



# Using habitat suitability modelling to assess the relationships between shrimp trawling and the distributions of deep sea corals

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Declaration of Own Work

I declare that this thesis, 'Using habitat suitability modelling to assess the relationships between shrimp trawling and the distributions of deep sea corals,' is entirely my own work, and that where material could be constructed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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#### List of Acronyms

- AUC Area Under Receiver Operating Curve
- CRS Coordinate Reference System
- GINR Greenland Institute of Natural Resources
- IBCAO International Bathymetric Chart of the Arctic Ocean
- IOZ Institute of Zoology, Zoological Society London
- MTSS Maximum Training Sensitivity plus Specificity Omission Value
- MTSST Maximum Training Sensitivity plus Specificity Test Omission Value
- NAFO Northwest Atlantic Fisheries Organization
- QGIS Quantum Geographic Information System
- ROC Receiver Operative Characteristic
- ROVs Remote Operated Vehicle
- U Current velocity in metres per second from West to East
- V Current velocity in metres per second from South to North
- WGS West Greenland Shelf

#### Abstract

The West Greenland shrimp fishery is currently undergoing an evaluation having been preliminarily awarded the MSC label of sustainability. As part of this, an understanding of the benthic environment and the relationship to fishing practices is required. However, assessing the state of benthic habitats of the deep sea is challenging due to a lack of occurrence records and the expense of additional sampling. Habitat suitability modelling is one method that can deliver predictions of suitable habitat locations of important species despite small data sets, and assess the influence of fishing activity.

This project has produced the first habitat suitability models for important corals across the fishing grounds of the West Greenland Shelf. Three important coral groups were studied, the gorgonian sea fan *Paragorgia arborea*, the soft coral family Nephtheidae, and the Pennatulacea, an order which consisted of data from two families for this study. Outputs from the modelling process were analysed to identify key predicted habitat areas, the importance of different environmental variables, and the relationships of these coral with fishing activity.

Fishing pressure was not a significant variable in the production of habitat suitability models for any of the coral groups. However, analysis of habitat suitability models excluding fishing pressure indicated more complex relationships may be at hand. The results of this study can help direct future *in situ* research, and can inform policy and fishing practices in order to ensure the protection of the benthic environment.

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## 1. Introduction

Humans have exploited resources from the oceans for thousands of years. However, modernization has dramatically changed the landscape of fishing practices, with expansions over the last 50 years occurring at a faster rate than ever before (Jennings, Kaiser & Reynolds, 2009). The development of new technologies, alongside the demands of an increasing human population, has led to fisheries being exploited to their maximum levels, or often, overexploited, leading to stock collapse (Jennings, Kaiser & Reynolds, 2009, Hutchings & Reynolds, 2004). Further to this, fishing practices often have severe negative impacts on non-target species and the wider environment (Frank et al., 2005, Roberts, 2002, Koslow et al., 2001).

Fisheries currently extract around 90 million tonnes from the ocean annually. However, catch levels have fallen each year since the late 1980's by approximately 0.4 million tonnes (Jennings, Kaiser & Reynolds, 2009, Morato et al., 2006). In the face of reduced yields from shallow seas, and aided by new technologies, industrial fishing has progressed to deeper parts of the oceans to exploit new stocks that can meet the demand of an expanding and more affluent human population (Norse et al., 2012, Morato et al., 2006). However, the deep sea is famously understudied, and the potential impacts for the deep sea marine environment from these fishing practices are considerable and numerous (Glover & Smith, 2003, Roberts, 2002). Concerns have been raised about the sustainability of deep sea stocks due to the life history traits of species found there; being long lived with low fecundity results in extremely vulnerability to population reductions from which recovery is not possible (Norse et al., 2012).

Conserving the marine environment by minimising the impact of fisheries is essential to maintain ecosystem functioning within the oceans (Worm et al., 2006). One method to help protect the marine environment is to encourage fisheries to adopt fishing practices that look to minimise negative impacts. This has been aided by a consumer preference for sustainable seafood products, resulting in demands for sustainable products from supermarket suppliers (Jaffry et al., 2004, Cummins, 2004). Many supermarkets now consider a sustainability label an essential requirement for any seafood products, with supermarkets such as Sainsbury's committing to only stocking sustainably certified seafood by 2020 (Sainsbury's, 2014, Cummins, 2004). The largest eco-labelling scheme for the identification of seafood products that can demonstrate sustainability and traceability is the MSC label from the Marine Stewardship Council (Christian et al., 2013). In order to achieve the MSC label, each business in the product supply chain has to undergo a traceability audit and meet the MSC Chain of Custody standard. Each fishery that undergoes an evaluation is assessed on three principles (Cummins, 2004):

