Title: Mapping and classifying the seabed of the West Greenland continental shelf

Author names and affiliations: S. Gougeon[a], K.M. Kemp[a], M.E. Blicher[b], C. Yesson[a*]

[a] Institute of Zoology, Regent's Park, London NW14RY, UK, [b] Greenland Institute of Natural Resources, Box 570, Kivioq 2, 3900 Nuuk, Greenland

* **Email address:** chris.yesson@ioz.ac.uk

* **Tel number:** 020 7449 6267, **Fax number:** 020 7586 2870

Abstract

Marine benthic habitats support a diversity of marine organisms that are both economically and intrinsically valuable. Our knowledge of the distribution of these habitats is largely incomplete, particularly in deeper water and at higher latitudes. The western continental shelf of Greenland is one example of a deep (up to 500m) Arctic region with limited information available. This study uses an adaptation of the EUNIS seabed classification scheme to document benthic habitats in the region of the West Greenland shrimp trawl fishery from 60ºN to 72ºN in depths of 61-725m. More than 2000 images collected at 224 stations between 2011-2015 were grouped into 7 habitat classes. A classification model was developed using environmental proxies to make habitat predictions for the entire western shelf (200-500m below 72ºN). The spatial distribution of habitats correlates with temperature and latitude. Muddy sediments appear in northern and colder areas whereas sandy and rocky areas dominate in the south. Southern regions are also warmer and have stronger currents. The Mud habitat is the most widespread, covering around a third of the study area. There is a general pattern that deep channels and basins are dominated by muddy sediments, many of which are fed by glacial sedimentation and outlets from fjords, while shallow banks and shelf have a mix of more complex habitats. This first habitat classification map of the West Greenland shelf will be a useful tool for researchers, management and conservationists.

Key words: benthic habitats; habitat modelling; vulnerable marine habitats; deep sea; trawling impact; sea bed imaging

1. Introduction

1.1 Background

Seabed habitats are a crucial part of marine ecosystems. The deep-sea habitats are rich in biodiversity and host many widespread and economically important species (Costello et al., 2010; Rex and Etter, 2010). However, our knowledge of the diversity and distribution of these habitats, as well as their functioning and vulnerability to anthropogenic stressors, is largely incomplete. Only 5-10% of all marine habitats have been mapped with a level of detail comparable to the terrestrial environment (Wright and Heyman, 2008), and this information deficit is more pronounced in polar regions and greater depths (Ramirez-Llodra et al., 2010).

Our knowledge of the geographical range of substrate types and species distributions that characterise benthic habitats is limited by the constraints of conventional seabed survey methods (Brown et al., 2011). This presents real challenges for resource management and for the identification and protection of vulnerable areas. Marine benthic habitat maps are necessary to study community associations, diversity and vulnerability (Ehler and Douvere, 2009; Reiss et al., 2014). There is an urgent need to improve data gathering, particularly for areas with active fisheries and areas of potential future exploitation such as Arctic zones with retreating seasonal sea ice. There are active benthic mapping projects being undertaken in Europe: MESH (Coltman et al. 2006), MAREANO (Buhl-Mortensen et al., 2015), BIOMOR (Mackie et al., 2006). These projects use approaches such as *in situ* sediment sampling, underwater video and stills photography to gather data for habitat mapping. In addition technologies such as acoustic backscatter and high-resolution seismic reflection (Kostylev et al., 2003; Anderson et al., 2008) can be used to infer basic habitats in unsampled areas. Predictive modelling based on environmental proxies is an approach that has been applied in the marine environment, and has the potential to produce large scale habitat maps without the requirement of direct sampling (Young and Carr, 2015).

Many schemes to categorise the seabed into habitat classes have been developed. Many of these use environmental and topographic parameters to define their classifications. Common divisions in classification systems include biogeographical regions, and depth (Greene et al., 1999; Allee et al., 2000; Roff and Taylor, 2000; Ehler and Douvere, 2009), geomorphology (Greene et al., 1999; Allee et al., 2000) and substrate type (Greene et al., 1999; Allee et al., 2000 Roff and Taylor, 2000; Ehler and Douvere, 2009; Mcbreen et al., 2011). Currents, wave exposure, relief and slope may also be used to delimit habitat classes (Leathwick et al., 2012). Habitat classifications are often developed in response to the specific conditions of a chosen depth range or geographical area (e.g.: the North-eastern North America Region (Valentine et al., 2005).) making them less directly applicable to areas that fall outside those parameters. Perhaps the widest ranging scheme is the European Nature Information System (EUNIS), which aims to cover all types of natural and artificial habitats in Europe including marine, coastal, freshwater and terrestrial (Davies et al., 2004). However, this classification scheme may not be suitable for areas outside of Europe and the deep-sea section is in need of further development (Galparsoro et al., 2012).

1.2 West Greenland

One area that typifies the deep/polar data deficit is the continental shelf of West Greenland. The West Greenland shelf includes a diverse range of benthic habitats due to the diversity of environmental and topographic conditions in this area (Yesson et al., 2015). The region incorporates many noteworthy topographic features including fjords, islands, shallow banks (>50m) and deep channels (>300m). The deep channels are connected to fjords, meltwater rivers, and tidewater outlet glaciers, which contribute to inorganic sedimentation on the seabed, and (in the case of glaciers) dropstone deposition (Thiede et al., 2011; Hogal et al., 2016). Alongside their role in sediment and dropstone deposition, glaciers and icebergs directly transform the seabed by scouring, which has been observed down to 600m (Gutt, 2001). West Greenland is home to large marine embayments: for example, Disko Bay is characterised by a rough and irregular seafloor at depths of 200-400 m (Hogan et al., 2012). Oceanography plays an important role in shaping seabed habitats. In southwest Greenland two water masses are predominant: the cold, low salinity, coastal water of the East Greenland Current; and the warmer, higher salinity, Atlantic water (Myers et al., 2007). The south west continental shelf of Greenland is dominated by a narrow, rocky, steep shelf slope and strong currents whereas in the north-western region a weaker current ambles over a wider shelf that experiences significant winter sea-ice (Buch, 2000; Yesson et al., 2015b). This diversity of environmental conditions, environmental influences and geomorphological and hydrographic features leads to a diversity and heterogeneity of benthic communities and habitats on the West Greenland shelf.

