, based on the number of annotations from all images for each station, adjusted for the area of the field of view in the images (8.23 m^2).

Station	Mean (standard deviation) density, individuals or colonies m^{-2}						
	Bryozoan (*A. gelatinosum*)	Anemones	Gorgonians	Mushroom soft corals	Cauliflower corals	Feather stars	Sponges
2017_PA_01_030	0.11 (0.17)	0.64 (0.51)	0.01 (0.03)	–	2.92 (1.25)	0.08 (0.17)	1.91 (0.70)
2018_SA_11_035	0.06 (0.10)	0.03 (0.07)	0.25 (0.23)	0.00 (0.02)	1.74 (0.91)	0.01 (0.03)	0.72 (0.50)
2018_SA_11_086	0.14 (0.18)	8.92 (3.75)	0.00 (0.03)	–	0.65 (0.71)	0.00 (0.01)	0.42 (0.37)
2018_SA_11_087	0.04 (0.08)	0.18 (0.29)	0.03 (0.14)	0.89 (2.14)	2.41 (1.65)	1.69 (2.08)	0.70 (0.63)
2018_SA_11_111	0.06 (0.13)	0.21 (0.18)	0.05 (0.13)	–	2.30 (1.17)	0.02 (0.09)	1.06 (0.63)
2018_SA_11_112	–	0.07 (0.12)	0.05 (0.17)	0.88 (1.57)	0.67 (0.85)	1.42 (2.50)	0.41 (0.34)
2018_SA_11_113	0.01 (0.06)	0.05 (0.08)	0.04 (0.13)	0.03 (0.13)	0.20 (0.28)	0.09 (0.22)	0.78 (0.53)
2018_SA_11_119	0.00 (0.02)	0.01 (0.03)	0.00 (0.03)	0.01 (0.04)	0.28 (0.66)	0.05 (0.13)	1.60 (0.68)
2018_SA_11_120	2.26 (1.68)	0.01 (0.04)	0.00 (0.05)	–	2.18 (1.98)	0.00 (0.02)	0.77 (0.60)
2018_SA_11_121	–	0.00 (0.02)	0.03 (0.08)	0.02 (0.10)	0.06 (0.12)	0.54 (0.63)	0.88 (0.52)
2019_HM_02_199	0.01 (0.04)	0.14 (0.25)	–	0.01 (0.06)	0.04 (0.10)	0.35 (0.79)	0.48 (0.43)
2019_HM_02_200	0.01 (0.03)	0.39 (0.29)	0.02 (0.05)	–	2.30 (1.69)	0.01 (0.03)	1.10 (0.91)
2019_HM_02_201	–	0.03 (0.09)	0.01 (0.04)	–	0.96 (0.86)	0.53 (0.79)	0.75 (0.60)
2019_SA_04_006	–	0.01 (0.04)	–	–	0.10 (0.12)	–	1.45 (0.77)
2019_SA_04_007	0.02 (0.06)	0.23 (0.26)	–	–	2.31 (1.91)	0.02 (0.05)	0.98 (0.65)
2019_SA_04_008	1.50 (1.01)	0.01 (0.03)	–	–	0.03 (0.08)	–	0.86 (0.47)
2019_SA_04_010	0.00 (0.02)	0.00 (0.02)	–	–	0.24 (0.27)	–	0.70 (0.45)
2019_SA_04_011	–	10.94 (2.85)	–	–	1.37 (0.61)	0.00 (0.02)	0.37 (0.31)

A dash (–) indicates the taxon was not observed in the images extracted from the video obtained at that station. Gorgonians includes the annotation labels Acanthogorgiidae, Paragorgiidae, Plexauridae, and Primnoidae. Sponges includes the annotation labels Axinellidae, Geodiidae, Polymastiidae, Rossellidae, Porifera massive, Porifera branching, and Porifera encrusting.

density was more evenly distributed (**Table 4**). There was also considerable variation in densities within stations demonstrated by the range in minimum and maximum values (**Table 5**). This indicates an inherent patchiness, which is illustrated by visualizing data from 2018_SA_11_087 (**Figure 5**). Areas where the assemblage is dominated by cauliflower corals, feather stars

TABLE 5 | The minimum and maximum (min-max) densities (individuals or colonies m^{-2}) of taxa observed within a single image for each station, based on the number of annotations adjusted for the area of the field of view in the image (8.23 m^2).

Station	Minimum and maximum (min-max) density within a single image, individuals or colonies m^{-2}						
	Bryzoan *(A. gelatinosum)*	Anemones	Gorgonians	Mushroom soft corals	Cauliflower corals	Feather stars	Sponges
2017_PA_01_030	0.00–0.49	0.12–1.94	0.00–0.12	–	0.97–6.32	0.00–0.73	0.49–3.40
2018_SA_11_035	0.00–0.36	0.00–0.24	0.00–0.85	0.00–0.12	0.12–3.89	0.00–0.12	0.00–2.79
2018_SA_11_086	0.00–0.85	0.85–18.23	0.00–0.24	–	0.00–5.47	0.00–0.12	0.00–2.19
2018_SA_11_087	0.00–0.36	0.00–2.43	0.00–1.22	0.00–13.37	0.00–8.63	0.00–8.38	0.00–4.01
2018_SA_11_111	0.00–0.61	0.00–0.85	0.00–0.73	–	0.12–4.62	0.00–0.73	0.12–2.55
2018_SA_11_112	–	0.00–0.49	0.00–1.09	0.00–6.80	0.00–3.52	0.00–11.66	0.00–1.22
2018_SA_11_113	0.00–0.49	0.00–0.36	0.00–0.97	0.00–0.97	0.00–1.34	0.00–1.09	0.00–2.92
2018_SA_11_119	0.00–0.12	0.00–0.12	0.00–0.24	0.00–0.24	0.00–6.56	0.00–0.85	0.24–3.40
2018_SA_11_120	0.00–7.90	0.00–0.24	0.00–0.49	–	0.00–8.38	0.00–0.12	0.00–3.40
2018_SA_11_121	–	0.00–0.12	0.00–0.36	0.00–0.49	0.00–0.49	0.00–2.07	0.12–1.94
2019_HM_02_199	0.00–0.24	0.00–1.46	–	0.00–0.36	0.00–0.49	0.00–4.13	0.00–1.82
2019_HM_02_200	0.00–0.12	0.00–1.22	0.00–0.24	–	0.00–5.83	0.00–0.12	0.00–5.59
2019_HM_02_201	–	0.00–0.36	0.00–0.12	–	0.00–2.67	0.00–2.19	0.00–1.70
2019_SA_04_006	–	0.00–0.12	–	–	0.00–0.36	–	0.24–3.28
2019_SA_04_007	0.00–0.36	0.00–1.34	–	–	0.00–9.36	0.00–0.24	0.24–3.65
2019_SA_04_008	0.00–5.22	0.00–0.12	–	–	0.00–0.36	–	0.12–2.31
2019_SA_04_010	0.00–0.12	0.00–0.12	–	–	0.00–1.34	–	0.00–1.82
2019_SA_04_011	–	6.56–16.28	–	–	0.24–3.40	0.00–0.12	0.00–1.22

A dash (–) indicates the taxon was not observed in the images extracted from the video obtained at that station. Gorgonians includes the annotation labels Acanthogorgiidae, Paragorgiidae, Plexauridae, and Primnoidae. Sponges includes the annotation labels Axinellidae, Geodiidae, Polymastiidae, Rossellidae, Porifera massive, Porifera branching, and Porifera encrusting.

and sponges (**Figures 5A,C**) are interspersed by patches of mushroom soft corals (**Figure 5B**) where other taxa are absent.

Significant positive and negative associations between pairs of taxa were observed (**Figure 6**). Cauliflower corals were positively associated with feather stars, gorgonians and anemones, which was more positive associations than any other taxa. Co-occurrence of cauliflower corals with feather stars and anemones was readily apparent in the imagery (**Figures 4A–D**).

There were other taxa, which could not be consistently identified and/or annotated in the imagery, but contributed to the structural diversity of the habitats. They can be observed in some sections of video and where abundant clearly form a significant component of this habitat. Specifically this includes, calcified bryozoans, from the families Celleporidae, Flustridae, Horneridae, Myriaporidae, and Phidoloporidae, as well as hydrozoans from the families Aglaopheniidae and Sertulariidae.

Substrates

The dominant substrates were coarse rocky ground (R and Rb), with these being the only substrates identified in 11 of the stations ($n = 18$) (**Figure 7**). Conversely, gravelly mud substrates (gM and GMb) were the only substrates in just two of the stations. Boulders were present at all the stations (**Figure 7**), and were typically observed intermittently during the course of a tow (**Figure 5**).

The number of annotations of some taxa varied with substrate. Anemones, mushroom soft corals, feather stars and cauliflower corals were more prevalent on hard substrates (R and Rb) (**Figure 8**). Habitats dominated by cauliflower corals and or feather stars were typically found where there was a heterogeneity in size of the rocky material, with a combination of gravel, cobbles, and boulders (**Figures 4A,C,D**). Conversely, patches of mushroom soft corals appeared to only be found on more uniform gravel substrates (**Figure 4E**). These differences in the size of rocky material were not quantified, with the exception of differentiating between the presence and absence of boulders.

DISCUSSION

Analysis of the imagery from 18 stations showed heterogeneity in the substrates and communities on the slope of the Toqqusaq Bank. This patchiness was observed within stations, with notable variation across single video sled tows as well as between stations. Several distinct assemblages were observed, in some cases the assemblage was dominated by a single taxa forming a patch of habitat, with anemone fields, mushroom soft coral beds and areas dominated by the bryozoan *A. gelatinosum*. The assemblages which appeared to be most structurally complex and diverse, were those characterized by high densities of cauliflower corals, feather stars and sponges. In such assemblages the combined effect of observed densities is a habitat with considerable structural heterogeneity, found on coarse rocky substrates. Intuitively, substrate likely plays an important part in determining the assemblage present. Previously, Baker et al. (2012) found that substrate type had a clear influence on the occurrence and abundance of deep-sea corals in the Labrador Sea, they reported that the greatest diversity was seen in video

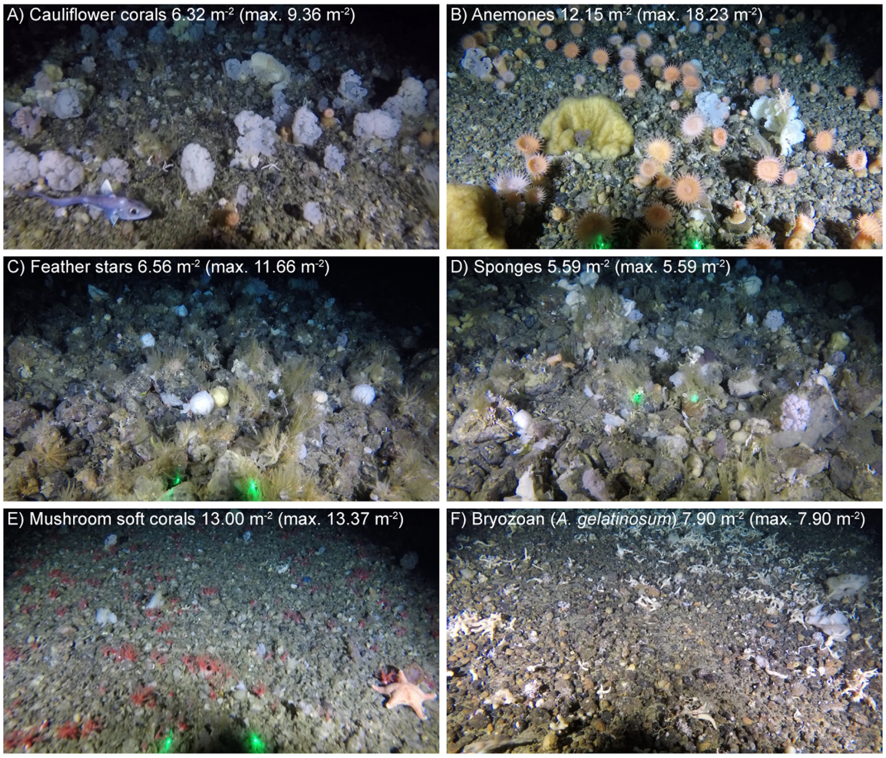

FIGURE 4 | Examples of different assemblages with high density of: **(A)** Cauliflower corals; **(B)** Anemones; **(C)** Feather stars; **(D)** Sponges; **(E)** Mushroom soft corals; and **(F)** Bryozoan (*A. gelatinosum*). Images were selected for illustrative clarity. The density of the highlighted taxa within each image is reported (along with the maximum observed density in all images for reference). Where present, laser dots (green) are 20 cm apart.

transects with a mosaic of substrate types. Many of the taxa selected for annotation in this study are sessile and require a hard substrate for attachment, for example it is known that most soft corals and gorgonians require hard substrates for larval settlement and growth (Pérez et al., 2016). Some taxa (anemones, mushroom soft corals, feather stars and cauliflower corals) showed a clear preference for the coarse rocky substrates, whilst annotations of other taxa were more evenly distributed across the substrate classes.

Defining Soft Coral Gardens

Habitat classification systems support conservation goals by providing universally understood definitions that can be used to describe and map the distribution of habitats, a necessary pre-requisite for spatial management (Howell et al., 2010). The term "coral garden" was first applied to dense aggregations of non-reef forming corals, dominated by gorgonians (Bullimore et al., 2013). A formal definition offered by the Oslo and Paris Conventions (OSPAR) applies to a much wider range of cold-water corals on both hard and soft substrates (ICES, 2007; OSPAR Commission, 2010). This definition captures a range of different habitats and does not therefore represent a single ecological unit (Bullimore et al., 2013).

In their cold-water coral classification scheme, Davies et al. (2017) proposes a biotope consisting of cold-water Alcyoniina on hard/mixed substrate, specifically, Nephtheidae (cauliflower corals) and *Anthomastus* sp. (mushroom soft coral, family: Alcyoniidae). Whilst the proposed biotope refers to *Anthomastus* sp., we suggest that this could be interpreted more broadly as mushroom soft corals, given: (i) the known diversity of mushroom soft coral species in the North Atlantic (Molodtsova, 2013); (ii) the taxonomic revision of genera in Alcyoniidae; and (iii) the fact that close relatives have similar gross morphologies and likely occupy similar niches. In the present study, the imagery does not allow greater taxonomic resolution with regards mushroom soft corals. The supplementary material in the Davies et al. (2017) classification scheme, describes the cold-water Alcyoniina on hard/mixed substrate biotope as being known from depths of 600 m in Iceland and Norway (Guillaumont et al., 2016) and provides an example image. The example image is comparable to the coral garden habitat described here. The NEAFC consider cauliflower corals to be a VME indicator taxa for a VME habitat type described as "cauliflower coral fields," which is listed as a soft-bottom habitat (NEAFC, 2014).

There is no accepted quantitative definition of soft coral gardens or coral gardens more broadly. Rogers et al. (2015) propose that to qualify the density of coral garden species must exceed 10 times the background level. Practically this relies on a good understanding of the background level which is rarely the case, including in this context. Further, since coral gardens by their nature are comprised of multiple species, it is not clear whether densities should be considered

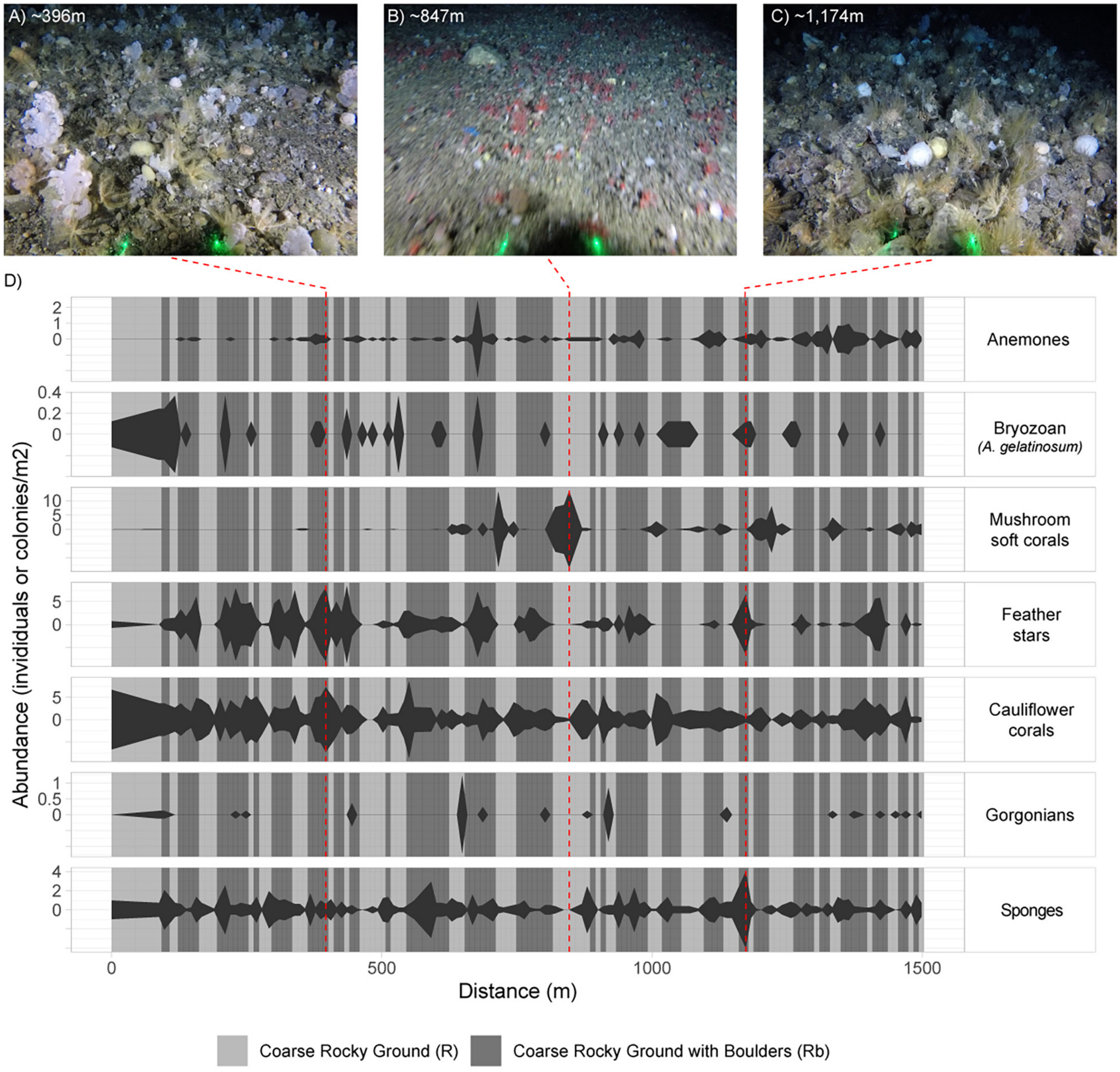

FIGURE 5 | Kite diagram showing variation in faunal abundance and substrate across an example station (2018_SA_11_087), based on fauna and substrate annotations of images sampled from the video. The width of kite is determined by the observed abundance in the image sampled at that distance along the tow. Distance is based on the speed of the vessel and the time elapsed from touchdown. The background is shaded according to substrate observed in each image. Substrate type and faunal abundance is interpolated between images to produce an illustrative representation. The example images **(A–C)** are included to illustrate the variation across the station as described by **(D)**. The left and right extremities of example images have been cropped and thus do not display the full field of view (FOV). Laser dots (green) are 20 cm apart.

individually or the combined density of the species present compared with combined background level. Thus, this study must rely on the application of "expert" judgment to make a determination and in doing so provide a quantitative description that can be used to inform the development of revised definitions in the future. This judgment is guided by the indicative densities in the description of the broader coral garden habitat type (ICES, 2007; OSPAR Commission, 2010). Specifically, these suggest colony densities of 1–7 m^{-2} generally, 0.5–2 m^{-2} for small gorgonians (Acanthogorgiidae and Primnoidae) and 0.01–0.02 m^{-2} for larger gorgonians (Paragorgiidae). It has been suggested that these ranges can be used to differentiate between comparatively sparse and dense coral gardens (ICES, 2007). These indicative density thresholds are not accompanied by a requirement for the density to be present over a minimum area, which would be

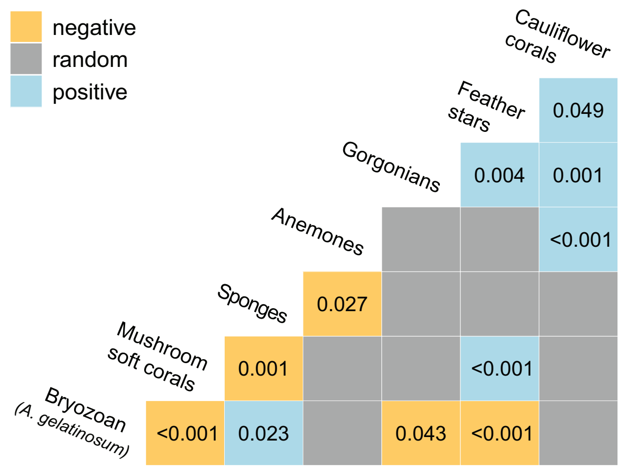

FIGURE 6 | Heat map showing the positive and negative associations between taxa as determined by a probabilistic co-occurrence model (Veech, 2013). For each pair the observed frequency of co-occurrence within images ($n = 1,239$) is either, significantly large and greater than expected (positive association), significantly small and less than expected (negative association), or not significantly different and approximately equal to expected (random association). Associations are considered significant where the probability of the observed frequency of concurrence is < 0.05 were the taxa distributed independently of one another. *P*-values are provided for significant associations.

a useful additional guidance, pending consensus among the scientific community.