- 1) Sustainable fish stocks
- 2) Minimise environmental impact
- 3) Effective management

#### 1.1 The West Greenland Shrimp Fishery

The West Greenland shelf (WGS) has been the site of major fishing industries since the early 1920s, originally founded on the exploitation of cod (Hamilton, Brown & Rasmussen, 2003). However, collapse of this fish stock in the 1970s resulted in a shift of fishery target to the deep water shrimp, *Pandalus borealis*, which was previously subject to a small scale inshore fishery that began in 1935 and had begun expansion in the 1950s (Lassen et al., 2013, Kingsley, 2007). This new fishery developed rapidly from 1972, and in 2009 accounted for over half the value of total exports from Greenland, contributing DKK 1 billion to a total export of DKK 1.9 billion (Lassen et al., 2013). The fishery currently maintains 44 vessels that catch the shrimp through the use of otter trawls, large cone shaped nets dragged along the sea floor. The invention of more sophisticated equipment, such as rolling rockhopper gear, has facilitated an expansion of fishing grounds, while also reducing the potential impacts on benthic habitats (Lassen et al., 2013, Hamilton, Brown & Rasmussen, 2003, Watling & Norse, 1998).

#### 1.1.1 MSC Evaluation

The West Greenland shrimp fishery is currently undergoing an evaluation of fishing practices, after being preliminarily awarded the MSC sustainability badge. In order to achieve the 2<sup>nd</sup> principle of the MSC standard, to minimise environmental impact, a detailed assessment of the impact on the benthic habitat must be carried out (Lassen et al., 2013). The Institute of Zoology (IOZ), as an independent organisation, has been asked to carry out this process. To help inform the decision on awarding the MSC sustainability label, an understanding of the environmental factors, habitat types and species distribution of these regions is essential, yet remains challenging due to the constrictions created by the deep sea environment (Ramirez-Llodra et al., 2010). A major component of the benthic habitats along the WGS are deep water corals, yet our understanding is severely limited by small sample sizes (Jorgensen, Tendal & Arboe, 2013). As habitat building components of the marine ecosystem, knowledge of any relationship between corals and trawling activity can greatly benefit the sustainability assessments of benthic habitats.

Due to the impracticalities of collecting continuous distributions of species such as corals, information must be extracted from the limited data records available. Habitat suitability modelling is a method of research that can deliver mapped predictions of distributions from small numbers of occurrence records, and is therefore extremely beneficial in areas where direct studies are difficult

to carry out, such as the deep ocean (Yesson et al., 2012, Bryan & Metaxas, 2007). For the West Greenland shrimp fishery assessment, habitat distribution models can provide descriptive information on the distribution of important deep sea corals. Further to this, relationships between corals and fishing activities can be investigated by incorporating fishing activity into the model production process, or by analysing the model distribution outputs alongside records of fishing activity. An understanding of relationships between the predicted areas of suitable habitat and fishing pressure can identify if any of these key habitat areas are vulnerable to fishing. Identification of coral habitat areas, and discovering potential vulnerabilities to fishing, can provide policy makers with expanded knowledge on the benthic environments over which their fishery operates, and thus aid the development of management strategies to achieve MSC sustainability.

#### 1.2 Aims

This project has two main aims. Firstly, it will produce habitat suitability models across the extent of the West Greenland shrimp fishing grounds for 3 key groups of deep sea corals. Outputs from these models will then be used for the second project aim, to assess relationships between fishing activity and suitable coral habitat.