The aims of this study are to 1) perform a habitat classification by employing a slightly modified version of the EUNIS scheme to incorporate habitats important in Greenland; 2) develop a classification model, based on the environmental characteristics of sampled stations to classify the entire western shelf into habitat classes without direct sampling, and with that 3) produce a continuous map of seabed classes over the western Greenlandic shelf.

2. Materials and Methods

2.1 Sea bed imaging

This study reused sea bed images collected by Yesson et al. (2015b; In Press) Photographic surveys of the sea floor were carried out from the M/T Paamiut over a period of 5 years, in collaboration with the Greenland Institute of Natural Resources (GINR). The image sampling was conducted using a drop camera, with each image covering approximately 0.3m^2. Ten images were captured at each sampling station with 1 minute of drift between images (drift typically 20-50m). Additional details of the sampling technique are provided in Yesson et al. (2015b; In Press). More than 2000 photographs of the seabed of the West Greenland shelf were examined, from 224 sites ranging from 60ºN to 72ºN and depths 61-725 m. A map showing the location of sites along the west Greenland continental shelf is presented in Fig.1.

2.2 Image processing – Habitat Classification

Photographs from each station were assigned to a habitat class based on a modified version of the EUNIS scheme (Davies et al., 2004). The majority of stations had all images fit into a single habitat class, in the rare instance of multiple classes observed at one station the predominant habitat class was selected to represent the station. A comparison between EUNIS, MAREANO, and the present classification is presented in Table 1. Images were processed using an ID template which was compiled as part of the project and incorporates the distinct seabed types encountered during analysis. The template was created by grouping different stations with the same features, for example substrate type (sand, mud, sandy-mud and rock) and substrate bioturbation (animal trails, burrows). Sedimentary structures such as ripple marks on seabed and the softness of the substrate were essential information for determining these categorisations into substrate types during image processing. Substrate colour also proved a helpful guide for classification. Each time a new seabed type was observed in an image, the main patterns were defined and the novel class was given a name and added to the template (Fig. 2). Some seabed classes have been grouped together in accordance with the updated Folk sediment triagon (Davies et al., 2004; Mcbreen et al., 2011), for example the 'gravelly muddy sand' class was grouped with 'gravelly muddy'. These classes were chosen because they are biologically meaningful as the quantity of mud has an important influence on the related biology (Bellec et al. 2009); the number of different habitat classes is thereby kept minimal. Data from these images were considered at station-level for analysis.

2.3 Habitat modelling and mapping

Benthic ecology in the ocean is influenced by both geomorphological aspects of the seabed and characteristics of the water column (Zajac, 2008). Environmental layers were chosen to provide geographical information on these characteristics (Table 2). Data were extracted from each environmental layer for every sampling station. Some stations lacked associated environmental data and in these cases a value was obtained from the closest available location within a 3500m limit. Inferred depths were obtained from a bathymetry grid using the package raster in R (http://CRAN.R-project.org/package=raster). A quality checking procedure was used to filter 224 records of depth layer data. Tiered grids of the global ocean data analysis (http://catalogue.myocean.eu.org/static/resources/myocean/pum/MYO2-ARC-PUM-002-ALL_V4.1.pdf) were assembled with the bathymetry grid using a depth tiered upscaling process carried out by a python script (Yesson et al., 2015a). Transformations were made to normalise the distribution of slope (log transformed) and current data (square root transformed) based on a manual inspection of distribution profiles. Variables showing high correlation can confound model fitting, therefore a pairwise correlation analysis of environmental layers was performed using Pearson correlation with the 'cor' function in the stats package of R (version 2.11.1, http-//www.R-project.org/) (Supplmentary Table SI). For pairs of variables showing high correlation (>0.9), one of the pair was excluded from the analysis. Rugosity (correlated with slope) and salinity (correlated with temperature) were removed at this stage.

Several methods have been developed to classify and describe habitats (Brown et al., 2011). Support Vector Machines (SVM) are a class of learning algorithm that are often used for supervised image classification tasks (Lu et al., 2011). An SVM model was implemented using the e1071 R package (Meyer et al., 2014). SVMs can support nonlinear classes by transforming the data using a kernel function into a high-dimensional feature space (Boser et al., 1992). The SVM model requires the assignment of two parameters: cost (C), which determines the quantity of data included in creating the decision boundary - a small value will consider more observations, and gamma (ɣ) - the kernel smoothing parameter that defines the shape and complexity of the resulting decision boundary. A range of values for both parameters were investigated based on the recommendations of Chang and Lin, (2011), these were C (range: -5:-13) and ɣ (range: -13:-

3). The combination of cost and gamma producing the best performing model was used for the final analysis. Evaluation of the model was based on a comparison of the predicted and actual class of the evaluation data. The Table of Agreement tabulates the predicted and observed classes, with proportions on the diagonal of this table signifying the number of correct predictions in each class. The Diagonal metric is derived from the Table of Agreement and is the overall proportion of correct predictions. The Kappa (κ) statistic is an adjustment of the proportion of correct predictions corrected for chance agreement. Both the Diagonal and Kappa metrics have a range of 0-1, with higher values indicating better performance.