Cauliflower corals are the most abundant corals in the study area. They make a significant contribution to structural complexity and exhibited more positive associations than any other taxa. They are therefore an obvious candidate to serve as an indicator species for this soft coral garden habitat. A mean density threshold of 1 colony m^{-2} is applied to determine those stations where the soft coral garden habitat is present. The lower bound of the generic indicative density suggested by OSPAR is used, as it is recognized that the study area is inherently patchy. To use a higher threshold would potentially exclude stations with patches of cauliflower corals at significant densities, indicating areas of coral garden. Excluding these would not recognize their presence in an ecosystem displaying a mosaic nature, with patches of soft coral garden present among differing substrates and assemblages. Those 8 out of 18 stations which meet this threshold are highlighted (**Figure 9**).

Does This Soft Coral Garden Constitute a Vulnerable Marine Ecosystem (VME)?

Soft coral gardens and cauliflower corals more generally, are both recognized as VMEs and VME indicators, respectively, by NEAFC, the RFMO for the Northeast Atlantic (NEAFC, 2014). Conversely, neither are considered a VME or indicator by NAFO, the RFMO for the Northwest Atlantic (NAFO, 2012). This apparent inconsistency could in theory reflect a fundamental difference in the nature of deep-sea benthic ecosystems in the Northwest Atlantic compared to those in the Northeast Atlantic, though no such rational is provided by either RFMO. More likely this is the product of differing interpretations of the VME definition by experts in separate RFMOs. This lack of coordination and harmonization between adjacent RFMOs has been noted by others (Bell et al., 2019). Therefore here, direct reference is made to the underlying VME definition, with each criteria addressed in turn (FAO, 2009).

Uniqueness or Rarity

There is no evidence to support recognition as a VME by virtue of the unique or rare criteria. The taxa observed have a wide distribution and are not known to be threatened globally. The rarity of the habitat is not known but similar assemblages have been reported elsewhere in the North Atlantic. The true spatial extent within Greenlandic waters is not known but it may well extend beyond the present study area along the continental slope.

Functional Significance of the Habitat

The soft coral garden habitat likely plays a functionally significant role, though this is not directly assessed here and only limited inferences can be made from the imagery. In general more is known about gorgonians than cauliflower corals. Buhl-Mortensen and Mortensen (2005) reported finding 114 associated species and nearly 4,000 individuals on the 25 *Paragorgia arborea* and *Primnoa resedaeformis* colonies they sampled. Krieger and Wing (2002) observed 10 mega faunal groups (rockfish, sea stars, nudibranchs, feather stars, basket stars, crabs, shrimps, snails, anemones, and sponges) associated with *Primnoa* spp., which was used to either prey on, suspension feed from, or provide protection. Cauliflower corals are known to host a variety of species. *Gersemia* spp. can be considered habitat-forming species, as the embryonic development of the basket stars (*Gorgonocephalus* spp.) may occur within the coral's tissues, with juveniles attached to the outside whilst feeding (Patent, 1970). As many as 118 small basket stars have been found on a single cauliflower colony (B. de Moura Neves, pers. comm.). Whilst not quantified, *Gorgonocephalus* spp. were observed on cauliflower corals in video and images in this study. The presence of cephalopods, decapods, Rajiformes and various fish was noted in images from this habitat. Grenadier fish (Macrouridae) and redfish (*Sebastes* spp.) were commonly encountered in videos and sampled images. Unpublished data from prawn stock assessment trawl and beam trawl surveys provides further insights into a rich community of benthic invertebrates associated with the observed soft coral garden habitat (**Supplementary Table 1**).

Fragility

The habitat should be considered fragile, as it is vulnerable to degradation by physical disturbance, especially trawling. The vulnerability of deep-sea gorgonians to trawling is well established (e.g., Freese et al., 1999; Witherell and Coon, 2000). The largest and perhaps most vulnerable species present was *Paragorgia arborea*. The ability to retract and recover from acute local injury may render cauliflower corals less vulnerable to mechanical disturbance than other corals with rigid skeletons and unretractable colonies (Henry et al., 2003). Nevertheless, these responses do not provide protection against removal. It

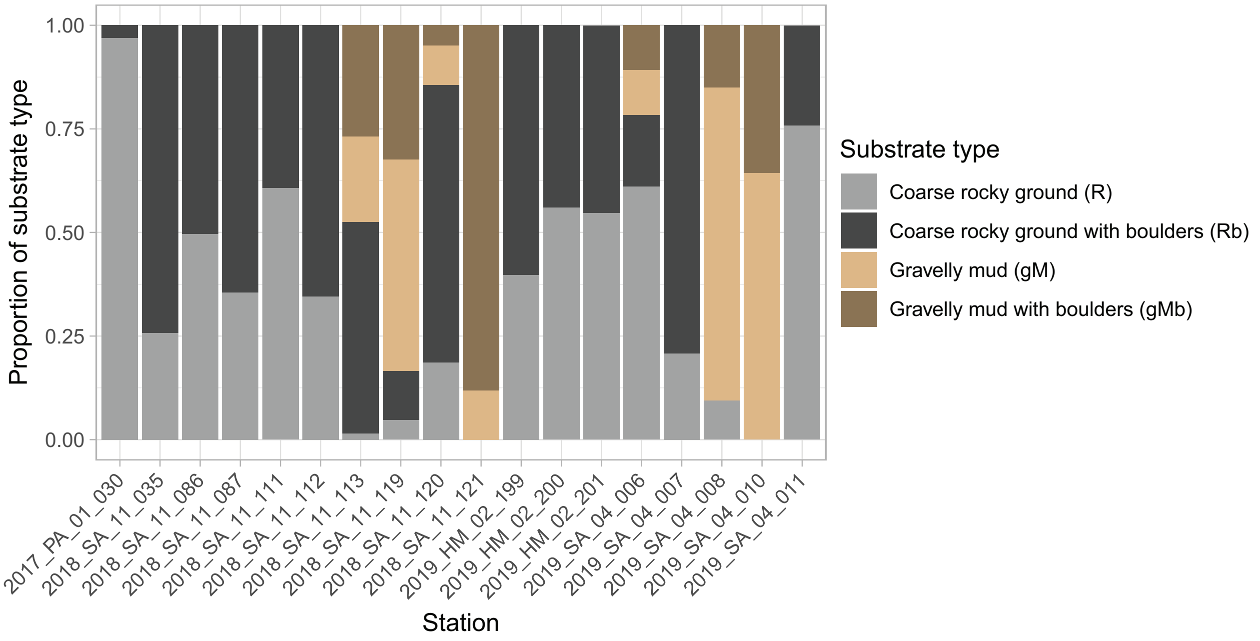

FIGURE 7 | Stacked bar chart showing proportion of each substrate type in images from each station. Substrate classes are based on the revised EUNIS Habitat Classification (Davies et al., 2004), as adapted by Gougeon et al. (2017) and further modified for the purposes of this study.

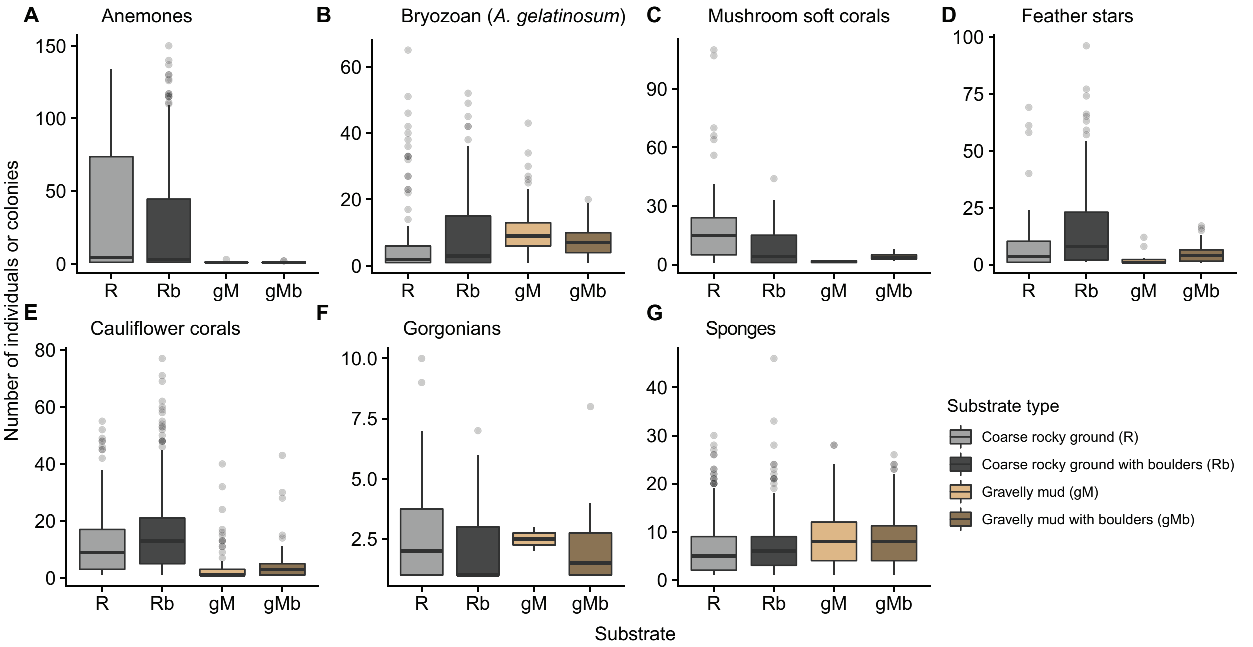

FIGURE 8 | Box-whisker plot showing the number of annotations of seven taxa **(A–G)** in images, which were annotated with one of four classes of substrate type. Substrate classes are based on the revised EUNIS Habitat Classification (Davies et al., 2004), as adapted by Gougeon et al. (2017) and further modified for the purposes of this study.

has been noted that cauliflower corals are prone to incidental bycatch in emerging deep-sea fisheries (Devine et al., 2019). Groundfish survey trawl data from the Grand Banks and Flemish Cap, confirm that soft coral biomass was the largest component of bycatch and that abundance was significantly lower in previously trawled areas (Murillo et al., 2010). In the Bering Sea, the biomass of *Gersemia* spp. has been found to be highest in untrawled areas (McConnaughey et al., 2000).

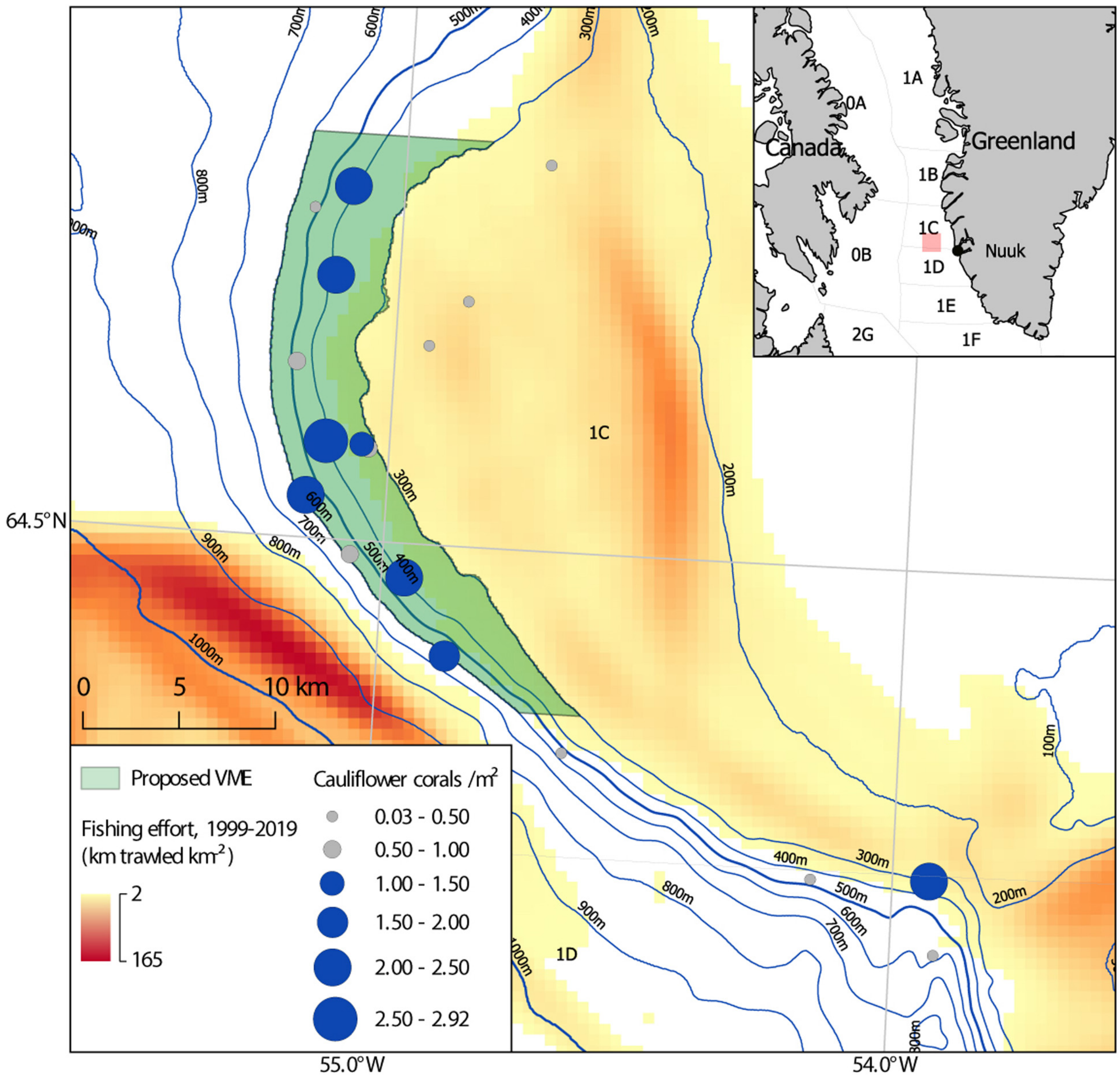

FIGURE 9 | Map of the 486 km^{2} proposed soft coral garden vulnerable marine ecosystem (VME) (light green), on the continental slope of the Toqqusaq Bank, west Greenland. NAFO Divisions are indicated. The mean density of cauliflower coral colonies is shown (circles), with those stations exhibiting a density $\geq$ 1 m^{2} highlighted in blue (< 1 m^{2} gray). Fishing effort is based on haul by haul logbook data from 1999 to 2019, used to determine km trawled km^{-2}.

Similarly, Jørgensen et al. (2013) consider *Gersemia fruticosa, G. rubiformis, Drifa glomerata,* and *Duva florida* to be at "high risk" from trawling and found the highest biomass outside trawled areas in the Barents Sea. In the present study the lowest densities of cauliflower corals were seen in those stations (2019_SA_006, 2019_SA_008 and 2019_SA_010) within the trawling footprint, with gorgonians and mushroom soft corals also being absent there. This supports the idea that the component taxa of this soft coral garden are vulnerable to trawling. It may be the case that this coral garden assemblage is only observed in the relatively narrow section of the continental slope that has not been subject to fishing pressure to date.

Life-History Traits of Component Species That Make Recovery Difficult

Slow growth and long-life are exhibited by component taxa of this habitat, rendering recovery slow. To date studies on growth rates and longevity in deep-sea octocorals have focused on gorgonians (Pérez et al., 2016), whereas cauliflower corals have received less attention, not least because of the challenges associated with measuring soft coral colonies. Sherwood and Edinger (2009) report gorgonian axial growth rates as little as 0.56 cm $year^{-1}$ for *Paramuricea* spp., 1.62 cm $year^{-1}$ for *Paragorgia arborea*, and 1.00 cm $year^{-1}$ for *Primnoa resedaeformis*, with ages exceeding 100 years. Laboratory study of larval and early growth of *G. fructicosa* and *D. florida*, found post-settlement growth to be very slow, suggesting a "sluggish recovery" following anthropogenic disturbance (Sun et al., 2011). Although, the authors note that this may be partially offset by the small size at sexual maturity and the potential for disturbance to release planulae from fertile colonies that grow into viable offspring. A similar study with *Drifa* sp. and *D. glomerata*, also suggested that early growth rates of primary polys was extremely slow with no budding of the primary polys of *Drifa* sp. in 21 months (Sun et al., 2010). Cordes et al. (2001) monitored *Heteropolypus ritteri* (mushroom soft coral; in the family Alcyoniidae; formerly in the genus *Anthomastus*) in the laboratory, finding slow initial growth became more rapid at intermediate size, before approaching an asymptote at 26–30 years. They observed that the slow growth and relative longevity was typical of other deep-sea organisms. Watling and Auster (2005) conclude that growth rates and patchy recruitment mean that recovery of alcyonacean communities following removal is likely to take a very long time.

Structural Complexity

Perhaps the most compelling justification for consideration as a VME, provided by the imagery collected, is the structural complexity created by the biotic components of this habitat. The combined effect of all the taxa annotated but especially cauliflower corals, feather stars, sponges and gorgonians, adds considerable structure at varying scales to the otherwise limited complexity of the coarse rocky substrates (**Figure 10**). Further structural complexity is added by the abundant bryozoans and hydrozoans that are present but were not quantified (**Figure 10**). As discussed above, these structures play a functional role in the ecosystems, for example by providing refugia and supporting filter feeding organisms, resulting in high diversity and abundance. These habitats are patchy in nature; denser areas of cauliflower corals are interspersed with other assemblages, for example, areas dominated by anemones (**Figure 4B**) and mushroom soft corals (**Figure 4E**). Similarly, substrates varied within and between stations from coarse rocky ground to gravelly mud substrates. This mosaic nature and resulting variation in structural complexity on a larger spatial scale, is likely to support greater diversity of species and functions.

Those highlighted stations (**Figure 9**) exhibiting the soft coral garden habitat, would appear to meet multiple criteria for a VME (FAO, 2009). Therefore it is proposed that this area be recognized as a VME.

Implications for Management

It is widely recognized that spatial closures are the most effective method of avoiding serious adverse impacts on VMEs (Bell et al., 2019). Executive Order No.4, 30 March 2017, Section 13, introduced by the Government of Greenland makes provision for the closure of areas to bottom gears where VMEs are identified in Greenlandic waters (Government of Greenland, 2017). The soft coral garden habitat identified is immediately adjacent to the MSC certified cold-water prawn (Cappell et al., 2018) and Greenland halibut fisheries (Cappell et al., 2017). This certification requires that measures are in place to ensure that fisheries do not cause serious or irreversible harm to VMEs (MSC, 2014). It should be acknowledged that the coarse rocky ground in the proposed VME area is not necessarily optimal for the prawn fishery and too shallow for the halibut fishery. Therefore, the most immediate threat maybe from the emerging cod fishery (ICES, 2019b), as the slope of the Toqqusaq Bank may be suitable ground for targeting cod. The soft coral garden habitat identified is also partially overlapped by a hydrocarbon exploration and exploitation license, which is currently pending (License: No. 2019/02) (Government of Greenland, 2020).

A bounding polygon for this candidate VME is proposed encompassing seven of the eight stations where the soft coral garden habitat was identified (**Figure 9**). These seven stations were spatially contiguous in the northern portion of the study area, within a 60 km span of continental slope. In the southern portion of the study area only one station (2018_SA_11_120) out of four exceeded the mean cauliflower corals density threshold ($> 1\ m^2$) used to determine the presence of the soft coral garden habitat. This suggests the soft coral garden habitat was not a dominant habitat there. On that basis the southern portion of the study area was not included in the proposed VME area.