Coral groups were defined to select deep sea corals that are thought to be interacting directly with fishing activities; that demonstrate life history characteristics that may be important to fishing activity relationships; and that make allowances for difficulties in identifying deep sea corals to the species level. The groups are as follows:

- 1. *Paragorgia arborea* A single species of sea fan which has, according to local fishermen reports, become less common within bycatch over recent years (Yesson, pers. comm.). The species is known to be extremely vulnerable to fishing impacts, suggesting the potential population decline may have been caused by fishing practices (Murillo et al., 2011).
- Nephtheidae- A family of soft corals which are the most common corals caught as bycatch along the West Greenland shelf (Jorgensen, Tendal & Arboe, 2013). As such, it is important to understand how they are impacted by disturbance from fishing activities.
- 3. Pennatulacea- An order of 16 families commonly called sea pens. This study will examine data from the Pennatulidae and Umbellulidae, the two most common families within the West Greenland fishery grounds (Jorgensen, Tendal & Arboe, 2013, Williams, 2011). They inhabit soft sediments, which are areas most commonly trawled by the shrimp fishery, potentially bringing about human impacts (Lassen et al., 2013, Williams, 2011).

In order to meet the project aims, the following objectives will be completed:

- Compile a database of coral group occurrence sites across the WGS.
- Produce suitable environmental variable raster grids to describe conditions of the benthic environment across the WGS and at coral occurrence sites.
- Create habitat suitability models for all coral groups across the fishing grounds on the WGS.
- Assess whether there is a relationship between the habitat suitability of each coral family and fishing pressure.

## 2. Background

#### 2.1 The Benthic Habitats of the Deep Sea and the Impact of Fishing

Maintaining biodiversity levels within deep sea environments is of critical importance to the ecosystem functioning and efficiency of global oceans (Danovaro et al., 2008). However, research has highlighted the vulnerabilities of these ecosystems to human activities (Roberts, 2002). A common form of deep sea fishing is trawling, but several studies have identified damage caused by this activity in many areas, including around the UK and Ireland, off the coast of Norway, and at sea mounts around New Zealand and Tasmania (Clark & Rowden, 2009, Hall-Spencer, Allain & Fossa, 2002, Koslow et al., 2001). Trawling has been found to have a variety of impacts on the sea floor and the benthic communities that inhabit the area, and been compared as having similar effects to the clear-cutting of terrestrial forest environments (Watling & Norse, 1998). In physical terms, the continued scraping along the sea floor from regular trawling results in a much smoother profile to the sea bed, and as such, there is much less habitat variety for organisms (Puig et al., 2012, Clark & Rowden, 2009). It is also thought to result in a number of changes to benthic ecosystems, by altering the community from one dominated by large sessile taxa such as corals and sponges, towards smaller, more motile species that are opportunistic feeders (Clark & Rowden, 2009, Kaiser et al., 1998).

Deep sea corals create habitats that hold high biological diversity, and are likely to be important to many species of fish and invertebrates across various life stages (Edinger, Wareham & Haedrich, 2007, Stone, 2006, Etnoyer & Morgan, 2003). They provide nurseries for juvenile organisms, providing shelter and protecting them from predators and strong currents, by providing shelter (Roberts & Hirshfield, 2004). Further, the importance of deep sea corals extends to larger animals, with 85% of large rockfish associated with corals despite no threats of predation as adults, yet this species is not predated as an adult form, suggesting other important relationships such as egg laying sites (Etnoyer & Morgan, 2003, Krieger & Wing, 2002). The direct relationships between motile animal species and corals is difficult to accurately ascertain due to their ability to travel across different habitats, however, it seems likely they play an important role for many commercially important species, due to the common occurrence of coral bycatch found within bottom contact fishing gear (Edinger, Wareham & Haedrich, 2007, Heifetz, 2002). These trends, of encouraging species diversity but being vulnerable to destructive activities, have resulted in a drive to identify and protect areas of coral occurrence (Bryan & Metaxas, 2007).

Corals are animals from the phylum Cnidaria that have "continuous or discontinuous calcium carbonate or horn-like skeletal elements" (Cairns, 2007). Deep sea corals are those that occur below

50m, and are thought to account for 65.6% of all coral species (Cairns, 2007). They differ from their shallow, tropical watered relatives due to a lack of the symbiotic algae that are able to photosynthesize (Cairns, 2007, Roberts & Hirshfield, 2004). Instead, deep water corals are filter feeders relying on ocean currents to draw nutrients, such as microscopic organisms or detritus, past them (Bryan & Metaxas, 2007, Roberts & Hirshfield, 2004). Deep sea corals can be exceptionally long lived which makes them extremely vulnerable to destructive human activities (Bryan & Metaxas, 2007). They are also difficult to identify to the species level, with reclassifications common, due to a lack of data, poor understanding of species boundaries, and the widening of genetic analysis (Herrera, Shank & Sánchez, 2012, Williams, 2011, Heifetz, 2002).