2.4 Confidence assessment

The image-base habitat classifications were compared with physical samples collected in an ad hoc manner using a grab sampler from 14 stations in 2015 (Fig. 1). The sediments were kept in 1.5 mL tubes before examination under a microscope (x400 magnification). Microscope images were taken with a Leica camera DFC 420C and images inspected for grain size analysis using Image J software (Schneider et al., 2012). Grain-size analysis is important to determine benthic habitat because the biology of any area of seabed with a grain size of mainly 2mm will be extremely different to the biology of seabed with cobbles or boulders (Wilson and Ramsay, 2009). Finally, an independent evaluation of model predictions were performed using seabed characteristic descriptions based on reports by fishermen for 30 traditional shrimp fishing areas along the west Greenlandic coast (Lassen et al., 2013, see Fig. 1). Although the categories presented in these reports are not an exact match to those used in this study, it is possible to group them together for comparative purposes. Four seabed categories used by Lassen et al. (2013) match the habitat classes presented in this study: mud substrate, gravelly muddy (an amalgamation of several categories - see Supplementary Table S2), bedrock with mud sediment (described as mixed rock with mud bottom / mixed but mostly muddy or rock with sometimes mud) and rock. No classes with sand substrate were directly described in Lassen et al. (2013). For this purpose, muddy-sand class, bedrock with sand sediment and gravelly sand were grouped with the closest substrate: mud, bedrock with mud sediments, and gravelly mud respectively. One thousand random locations with the reported fishing areas were selected and assigned seabed characteristics from Lassen et al. (2013) for comparison with model predictions.

3. Results

3.1 Habitat Classification

Seven habitat classes were identified as relevant for a broad-scale classification of the West Greenland continental shelf (Fig. 2, 3 and Table 1). Mud sediments (M) (grain size <0.06mm) were identified by the softness of the sediments as well as the presence of invertebrate burrows. Muddy-sand (mS) sediments are identifiable by the presence of ripples on the seabed as well as the contrast between the mud and sand sediments. The mixed sediments such as gravelly muddy (gM) are found usually with some small pebbles (2-4mm). Coarse sediment such as gravelly sandy (gS) is recognizable by the presence of animal tracks that are specific to sandy sediments with pebbles (4-64mm). Areas with no unconsolidated sediments visible are described as coarse rocky ground. Bedrock with sand sediment (sR) or mud sediment (mR) are kept distinct from the other classes because there are significant areas where bedrock occurs at the seabed surface in association with a thin, often discontinuous, covering of sediment.

3.2 Habitat classes and environmental conditions

The categories mud and gravelly mud appear mostly in deeper waters (Fig. 3). Coarse sediments including bedrock with mud, sand sediments and gravelly sandy areas are found in the same geographic range as rocky areas. However sandy substrates (sandy bedrock and muddy-sand) are present in shallower areas. These classes are strongly separated by temperature and latitude, with muddy areas (mR, M, gM, mS) appearing in northern, colder areas and sandy and rocky areas typically encountered further south in warmer regions with stronger currents. Gravelly sandy substrate incorporates the largest variation in temperature and latitude and is the most widespread sediment along the coastline of the West Greenlandic shelf (Fig. 5).

3.3 Predictive model

The SVM habitat classification model used an optimised cost value of 2 and gamma of 0.5. The overall accuracy, based on an evaluation of predictions for areas with direct observations, demonstrated good model performance. The proportion of correctly predicted sites (Diagonal statistic) is 0.84 with a kappa statistic of 0.81. The table of agreement presents the proportions of classes that are correctly classified (Table 3). The classes best predicted by the model are : gravelly sandy substrate (proportion correctly identified 0.91), coarse rocky ground (0.88), gravelly muddy (0.87), muddy-sand (0.86) and mud (0.85).

Habitat class bedrock with thin layer of mud, (proportion correctly identified 0.76) and bedrock with thin layer of sand, (0.73) proved more difficult for the model to predict.

3.4 Habitat map

The SVM model used to predict habitat classes over the entire region (Figure 5) indicated that mud habitat covers the largest area (78,537 km^2) typically in deeper basin areas (>500m) particularly in the north of the study area and Disko Bay. Other habitat types covering a large extent are gravelly sandy (steep parts of continental slope), bedrock with mud sediment (along the coast) and gravelly mud. Coarse rock ground habitat is found at Toqqusaq and Sukkertoppen Banks. Rocky habitats (R, mR, sR) cover a little over a quarter of the region, in total 69,683 km^2. The proportion of each habitat class across NAFO regions is shown in Fig. 4.

3.5 Independent model evaluation

A separate evaluation of the model was performed using reports of seabed characteristics by fishermen (Lassen et al. 2013). There is broad agreement between our predictions and the independent evaluation data. Areas of highest agreement are found in small fishing banks (areas 1,2,4,8) in the range of 60-80% agreement, and even 100% agreement in some small regions near Nuuk. Lower agreement is found in areas described as uniformly rocky (areas 17, 24, 22), while the model presents a more complex picture of muddy and rocky habitats (Supplementary Table S2)

4 Discussion

4.1 Distribution of habitats

Overall, there is a general pattern that deep channels and basins are dominated by muddy sediments, while shallow banks and shelf have a mix of more complex habitats. There is a north south divide, where sedimentary habitats are more dominant in northern, cooler areas, under more direct influence of glaciers, where long, deep channels on a wide shelf and lower current speeds facilitate sedimentation (Dowswell et al., 2014; Yesson et al., 2015; Yesson et al., In Press). Further south there are a higher proportion of rocky habitats, possibly explained by warmer temperatures causing the retreat of glaciers deeper into fjords, so glacial facilitated deposition occurs inland, or is transported quickly over the narrow shelf by stronger current speeds (Boertmann and Mosbech, 2011). Mud habitat was the most commonly observed and predicted habitat, covering around a third of the region. Disko bay was shown to have extensive muddy habitat, which agrees with direct observations of thick seabed sedimentation linked to glacial retreat (Hogan et al., 2012). More mud was predicted for the Uummannaq area north of Disko Island, which is highly affected by glacial sedimentation (Dowdswell et al., 2014). The mixed seabed around Disko Bank may be associated with the proximity of numerous calving glaciers (Weidick and Bennike, 2007; Hogan et al., 2016), which deposit drop stones and sediments. The predominance of rocky habitats around Toqqusaq and Sukkertoppen Banks coincides with the outcrop of Paleogene basalt observed in Geology maps (Rignot et al., 2010).