The depth range (314–585 m) of those eight stations where the soft coral garden habitat was found is used as the upper and lower boundary on the continental slope of the Toqqusaq Bank. For both pragmatic and precautionary reasons this is rounded down to 300 m and up to 600 m. Bathymetric contours are used to form the eastern (300 m contour) and western (600 m contour) edges of the polygon. The latitudinal extent is determined by the latitude of the most northerly (2019_SA_04_007) and southerly (2018_SA_11_035) of these seven stations. A 5 km latitudinal buffer is added, rounded to the nearest minute (one nautical mile). The proposed VME area can be described as the area with depths of 300–600 m between 64°50′N and 64°22′N on the western edge of the Toqqusaq Bank. This 486 km^2 area, spans ∼60 km of the continental slope and is intended to be pragmatic from a spatial management perspective, whilst affording protection to known areas of this soft coral garden habitat.

The VME area proposed here is based on multiple, adjacent observations, which are sufficient to justify the introduction of spatial management measures. It is acknowledged that the data show this soft coral garden habitat is present toward the southern extremity of the study area at a single station. Thus patches of this habitat are present along at least 100 km^2 of continental slope. The true spatial range may well be greater, possibly extending a considerable distance along the continental slope of west Greenland. Management and future research should draw on other data, including unpublished GINR surveys (stock assessment trawl bycatch and beam trawls). Further research should address whether the VME area proposed in this study should be extended, especially in terms of its latitudinal extent.

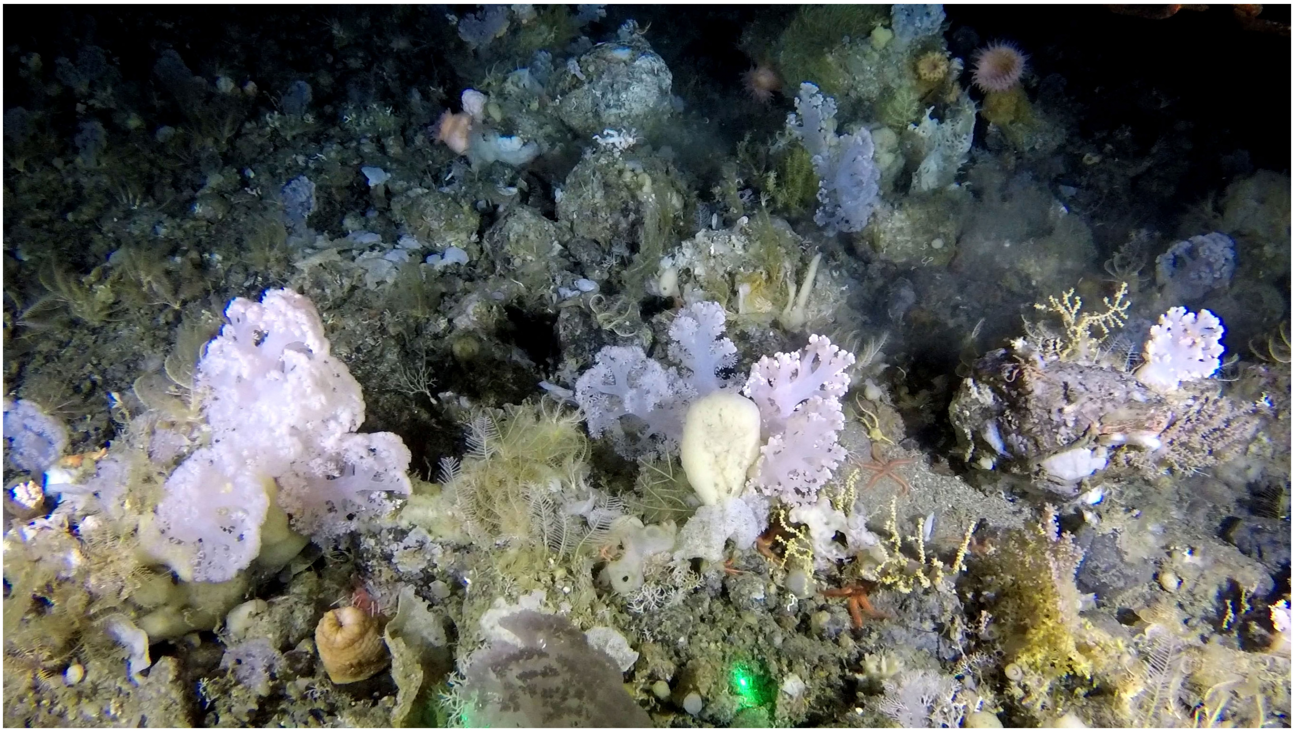

FIGURE 10 | Example still showing the structural complexity of the soft coral garden habitat, from Station 2018_SA_11_087, at a depth of 585 m, on the continental slope of Toqqusaq Bank, west Greenland. Cauliflower corals, feather stars, gorgonians, sponges, anemones, brittle stars, hydrozoans, and calcified bryozoans, are present. Laser dots (green) are 20 cm apart; the left hand dot is partially obscured.

The role of fishing effort, substrate and other environmental variables should be subject to investigation, as one or more of these may explain the distribution of this habitat and abundance of its component species.

Limitations

A fundamental methodological decision was to annotate images sampled from stills rather than directly analyze videos. This was in part due to pragmatic constraints (time) but also provides greater scope for revision and further work on the images and annotations. However, it should be acknowledged that a considerable amount of data contained in the videos are therefore excluded. This impacts our understanding of the abundance of sparser (e.g., *Paragorgia arborea*) and mobile fauna, particularly fish, which are less likely to be sampled in images.

The nature of imagery means only certain taxa can be identified and limits the taxonomic resolution that can be obtained during annotation. A more complete taxa inventory based on unpublished beam trawl and stock assessment trawls from the proposed VME area is included for reference (**Supplementary Table 1**). Efforts were made to annotate different sponge taxa and morphologies but these were ultimately aggregated to achieve consistency. Aggregation of multiple taxa to a parent label, for example into "sponges," results in a more general picture and does not allow more specific taxa associations with other taxa and substrates to be determined. The approach of annotating individuals or colonies means some taxa (e.g., hydrozoans) that formed significant components of the habitats were not quantified in this study. To do so would require a different annotation strategy and likely require considerably more time investment, the latter being a familiar problem in the benthic imaging field.

The resolution within the substrate classes themselves limited their explanatory power. In the images gorgonians were only ever seen attached to hard substrates. It was anticipated that inclusion of a sub-class "with boulders" into gravel mud, would add explanatory power accounting for the presence of gorgonians in gravelly mud substrates. Clearly this was not adequate, with some gorgonians annotated on gravelly mud substrates (gM) (**Figure 8**). In such cases the gorgonians were attached to rocky material that did not exceed the 20 cm boulder threshold, thus the substrate in the image was classed as gravelly mud (gM) and not gravelly mud with boulders (gMb). The proportion and size of hard substrates for attachment varies considerably within classes and some images exhibit a range of substrates. A higher resolution approach to substrate annotation would enable further conclusions to be drawn regarding the relationship between substrates and the observed assemblage and abundance of taxa. This could be achieved by the introduction of additional substrate classes or sub-classes, or alternatively by applying substrate labels to discrete areas within the images. The optimum approach would depend on the question(s) being addressed.

CONCLUSION

Despite the limitations identified, the benthic video sled employed proved to be a low-cost effective tool to collect imagery suitable for identifying and providing a quantitative description of a proposed VME. This allowed the first description of this soft coral garden habitat, characterized by a high density of cauliflower corals, on the continental slope of the Toqqusaq Bank. This structurally complex habitat appears to meet the definition of a VME as provided by the FAO. The vulnerability and potential ecological value mean there is a need for effective spatial management measures, given the proximity of economically important halibut and prawn fisheries along with the emerging cod fishery. A candidate VME area of 486 km^2 is therefore proposed, from which activities liable to cause serious or irreversible harm, such as benthic trawling, should be excluded.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

SL, MB, NH, KK, and CY contributed to the conception and design of the study. SL, MB, NH, MF, and CY collected the video imagery. BS-S performed the image extraction and annotation. RN and KZ prepared fishing effort data. SL and CY conducted the analyses and produced the figures. SL drafted the manuscript. All authors contributed to manuscript revision, read and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2020.00460/full#supplementary-material

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Appendix III

Paper III

The results and discussion in the following paper are presented in Chapter 7, whilst the methodology is described in Chapter 4.

Long, S. and Jones, P.J.S. (2021). Greenland's offshore Greenland halibut fishery and role of the Marine Stewardship Council certification: A governance case study. *Marine Policy* 127. doi: j.marpol.2020.104095.

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Greenland's offshore Greenland halibut fishery and role of the Marine Stewardship Council certification: A governance case study

Stephen Long [a,b,*], Peter J.S. Jones [a]

[a] *Department of Geography, University College London, UK*
[b] *Institute of Zoology, Zoological Society of London, UK*

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ABSTRACT

The Marine Stewardship Council (MSC) certification is the market-leading seafood eco-label, including in deep-sea fisheries, about which there are growing concerns around sustainability. Greenland is economically dependent on deep-sea fisheries, including for Greenland halibut (*Reinhardtius hippoglossoides*). The offshore halibut fishery, which employs demersal trawls (800–1,400 m), obtained MSC certification in 2017. This provides an opportunity to critically assess the governance of deep-sea resources, with reference to the MSC certification. The Marine Protected Area Governance (MPAG) framework, originally designed to analyse MPAs and adapted for this study, finds an effective system of state-led governance, supported by scientific, certification and industry actors. Arising from its socio-economic importance, the industry's considerable influence is used to align management with the MSC certification. Outcomes directly attributable to engagement with the MSC certification include the introduction of a management plan and new benthic research programmes. However, questions are raised about the certification, providing case study examples of existing criticisms. Assessments are weak with respect to benthic habitats and over-reliant on the definitive, expert judgement of Conformity Assessment Bodies (CABs), whose independence is questioned. Separate MSC assessments of Greenlandic and German vessels in the fleet provided an opportunity to consider the consistency and robustness of the process, which raised serious concerns. Two different CABs found the benthic impact of vessels using the same gear in the same area to be sustainable, by employing fundamentally different and conflicting logic. This represents a serious failing of certification process, undermining the assurance it is intended to provide.

1. Introduction

The over-exploitation of continental fish stocks, growing demand for seafood and advances in fishing technologies have driven fishing into deeper waters [1–3]. Covering ~65% of the earth, deep-seas (depths >200 m) [4] are low productivity ecosystems: species typically exhibit high longevity, slow growth, late maturation and low fecundity [2,5]. Consequently, deep-water stocks are vulnerable to over-exploitation, whilst benthic habitats can be significantly and even irreversibly impacted [2,6]. The sustainability of deep-sea fisheries has been repeatedly questioned, with calls for improved fishery management and conservation measures [1,3,7].

Eco-labelling has been identified as a market-based mechanism with the potential to promote sustainable fishery management [8], including in the deep-sea. The most established seafood eco-label, the Marine Stewardship Council (MSC) certification, was founded in 1997 and now certifies 13% of global wild-capture seafood [9]. However, there are growing and high-profile criticisms from environmental NGOs [10,11], including original founders WWF [12] and scientists [13–15]. A key concern is the habitat impacts of certified fisheries, particularly those employing towed demersal gears, especially in poorly known deep-sea ecosystems where recovery can be extremely slow [10,16]. There is therefore a need to critically assess the role of the MSC certification in the governance of deep-sea fisheries.

Greenland's fisheries sector accounts for 80–95% of the country's export income [17–19]. The most important fisheries are for prawns (*Pandalus borealis*) and Greenland halibut (*Reinhardtius hippoglossoides*), which both operate in deep-seas and account for 45% and 30% of Greenland's fisheries export income respectively [19]. The deeper of these, the offshore halibut fishery, employs demersal trawling gear in depths of 800 to 1400 m [20] from Greenlandic and foreign vessels. The Greenlandic portion of the fleet obtained MSC certification in May 2017

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* Corresponding author.Department of Geography, University College London, UK.
E-mail address: stephen.long.16@ucl.ac.uk (S. Long).

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[21], followed by the German vessels in June 2019 [22].

The Marine Protected Area Governance (MPAG) framework was developed to provide a structured, empirical approach for critically analysing the governance of Marine Protected Areas (MPAs) [23]. There is a need for an equivalent tool and approach for assessing the governance of fisheries. As both MPAs and many fisheries are discrete areas subject to management, this study tests the applicability of the MPAG framework to a fishery, with specific reference to the role of the MSC certification.

2. Methods

The MPAG framework has been applied to over 50 case studies [24], yielding insights into the effectiveness and equity of marine governance with applications for managers. The structure of the MPAG framework [23] is adopted here and provides the headings for Sections 3-9, inclusive. A key component of this framework is the use of empirical data to identify the incentives adopted within the area being governed. The MPAG framework described by Jones [23] and further discussed elsewhere [25], identifies 36 potential incentives from five categories (Economic, Communication, Knowledge, Legal and Participation). The framework and methodology are detailed and discussed by Jones and Long (in prep, this issue), where the findings of multiple case studies are also compared.

The framework was previously applied to the Ankobohobo crab fishery, Madagascar, an area without any formal MPA designation [26]. In both this study and the prior example, only minor adaptation of the MPAG framework is required to address the governance of a fishery. Specifically, in the absence of formal MPA objectives, the objectives of the Greenlandic government and industry are considered (see, '4. Objectives').

The analysis was conducted using primary and secondary empirical data. Primary data was collected through interviews and observation. Secondary data was obtained from reviews of publicly available documents related to MSC certification, peer-reviewed articles, grey literature and legislation.

Qualitative interview data were collected, following the method employed by Jones [27]. Semi-structured interviews were used to capture the perspectives of actors with knowledge and experience related to the fishery, the governance context and/or the MSC certification. Interviewees were snowball sampled [28] from initial informants from six broad categories of actors (Table 1). A total of 19 interviews were conducted in English, between October 2017 and March 2019, with a median duration of 79 min (range: 35–150 min). On two occasions, at the request of the interviewees, the interview was conducted with two people from the same organisation present. All interviews were recorded with prior permission and were anonymised in accordance with the study's ethics approval. A summary of each interview was prepared from a recording, which interviewees were given the opportunity to review and amend, as a means of verifying that their views had been correctly captured and represented. The summaries include *verbatim* quotes, which are reproduced here where pertinent. This process ensured the resulting summaries best represented the interviewees' considered opinion, drawing on their in-depth knowledge and gave them the opportunity to add further detail, clarification or emphasis. The verified summaries were coded in NVivo [29] to collate insights into the governance approach, identify emergent themes and highlight divergent perspectives. For example, text was given an incentive specific code where it provided evidence of one of the 36 potential incentives being employed and/or being in need of strengthening. Additional codes were introduced as key issues emerged. This coding approach allowed all information pertaining to a particular topic to be readily reviewed and compared.

Table 1
The number of interviews and interviewees by category. Categories of interviewees are, Scientist (SC), Fishing industry (FI), environmental non-government organisation (NGO), State actors, Conformity Assessment Body (CAB) and Marine Stewardship Council (MSC). The category 'CAB' includes permanent employees and assessors contracted by CABs. The category 'FI' includes individuals representing both commercial entities and Greenlandic fishers. Three of the interviewees (SC1, SC2 and SC3) categorised as 'SC' worked in a scientific capacity for a state funded research organisation and so had a dual perspective. Reference codes are used to attribute quotes.

Category	Number of interviews	Number of interviewees	Reference codes
Scientist (SC)	5	5	SC1 – SC5
Fishing industry (FI)	4	5	FI1 – FI4
eNGO (NGO)	2	2	NGO1 and NGO2
State actors (ST)	2	3	ST1 and ST2
CAB (CAB)	2	2	CAB1 and CAB2
MSC (MSC)	4	4	MSC1 – MSC4
ALL	**19**	**21**	

The first author participated in the Greenland Institute of Natural Resources' (GINR) halibut and coldwater prawn stock assessment cruises between 2017 and 2019. During these cruises, benthic habitats were also surveyed, including in the fishery and adjacent areas. Involvement in this research served as an opportunity to develop an understanding of the fishery and the stock assessment process, and also acted as gateway to actors. In August 2018, the first author attended, the first MSC surveillance audit of the West Greenland Offshore Greenland Halibut Fishery (WGOGHF) [30], as both an observer and participant, at the invitation of the fishery client, Sustainable Fisheries Greenland (SFG). The first author presented a preliminary report [31] on habitat surveys, on behalf of the Zoological Society of London (ZSL). The first author's dual role was explicitly stated at the start of the meeting and the informed prior consent of all participants was deemed to have been gained.

The first author's active engagement with benthic habitat research, collaboration with GINR, relationship with SFG and participation in the MSC assessment process are explicitly recognised. The perspective offered in this study is therefore that of both an observer and participant. Naturally, this positioning influences the analysis presented here, but also resulted in insights and access that could not otherwise be obtained. Furthermore, the MPAG framework provides for a broad analysis of the governance of the Greenland halibut fishery, which helped avoid any perceptual biases by a single observer and analyst.

3. Context

Greenland, a constituent part of the Kingdom of Denmark, has a small population of ~56,000, which has been stable since the early 1990s [32,33]. The Home Rule Act 1979 and Self-Rule Act 2009 transferred legislative and executive power to Greenland, granting the right to manage all natural resources in Greenland and its exclusive economic zone (EEZ) [34]. The state capacity in 2018 calculated as a mean of scores (−2.5 to +2.5) for six dimensions of governance indicators was 1.4 (Denmark: 1.6), with an average percentile ranking of 89.5% [35,36]. This indicates a relatively high state capacity for governance.

Greenland left the European Union (EU) in 1985, principally to secure management of, and access to, fish stocks within its EEZ [32,37,38]. Economically, Greenland remains dependent on Denmark, relying on an annual grant of 3.4 billion DKK (~500 million USD) set in 2009 and adjusted annually for inflation, which supports nearly half the public spending budget [32]. In 2016, this subsidy accounted for 20.3% of the GDP [39]. In 2015, GDP was 2.4 billion USD, since 2014 annual GDP growth has been positive, fluctuating between 0.3 and 7.7% [39]. Despite a relatively high GDP per capita of 41,800 USD (Purchasing Power Parity), some 16.2% of the population live below the poverty line [40]. Around 10% of the workforce is unemployed [33], with half the population (men 57%; women 42%) not having received education beyond primary school [32]. These challenges are exacerbated by the isolated nature of many Greenlandic communities.

3.1. Fishing in Greenland

The economic, political, social and cultural importance of fishing in Greenland cannot be overstated. The past century has seen a transition from subsistence hunting and fishing to an economy based on the public sector and commercial export fisheries [33]. Over 80% of the country's export income comes from prawn and halibut fisheries [18,37,41]. Fisheries are divided into the inshore and offshore sectors, which are spatially separate and have different management and social-economic contexts [18].