#### 2.1.1 Paragorgia arborea

*Paragorgia arborea* is the most common species of the family Paragorgiidae found in the North Atlantic Ocean (Herrera, Shank & Sánchez, 2012). It can grow to sizes above 2.5m, though the use a thickly branched structure, that often occurs in the form of a fan-shaped colony (Mortensen & Buhl-Mortensen, 2005, Etnoyer & Morgan, 2003). *P. arborea* is a filter feeder, so depends on water currents in order to bring food particles past the colony (Mortensen & Buhl-Mortensen, 2005). It has been found in densities of up to 49 colonies per 100m<sup>2</sup> off the coast of Nova Scotia, but within areas of suitable habitat distribution is often patchy, indicating the influence of local scale factors on individual location (Mortensen & Buhl-Mortensen, 2004). The size, age and slow growing nature of *P. arborea*, as well as their vulnerability to physical disturbances and habitat forming properties, indicate they are highly vulnerable to fishing impact (Murillo et al., 2011, Sherwood & Edinger, 2009).

Within the North Atlantic, previous studies suggest *P. arborea* inhabits a temperature range between 4 and 8°C, and a stable salinity around 35‰ (Tendal, 1992). Most of the occurrence records available for the species indicate that it tends to favour depths below 1000m, although it is capable of existing in a very wide range of depths (Herrera, Shank & Sánchez, 2012, Etnoyer & Morgan, 2003). Video surveys from remote operated vehicles (ROVs) have suggested they only occur in areas of hard substrate (Baker et al., 2011). Often, this is on substrate that protrudes above the sea floor, such as the tops of boulders, allowing the coral to extend out into stronger and more consistent currents (Murillo et al., 2011, Mortensen & Buhl-Mortensen, 2005).

#### 2.1.2 Nephtheidae

The Nephtheids are a family of soft corals that are found within both cold and temperate environments, and as such have a wide ranging distribution across the globe (Kenchington et al., 2009, Heifetz, 2002, Dinesen, 1983). Nephtheids are passive suspension feeders, and as such rely on

currents to bring a supply of food, including detritus (Sherwood et al., 2008). Species within this family, such as *Duva florida*, are commonly found at shallower depths than other deep water corals (Murillo et al., 2011). They seem to be tolerant of varying conditions, including low pressure and daily temperature changes that occur in laboratory experiments, which suggests a relatively variable habitat niche (Sun, Hamel & Mercier, 2011). Nephtheids attach to hard substrates, but can be found on both hard and soft bottomed environments (Murillo et al., 2011, Kenchington et al., 2009).

Studies have also highlighted the resilience of Nephtheid species. *Gersemia rubiformis* was found to be relatively resistant to disturbances that attempted to replicate the effects of trawling. The ability of this species to retract and survive repeated crushing highlights the possibility that this soft bodied coral family may be equipped to survive benthic fishing activities (Henry, Kenchington & Silvaggio, 2003). Some research suggests that if a fertile adult Nephtheid is broken apart, due to a destructive process like trawling, the fragments could potentially grow into viable offspring (Sun, Hamel & Mercier, 2011). However, the survival rates of *Gersemia rubiformis* offspring created in this manner were low, which questions the prospects for long term survival for these fragmented organisms (Henry, Kenchington & Silvaggio, 2003). The impacts of trawling on species belonging to the Nephtheidae family are clearly complex, with in situ experiments incredibly difficult to achieve.

#### 2.1.3 Pennatulacea

The Pennatulaceans, or sea pens, are a morphologically distinct order consisting of 16 families, with species found in a wide range of habitats and locations (Williams, 2011). An individual sea pen consists of a single large primary polyp called an oozoid, consisting of a muscular peduncle that is anchored into soft sediment, and a rachis, that pushes above the surface of the sediment into the ocean currents, where secondary polyps branch off into the currents to collect nutrients (Williams, 2011). As the peduncle requires anchoring, sea pen distribution is usually limited to soft sediment and can provide significant habitat variety in such locations, which can be of benefit to other organisms such as small invertebrates (Murillo et al., 2011, Tissot et al., 2006). As such, sea pens can act as important nursery grounds for many fish, including commercial stocks such as the redfish, *Sebastes ssp.* (Baillon et al., 2012). They are often caught as bycatch, suggesting that fishing may well have negative impacts on population numbers (Baillon et al., 2014).