4.2 Classification

The habitat classification system presented in this study is closely aligned to existing classification systems such as EUNIS and MAREANO (Table 1). Our scheme augments to the EUNIS classification by adding classes based on substrata characteristics, which has been recommended by Galparsoro et al. (2012). This closely follows the MAREANO scheme, designed for the Norwegian Arctic, which identifies more habitats based on substrata (Buhl-Mortensen et al., 2015). Our Greenlandic Arctic classification reveals similar patterns of mud substrate in deeper areas with weak currents, and gravelly sand sediments in shallower areas with stronger currents or wave action (Bellec et al., 2009).

Further work could be done to include habitats determined by biotic characters. Biotic characteristics can be used to describe seabed habitats, for example benthic bioherms (mound or reef-forming organisms) such as *Lophelia pertusa* reefs, have been described as deep-sea habitats within EUNIS. However, no cold-water reefs have been observed in our study area, the only direct observation of *Lophelia* on the Western shelf is on the shelf margin (between 800-1000 meters depth) in the Southern region (Tendal et al., 2013). Another potential bioherm in the region could be coral garden habitat, but the large gorgonians that typify these habitats such as *Paragorgia arborea* or *Primnoa resedaeformis* are incredibly rare occurrences on the West shelf, and have never been reported in dense aggregations (Jørgensen et al., 2014; Tendal, 1992).

4.3 Environment

Our classification was strongly related to temperature, which indirectly affects the seabed via influence on sea ice cover, glaciation and associated sedimentation and deposition (Thiede et al., 2011; Hogal et al., 2016). Slope is a proxy for substrate type, as highly sloped areas are subjected to less sediment deposition, resulting in the exposure of rocky outcrops (Genin et al., 1986). No clear pattern of habitat class and slope emerged here, which may result from the coarse spatial resolution failing to detect important local scale patterns (Wilson et al., 2007), or from sampling bias (as the drop camera is designed for use in flat environments and often fails in high sloping areas).

4.4 Methodology

There are important methodological issues to consider when evaluating this study. The quality of the environmental data was the main foundation of the model developed here. Habitat modelling is a predictive tool and consequently the environmental variables used should not be considered to be perfect descriptors of the deep-sea environment. Spatial resolution was an important characteristic in our study that influenced the resulting habitat map. Seabed habitats can vary over relatively short distances, and our predictions assign single habitat classes to 3.5 x 3.5 km grid cell, which may encompass multiple habitats. Using environmental data at finer scales would provide better resolution, and would give better detection of smaller features that can be missed on coarser grids (Rengstorf et al., 2012). However, climatic factors, such as temperature, which was important to our model, have higher spatial autocorrelation than topographic features and are often more suited to continental scale analyses (Pearson and Dawson, 2003). The characteristics of currents present in a region did not emerge as strong predictors of habitat classification in this study. Improvement of the spatial resolution of current data will potentially improve the influence of this variable in distribution modelling (Yesson et al., 2012).

4.5 Trawling

One potentially habitat-transforming variable not considered in this analysis was trawling, which is widespread in the region (Yesson et al., in press). Deep-sea benthic habitats can be especially vulnerable to fishing impacts (Watling and Norse, 1998; McConnaughey et al., 2000; Roberts, 2002). Trawling gears shift boulders and flatten sedimentary bedforms causing an increasingly homogenous habitat as trawling persists

(Rice, 2006). This can result in the reduction of rocky habitats and an increase in soft sediment areas. In our habitat map, rocky habitats were less common than flat, muddy habitats. It is difficult to discount the possible impact of long term trawling in shaping the habitats of the region as the West Greenland Coldwater Shrimp Trawl Fishery has targetted *Pandalus borealis* between depths of 150 and 600m since the 1950s (Lassen et al., 2013). The impact of the fishery has been focussed on soft sediment regions such as Disko Bay (Hammeken Arboe, 2014), but regions with rockier habitats have been trawled and the impact on these areas may be more detrimental to benthic fauna (Yesson et al. in press). As the shrimp move northwards in response to changing environmental conditions (Jørgensen et al., 2013), habitat maps such as the one presented in this study can provide useful information for conservation management.

5 Conclusion

This is the first attempt at benthic habitat classification for the West Greenland shelf. A map of this classification is provided as supplementary material and will be a useful tool for researchers, managers and conservationists.

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Figure Captions

Fig.1. Location of sampling stations within statistical areas of the Northwest Atlantic Fisheries Organisation (NAFO areas 1A-1F). Seabed photographs were taken on five cruises over five years between 2011 and 2015. (Map coordinate reference system epsg:3411)