The labour intensive inshore fishery employs small vessels with catches landed and processed locally. Conversely the high-capital, high productivity, offshore fishery consists of factory trawlers [42], which land the majority of catch overseas. The increasingly modernised industry employs a decreasing share of the population, with only 4.8% employed directly in fishing and a further 3% in the wider industry [41,43]. Nevertheless, inshore fisheries are a vital income source, especially for the 8000 people living in the smaller coastal settlements, many of

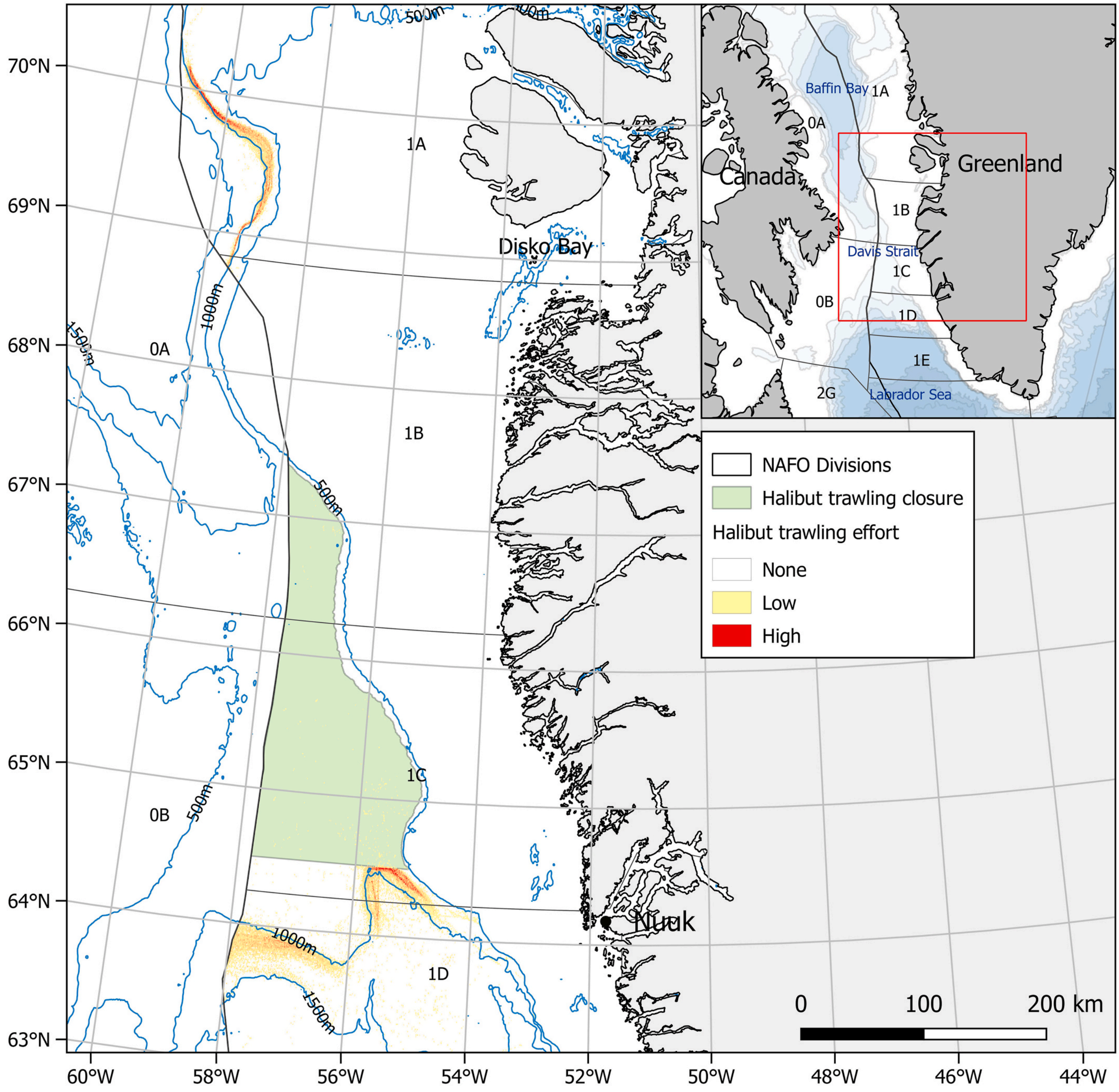

Fig. 1. Map of trawling effort in the Greenland halibut fishery, west Greenland. Fishing effort data was obtained from Global Fishing Watch (GFW) and represents hours of trawling effort at depths >600 m in the Greenlandic EEZ, from 2012 to 2016 inclusive, normalized to a 500 m grid [51]. The closure to halibut trawling between 64°30′N and 68°00′N is shown (green polygon) [48]. For clarity, this is clipped to the 600 m bathymetric contour, as trawling is permitted for other target species, predominantly prawns, this trawling occurs at depths <600 m. Thus the area shown (green) represents the area not subject to any commercial trawling. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

whom directly or indirectly rely on fishing [43]. The offshore industry is dominated by two companies, Polar Seafood and Royal Greenland, the latter of which is 100% government-owned. These two companies share the vast majority of the offshore quota. Further, they own processing plants for handling catch, including from coastal fisheries, where they have invested in the inshore fleet. These separate but intertwined fishery sectors present complex issues around equity, productivity and sustainability, both economic and environmental, which are explored by Snyder et al. [38]. Bi-lateral agreements permit vessels from Norway, Russia, Faroe Islands and some EU member states to operate offshore in Greenland's EEZ [21,39,44,45].

3.1.1. *The offshore Greenlandic halibut fishery*

As a high-value species, halibut is the second most important fishery target in Greenland (after prawns), accounting for 14% of the total catch by weight between 1990 and 2010 [46] and 20% of export revenue in 2010 (prawns: 50%) [32]. The inshore fishery accounts for a greater proportion of the halibut catch [47]. In 2017, Greenlandic vessels landed 38,192 tonnes of halibut, of which 24,790 tonnes was from inshore (13,402 tonnes offshore) [39].

Greenland's offshore Greenland halibut fishery operates in two spatially discrete areas, northern (NAFO 1B) and southern (NAFO 1CD) (Fig. 1) [20]. Vessels >75 tonnes Gross Registered Tonnage (GRT) must fish >3 nautical miles (nm) offshore and fishing for halibut is prohibited by Executive Order between 64°30′N and 68°00′N to protect juveniles [48]. Reportedly, the fishery footprint (Fig. 1) has remained static [21,22], because these areas continue to be productive, with minimal risk of gear loss, rather than due to regulatory restrictions. Vessels employ bottom trawls with rock hopper gear and heavy (>2 tonnes) trawl doors [21]. Nets must use a minimum of 100 mm mesh in the wings and 140 mm mesh in the cod-end [48]. Twin-rigged nets separated by a roller clump are used by some vessels.

Additionally, the WGOGHF is seeking to extend the scope of its MSC certification to include a single longline vessel. This may mean an increased footprint, as longline gear is deployed in new areas to avoid gear conflicts [49]. To date, there has only been limited irregular longlining [50], mainly by Norwegian vessels.

The Greenlandic vessels, represented by SFG, form the WGOGHF, which obtained MSC certification in May 2017 [21]. SFG is a tax-exempt organisation, formed for this purpose, whose members include: Royal Greenland; Polar Seafood; other smaller commercial entities; Grønlands Erhverv/Sulisitsisut (Greenland Business Association, GE) and Kalaallit Nunaanni Aalisartut Piniartullu Kattuffiat (the Fishers' and Hunters' Association of Greenland, KNAPK). The Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF) is formed of German vessels and was certified in June 2019 [22], operating only in the southern area (NAFO 1C + D) (Fig. 1). Hereafter, unless otherwise specified, 'the fishery' refers to all offshore halibut fishing in the western Greenlandic EEZ, whilst WGOGHF and DSWGHF refer to the MSC certified Greenlandic and German components of the fishery, respectively.

3.1.1.1. *Stock*. The North Atlantic Fisheries Organisation (NAFO), which is the regional fisheries management organisation (RMFO), considers the halibut stock in NAFO 0 + 1 to be part of a larger population complex, distributed throughout the Northwest Atlantic [52]. Uncertainties remain concerning the population structure, larval dispersion, migration and spawning [53,54]. The prevailing assumption is that individuals entering fjords become resident, with limited emigration, particularly from Greenland's north western fjords [55]. Hence, the inshore populations are considered 'dead-end stocks', although recent research is challenging this assumption [56]. It is thought the offshore stock is relatively stable and the current levels of exploitation are sustainable [21,22].

3.1.1.2. *Historic management (stock assessment, TAC and landings)*. The commercial catches of halibut were first reported in the Davis Strait in the mid-1960s [50,52], with significant increases in the early 1970s [47]. Quota regulation was introduced in 1976 for NAFO Subareas 0 + 1, with a total allowable catch (TAC) of 20,000 tonnes [52]. Comprehensive stock assessments led by NAFO were introduced in 1994, amid concerns about declining stocks, which saw the TAC lowered from 25,000 to 11,000 tonnes [50]. Since then, offshore catches have followed the TAC in NAFO 0, 1A (offshore) and 1B–F, which has been increased in a step-wise fashion, with 34,661 tonnes landed in 2017 [52].

3.1.1.3. *Current management (stock assessment, TAC and landings)*. In NAFO Subareas 0 and 1, two separate stock assessment surveys are conducted by the Department of Fisheries and Oceans Canada (DFO) and GINR respectively. The NAFO Scientific Council advises on the TAC for NAFO 0 + 1, this is divided 50/50 between Greenland and Canada, based on a non-binding agreement (Table 2) [21,57]. Since 2002, this stock advice has been provided separately for the northern area (0A and 1AB, excluding 1A inshore) and the southern area (0B and 1C–F). The Greenlandic Government then sets the TAC in consultation with the Fisheries Council (see, 6. Governance Framework) and divides this among the Greenlandic fleet and non-Greenlandic vessels according to bilateral agreements. Quotas for the Greenlandic fleet are distributed on the basis of historic fishing rights, capacity and through consultation with the Fisheries Council [57].

4. Objectives

The explicit aim of the management authorities is to ensure the ecological and economic sustainability of the fishery. The Fisheries Act 1996, states that its purpose *'is to ensure appropriate and biologically responsible use of fish stocks'* and that attention should be given to *'economic and employment considerations in the fishing industry, the processing industry and other related industries'* [61]. This is closely aligned with NAFO's objective for the NAFO Convention Area: *'to ensure long term conservation and sustainable use of the fishery resources in the Convention Area and, in so doing, to safeguard the marine ecosystems in which these resources are found'* [62].

4.1. *Industry objectives*

The primary objective of the industry in seeking MSC certification was to maintain access to markets. The MSC certification seeks to use market forces to promote sustainable fishing [63–65], where certification costs are balanced by competitive advantages [66], such as, price premiums and access to markets [15]. The latter has become increasingly important since the MSC helped mainstream fisheries sustainability and develop the market for sustainable seafood [67]. The clear consensus among interviewees was that, rather than seeking a price premium, the driver was to secure access to the lucrative European market, as previously reported by Jacobsen et al. [50]. CAB2 explained that '*if you want to sell your fish on the European market then you need MSC certification*' and therefore the industry's response was '*ok if that's the commercial conditions in which we have to operate then we'd better get the stamp*' (CAB2).

A secondary objective may be to achieve corporate social responsibility (CSR) goals, specifically concerning environmental sustainability. Sustainable sourcing is now well-established in the CSR strategies of global seafood industry actors [14]. Indeed, Royal Greenland (WGOGHF), Polar Seafood (WGOGHF) and Parlevliet & Van der Plas, the parent company of Doggerbank Seefischerei (DSWGHF), all have CSR statements that make explicit reference to fishing sustainably. MSC3 reported '*one of the most important drivers for certification now is … the corporate social responsibility of the big retailers … they want to be seen to be being responsible, it's something their shareholders will demand of them*'.

Table 2
NAFO Scientific Council Greenland halibut stock advice for NAFO Subdivisions 0 + 1, from 2010 to 2019. The Greenlandic share of this advice (50%, by bilateral agreement), Total Allowable Catch (set by the Greenlandic Government) and catch is provided for the northern and southern areas of the halibut fishery, west Greenland. Inshore fisheries are excluded for NAFO 1A but included for all other areas (NAFO 1B–F). Where information was not available in the public domain this is indicated ('n/a').

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
NAFO advice[a]										
0A + 1A (offshore) + 1B	13,000	27,000	13,000	13,000	16,000	16,000	16,000	17,150	17,150	-[a]
0B + 1C–F	14,000	27,000	14,000	14,000	14,000	14,000	14,000	15,150	15,150	-[a]
0 + 1A (offshore) + 1B–F	27,000	27,000	27,000	27,000	30,000	30,000	30,000	32,300	32,300	36,370
Greenlandic share (50%)										
Northern Area (Baffin Bay), 1A (offshore) + 1B										
Advised (tonnes)[b]	6500	6500	6500	6500	8000	8000	8000	8575	8575	n/a
TAC (tonnes)[c]	6500	6500	6500	6500	8000	8000	8000	8575	8575	n/a
Catch (tonnes)[d]	6462	6472	6459	6513	7985	8016	8335	8655	n/a	–
Southern Area (Davis Strait), 1C–F										
Advised (tonnes)[b]	7000	7000	7000	7000	7000	7000	7000	7575	7575	n/a
TAC (tonnes)[c]	7000	7000	7000	7000	7000	7000	7000	7575	7575	n/a
Catch (tonnes)[d]	7256	6902	7432	8250	8511	8432	8849	9616	n/a	–

NAFO Scientific Council stock advice [58].

[a] From June 2018 the NAFO Scientific Council no longer provides separate advice for 0A+1A (offshore)+ 1B and 0B + 1C–F [59].

[b] The advised TAC is 50% of the NAFO advice by bi-lateral agreement between Greenland and Canada. Data: 2014 to 2018, Government of Greenland [60]; 2011 to 2013, Cappell et al. [21].

[c] The TAC is set by the Greenlandic Government in consultation with the Fisheries Council. The figures presented from 2014 to 2018 are provided by the Greenland Government [60]. The figures presented from 2011 to 2013 are from the MSC assessment of the WGOGHF [21].

[d] Data: NAFO [59].

5. Drivers/conflicts

5.1. *Economic dependence*

In Greenland, fishing is important at the macro-economic level, accounting for 80% of exports [18] and generating significant tax revenues. At the micro-economic level it provides employment, household income and cash for subsistence hunters in isolated communities [68]. Interviewees described how '*it is not a normal economic situation in Greenland*' (FI1), when you are dealing with fisheries in Greenland you are '*dealing with the economy [interviewee's emphasis]*' (CAB2).

This dependence explains why efforts since 2003 to reform the existing Fisheries Act have yet to reach a conclusion. Politicians have been unable to reach a consensus positon that balances calls for a more equitable distribution of quotas, whilst maintaining an efficient and productive industry. The revision is *'such a sensitive and controversial area'* (FI2) that progress has not been made and has become '*a never-ending story*' (NGO2). This demonstrates the challenge of governance in this context.

5.2. *Industry influence*

In a country dependent on fisheries, the industry exercises considerable influence, which arises from several factors. Firstly, Royal Greenland and Polar Seafood exercise a near duopoly, accounting for the majority of production in the fisheries sector, reportedly 77% in 2011 [42]. Secondly, the larger of these, Royal Greenland, is 100% government-owned, which some interviewees suggested is an obvious conflict of interest for the government. Lastly, the industry has a dual positioning. On the one hand it sustains the national economy, generating revenue from the highly productive offshore fisheries. Simultaneously, these companies support inshore fisheries and communities by operating processing plants, which are of '*lifeline significance*' [38], making the industry indispensable mediators of coastal development [18].

The industry is able to exercise influence at a policy level. Jacobsen et al. [43] identified an influential '*grand reform network*', with the fishing industry and banks at the centre, lobbying for the introduction of individual transferable quotas (ITQs) in the prawn fishery. This successfully led to a paradigm shift in Greenlandic fishery governance, towards economic profitability and closer adherence to biological advice, associated with a new government in the period 2009–2012 [37,69]. Interviewees confirmed that the industry, '*share the rationality with the banks … and the Ministry of Finance'* (SC4), which collectively are a powerful lobby.

5.3. *Unknown impacts on deep-sea habitats*

The paucity of knowledge on deep-sea ecosystems presents significant challenges to evidence-based management. MSC3 acknowledged, '*in terms of having a quantitative basis and scientific basis to underpin any policy decisions it is almost impossible for most of the deep-sea'* (MSC3). The halibut and prawn fisheries are not exceptions. At the point the industry in Greenland first engaged with the MSC certification, '*there had been no research at all about the seabed before that time*' (FI4). Another interviewee stated '*we did not have much knowledge about seabed … [and] impact on the seabed'* (ST1).

5.4. *Inshore over-exploitation*

In contrast to the offshore fishery, quotas routinely exceed advice and are often raised during the season in response to pressure from fishers [37]. SC1 confirmed that, '*generally the rule is that in the inshore areas the advice is not followed*'. This is driven by overcapacity in the inshore fleet and limited other employment opportunities, '*there are so many fishermen there and they all need enough [quota] to fish*' (MSC1). Inshore fishers are a key source of votes and thus are successful when lobbying to raise TACs and exceed scientific advice [37]. Over-exploitation is most pronounced in Disko Bay, where catch per unit effort (CPUE) is declining [70]. FI3 described the inshore fishery as '*hopelessly overfished*'. However, the current understanding of halibut stock dynamics suggests over-exploitation inshore will not negatively impact the offshore stocks.

Nevertheless, the inshore fishery is impacting the offshore fishery. The inshore Nuuk fjord halibut fishery is not subject to assessment or quotas, with only a licence required to enter the fishery. Following past collapse, catches were <500 tonnes prior to 2013. Subsequently, catches have increased, varying between 1000 and 2000 tonnes, due primarily to increased effort [52]. Catches are recorded in the totals for NAFO 1C–F. Currently the offshore fishery utilises the entire TAC for NAFO 1C–F. The combination of offshore and (unlimited) inshore catch has resulted in the TAC being exceed in NAFO 1C-D since 2013 (Table 2)

[21]. The certifications of both the WGOGHF and DSWGHF include specific conditions requiring this situation to be addressed (see, 6.1 MSC Certification) [21,22]. It is unclear whether this will be resolved by reducing offshore catches and/or increasing inshore regulation. The recent surveillance audit of the WGOGHF noted that progress to address this issue was behind schedule [71]. The MSC certification is a pre-requisite for accessing the European market. Failure to address this condition, resulting in withdrawal of the certificate from either the WGOGHF, or the DSWGHF, would have significant adverse financial impacts.

5.5. *Reliance on non-binding bilateral stock sharing agreement*

The NAFO Scientific Council advises on the TAC for NAFO 0 + 1, based on a non-binding understanding that this is divided 50/50 between Greenland and Canada (Cappell et al., 2017, Ministry of Fisheries Hunting and Agriculture, 2016). The resilience of this arrangement has not been stress tested as the advised TAC provided by NAFO has been steadily increasing over the past decade (Table 1). In contrast, the combined Greenland-Canada prawn catch exceeds the NAFO advised TAC, as the parties are unable to agree to agree on a bilateral sharing arrangement and so unilaterally set TACs separately. This issue was subject to a condition in the MSC certification of the West Greenland Coldwater Prawn Fishery in 2013 but has not yet been resolved [44,72].

6. Governance framework

The fishery is governed by the state, with co-operation from Canada and Denmark (Fig. 2). The legal framework for fisheries management is provided by the Fisheries Act, 1996 [61] and subsequent amendments. Executive Orders introduce further regulation relating to: gear requirements; spatial closures [48]; bycatch [73]; an observer programme [74]; and reporting requirements for offshore vessels [75]. Specific to the halibut fishery, a halibut management plan has been in place since July 2016 [57].

Fisheries management is the responsibility of the Department of Fisheries in the Ministry of Fisheries Hunting and Agriculture (MFHA). The Ministry of Environment and Nature *'has very little'* (ST2) involvement in the management of fisheries and their environmental impacts. Greenland Fisheries Licence Control (GFLK) is a subsidiary of the MFHA responsible for: the issuing of licences; recording catch statistics; inspecting landings; reviewing and managing logbook data; and overseeing observer programmes. GFLK also contribute to the development and implementation of new regulations. Interviewees agreed that whilst GFLK nominally sits within the MFHA, it is *'rather autonomous'* (SC2) and an *'entity of their own'* (SC4). In addition to the state, the MSC certification, industry and scientific actors play significant roles in the governance structure, formally and otherwise (Fig. 2).

6.1. *MSC certification*

The MSC Standard complies the UN FAO's Code of Conduct for Responsible Fishing, Global Sustainable Seafood Initiative (GSSI) guidance, ISEAL codes and relevant International Standards Organisation (ISO) standards. The Standard consists of three principles: sustainable target stocks (P1), environmental impact (P2) and effective management (P3) [76]. The three principles are assessed by 28 performance indicators (PIs), for which a score between 0 and 100 is given. Scoring

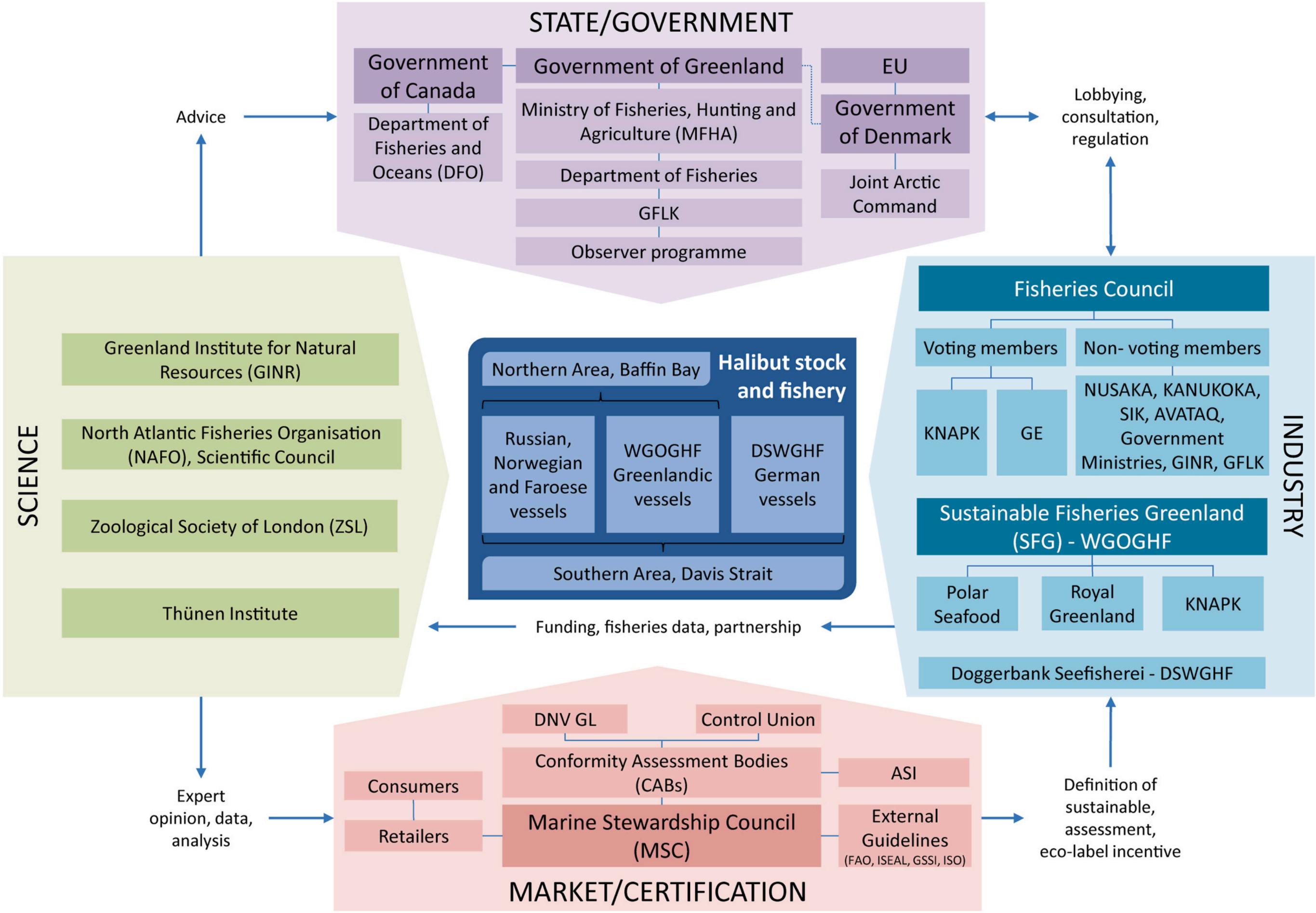

Fig. 2. Representation of the governance framework for the offshore Greenland halibut fishery, west Greenland.

below 60 for any PI results in failure, whilst scores from 60 to 79 attract a condition requiring a specified improvement within a set timeframe. The average of PIs for each principle must exceed 80 for a fishery to be certified. Following initial certification, an annual surveillance audit is conducted, followed by a full re-assessment after five years.