Species from the Pennatulidae family more commonly occur at shallower depths than other sea pens, whereas the Umbelulidae family tend to feature at deeper locations (Baker et al., 2011, Williams, 2011, Langton et al., 1990). There is a significant lack of research for both the distribution and ecological factors associated with the Pennatulacea (Langton et al., 1990). Further to this,

difficulties of identifying organisms to the species level are prominent, with genetic analysis indicating that revisions may be required (Dolan et al., 2013).

#### 2.2 Habitat Suitability Modelling

Data collection on deep sea corals has traditionally been very expensive, using ROVs or submersibles to carry out visual surveys, or damaging, in the form of trawling or dredging and collecting bycatch samples (Stone, 2006, Mortensen & Buhl-Mortensen, 2004, Koslow et al., 2001). An alternative method, habitat suitability modelling, has gained popularity for predicting the potential distribution of species where little data is available or challenges prevent a large scale sampling process (Bean, Stafford & Brashares, 2012). Often it provides a viable option to study incomplete or past datasets, and is a practical and cost effective approach that can provide highly valuable predictions to benefit the conservation of species (Yesson et al., 2012, Elith et al., 2006).

Habitat suitability models have traditionally been produced using general-purpose statistical methods, which require both presence and absence data. However, absence data is rarely available, and difficult to collect accurately. Additionally, when trying to predict potential distributions of species, absence data brings with it the risk of reducing the effectiveness of the model by potentially restricting the use of suitable conditions. A location may be marked as absence data although the conditions may in fact be suitable; a lack of species presence could have been caused by other factors, such as biological interactions (Anderson, Lew & Peterson, 2003, Anderson, Peterson & Gómez-Laverde, 2002). Many methods, including Maxent and Ecological Niche Factor Analysis (ENFA), have been developed to overcome the need for absence data (Peterson et al., 2011).

#### 2.2.1 Maxent

Maximum Entropy Modelling, or Maxent, produces habitat suitability models via a form of machine learning, and has gained popularity within the scientific community since its release due to strong performance in many modelling experiments (Wisz et al., 2008, Phillips, Anderson & Schapire, 2006, Elith et al., 2006). Observation data is used to assess environmental variables from which the species of study is known to be able to exist within. The maximum entropy model uses environmental variable values at the occurrence locations to find the distribution of maximum entropy, which can be described as 'that which is most spread out, or closest to uniform', based on the constraints of the environmental factors at the occurrence sites and using comparisons of the variable ranges from surrounding background data (Phillips, Anderson & Schapire, 2006).

Maxent has been reported to outperform more classical methods for habitat suitability modelling, such as BIOCLIM and GARP, when dealing with small data sets (Wisz et al., 2008, Pearson et al., 2007). Often, the species most suitable for habitat suitability models are those that we know very

little about. As such, the data sets available for these organisms can be very small. Small data sets are widely considered a drawback to successful modelling, and can certainly limit the level to which a model should be relied upon (Bean, Stafford & Brashares, 2012). However, as the field of habitat suitability modelling advances, much work is going into developing appropriate techniques for producing these models from small data sets (Shcheglovitova & Anderson, 2013, Pearson et al., 2007).

#### 2.2.2 Habitat suitability modelling of deep sea corals

The nature of the deep sea ensures that habitat suitability modelling is one of the most appropriate ways in which to gain knowledge on these environments. As such, there are many studies that have used habitat suitability modelling to map deep water corals, ranging from single species, *Lophelia pertusa*, to global predictions of coral suborders (Yesson et al., 2012, Davies et al., 2008). Previous modelling attempts to predict habitat suitability for the Paragorgiidae family have found factors such as steep slopes and rocky substrate to be significant predictors, which highlight areas that are topographically complex (Bryan & Metaxas, 2007, Leverette & Metaxas, 2005). Other factors identified as important are temperature and chlorophyll a levels (Bryan & Metaxas, 2007). However, these studies have received some criticism for being at too course a resolution to accurately model some areas, and of not supporting models through in situ verification (Etnoyer & Morgan, 2007). While habitat suitability modelling studies for deep sea have been carried out in many areas, such as Newfoundland, Canada, Greenland has yet to be analysed except for global studies (Yesson et al., 2012, Murillo et al., 2011).