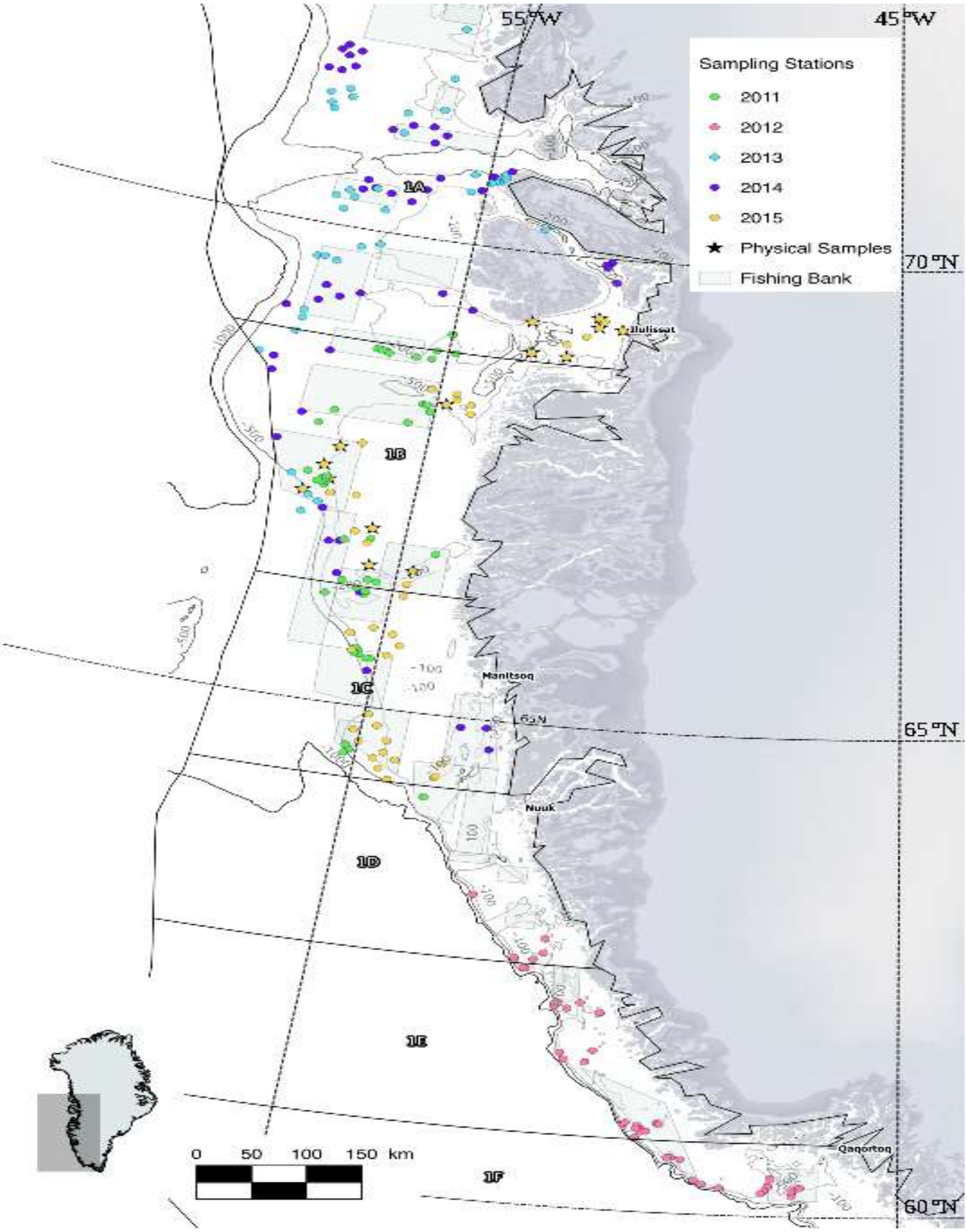


Fig. 2. Benthic images illustrating each of the seven habitats encountered. (A) Muddy sand sediments with ripples and invertebrates burrows at a depth of 310 meters. (B) Muddy sediments with invertebrate burrows and Pandalus borealis (Decapoda) at a depth of 374 meters. (C) Bedrock with mud (<0.06mm), boulder (0.25-3m) and pebbles (4-64mm) at a depth of 269 meters (large sponge coral (Porifera), Ascidians (Ascidiacea), brittle stars (Ophiuroidea), worms (Sabellidae), bryozoans (Bryozoa) and Decapoda). (D) Bedrock with sand (0.06-2mm) sediment with boulder (0.25-3m) and pebbles (4-64mm) at a depth of 164 meters (Bryozoans (Bryozoa), shells (Bivalvia), brittle stars (Ophiuroidea), and Zoantharia sponges (Porifera)). (E) Gravelly muddy sediments (<0.06mm) at a depth of 198 meters (bryozoans (Bryozoa), shells (Gastropoda), brittle stars (Ophiuroidea), sea anemones (Actinaria) and sponges (Porifera)). (F) Gravelly sandy sediments (0.06-2mm) with animal tracks at a depth of 175 meters (bryozoans (Bryozoa), shells (Gastropoda)). (G) Coarse rocky ground with occasional boulder (0.25-3m), cobbles (64-256mm) and pebbles (4-64 mm) at a depth of 388 meters (soft corals (Alcyonaceae), Stylasteridae, Zoantharia sponges (Porifera), hydroids (Hydroidolina), bryozoans (Bryozoa), Gastropoda, sea brittle stars (Ophiuroidea), worms (Nemertea) and chiton (Polyplacophora)).