Assessments, annual audits and re-assessments are conducted by Conformity Assessment Bodies (CABs), who are responsible for assembling a team of assessors with the required background, training and experience. Draft assessments are subject to peer review, technical oversight by the MSC and stakeholder comments. CABs are contracted by the fishery client and subject to oversight by Assurance Services International (ASI). The fishery client represents the components of the fishery seeking certification. In this fishery these are SFG (WGOGHF) and Doggerbank Seefischerei (DSWGHF).

The Standard requires that where there is overlap between an existing certified fishery and a fishery under assessment, the CAB is responsible for harmonising the new assessment to ensure the consistency of outcomes between fisheries. This was the case for the DSWGHF, which was assessed subsequent to the certification of the WGOGHF. Conditions are summarised for the WGOGHF and DSWGHF (Table 3).

6.2. Industry

The Fisheries Act established the Fisheries Council, which the government is obliged to consult on matters of fisheries policy, including the setting of TACs [37,61]. The Fisheries Council has two voting members, GE and KNAPK, representing the industry and fishers respectively. Additionally, representatives from the following are non-voting contributors: MFHA, Ministry of Finance, Ministry of Nature and Environment, GINR, GFLK, Association of Municipalities (KANUKOKA), Employee's Union (SIK), Employer's Association (NUSUKA) and the Nature Protection Association (AVATAQ, an environmental NGO). The Fisheries Council meets regularly but does not necessarily always formally assemble, instead members can be consulted by email [21,37]. Polar Seafood and Royal Greenland can liaise directly with the MFHA and apply their considerable influence (see, 9.2 Is the industry driving governance?).

The industry has promoted research to improve knowledge of the nature and distribution of habitats and the impacts of trawling. SFG have engaged ZSL, whilst Doggerbank Seefischerei has engaged the Thünen Institute (see, 6.3 Scientific Advice). These actions by industry were directly attributable to the requirements of the MSC Standard and conditions of certification (Table 3).

Table 3
Summary of certification conditions for MSC certified fisheries in the offshore halibut fishery, west Greenland. The Principle (P), performance indicator (PI), condition and timeline for resolution are summarised based on the MSC public certification reports (PCRs).

Principle	PI	Summary of condition	Timeframe
West Greenland offshore Greenland halibut fishery (WGOGHF), certified 2017 [21]			
P1 - Stock	1.2.2	Ensure the TAC advised for Greenland halibut for NAFO stock in SA 0A, 1a (offshore) and 1B–1F (including inshore catches) is not exceeded.	2020
P2 - Ecosystem	2.4.1	Ensure commonly encountered habitats are highly unlikely to reduce structure and function to a point where there would be serious or irreversible harm.	2021
P2 - Ecosystem	2.4.2	Introduce management provisions to ensure footprint of the fishery is such that habitat outcome score is maintained.	2020
P2 - Ecosystem	2.4.3	Improve information on nature, distribution, vulnerability and impact of the fishery on main habitats.	2021
Doggerbank Seefischerei West Greenland Halibut Fishery (DSWGHF), certified 2019 [22]			
P1 - Stock	1.2.2	Tools in use are appropriate and effective in achieving the exploitation levels required under the harvest control rules (HCR).	2023
P2 - Ecosystem	2.4.2	Management should include provisions for managing the extent of the fishery interactions with commonly encountered habitats. The fishery should encourage and help improve the knowledge base on the distribution of VME indicator species, and encourage protection where they occur in concentrations.	2023
P2 - Ecosystem	2.4.3	Improve understanding as to the vulnerability of the main habitats, with regards to the gears used and recovery times. Implement appropriate habitat sampling in the area where the fishery operates, which allows the possibility of trends to be determined.	2022

6.3. Scientific advice

Scientists at GINR are responsible for conducting stock surveys and serve as experts in the NAFO Scientific Council. NAFO is responsible for undertaking halibut stock assessments and delivering TAC advice to Greenland and Canada. This advice is based on data from both surveys and fisheries in the respective EEZs.

GINR advises the government directly and through participation in the Fisheries Council. GINR has also developed a programme of benthic research, combining stock assessment bycatch data, beam trawl sampling and seafloor imagery. The latter is collected by means of a towed benthic video sled in partnership with ZSL. To address knowledge gaps that represented a potential barrier to certification, SFG engaged ZSL to conduct photographic survey work. Initially in the prawn fishery using a drop camera [77,78], this was subsequently extended to the halibut fishery, employing a benthic video sled [79]. ZSL was directly funded by SFG, with additional funding for an IUCN BEST 2.0 project in which SFG acted as partners and co-funders. The survey work is undertaken in collaboration with GINR during annual stock surveys cruises. To support the certification of the DSWHF, Doggerbank Seefischerei engaged the Thünen Institute to analyse bycatch data from German vessels in the fishery on an ongoing basis [22]. SFG also funded PhD research into vulnerable marine ecosystems (VMEs) in Greenland [80].

7. Incentives

Drawing on the MPAG framework's taxonomy of 36 incentives, those incentives employed in the governance of the halibut fishery were identified (Table 4 and Supplementary Information Table 1). A total of 25 incentives were identified, of which seven are important priorities for strengthening, with no incentives identified as important priorities for introduction.

8. Effectiveness

The MPAG framework proposes a scale of effectiveness from 0 (ineffective) to 5 (wholly effective), with qualitative descriptors [23], indicating the extent to which the governance framework addresses the potential impacts, conflicts and drivers identified. Here, a score of 4 '*most impacts addressed but some not completely*' is assigned.

Many deep-sea fisheries have exhibited a 'boom and bust' cycle, examples of long-standing sustainably exploited target stocks being rare [2,5]. The offshore halibut fishery is perhaps a notable exception, with a comparatively long history of exploitation (>40 years). Stock assessments since 1994 show relative stability, accordingly the advised TAC has been incrementally increased [52,84].

The state-led system of governance is complemented by input from scientific, market-based certification and industry actors. This includes the Fisheries Council, an effective participatory mechanism for consultation, particularly important in a context where fisheries are integral to

Table 4

a-e: Tables a-e summarises incentives employed in the halibut fishery, west Greenland. Incentives are from one of five categories of incentive: a) economic, b) communication, c) knowledge, d) legal and e) participation. Those incentives in need of strengthening are identified (Y = used; Y* = Used, in need of strengthening). These are selected from the 36 incentives (I-1 to I-36) in five categories identified by Jones [23]. The authors' assessments that an incentive is employed and that an incentive requires strengthening, are based on document analysis and interview findings. A more detailed discussion of each incentive is also provided (Supplementary Material, Table 1).

Incentive (I)	Used	How/why?
a) Economic incentives		
I-3. Reducing the leakage of benefits	Y*	Greenlandic vessels must land 25% of catch in Greenland and officers on Greenlandic vessels must have residency status (lived and paid tax in Greenland for >2 years). There are calls for a revised Fisheries Act to reduce the leakage of benefits.
I-4. Promoting profitable and sustainable fisheries and tourism	Y*	The Fisheries Act, Executive Orders and management plan aim to ensure exploitation is sustainable. Overcapacity drives overexploitation in the inshore fishery.
I-5. Promoting green marketing	Y	The Greenlandic and German components of the offshore halibut fishery have obtained MSC certification.
I-8. Investing fishery income/ funding in facilities for local communities	Y	The fishery is a significant contributor to the public purse through tax, duties and licences [19], thus supporting state expenditure.
I-9. Provision of state funding	Y	GINR is funded by the state and conducts stock assessment surveys. A new state-funded research vessel is currently under construction. SFG benefits from tax exemption.
I-10. Provision of NGO, private sector and user fee funding	Y	SFG have funded of a programme of benthic research led by ZSL. This has also been supported by the IUCN BEST 2.0 Grant programme. Licensing of vessels generates revenue for the state.
b) Communication incentives		
I-11. Raising awareness	Y	MSC eco-label promotes consumer awareness of sustainability issues. Research has been shared by ZSL with audiences in Greenland and beyond, though various platforms, including an online game [81].
I-12. Promoting recognition of benefits	Y*	Initially sceptical attitudes among industry and government actors have changed, recognising the role of MSC certification in accessing markets. Limited awareness of eco-labelling and its benefits persists among inshore fishers.
I-13. Promoting recognition of regulations and restrictions	Y	GFLK are responsible for communicating the regulations. The observer programme provides a point of contact on some vessels.
c) Knowledge incentives		
I-14. Promoting collective learning	Y*	Stock surveys are conducted by Greenland (GINR) and Canada (DFO), NAFO Council conducts the analysis and provides TAC advice. Partnerships (SFG-ZSL and Doggerbank Seefisherei-Thünen Insititute) promote collective learning by industry and scientific actors. Both certification assessments place emphasis on the collection and sharing of benthic bycatch data [22,82]. However, effective collective learning must be based on data collectors having adequate knowledge, skills and training, which are currently lacking.
I-15. Agreeing approaches for addressing uncertainty	Y	The management plan stipulates that TAC should follow advice but can only deviate from the prior year TAC by a maximum of 15% (up or down). This addresses uncertainty by providing a predetermined strategy.
I-16. Independent advice and arbitration	Y*	Independent scientific advice is provided by NAFO, GINR, DFO, Thünen Institute and ZSL. CABs act as an arbiter, determining whether a fishery meets the MSC Standard. CABs are subject to oversight by ASI. The relationship between CABs and fishery clients observed in this study could be better characterised as a consultant-client relationship, rather than an independent assessor-subject relationship. Some interviewees felt strongly that the independence of CABs needs to be strengthened.
d) Legal incentives		
I-17. Hierarchical obligations	Y	The United Nations General Assembly called upon States to take action to protect vulnerable marine ecosystems (VMEs) in high seas [83]. This definition has been incorporated into the MSC Standard [76]. The MSC Standard is aligned with UN FAO guidance. Non-Greenlandic vessels are subject to fisheries regulations of their home states in addition to relevant Greenlandic regulation.
I-18. Capacity for enforcement	Y*	Enforcement is the responsibility of Joint Arctic Command (a naval component of the Danish armed forces) in cooperation with the Greenland Police. An observer programme is operated by GFLK. Additionally, German vessels have observers from the Thünen Institute in accordance with EU requirements. However, observer coverage is poor.
I-19. Penalties for deterrence	Y	The Fisheries Act details sanctions and fines for infringements.
I-20. Protection from incoming users	Y	Quotas and licenses are strictly controlled, foreign flag vessels are only permitted through bilateral agreements. There is no evidence of illegal, unregulated or unreported fishing in the offshore fishery.
I-21. Attaching conditions to use, property rights, decentralisation, etc.	Y	MSC certification includes explicit conditions with specified timeframes. These are monitored through annual surveillance audits. This appears to be an effective incentive.
I-22. Cross-jurisdictional coordination	Y*	There are bilateral fisheries agreements with the European Union, Norway, the Faroe Islands and Russia. There is a need to strengthen the non-binding basis on which the TAC is split between Greenland and Canada.
I-23. Clear and consistent legal definitions	Y	The Fisheries Act (1996), subsequent amendments and Executive Orders provide a clear and consistent legal basis [61].
I-25. Legal adjudication platforms	Y	The Fisheries Council established by the Fisheries Act [61] is an adjudication platform, allowing conflict to be addressed and regulated. The Council considers matters relating to fisheries such as management plans, new Executive Orders and quota setting.
I-26. Transparency, accountability and fairness	Y	Stock assessment reports are made publicly available by NAFO. The MSC assessment process provides some opportunity for stakeholders to engage. The MSC Standard and assessment documentation are publicly available.
e) Participation incentives		

(*continued on next page*)

Table 4 (*continued*)

Incentive (I)	Used	How/why?
I-28. Establishing collaborative platforms	Y	The Fisheries Council is a collaborative platform, described as an *'important institution'* and part of a *'special political model where you make sure to have the actors are represented in the decision making'* (SC4). SFG is a collaborative industry platform. The NAFO Scientific Council consists of experts from multiple states working together to conduct stock assessments.
I-33. Building trust and the capacity for cooperation	Y	Although Royal Greenland and Polar Seafood are direct competitors, SFG has worked effectively as a cooperative platform. Collaboration through SFG has also *'contributed to an improved and more productive relationship'* between KNAPK and Royal Greenland.
I-34. Building linkages between relevant authorities and user representatives	Y	The Fisheries Council provides a linkage between stakeholders and the MFHA. Interviewees described the Fisheries Council positively as an effective participatory approach to stakeholder consultation.
I-36. Potential to influence higher institutional levels	Y	The Fisheries Council provides a formal mechanism to influence higher institutional levels, e.g. the MFHA (Fig. 2). The economic dependence of Greenland on fisheries means that both the offshore industry and inshore fishers are able to influence higher institutional levels. This influence is not necessarily always a positive outcome from a sustainability perspective.

the economy and society. The MSC has acted as an external agency, setting a sustainability agenda and directing the industry's considerable influence. Tangible outcomes include the introduction of a management plan and a programme of research to address the limited knowledge of benthic habitats and trawling impacts. This has undoubtedly improved the effectiveness of governance, *'once we have management plans in place … it was easier to persuade the politicians [to follow scientific advice] … you have to apply the management plan otherwise you lose the MSC [certification]'* (ST1).

In terms of the sustainability of the benthic ecosystem impacts, it is hard to assess the effectiveness of the governance framework. This limitation was recognised by CAB1, '*the difficulty with the habitats outcome part is it is not as strongly evidence-based as you would like, there is a lot of expert judgement going on*'. Ongoing benthic research will provide an opportunity to quantitatively determine the impacts of trawling and further assess the effectiveness of governance with regards to the wider ecosystem.

Critics of the MSC have often highlighted the fact that certification does not necessarily result in changes on the water [e.g. 85]. The MSC's rebuttal is that the certification seeks to promote a much wider programme of change on and off the water [86]. In this fishery the key changes described have been off the water. This was acknowledged by FI2 *'nothing has changed in the Greenland halibut fishery [on the water] as a result of the MSC certification. They fish according to the same rules, they use the same gear and they fish in the same area'*. Certification has not limited the use of heavy demersal trawling gear over a large area, which likely has significant impacts on deep-sea benthic habitats, as has been demonstrated elsewhere [1,6,87,88]. The footprint, whilst reportedly stable, is not currently constrained.

9. Cross cutting issues

9.1. The role of the Ministry of Fisheries, Hunting and Agriculture

Governing the largest industry in an undiversified economy is inherently challenging, demonstrated by the long-running but unsuccessful efforts to revise the existing Fisheries Act. Challenges are compounded by a high ministerial turnover, *'we have had eight Ministers of Fisheries within the last four, five years'* (ST2). Some interviewees were highly critical of the MFHA's capacity, in terms of the number of people and their skills. SC3 described how there is '*very weak management in Greenland … the department [MFHA, Fisheries Department] who should be managers doesn't have the knowledge to manage*'. They continued, '*there are not the skills needed for making sound management and there's no will to get the skills'* (SC3).

Civil servants were supportive of certification and '*spent a lot of resources trying to convince our politicians that MSC is a good idea'* (ST1). The MSC certification process generated a *'lot of work from our part [MFHA] but also for the companies [SFG] and it entails cooperation and working groups, numerous meetings, numerous hearings - we spend a lot of resources … [and] a lot of time in the administration attempting to facilitate'* (ST1). SFG and CABs requested *'an incredible amount of data',* creating a significant amount of work for GFLK, which at times was *'a show-stopper'* (ST2).

The implementation of management plans, attributed to engagement with the MSC certification, has had positive impacts for MFHA. Without management plans, stocks are *'under pressure all the time'*, as fishers and/or the industry lobby to increase quotas or access new areas, *'the pressure is taken off by the MSC'* (NGO2). Following the implementation of management plans, '*the discussion about setting the quota … is a simple administrative process … we [management] just open the book [management plan] and we can see what we have to do'* (ST2). ST1 described how *'once we have management plans in place … it was easier to persuade the politicians [to follow scientific advice] … you have to apply the management plan otherwise you lose the MSC'*.

9.2. Is the industry driving governance?

Previous studies have recognised the significant lobbying power of the Greenlandic fishing industry [18,43]. Pursuit of MSC certification provided an opportunity to see how the industry exercises this influence. There was little doubt among interviewees representing the breadth of actors that the administrative changes required were driven by the industry.

> '*Basically the industry came to the fishery Ministry and said you need to make a management plan for this fishery if we are going to have it MSC certified*'. During this process *'the civil servants saw themselves as facilitators of [the development of] these management plans'*. Specifically, the civil servants felt their responsibility was only to *'arrange a meeting between biologists [GINR] on the one side and the industry on the other, and then they should agree'* (SC4).

'[SFG] are pretty much running the MSC process and the administration is just running after the industry. In practice the industry is doing all the work and the administration is just trying to keep up. It is never coming from the politicians, it is coming from the industry' (NGO2).

> *'SFG had to write three of the existing management plans because the Ministry of Fisheries didn't have any employees who knew how to do it and it didn't have the time to'* (FI2).

Interviewees' descriptions of the extent to which SFG were involved in the actual preparation of the management plan varied. SFG clearly had a hands-on role, which, depending on the account, ranged from drafting the document to being consultees. Whilst there was agreement that outcomes such as the introduction of a management plan were positive, some questioned the legitimacy of the process.

> ‘*People at the GINR wondered, is it enough for the managers just to be facilitators or should they take a more leading role?*’ (SC4).

> ‘*That this is not how things should be, it should be the manager who writes the management plans … [rather than] adopt a management plan that it didn't write itself*’ (FI2).

Evidently, the industry is able to exert considerable control in the governance of the fishery, and whilst some have concerns about this, others ‘*don't see it as a problem*’ (CAB2). Those of the latter opinion think it is an important for Greenland's key industry to promote its interests. The MSC has incentivised the industry to align management and governance with the Standard, which is in accordance with the MSC Theory of Change. ‘*It's not the MSC that makes changes happen, it's our partners and the MSC acts as a catalyst or facilitator*’ (MSC4). Whilst the MSC Theory of Change describes a cyclical feedback loop, the empirical evidence here suggests a more linear model. The MSC's influence on the market has created demand for certified seafood, as described by Ponte [67]. Responding to this demand, the industry, principally Polar Seafood and Royal Greenland, have steered the state actors, dictating developments in the management and governance of the fishery (Fig. 3). The critical question is ‘does this result in a more sustainable fishery’? The answer depends on the adequacy of the MSC Standard and assessment process.

9.3. *MSC certification: defining and assessing sustainability*

The Standard codifies the MSC's definition of sustainable, which is intended to be as ‘*reputable and scientifically based as possible*’ (MSC3). Although there are quantitative elements, it is fundamentally qualitative and requires the exercise of judgement by CABs, a process informed by MSC guidance.