#### 2.3 Study Site

The study site for this project is the extent of the West Greenland shrimp fishery grounds. The Northwest Atlantic Fisheries Organisation (NAFO) defines this as regions 1 A-F although the actual areas of fishing vary from this (Figure 2.1). This study specifically looks at areas fished, so is limited to approximately 73° North, although reaches around the Eastern coast of Greenland to approximately 40° West. The extent of the study is further defined by a maximum depth of -1500m, leading to just over the boundary of the continental shelf.



Figure 2.1 - Fishing grounds of West Greenland as divided by the NAFO (NAFO, 2014)

## 3. Methods

#### 3.1 Methodological Framework

Due to the challenges associated with collecting large volumes of sample benthic species, habitat suitability modelling carried out in this research can improve the understanding of the wider benthic habitat across the WGS. Occurrence data was obtained from bycatch samples, camera station photos and a literature search and analysed alongside environmental data to assess what factors influence the locations of these organisms. The study also examined whether fishing pressure has a role in the habitat suitability models, which could infer an impact on benthic habitats. Analysis was carried out in QGIS version 2.2.0 Valmiera, R version 3.1.0, Microsoft Office Excel 2013 and Maxent version 3.3.3 unless otherwise stated.

Occurrence data of the selected coral groups will be collected and sorted into appropriate data sets. Alongside this, environmental variables will be produced from available resources for habitat suitability modelling. Creating habitat suitability models with fishing pressure as a variable allows the assessment of its impact on corals. If it is an important variable in the construction of the habitat suitability models, this suggests it has direct influences on occurrence distributions. Further methods to assess the relationship between potential habitats of corals and fishing pressure will be analysed by additional statistical analysis of habitat suitability models.

#### 3.2 Occurrence Data

Observations of coral specimens were gathered from three sources. Firstly, bycatch samples were collected from four research expeditions between 2011 and 2014 that were organised by the Greenland Institute of Natural Resources (GINR). The research vessel M/T Paamiut carried out bottom trawl surveys, using rock hopper ground gear. Trawls covered a depth up to 1500m, with trawl speeds ranging between 2.5 and 3 knots, and lasting 15 to 30 minutes. Coordinates of each trawl were recorded and logged alongside every bycatch sample collected from that same trawl. Bycatch from these trawls were frozen, and sent to IOZ for analysis, where coral samples were identified to the lowest taxon possible (Kenchington et al., 2009). Secondly, during these research trips, data were collected in the form of photographic images of benthic communities, using a weighted camera dropped to the sea bed. Pictures were taken directly overhead of a  $1m^2$  area, with coordinate data recorded for each camera drop location. Photograph images were then saved and have been analysed at IOZ, identifying all species to the lowest possible taxon. Coral data and coordinate locations were then extracted from the photographs.

Thirdly, a literature and database search was carried out for additional occurrence data for any species suitable for each coral group, as recorded in the Northwest Atlantic Fisheries Organization (NAFO) coral guide (Kenchington et al., 2009). The parameters of this search allowed for only recent historical data to be included (post 2000) due to the changing environmental conditions of the North Atlantic over time, most likely under the influence of climate change, that could have resulted in changes in areas of suitable habitat over time (Serreze et al., 2000). As species coordinates were not available from some literature, images of maps showing specimen locations were georectified (using the georeferencer plugin of QGIS v 2.2.0). Point locations were extracted from the georeferenced image by manually pointing and clicking on locations with specimens for each relevant family (using the Add Feature tool in QGIS). The distribution map data points were compared to locations already recorded in the vector layers to ensure no location data for a species was double entered.

Databases were created for each coral group containing coordinate location data. Records were removed from a dataset when more than one sample was recorded at the same location. Data accuracy was evaluated by comparing recorded depth from the bycatch samples with inferred depth from bathymetry data. Inferred depths were obtained from a bathymetry grid using the Point Sampling tool in QGIS. Records with differences of greater than 500m between the two depth values were omitted (Yesson et al., 2012). Furthermore, depth profiles from occurrence data were compared to profiled species depth ranges. Records outside the reported ranges by more than 100m were removed from the study (Kenchington et al., 2009).

#### 3.3 Environmental Data

Data on fishing levels by the West Greenland shrimp fishery were provided in the form of a raster grid by Dr Chris Yesson for the project, courtesy of data on the start and end point of trawl locations provided by GINR. This data grid contained the number of hours of shrimp trawling that took place between 1986 and 2010, across 3.5 x 3.5km pixels, resulting in a pixel area of 12.25km<sup>2</sup>. The data within this raster layer was log transformed using the RasterCalc plugin to produce a concise scale of fishing pressure (QGIS version 1.8.0 Lisboa). All other variables used were constructed to match these dimensions, in order to ensure uniformity for the modelling process.