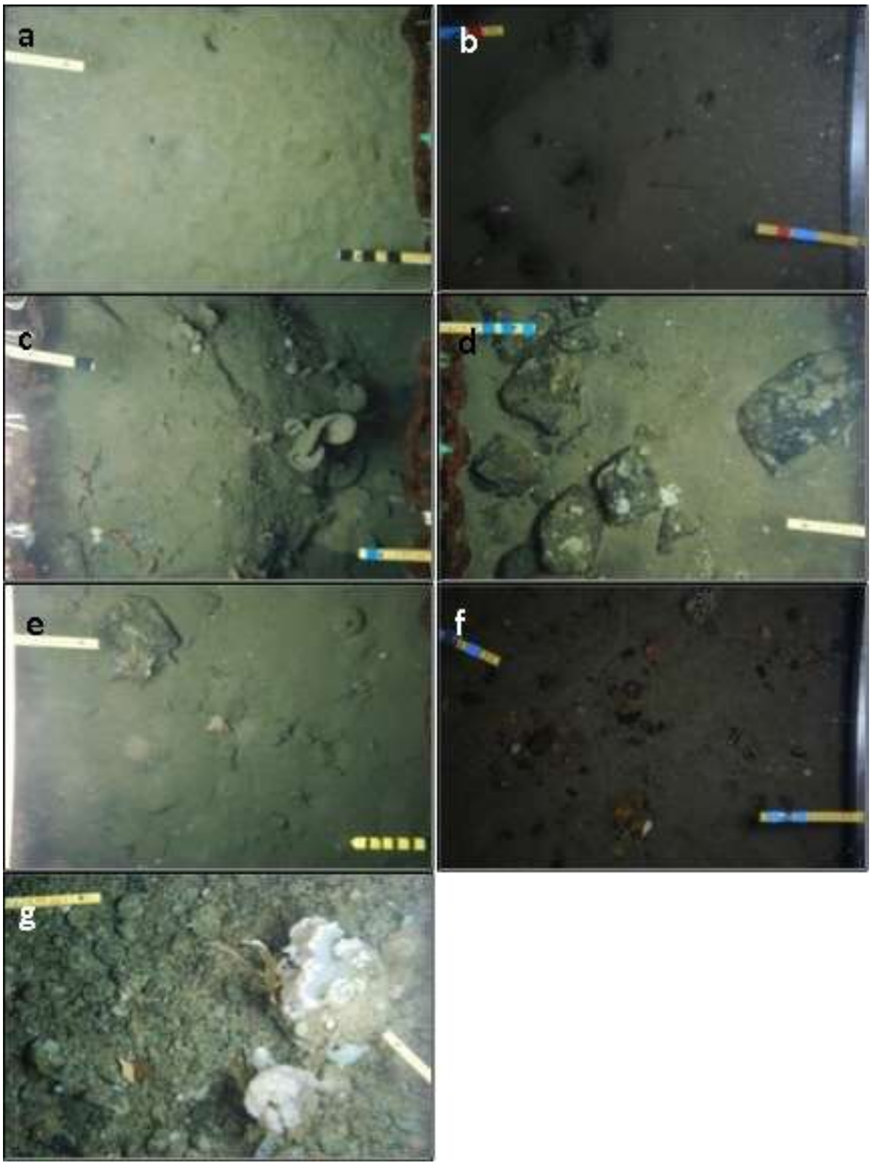


Fig. 3. Box plots of the main environmental variables gathered from observation data: Depth (m), Temperature (°C), Latitude (°N) plotted against substrate types. Horizontal lines indicate median values, boxes indicate quartiles, whiskers show standard deviation, and open circles are outliers.