Interviewees, including from the MSC, noted the disparity between consumer expectations and the technicalities of the Standard: *‘the science of sustainability is different from the public perception of sustainability’* (MSC1). This arises because consumers are rarely familiar with the realities of commercial fishing, for example the high-impact, heavy gear employed in deep-sea trawling. There is an important distinction to be made between impactful and sustainable. The Standard allows for the certification of fisheries that can have significant impacts, including at large spatial scales, providing they meet the Standard's definition of sustainable. Meanwhile, consumers, ‘*do not necessarily understand the difference between what is sustainable and what is impactful*’ (MSC3). Some interviewees accuse the MSC of being *‘disingenuous and misleading to consumers’* in allowing this disparity to persist (SC5). This issue is best expressed by Roberts [16], who questions whether elements of the Standard would *‘pass the person on the street test, would the average person think a policy is right or wrong?*‘.

There are existing technical criticisms of the MSC from NGOs and academics that are pertinent to this fishery and were echoed by some interviewees. These are the independence of CABs, the inconsistency of harmonisation and the assessment of benthic habitat impacts. SC5 warned that the Standard's credibility is seriously comprised, *‘they have got to change and if they don't change they will be yesterday's organisation … they either reform or die’*. NGO1's opinion was that the Standard is ‘*so weak*’ and *‘vague’* it renders assessments open to interpretation and *‘leaves room for CABs to make money’*. This perspective is supported by the issues highlighted around the independence of CABs, the failure of harmonisation and the weaknesses in the assessment of the benthic habitat impacts, which are discussed below. Notably, to date, significant criticisms have not emerged from consumers or retailers. These stakeholders are core to the MSC's financial model and Theory of Change, ‘*we would see significant trouble … if the retailers stopped trusting the MSC*’ (MSC4).

Interviewees representing CABs and the MSC dismissed criticisms around independence citing the safeguards in place, such as oversight by ASI. The ASI is responsible for ensuring CABs act in compliance with the MSC Certification Requirements, non-compliance resulting in sanctions, such as suspension of the CAB, which are detailed on the ASI website. Conversely, others questioned whether CABs *‘as judge and jury have too much control over the outcome, this leads to risks that they will favour the client … because they are being paid by them’* (SC5). The relationship between CABs and fishery clients observed in this study would arguably be better characterised as a consultant-client relationship, rather than an independent assessor-subject relationship.

There are simple measures that the MSC could take to address these concerns, and strengthen the incentives described here (Table 4e, I-30). CABs are incentivised to certify fisheries as this potentially secures future business in the form of annual audits and re-assessments. The WGOGHF initial assessment, two subsequent surveillance audits and scope extension were all conducted by the same CAB, DNV GL [21,30, 89]. A simple fix would be to require fishery clients to contract different CABs for re-assessments or surveillance audits. This would reduce the risk of CAB-client relationships developing in such a way that incentivised CABs to make favourable assessment and have the added benefit of introducing a ‘fresh pair of eyes’. Another benefit would be the proliferation of CABs and assessors, in what is currently recognised as a small

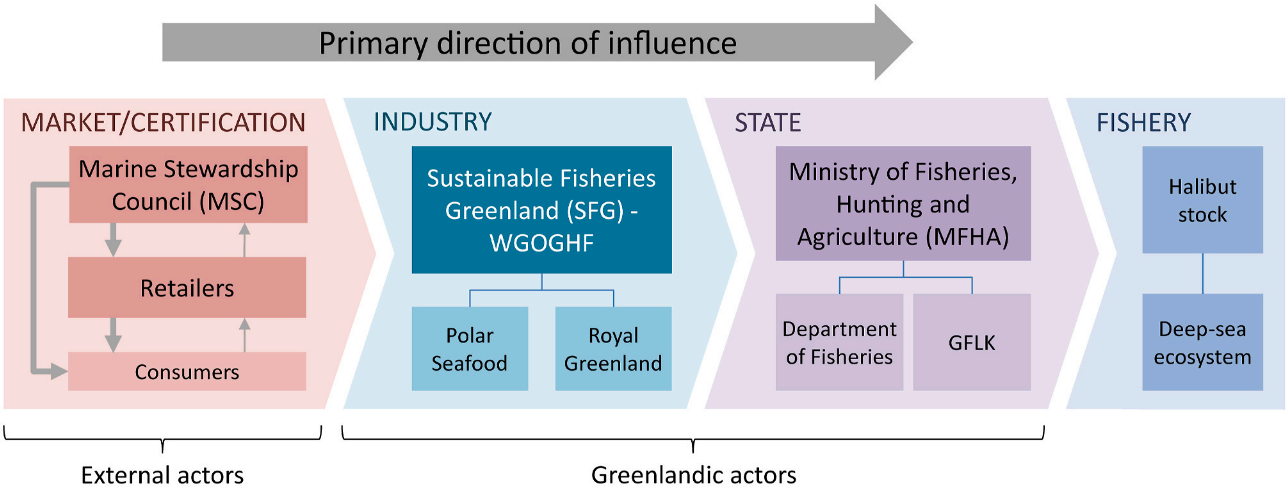

Fig. 3. Representation of the influence of key Greenlandic and external actors in steering the governance of the offshore Greenland halibut fishery, west Greenland. Grey arrows indicate the direction of influence/steer, scaled to suggest relative strength.

pool [90]. The process by which stakeholder, MSC technical oversight and peer review comments are handled could be improved. By design, the process of producing the assessment report is similar to the publishing of academic papers. A critical difference is that the CAB acts as both the author and editor: they are responsible for determining if their response to comments is sufficient and making the decision to publish. There are multiple examples in the certification of the DSWGHF and WGOGHF where the CAB's response is not to make any material changes to the score, i.e. changes that would result in a further condition or failure [21,22]. There is an obvious risk of abuse in a system where the roles of author and editor are played by a single entity employed by the fishery being assessed.

Harmonisation is an inbuilt test of the certification process, determining whether the assessment process is consistent. Vessels in the DSWGHF operate within a subset of the area exploited by the previously certified WGOGHF, employing the same gear and subject to the same Greenlandic regulations. Thus some components of the assessment required harmonisation, including P2 [22]. Two stakeholders, SFG and ZSL, made written submissions questioning the consistency of the assessments and harmonisation.

SFG details the rational for believing that the conditions for the DSWGHF are not harmonised with those for the WGOGHF. The CAB's (Control Union) response is that *'there is no material difference in the conditions'* for the WGOGHF and DSWGHF [22]. This is demonstrably not the case given there was one less P2 condition imposed on the DSWGHF fishery (Table 3). This difference is not trivial as conditions are the mechanism by which the certification drives fishery improvements and are core to the MSC's Theory of Change. ZSL's submission is considered in the following section (9.4 Benthic Impacts).

9.4. Benthic impacts

The consensus among interviewees was that trawling impacts are considerable within the fishery. SC1 stated, '*when you have a [deep-sea] trawl fishery there is only very little left of the original fauna*'. NGO2 described how, '*[the industry has] trawled the same areas for the last ten, fifteen, twenty years … there is nothing left there*'. FI3 explained that the gear used to target halibut is very heavy*, 'it is rigged in a way that it takes the top off the seafloor'*.

Given the widely accepted vulnerability of deep-sea benthic habitats and slow speed of recovery, spatial management is often cited as the most appropriate option [91]. This is implicitly recognised within the MSC Standard, which requires that fisheries do not cause '*the reduction in habitat structure, biological diversity, abundance and function such that the habitat would be unable to recover to at least 80% of its unimpacted structure, biological diversity and function within 5-20 years, if fishing were to cease entirely*' [76]. The implication is that habitat within the footprint of fishery can be wholly and irreversible altered provided that, outside of the fishery, 80% of the habitat remains unimpacted. This is effectively a quantitatively defined ratio for spatial management. It is on this basis that the WGOGHF was found to be sustainable with respect to benthic impacts (P2.4.1) [21].

The WGOGHF assessment reports that the total area trawled in a three year period by the Greenlandic halibut fleet was 14,963 km^2 and that this footprint is stationary [21]. The impacted area is compared with 270,000 km^2, the total area >500 m in west Greenland, from which it is concluded that 94.5% of the habitat remains unimpacted. Assuming all areas within the western half of Greenland's EEZ >500 m represent equivalent habitat represents a gross simplification. At the very least, this should be constrained to the depth range (800–1,400 m) within which trawling occurs, as conditions and thereby the habitats hundreds and thousands of meters deeper will be very different. The fishery operates in two discrete areas of the comparatively shallow Davis Strait. The Davis Strait acts as a bathymetric bottleneck between the deeper Labrador Sea and Baffin Bay basins (Fig. 1), uniquely shaping the hydrographic conditions. A more nuanced approach would consider abiotic factors including temperature, salinity, current and slope characteristics within the fishery and to what extent they are replicated elsewhere. MSC2 agreed that, '*[the CAB] haven't defined the [spatial extent of the] habitats effectively*', and explained that '*as evidenced by the technical oversight that we [the MSC] raised … we weren't particularly satisfied with the rationale presented'*, but noted that *'[the MSC] are a stakeholder in the process, they [the CAB] are not mandated to change their information, we're not replacing their expert knowledge'*. Ultimately, the fishery was certified on this basis of this simplistic, somewhat cursory analysis of benthic impacts.

Subsequently and conversely, the DSWGHF assessment found the recovery of habitats impacted within the footprint is likely to be sufficiently fast to ensure recovery of at least 80% of structure and function within 20 years [22]. This was subject to a detailed stakeholder submission by ZSL, whose principle concern was that the CAB's assessment was inappropriately based on a global analysis of trawl impacts by Hiddink et al. [92]. The meta-analysis of Hiddink et al. [92] drew on shallow shelf fisheries predominantly at depths <50 m, with only one 'deep' fishery at just 400 m.

The harmonisation, or lack thereof, demonstrates serious failings in the consistency and robustness of the MSC assessment process. Clearly the rationale employed in each assessment is questionable in terms of the scientific rigour, though some may dismiss this as differences in expert option. However, critically the fundamental basis on which two overlapping fisheries employing the same gear were found to be sustainable in terms of ecosystem impacts (P2, PI 2.4.1), was wholly different and contradictory. This is not trivial, in that two CABs applied the same Standard and yet employed directly contradictory arguments to find that the habitat impacts were sustainable.

9.4.1. Vulnerable marine ecosystems (VMEs)

The United Nations General Assembly (UNGA) Resolution 61/105 called upon States to take action to protect vulnerable marine ecosystems (VMEs) [83], which are deep-sea habitats of biodiversity value that are vulnerable to physical disturbance. Identification of VMEs has frequently been based on the occurrence of significant concentrations of VME indicator species, such as cold-water coral or sponges, which is a matter of expert judgement in the absence of explicit thresholds [93].

VMEs are now explicitly incorporated in the MSC Standard [76]. States and RMFOs have not yet adopted consistent approaches for identifying and protecting VMEs, and knowledge gaps remain [94,95], including in the northwest Atlantic. MSC2 notes that for MSC assessments, 'a *perennial issue has been the identification and understanding of management frameworks around vulnerable marine ecosystems (VMEs)*'.

The fishery's management measures include move-on rules to protect VMEs. Specifically, vessels must cease fishing, move a minimum of 2 nm and inform GFLK in the event that 300 kg of live sponges or 60 kg of live corals are taken in one trawl [48]. The inadequacy of move-on rules in general has been discussed elsewhere [93]. In this fishery, the large mesh (140 mm cod-end) employed means many VME indicator species can be impacted without forming a significant component of the landed bycatch. There are no reports of move-on rules having been triggered, confirmed by GFLK and stated in both MSC assessments [22,44]. This may indicate that VMEs are absent from this area. Conversely, VMEs may be present and subject to damage without triggering the move-on rules. This is compounded by the fact that fishers lack the required knowledge and skills to identify benthic bycatch (Table 4c, I-14). A better management approach would employ spatial exclusions informed by an improved understanding of VME distribution.

Engagement with the MSC has resulted in ongoing research, supported by the industry, into the distribution of VMEs and impacts of trawling. To date this research has resulted in the identification of a candidate soft coral garden VME, immediately adjacent to the southern portion of the halibut fishery in shallower water (300–600 m) [79]. The response of the actors to this newly proposed VME will serve as a test of the governance framework and its capacity for adaptive management.

9.5. Role of NGOs

Despite having an economy dependent on natural resource exploitation, environmental NGOs (eNGOs) in Greenland are conspicuous by their absence. WWF is the only international eNGO with a permanent presence, maintaining a one-person office in Nuuk. This is partly because of a long-standing antipathy towards eNGOs arising from past campaigns against marine mammal hunting.

A key component of the MSC model is stakeholder engagement, including from eNGOs. '*It benefits fishery assessments when there is engagement from NGOs … in areas where there is less presence [of NGOs], you are going to have less scrutiny, it's obvious*' (MSC2). There is very little input from NGOs to these assessments compared with other MSC certifications of trawl fisheries in the North Atlantic. MSC3 conceded that the halibut fishery assessment would have '*undoubtedly*' received more scrutiny in other contexts. The certification assessments and governance framework would benefit from more critical perspectives.

10. Conclusion

The importance of fishing to Greenland means effective governance of marine resources is critical, making it an ideal context to consider the effectiveness of market-based mechanisms, such as MSC certification, to promote sustainable fishery management. Indeed, there can be few, if any, countries with a higher proportion of their GDP MSC certified.

The MPAG framework served as an appropriate tool to critically analyse the governance of this fishery and the role of the MSC certification. The framework could readily be applied to other fisheries. The study found an effective state-led system of governance supported by scientific, certification and industry actors. Previous MPAG studies have shown that effective governance requires a diversity of actors and related incentives [96], as is the case here, with a wide range of actors from within and beyond Greenland. Collectively they operate a diversity of interacting and mutually supportive incentives from all five categories, including the collaborative role of the Fisheries Council (I-28), a participatory incentive that enjoys widespread support. This Fisheries Council model could be replicated elsewhere to ensure adequate representation of stakeholders, providing them with direct access to policy makers and managers. This can contribute to more equitable and transparent governance of marine reources.

The MSC certification provides a strong market steer for the industry's considerable influence. Engagement with the MSC led to a new paradigm, from which there emerged '*an interesting dynamic between the companies and the Government because the companies come and ask to be regulated, which is otherwise very rare*' (ST1). Outcomes include the introduction of a halibut management plan and a program of benthic research delivered through new partnerships between industry and scientific actors. Whilst certification has undoubtedly strengthened the governance of the fishery with tangible changes, significant issues remain. It is uncertain how challenges in the inshore fishery will impact the offshore fishery and whether the MSC certification can achieve similar results in this contested small-scale fishery.

The MSC considers this and other certified Greenlandic fisheries as prime examples of the Theory of Change in action. Interviewees described how the '*the MSC theory is in practice in Greenland*' (MSC1), where '*fishery improvements, in our eyes, have been levered in through certification*' (MSC2). Accordingly, the halibut fishery has been repeatedly highlighted by the MSC in annual reports and other external communications [9]. It may surprise some to see a demersal trawl fishery, employing heavy gear in poorly known deep seas, held up as a flagship example of sustainability. This demonstrates the subjective nature of the term, to some extent sustainability is in the eye of the beholder. For these reasons it is important that certifications are transparent, robust and consistent if they are to be credible.

However, the study provides specific examples of existing criticisms of the MSC certification. The assessment of habitat impacts is weak and over-reliant on the expert and definitive judgement of CABs, whose independence has reasonably been questioned. The issue is compounded by the limited presence of critical voices. The most serious concern is the lack of harmonisation between the two assessments of overlapping fisheries. Greenlandic and German vessels employing the same gear in the same area were found to be sustainable with respect to benthic impacts, by CABs which employed fundamentally different and conflicting logic. This represents a serious failing of the assessment process, compromising one of the MSC three principles of sustainability. The MSC certification and indeed any eco-label, must ensure that the process is robust, consistent and independent, which was not always the case in this study. This could be addressed by the simple but fundamental measures suggested here. For example, requiring the original CAB to be changed in subsequent assessments and removing the dual role of author and editor that CABs enjoy in the reporting process. The future of the MSC certification and the assurance it provides arguably relies on proactively addressing these growing and significant concerns.

Growing knowledge of benthic habitats is providing new insights into the nature and distribution of deep-sea habitats, including VMEs, and the impacts of trawling. This will provide an opportunity to objectively and quantitatively review the sustainability of this fishery in terms of the wider ecosystem. This should be used to re-assess the effectiveness of governance and the validity of the MSC certifications, with applications to the future management of this fishery and others.

Declaration of competing interest

The habitat surveys are part of an ongoing collaboration between Zoological Society of London (ZSL) and GINR, contributing to the Initiating North Atlantic Benthos Monitoring (INAMon) project and an IUCN BEST 2.0 project (#1586). The IUCN BEST 2.0 project is led by the ZSL, with Sustainable Fisheries Greenland (SFG), as a partner and cofunder.

CRediT authorship contribution statement

Stephen Long: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Visualization. **Peter J.S. Jones:** Conceptualization, Methodology, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpol.2020.104095.

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Appendix IV

Paper IV

The results presented in the following paper are detailed in Chapter 6, whilst the methodology is described in Chapter 4.

Long, S., Blicher, M.E., Hammeken Arboe, N., Fuhrmann, M., Kemp, K.M., Nygaard, R., Zinglersen, k., Yesson. C. (2021) Deep-sea benthic habitats and trawling impacts in the offshore Greenland halibut fishery, Davis Strait, west Greenland. *ICES Journal of Marine Science* 78(8), 274. doi: 10.1093/icesjms/fsab148

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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*

Long, S., Blicher, M. E., Hammeken Arboe N., Fuhrmann, M., Darling, M., Kemp, K. M., Nygaard, R., Zinglersen, K., and Yesson, C. Deep-sea benthic habitats and the impacts of trawling on them in the offshore Greenland halibut fishery, Davis Strait, west Greenland. – ICES Journal of Marine Science, 78: 2724–2744.