Bathymetry data of the Arctic Circle was obtained from the International Bathymetric Chart of the Arctic Ocean (IBCAO), in the form of a raster grid of a resolution of 500 x 500m pixels (Jakobsson et al., 2012, IBCAO, 2012). The bathymetry grid was clipped and warped to a Coordinate Reference System (CRS) defined by the Log Fishing raster layer; this was a user constructed CRS that used the IBCAO CRS and rotated it to centralise Greenland (+proj=stere +lat\_0=90 +lat\_ts=75 +lon\_0=-45 +k=1 +x\_0=0 +y\_0=0 +datum=WGS84 +units=m +no\_defs). The Terrain Analysis tool in QGIS was used to

produce layers of slope and ruggedness. All 3 raster layers were then downscaled to a pixel size of 3.5 x 3.5km, to match the pixel size of the Log Fishing raster layer. An additional slope layer was constructed using LandSerf (v2.3) by examining the surrounding 35km (covering the nearest 10 pixels) using an inverse squared distance weighting. This represents a slope value representative of the broader continental shelf scale (Wilson et al., 2007).

Environmental layers of temperature, salinity and current velocity, in the form of U (m/s from West to East) and V (m/s from South to North), were obtained in the form of depth tiered monthly averages between the years 1991 to 2010, with a pixel size of 12.25 x 12.25km (MyOcean, 2014). Multi-year means were constructed using the command line raster calculator gdal\_calc.py (Yesson, 2014). Data were extracted to produce depth tiered raster grids over a five year average (2006 to 2010). Raster grids of the environmental conditions present at the sea floor were then obtained from the depth tiered raster grids through a 'cookie cutter' upscaling process, carried out by a bespoke python script by Dr C. Yesson first used by Taylor et al (2013) (Table 3.1) (Taylor et al., 2013, Davies & Guinotte, 2011). This used the project bathymetry layer to extract the environmental data relevant to the sea floor from the depth tiered grids, and upscaled the pixel size to 3.5 x 3.5km.

Background data is required for the habitat suitability modelling process in order to represent the range of environmental conditions that occur within the study site, while also acting as pseudoabsences when absence data is unavailable (Phillips & Dudík, 2008). Ten thousand random data points were selected for modelling through the random point sampling tool in QGIS. These were then used alongside the point sampling tool to drill down and collect the values directly under each point for each of the environmental raster layers. A correlation analysis was conducted using the environmental data from the background points. Environmental variables were compared against one another using a Spearman's Rank Correlation Coefficient, with high correlations (> 0.7) resulting in the removal of one of the correlated layers. If two environmental layers are heavily correlated then this can lead to over-fitting of the model; removing one of the layers from the analysis ensures the variables tested remain distinct (Yesson et al., 2012).

## Table 3.1 - Environmental layers constructed for habitat suitability modelling.

Environmental	Source	Original	Description
Layer Name		resolution	
Depth	IBCAO	0.5 x 0.5km	Derived from IBCAO bathymetry layer and
			downscaled using QGIS, the layer displays the
			depth of the sea floor.
Fine Slope	IBCAO	0.5 x 0.5km	Produced by terrain analysis in QGIS from
			IBCAO bathymetry grid and then downscaled
			within QGIS.
Coarse Slope	IBCAO	3.5 x 3.5km	Slope layer produced in LandSerf, from IBCAO
			bathymetry grid, with values representing slope
			over a distance of 35km.
Ruggedness Index	IBCAO	0.5 x 0.5km	Layer produced by terrain analysis in QGIS from
			IBCAO bathymetry grid and downscaled within
			QGIS.
Temperature	MyOcean	12.25 x	Temperature in degrees Celsius, from the
		12.25km	TOPAZ4 Arctic Ocean Reanalysis dataset, up-
			scaled using a cookie cutter process from a
			bespoke python script.
Salinity	MyOcean	12.25 x	Salinity (PSU) obtained from the TOPAZ4 Arctic
		12.25km	Ocean Reanalysis dataset; up-scaled using a
			cookie cutter process.
U	MyOcean	12.25 x	Current value detailing velocity in metres per
		12.25km	second from West to East, from the TOPAZ4
			Arctic Ocean Reanalysis dataset, and up-scaled.
V	MyOcean	12.25 x	Current value in metres per second from South
		12.25km	to North, taken from the TOPAZ4 Arctic Ocean
			Reanalysis dataset, and up-scaled.
Log Fishing	Dr C. Yesson	3.5 x 3.5km	Log values of number of hours trawled by the
	from data		Greenland shrimp fishery, 1986-2010
	supplied by		
	GINR		