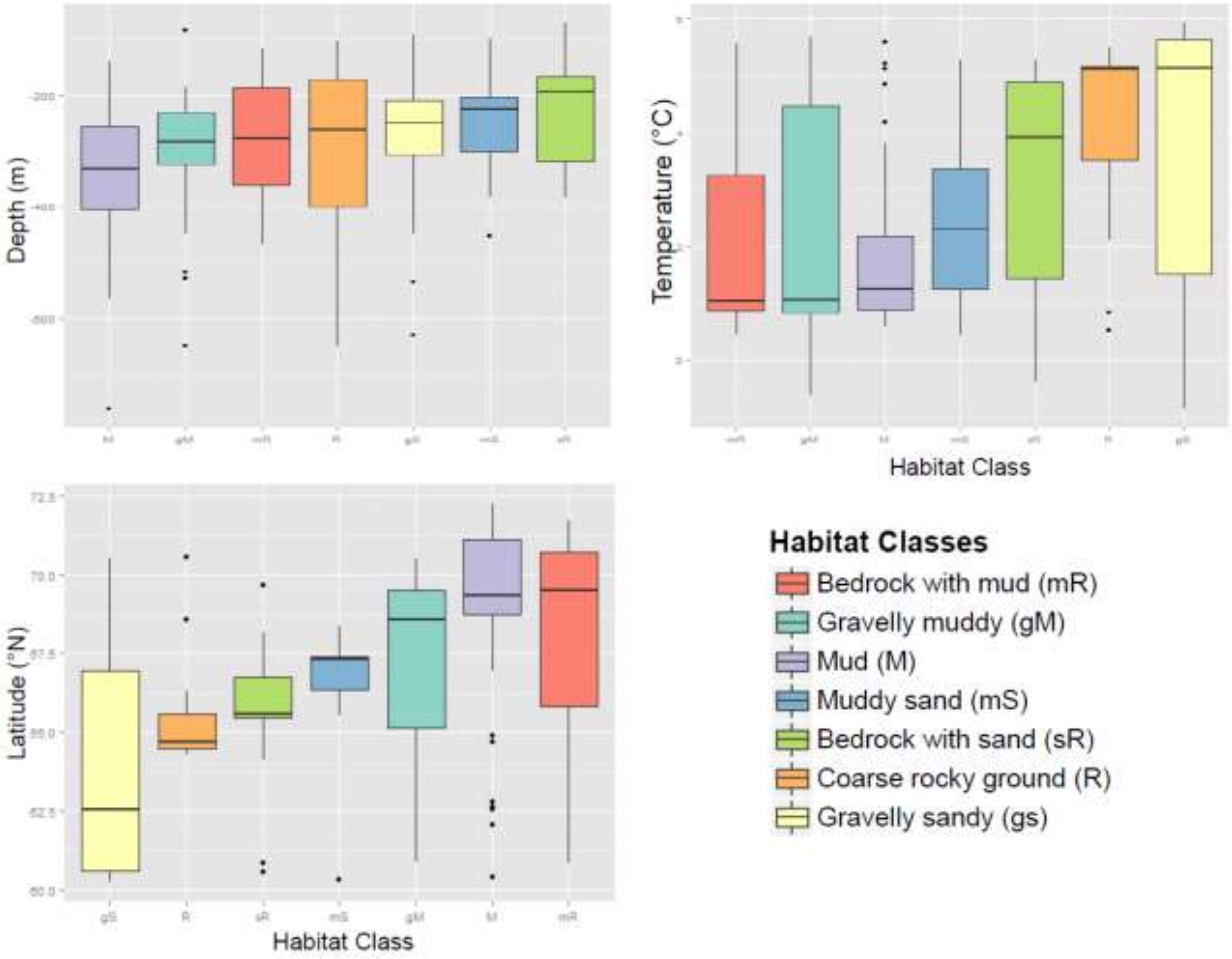


Fig. 4. Habitat class proportion by NAFO regions. Bar plot widths are proportional of the subsequent NAFO area and total areas for each habitat class are represented in the legend (km^2).

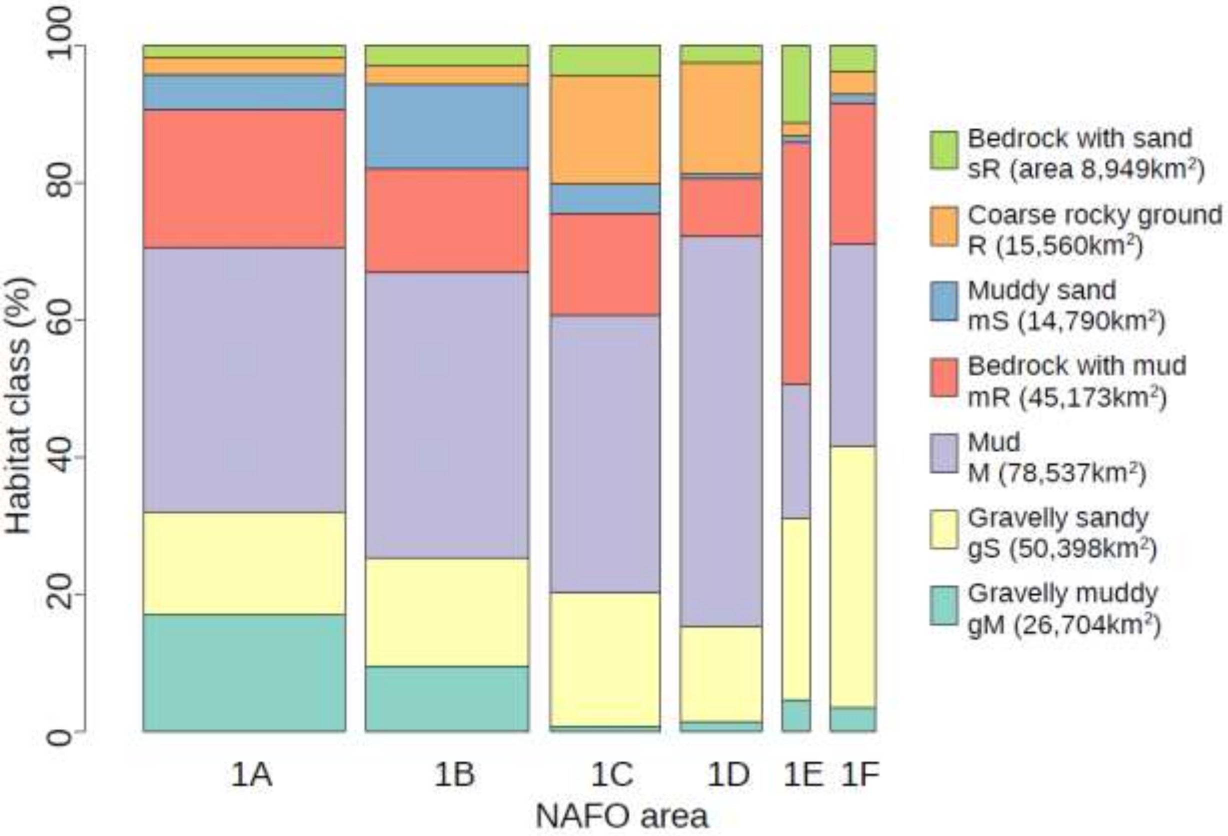
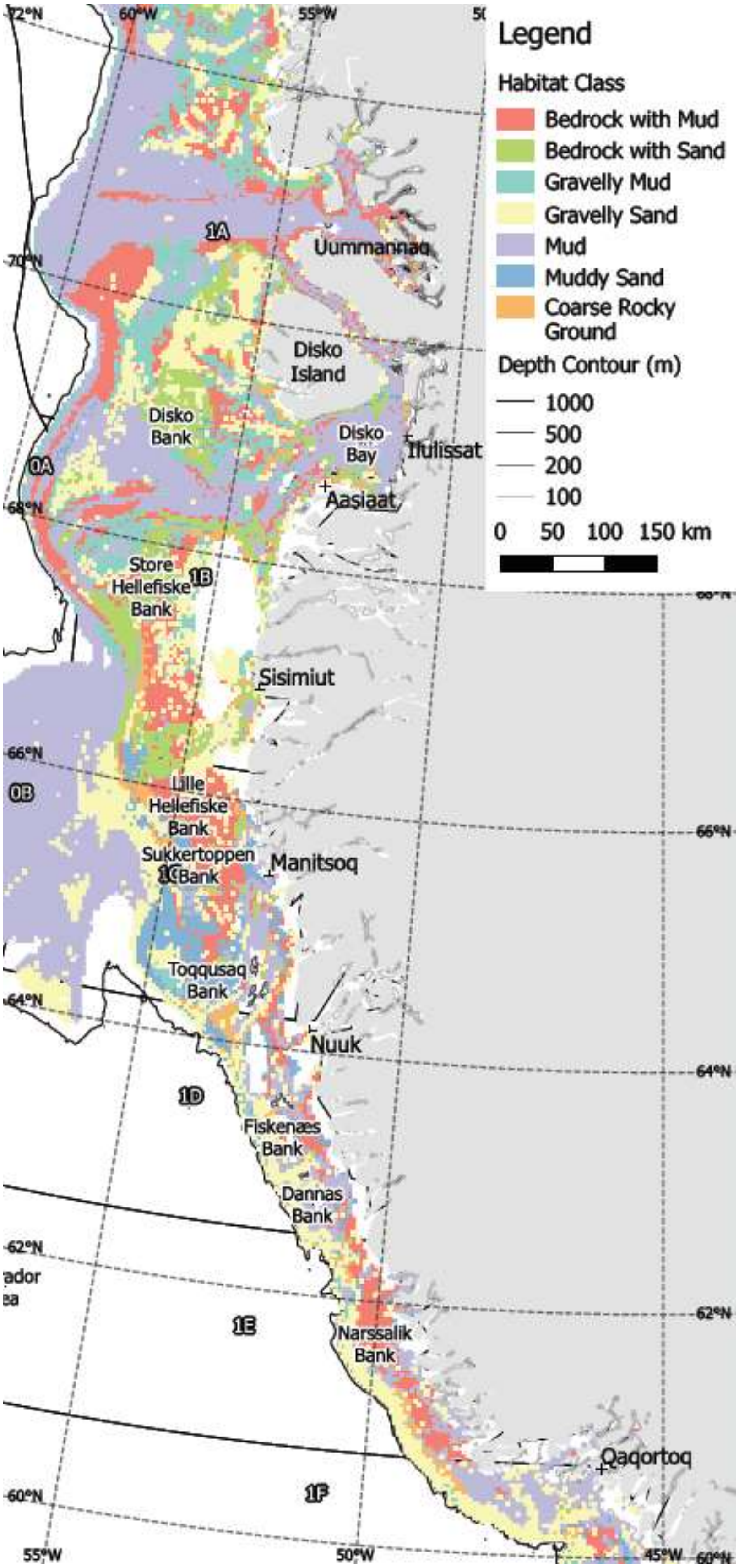