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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 (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

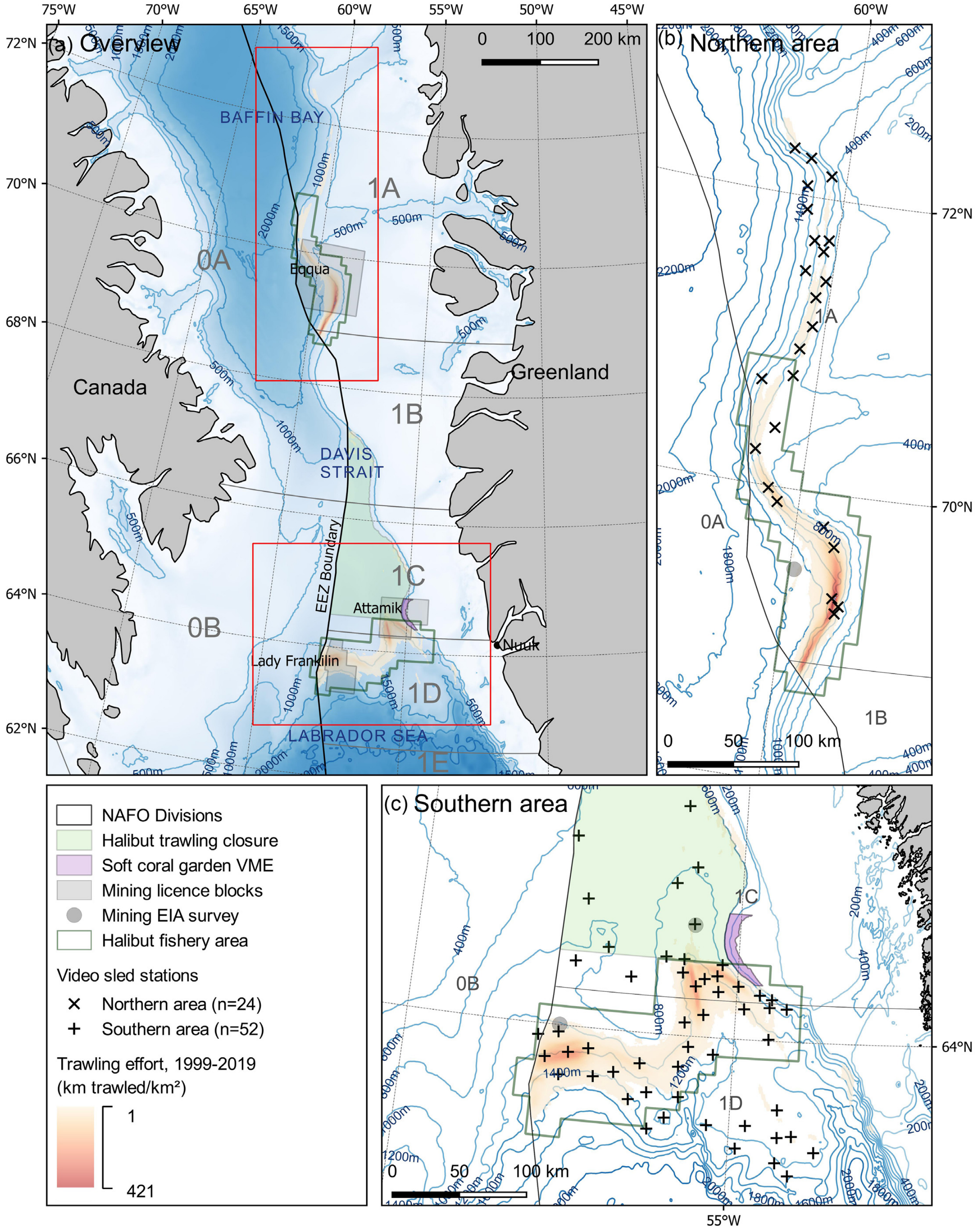

Figure 1. Map showing (a) the offshore Greenland halibut fishery, west Greenland; (b) the northern area of the fishery; and (c) the southern area of the fishery. The position of video sled stations ($n = 76$) is shown in (b) and (c). Bathymetric contours are drawn at 500 m intervals in (a) and 200 m 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/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 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 m^2, 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 (m^2)	8074	20764	28838
Number of fauna annotations	1184	11878	13062
Annotations /m^2	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 (âC)			
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/km^2)			
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

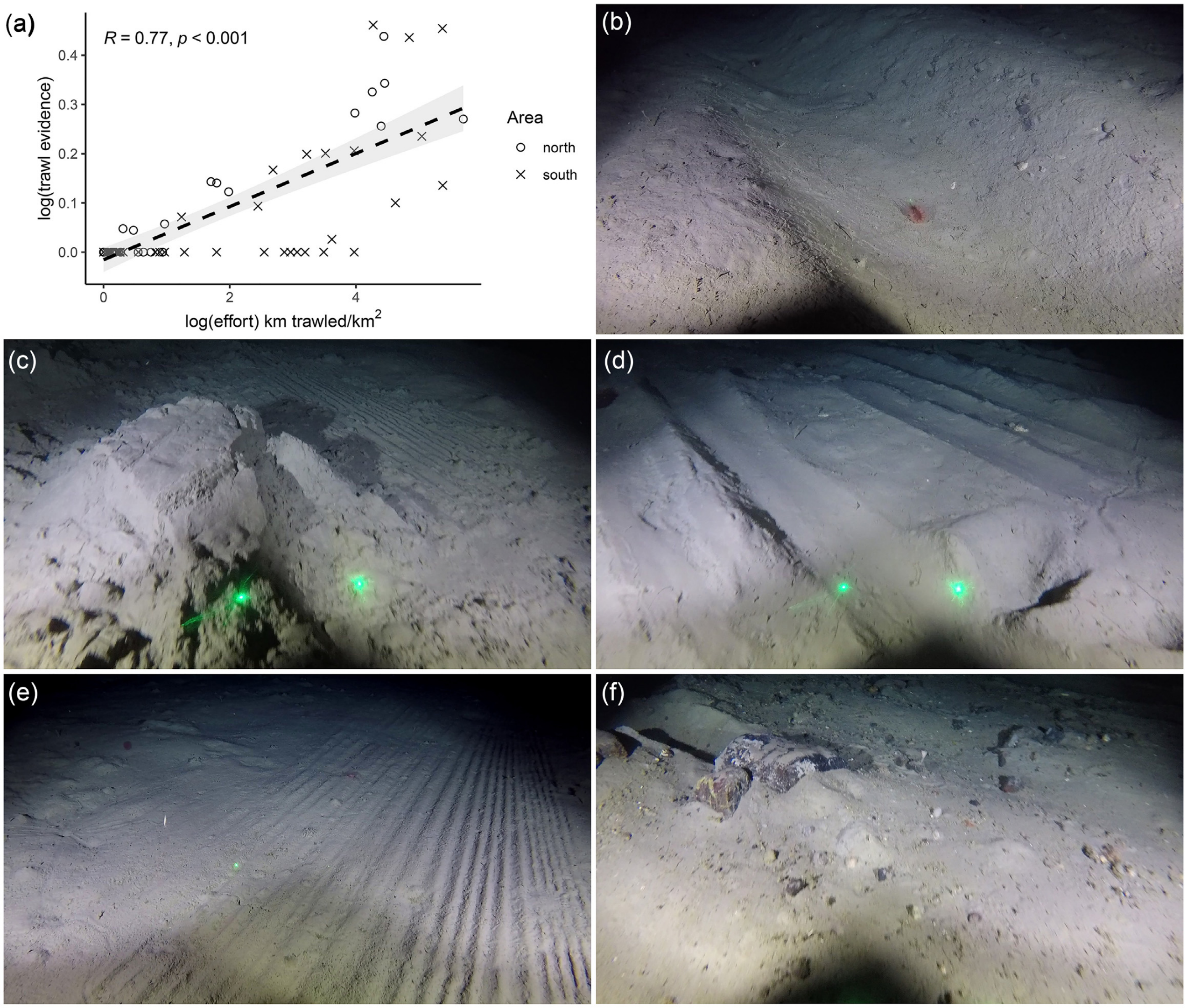

Figure 2. Panel (a) Relationship between the proportion of images observed with trawl evidence and effort at video sled stations. Where, effort is determined by sampling along the sled path from a raster derived from logbook trawling effort data from 1999-2019 (see, 2.4 Mapping and 2.5 Station metadata). 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/m^2. Conversely, *H. finmarchica* was absent from the majority of stations, being recorded at just nine. A maximum of 3.47 *H. finmarchica*/m^2 were observed at the station level with the maximum within an image being 4.50 individuals/m^2. 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/m^2) (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.

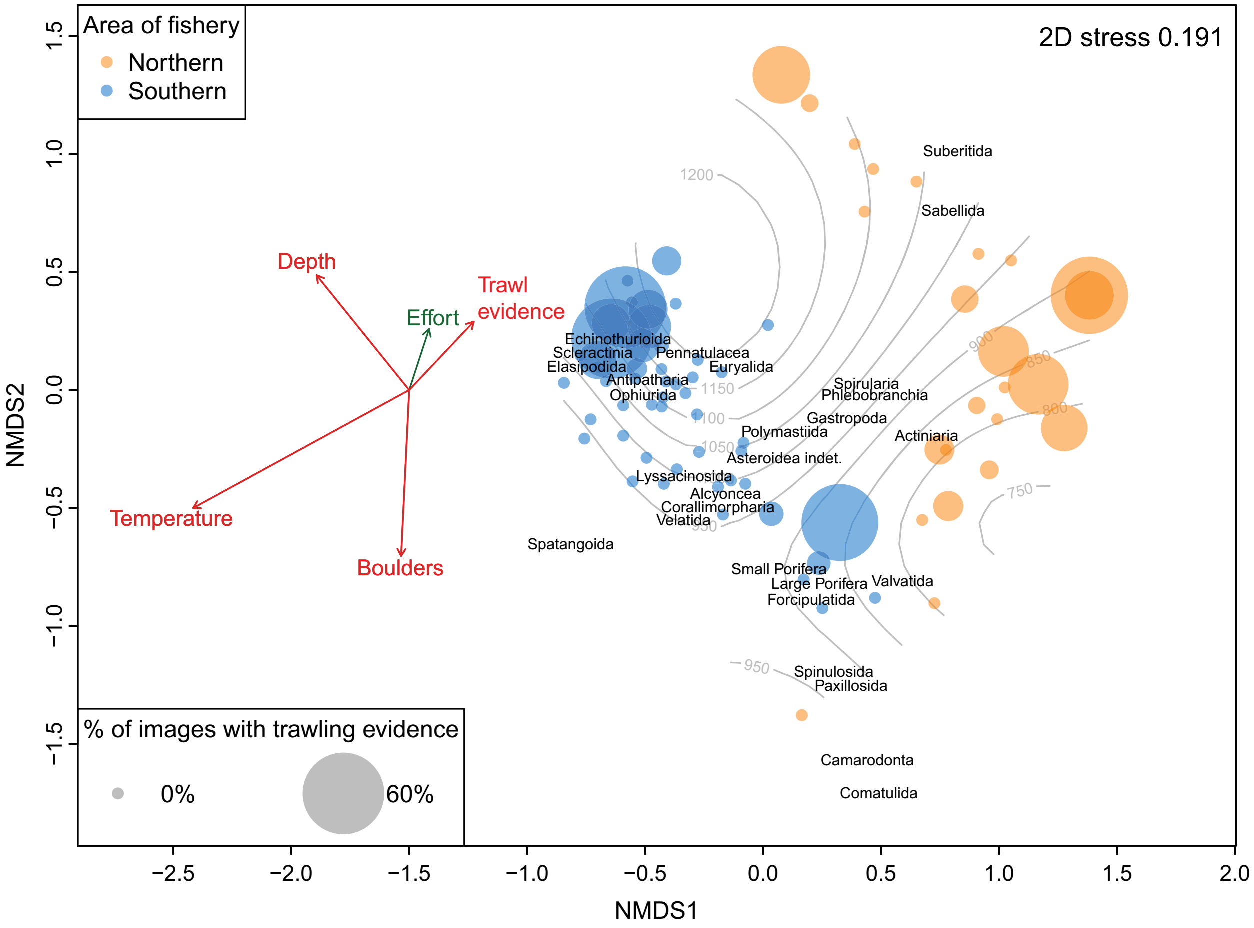

Figure 3. NMDS ordination of the benthic fauna assemblage observed in video sled images. Stations (filled circles, $n = 76$), from the northern (yellow, $n = 24$) and southern (blue, $n = 52$) areas are scaled by trawling evidence observed at each station. Fitted vectors of environmental variables are 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

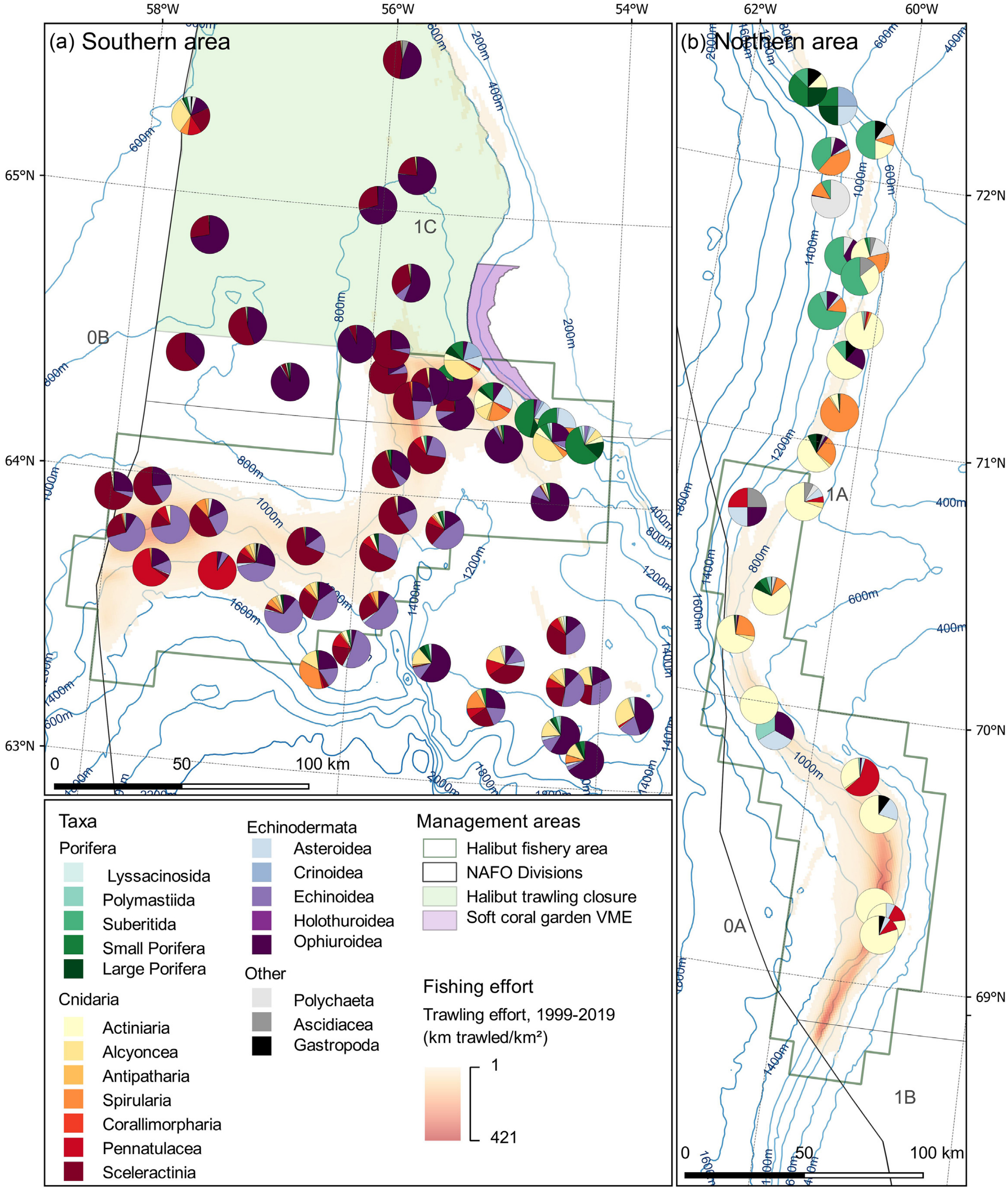

Figure 4. Community composition by station from image annotation data. Classes containing VME indicator taxa are presented at the Order level, all other taxa are aggregated to the Class level.

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*/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

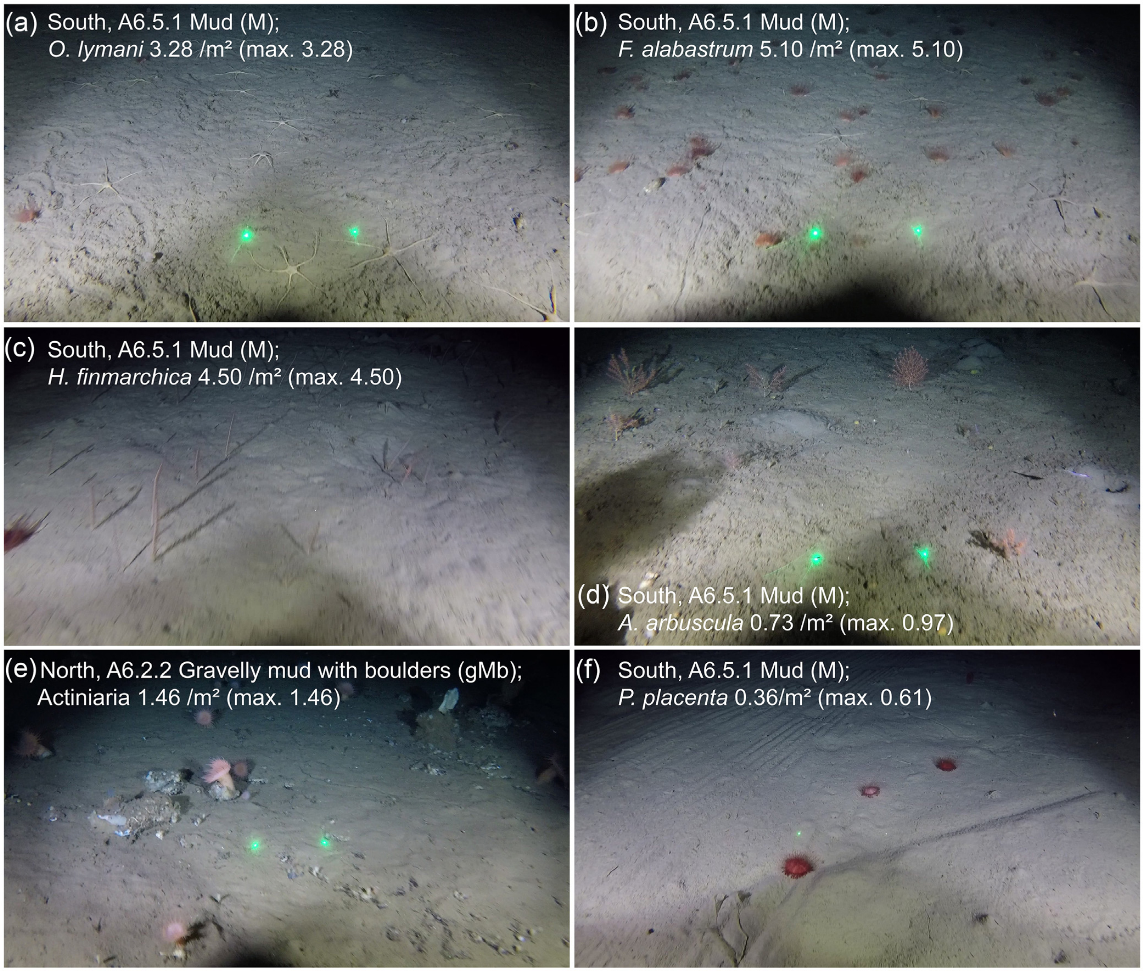

Figure 5. Example images of different communities seen in the imagery. The area from which the image was obtained is indicated along with the substrate type. The density of dominant or notable taxa in each image is shown, followed, in parentheses, by the maximum density observed in any image for reference. 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 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.

Phylum			VME Indicator?		Number of stations present at			Number of observations			Maximum observed density (taxa/m^2)		
Class	**Order**	**Taxa**	**NAFO**	**NEAFC**	**North ($n = 24$)**	**South ($n = 52$)**	**All ($n = 76$)**	**North**	**South**	**All**	**Image level**	**Station level**	**Area**
Porifera													
Hexactinellida	Lyssacinosida	*Asconema foliatum*	Yes	Yes	0	14	14	0	36	36	0.36	0.02	S
Demospongiae	Polymastiida	Polymastiidae	Yes	Yes	5	13	18	18	25	43	0.36	0.02	N
	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
	Sceleractinia	*Flabellum alabastrum*	No	Yes	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/m^2)		
Class	Order	Taxa	NAFO	NEAFC	North ($n = 24$)	South ($n = 52$)	All ($n = 76$)	North	South	All	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	No	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/m^2)	
Class	**Order**	**Taxa**	**NAFO**	**NEAFC**	**North (*n* = 24)**	**South (*n* = 52)**	**All (*n* = 76)**	**North**	**South**	**All**	**At the station level**	**Area**
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
	Sceleractinia	*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.

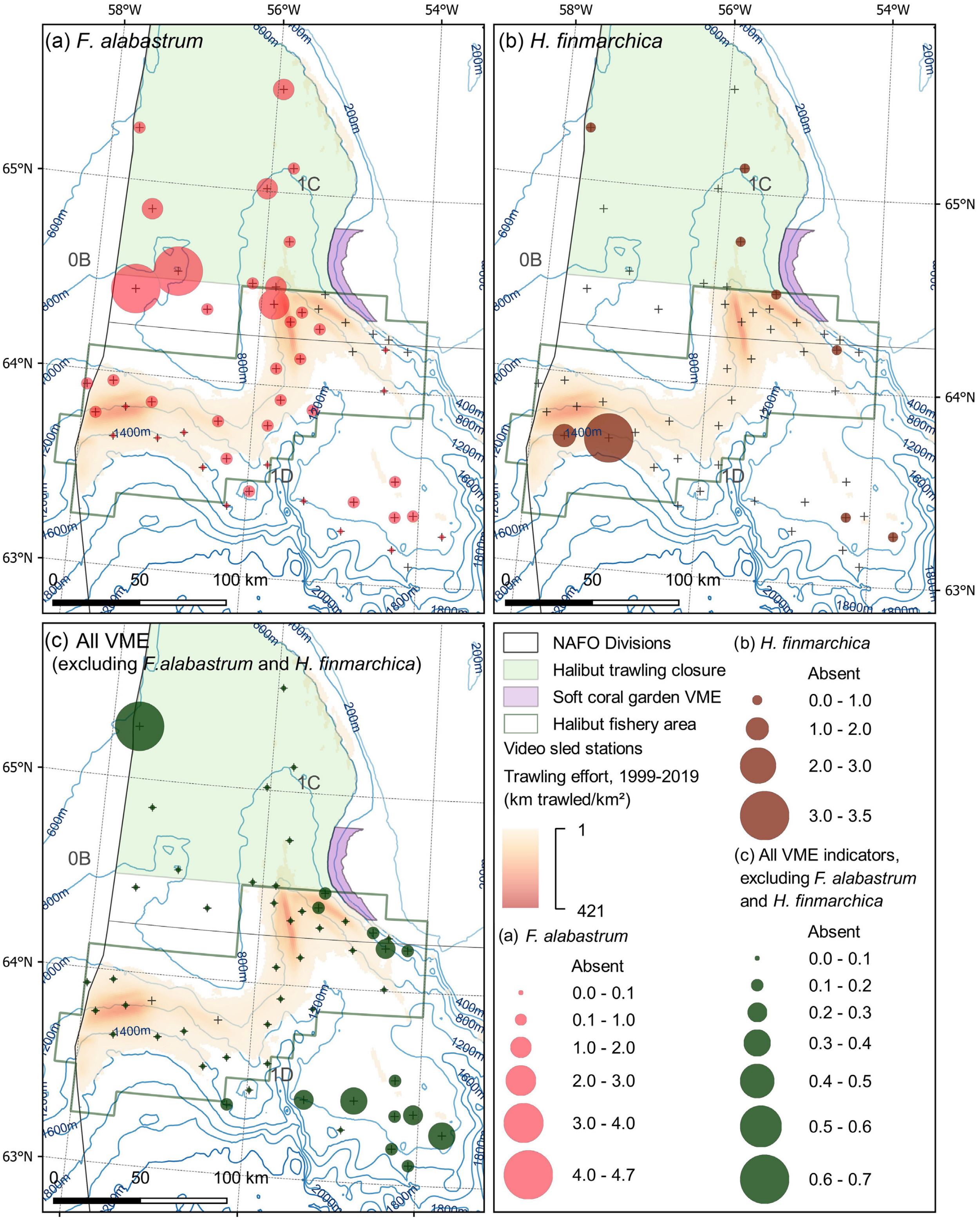

Figure 6. Map showing the density (individuals or colonies /m^2) at stations in the southern area ($n = 52$) for: (a) *F. alabastrum*; (b) *H. finmarchica*; and (c) all VME indicators (excluding *F. alabastrum* and *H. finmarchica*). The EEZ is drawn (solid black line).