Fig. 5. West Greenland habitat map developed with an image survey and a SVM model approach. Map coordinate reference system epsg:3411.



Tables

Table 1

A comparison of the habitat classification system used in this study with the EUNIS and MAREANO schemes.

EUNIS (Level 3) (Davies et al., 2004)	**MAREANO (Bellec et al., 2009)**	**Structure of the proposed habitat classification system**
A6.1: Deep-sea rock and artificial hard substrata	Bedrock	Coarse Rocky Ground
A6.2: Deep-sea mixed substrata	Gravelly sandy mud	None
	Gravelly muddy sand	None
	None	Gravelly mud
	Gravelly sand	Gravelly sand
	Sandy gravel	None
	Gravel, cobbles and boulder	None
A6.3: Deep-sea sand	Sand	None
A6.4: Deep-sea muddy sand	None	Muddy sand
None	Sandy mud	None
A6.5: Deep-sea mud	Mud	Mud
A6.6: Deep-sea bioherms	Not described	No bioherms have been observed in Greenland (only once in the shelf margin (Tendal et al., 2013))
A6.7: Raised features of the deep- sea bed	Not described	Not described
A6.8: Deep-sea trenches and canyons, channels, slope failures and slumps on the continental slope		
A6.9: Vents, seeps, hypoxic and anoxic habitats of the deep-sea Level		
Not described	Thin/discontinuous sediment cover	Bedrock with Mud, boulder and pebbles Bedrock with Sand, boulder and pebbles

Table 2

Environmental variables used in this study for habitat mapping with description and references. IBCAO = International Bathymetric Chart of the Arctic Ocean (http://www.ibcao.org/). MyOcean has been renamed as the Copernicus marine environment monitoring service (http://marine.copernicus.eu/)

Variable	Source	Native resolution	Unit	Description
Depth	IBCAO	0.5 x 0.5km	Meters	Derived from IBCAO bathymetry layer and downscaled using QGIS.
Fine Scale Slope	IBCAO	0.5 x 0.5km	Degrees	Produced by terrain analysis in QGIS from IBCAO bathymetry grid and then downscaled within QGIS.
Coarse Scale Slope	IBCAO	3.5 x 3.5km	Degrees	Slope layer produced in LandSerf, from IBCAO bathymetry grid, with values representing slope over a distance of 35km.
U	MyOcean	12.25 x12.25km	Meters per second	Current value detailing velocity in metres per second from West to East, from the TOPAZ4 Arctic Ocean Reanalysis dataset, and up-scaled.
V	MyOcean	12.25 x12.25km	Meters per second	Current value in metres per second from South to North, taken from the TOPAZ4 Arctic Ocean Reanalysis dataset, and up-scaled.
Temperature	MyOcean	12.25 x12.25km	Degrees Celsius	Obtained from TOPAZ4 Arctic Ocean Reanalysis dataset, upscaled using a cookie cutter process from a bespoke python script.

Table 3

Table of agreement for the best performing model. (gM= Gravelly muddy, gS = gravelly sandy, M=mud, mR=bedrock with mud, mS=muddy sand, R=coarse rocky ground and sR=bedrock with sand).

Observed \ Predicted Class	gM	gS	M	mR	mS	R	sR	Total	Agreement
gM	26	2	1	0	1	0	0	30	0.87
gS	1	39	0	2	0	0	1	43	0.91
M	4	0	41	3	0	0	0	48	0.85
mR	4	1	4	32	1	0	0	42	0.76
mS	0	3	0	1	25	0	0	29	0.86
R	1	0	1	0	0	15	0	17	0.88
sR	0	0	1	2	1	0	11	15	0.73