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	($X^2 = 19.67, \mathrm{df} = 49, p < 0.001$)	
		Effort	− 0.115	0.049	($X^2 = 4.19, \mathrm{df} = 49, p = 0.041$)	

[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 /m^2 (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/m^2; 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/m^2. 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 km^2 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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Appendix V

The 36 incentives in five categories in the MPAG framework. From: (Jones, 2014)

Category (Number of incentives)	**Incentives**
Economic (10)	1. Payments for ecosystem services
	2. Assigning property rights
	3. Reducing the leakage of benefits
	4. Promoting profitable and sustainable fisheries and tourism
	5. Promoting green marketing
	6. Promoting diversified and supplementary livelihoods
	7. Providing compensation
	8. Investing MPA income/funding in facilities for local communities
	9. Provision of state funding
	10. Provision of NGO, private sector and user fee funding
Communication (3)	11. Raising awareness
	12. Promoting recognition of benefits
	13. Promoting recognition of regulations and restrictions
Knowledge (3)	14. Promoting collective learning
	15. Agreeing approaches for addressing uncertainty
	16. Independent advice and arbitration
Legal (10)	17. Hierarchical obligations
	18. Capacity for enforcement
	19. Penalties for deterrence
	20. Protection from incoming users
	21. Attaching conditions to use, property rights, decentralisation, etc.
	22. Cross-jurisdictional coordination
	23. Clear and consistent legal definitions
	24. Clarity concerning jurisdictional limitations
	25. Legal adjudication platforms
	26. Transparency, accountability and fairness
Participation (10)	27. Rules for participation
	28. Establishing collaborative platforms
	29. Neutral facilitation
	30. Independent arbitration panels
	31. Decentralising responsibilities
	32. Peer enforcement
	33. Building trust and the capacity for cooperation
	34. Building linkages between relevant authorities and user representatives
	35. Building on local customs
	36. Potential to influence higher institutional levels

Appendix VI

Interview semi-structure

Date:
Place:
Name:
Interview ref code:
Job/role/position:
Organisation:
Relationship/experience/knowledge of:

- the W Greenland Halibut fishery
- Wider Greenland fishing industry
- Deep-sea and Arctic fisheries/ecosystems
- MSC scheme

How is the fishery managed?

- History of the fishery and management?
- Who manages it?
- Management measures/MPAG incentives in place?
- Who has power/influence to direct management? Power of Industry/SFG in undiversified economy?
- Relationships between actors (GINR, GLFK, SFG, MSC, NAFO, fishers, supply chain)
- Managing ecosystems impacts and associated uncertainty around deep-sea unknowns?
- Inshore/offshore artisanal/industrial fishery relationship
- Canada relationship and management of stock/quota across EEZ? Legal basis?
- Non-Greenlandic vessels (not certified), impacts/management?
- Threats/challenges? Expansion of the fleet or footprint
- Improvements (governance structure or incentives needed/strengthening) to address threats?
- Role of the observer programme?
- Impact of Greenland's socio-economic context on management?

Role of the MSC scheme?

- Why apply? Benefits realised or perceived (e.g. access to market, price, improved management or sustainability)?
- What (if any) changes have been brought about by participation in the MSC scheme?
- Relationship between CAB (auditor/assessor) and the client (SFG)? How were they selected?
- Rigour of the assessment procedure?
- Principal 2 and deep-sea habitats and VMEs
- Reconciling uncertainty of deep-sea impacts and Principle 2? What level of impact would render the fishery uncertifiable? Would a new fishery pass P2 or is a 'damage already done' logic applied to the existing footprint?
- Adequacy of move-on rules to protects VMEs in relation to P2?
- Opinion of conditions applied in the assessment?
- Expectations of audit and review processes?
- Threats/challenges to certification?

- What does the certification offer consumer (in principal and practice)?

Overall opinion of the effectiveness of the management and the role of the MSC certification in this?

Appendix VII

The following table details invertebrate fauna identified from physical sampling in the proposed soft coral garden vulnerable marine ecosystem (VME) described in Chapter 5. This table was originally published as supplementary information in Long *et al.* (2020).

Invertebrate taxa identified in stock assessment survey trawls (Cosmos) and beam trawls within the candidate vulnerable marine ecosystem (VME) area. This consists of observations from three Cosmos trawls and two beam trawls, conducted at depths from 308-569 m. A total of 146 unique taxon identifiers were used (Taxon identifiers) to record catch. For each taxon the phylum, class, order, family, genus and species are reported as appropriate. Data provided by the Greenland Institute of Natural Resources (GINR).

Phylum	**Class**	**Order**	**Family**	**Genus species**	**Taxon identified**
Annelida	Polychaeta				Polychaeta
		Eunicida			Eunicida
			Eunicidae	*Eunice pennata*	*Eunice pennata*
			Lumbrineridae		Lumbrineridae
		Phyllodocida	Aphroditidae	*Aphrodita hastata*	*Aphrodita hastata*
				Laetmonice filicornis	*Laetmonice filicornis*
			Polynoidae	*Eunoe sp.*	*Eunoe sp.*
		Sabellida			Sabellida
		Terebellida	Flabelligeridae	*Brada inhabilis*	*Brada inhabilis*
Arthropoda	Hexanauplia	Scalpelliformes	Scalpellidae	*Ornatoscalpellum stroemii*	*Ornatoscalpellum stroemii*
	Malacostraca	Amphipoda	Ampeliscidae	*Ampelisca eschrichtii*	*Ampelisca eschrichtii*
			Epimeriidae	*Epimeria loricata*	*Epimeria loricata*
			Eusiridae	*Rhachotropis aculeata*	*Rhachotropis aculeata*
			Leucothoidae	*Leucothoe spinicarpa*	*Leucothoe spinicarpa*
			Stegocephalidae	*Stegocephalus inflatus*	*Stegocephalus inflatus*
		Decapoda	Benthesicymidae	*Gennadas elegans*	*Gennadas elegans*
			Bythocarididae	*Bythocaris sp.*	*Bythocaris sp.*
			Crangonidae	*Sabinea sarsii*	*Sabinea sarsii*
				Sabinea septemcarinata	*Sabinea septemcarinata*
			Lithodidae	*Lithodes maja*	*Lithodes maja*

			Munididae	*Munida sp.*	*Munida sp.*
			Paguridae	*Pagurus pubescens*	*Pagurus pubescens*
			Pandalidae	*Pandalus borealis*	*Pandalus borealis*
				Pandalus propinqvus	*Pandalus propinqvus*
			Pasiphaeidae	*Parapasiphae sulcatifrons*	*Parapasiphae sulcatifrons*
			Sergestidae	*Eusergestes arcticus*	*Eusergestes arcticus*
			Thoridae	*Lebbeus polaris*	*Lebbeus polaris*
		Isopoda	Aegidae	*Aega psora*	*Aega psora*
				Aegiochus ventrosa	*Aegiochus ventrosa*
		Lophogastrida	Gnathophausiidae	*Gnathophausia zoea*	*Gnathophausia zoea*
	Pycnogonida	Pantopoda	Nymphonidae	*Nymphon grossipes*	*Nymphon grossipes*
				Nymphon hirtipes	*Nymphon hirtipes*
				Nymphon stroemi	*Nymphon stroemi*
Brachiopoda					Brachiopoda
	Rhynchonellata	Terebratulida	Cancellothyrididae	*Terebratulina septentrionalis*	*Terebratulina septentrionalis*
			Zeilleriidae	*Macandrevia cranium*	*Macandrevia cranium*
Bryozoa	Gymnolaemata	Cheilostomatida	Celleporidae		Celleporidae
				Celleporina sp.	Celleporina sp.
			Flustridae		Flustridae
				Terminoflustra barleei	*Terminoflustra barleei*
			Myriaporidae	*Leieschara coarctata*	*Leieschara coarctata*
			Phidoloporidae	*Reteporella sp.*	*Reteporella sp.*
				Reteporella grimaldii	*Reteporella grimaldii*
		Ctenostomatida	Alcyonidiidae	*Alcyonidium gelatinosum*	*Alcyonidium gelatinosum*
	Stenolaemata	Cyclostomatida	Horneridae	*Hornera lichenoides*	*Hornera lichenoides*
			Tubuliporidae	*Idmidronea sp.*	*Idmidronea sp.*
Chordata	Ascidiacea				Ascidiacea
		Phlebobranchia	Ascidiidae	*Ascidia sp.*	*Ascidia sp.*
				Ascidia prunum	*Ascidia prunum*

		Stolidobranchia	Molgulidae	*Molgula oculata*	*Molgula oculata*
Cnidaria	Anthozoa	Actiniaria	Actinostolidae	*Actinostola sp.*	*Actinostola sp.*
			Hormathiidae	*Actinauge sp.*	*Actinauge sp.*
				Actinauge cristata	*Actinauge cristata*
		Alcyonacea	Acanthogorgiidae	*Acanthogorgia armata*	*Acanthogorgia armata*
			Alcyoniidae	*Heteropolypus insolitus*	*Heteropolypus insolitus*
			Nephtheidae		Nephtheidae
				Drifa glomerata	*Drifa glomerata*
				Duva florida	*Duva florida*
				Gersemia fruticosa	*Gersemia fruticosa*
			Paragorgiidae	*Paragorgia arborea*	*Paragorgia arborea*
			Primnoidae	*Primnoa resedaeformis*	*Primnoa resedaeformis*
	Hydrozoa				Hydrozoa
		Anthoathecata	Bougainvilliidae		Bougainvilliidae
			Eudendriidae	*Eudendrium sp.*	*Eudendrium sp.*
				Eudendrium capillare	*Eudendrium capillare*
				Eudendrium rameum	*Eudendrium rameum*
			Stylasteridae		Stylasteridae
		Leptothecata	Aglaopheniidae		Aglaopheniidae
				Aglaophenopsis bonnevieae	*Aglaophenopsis bonnevieae*
				Aglaophenopsis cornuta	*Aglaophenopsis cornuta*
				Cladocarpus formosus	*Cladocarpus formosus*
				Cladocarpus integer	*Cladocarpus integer*
				Cladocarpus pourtalesii	*Cladocarpus pourtalesii*
			Campanulariidae	*Rhizocaulus verticillatus*	*Rhizocaulus verticillatus*
			Haleciidae	*Halecium beanii*	*Halecium beanii*
			Lafoeidae	*Grammaria abietina*	*Grammaria abietina*
				Lafoea dumosa	*Lafoea dumosa*
				Lafoea grandis	*Lafoea grandis*
			Plumulariidae	*Nemertesia antennina*	*Nemertesia antennina*

			Sertularellidae	*Sertularella rugosa*	*Sertularella rugosa*
			Sertulariidae	*Abietinaria abietina*	*Abietinaria abietina*
				Diphasia fallax	*Diphasia fallax*
				Hydrallmania falcata	*Hydrallmania falcata*
				Thuiaria articulata	*Thuiaria articulata*
				Thuiaria laxa	*Thuiaria laxa*
				Thuiaria thuja	*Thuiaria thuja*
			Symplectoscyphidae	*Symplectoscyphus tricuspidatus*	*Symplectoscyphus tricuspidatus*
			Zygophylacidae	*Zygophylax pinnata*	*Zygophylax pinnata*
	Scyphozoa				Scyphozoa
		Coronatae	Atollidae	*Atolla wyvillei*	*Atolla wyvillei*
			Periphyllidae	*Periphylla periphylla*	*Periphylla periphylla*
Echinodermata	Asteroidea				Asteroidea
		Brisingida	Brisingidae	*Novodinia sp.*	*Novodinia sp.*
		Forcipulatida	Asteriidae	*Leptasterias sp.*	*Leptasterias sp.*
		Paxillosida	Astropectinidae	*Leptychaster arcticus*	*Leptychaster arcticus*
		Spinulosida	Echinasteridae	*Henricia sp.*	*Henricia sp.*
		Valvatida	Goniasteridae	*Ceramaster granularis*	*Ceramaster granularis*
			Solasteridae	*Crossaster papposus*	*Crossaster papposus*
				Lophaster furcifer	*Lophaster furcifer*
				Solaster sp.	*Solaster sp.*
		Velatida	Pterasteridae	*Pteraster militaris*	*Pteraster militaris*
				Pteraster pulvillus	*Pteraster pulvillus*
	Crinoidea	Comatulida	Antedonidae	*Poliometra prolixa*	*Poliometra prolixa*
	Echinoidea	Camarodonta	Strongylocentrotidae	*Strongylocentrotus sp.*	*Strongylocentrotus sp.*
		Spatangoida	Schizasteridae	*Brisaster fragilis*	*Brisaster fragilis*
	Holothuroidea	Dendrochirotida	Psolidae	*Psolus sp.*	*Psolus sp.*
	Ophiuroidea				Ophiuroidea
		Amphilepidida	Ophiactidae	*Ophiactis abyssicola*	*Ophiactis abyssicola*
			Ophiopholidae	*Ophiopholis aculeata*	*Ophiopholis aculeata*

		Euryalida	Gorgonocephalidae	*Gorgonocephalus sp.*	*Gorgonocephalus sp.*
				Gorgonocephalus lamarckii	*Gorgonocephalus lamarckii*
		Ophiacanthida	Ophiacanthidae	*Ophiacantha sp.*	*Ophiacantha sp.*
				Ophiacantha anomala	*Ophiacantha anomala*
				Ophiacantha bidentata	*Ophiacantha bidentata*
				Ophiacantha spectabilis	*Ophiacantha spectabilis*
			Ophiomyxidae	*Ophioscolex sp.*	*Ophioscolex sp.*
				Ophioscolex glacialis	*Ophioscolex glacialis*
		Ophiurida	Ophiuridae	*Ophiura robusta*	*Ophiura robusta*
				Ophiura sarsii	*Ophiura sarsii*
Mollusca	Bivalvia	Pectinida	Pectinidae	*Chlamys islandica*	*Chlamys islandica*
				Delectopecten vitreus	*Delectopecten vitreus*
	Cephalopoda	Octopoda	Bathypolypodidae	*Bathypolypus bairdii*	*Bathypolypus bairdii*
		Oegopsida	Gonatidae	*Gonatus fabricii*	*Gonatus fabricii*
		Sepiida	Sepiolidae	*Rossia sp.*	*Rossia sp.*
	Gastropoda				Gastropoda
		Neogastropoda	Buccinidae	*Beringius sp.*	*Beringius sp.*
				Buccinum fragile	*Buccinum fragile*
		Nudibranchia	Arminidae	*Heterodoris robusta*	*Heterodoris robusta*
			Dorididae		Dorididae
			Doridoxidae	*Doridoxa sp.*	*Doridoxa sp.*
		Trochida	Margaritidae	*Margarites groenlandicus umbilicalis*	*Margarites groenlandicus umbilicalis*
	Polyplacophora	Chitonida	Ischnochitonidae	*Stenosemus albus*	*Stenosemus albus*
	Solenogastres				Solenogastres
Porifera					Porifera
	Demospongiae	Axinellida	Axinellidae		Axinellidae
		Poecilosclerida	Cladorhizidae	*Asbestopluma (Asbestopluma) pennatula*	*Asbestopluma (Asbestopluma) pennatula*
			Coelosphaeridae	*Histodermella sp.*	*Histodermella sp.*

			Microcionidae	*Antho (Antho) dichotoma*	*Antho (Antho) dichotoma*
			Mycalidae	*Mycale sp.*	*Mycale sp.*
		Polymastiida	Polymastiidae	*Polymastia sp.*	*Polymastia sp.*
		Tethyida	Tethyidae	*Tethya citrina*	*Tethya citrina*
		Tetractinellida	Geodiidae	*Geodia sp.*	*Geodia sp.*
				Geodia barretti	*Geodia barretti*
			Tetillidae	*Craniella cranium*	*Craniella cranium*
			Theneidae	*Thenea muricata*	*Thenea muricata*
	Hexactinellida	Lyssacinosida	Rossellidae	*Asconema sp.*	*Asconema sp.*

Appendix VIII

The following two tables provide the information required to recalculate the assessment of the size of the fishery relative to the total area of equivalent habitat as presented in the WGOGHF MSC assessment (Cappell *et al.*, 2017).

Area of the fishery as reported in the WGOGHF MSC assessment and determined from logbook trawling data from 1999-2019 (see, 4.1.4 Mapping). For reference, the size of the fishery area (i.e. the area in which the fishery is permitted to operate) as defined by the Revised Halibut Fishery Management Plan (2021-2025) is given.

Descriptions of the size of the fishery (reference(s))	**Area (km²)**
Trawling footprint per WGOGHF MSC assessment (Cappell *et al.*, 2017)	
All (NAFO 1A-E)	14,963
Trawling footprint per logbook data (Figure 3.2, 4.1.4 Mapping)	
Northern area (NAFO 1A+B)	5,780
Southern area (NAFO 1CDE)	9,323
All (NAFO 1A-E)	15,103
Revised Halibut Fishery Management Plan, fishery area (MFHA, 2021)*	
Northern area (NAFO 1A+B)	12,285
Southern area (NAFO 1CDE)	16,142
All (NAFO 1A-E)	28,427

*The fishery area set out in the Revised Halibut Fishery Management Plan is drawn based on a grid system used by Greenlandic fishery management authorities. Cells in this grid adjacent to the EEZ median line overlap the Canadian EEZ. For the purposes of this calculation any portion of the fishery area described by the revised management plan which overlaps the Canadian EEZ has been excluded, as vessels in the fishery's fleet are required to fish within Greenlandic waters. The size of fishery area set out in Revised Halibut Fishery Management Plan inclusive of the overlap with the Canadian EEZ is 29,982 km² (as opposed to 28,427 km² area detailed above).

The size of the trawling footprint and the fishery area (as defined by the Revised Halibut Fishery Management Plan) relative to different estimates of the total area of 'equivalent' habitat. Calculations are made using the values reported in the table above.

Method of determining the total area of 'equivalent' habitat	**Area (km²)**	**Percentage of the total area of 'equivalent' habitat (%) occupied by:**	
		The trawling footprint	**Revised management plan fishery area**
WGOGHF MSC assessment (Cappell *et al.*, 2017)			
West Greenland* >500m	269,282	5.6	10.6
Constrained by depth (700 m ≥ depth ≤ 1,500 m)			
NAFO 0+1	201,616	7.5	14.1
NAFO 1 †	86,512	17.5	32.9
NAFO 1A-E			
Northern area (NAFO 1A+B)	44,967	12.9	27.3
Southern area (NAFO 1CDE)	38,629	24.1	41.8
All (NAFO 1A-E)	83,596	18.1	34.0

* The WGOGHF MSC assessment reports that *"the total area of seabed deeper than 500 m in Western Greenland is 269,282 km²"*. In the assessment report *'Western Greenland"* is not defined explicitly in the text, although a figure (see; Figure 14, Cappell *et al.*, 2017) presents the area to which they refer. The western boundary is the EEZ. The southern boundary is the boundary between NAFO 1E and NAFO 1F. It is not clear what forms the Northern boundary, though it is close to the northerly extent of NAFO 1A. The eastern boundary follows the coast excluding inshore areas. Thus the area is approximately equivalent to NAFO 1A-E (excluding inshore waters).

† The WGOGHF MSC assessment describes the geographical area of the 'Unit of Assessment (UoA)' as being *"NAFO Subareas 1 (A,B,C,D,E,F)"*, i.e. NAFO 1.