The environmental conditions present at occurrence data locations were obtained using the point sampling tool. Data was then analysed in R to produce visual representations of variations in environmental factors relating to each coral group.

#### 3.4 Habitat Suitability Modelling

Habitat suitability models for each of the families were carried out using the software programme Maxent (Phillips, Anderson & Schapire, 2006). Data was input using the samples-with-data format, allowing for an increase in computing speed while not reducing model performance, while also ensuring chosen background data was used for modelling (Phillips & Dudík, 2008). Models were only produced to map habitat suitability up to a depth of 1500m, in accordance with the maximum depth of the trawl sampling from the M/T Paamuit. Environmental data for species and background data was extracted using the point sampling tool in QGIS.

Only linear and quadratic features were selected for the modelling process, due to small sample sizes for some datasets, and the higher potential of the other feature types to result in overfitting of the model. Linear and quadratic relationships were also more likely to meet the expectations of responses (Yesson, pers. comm.) The Maxent model output format was kept as logistic, which is default and gives a probability of presence output between 0 and 1, while the additional options of 'faded clamping' and 'use species with missing data' options were selected.

#### 3.4.1 Model Tuning and Evaluation

Model tuning was carried out in order to select the most appropriate parameters for the final models. Models were repeated with variations of the regularization values as follows: 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2 (Shcheglovitova & Anderson, 2013). The most appropriate parameters for each model were selected based on the lowest maximum training sensitivity plus specificity test omission (MTSST) threshold values. This threshold value was chosen due to its perceived effectiveness with presence only data (Liu, White & Newell, 2013). When more than one regularization value resulted in the same omission score, the model settings were then selected on the highest test Area Under the Curve (AUC) scores from the receiver operating characteristic (ROC) plot. The AUC is a non-parametric statistic that is independent of threshold values, and demonstrates the likelihood that the model is able to rank a presence record higher than a record of background data. Values are given between 0 and 1, with 0.5 representing random predictions. The closer the output value from the model to 1, the stronger the models performance (Peterson et al., 2011, Fielding & Bell, 1997).

With sufficient data (>25), model evaluation took place via a masked geographical approach, as this provides a more robust evaluation than the Maxent defaults (Radosavljevic & Anderson, 2014). Occurrence data was split into three subsets based on geographical location, with dividing sections

based on lines of latitude. The background dataset was also divided via these same lines of latitude. Maxent models were run using 2 subsets as training data, and the third dataset of occurrence data and background data as test data. Three models were run so that each subset was used as a test dataset. If the occurrence datasets had less than 25 records, models were evaluated using the crossvalidate evaluation settings to produce a jackknife n-1 evaluation process, as this has been demonstrated to be an appropriate method to evaluate models based on very small data sets (Shcheglovitova & Anderson, 2013, Pearson et al., 2007). This method selects one occurrence point as test data, with all other data points used as training data. The model then repeats with a different data point selected as test data each time, until all data points have been used as the single point of test data (Pearson et al., 2007).

#### 3.4.2 Model Outputs

Additional outputs selected within Maxent were the jackknife measure of variable importance, which runs the model but excludes one environmental variable each time, in order to see how effective the model is without a variable, and then runs a model using only a single variable each time. Another output selected was 'create response curves' for each variable for the model, which creates plots of each environmental variable used in the model, and details how their values influence the habitat suitability output.

Final model versions were run twice, once with Log Fishing selected as a variable, and once where it was not. The models produced using the Log Fishing variable were used to assess its importance as a variable on model construction. Output from the models without Log Fishing as a variable were used to assess further relationships with fishing, without risking accounting for it twice. Using the background data points in QGIS, the habitat suitability index was extracted alongside the Log Fishing values. These were analysed in R using the smooth.spline argument. The maximum training sensitivity plus specificity threshold was also used to produce binary habitat maps. Values over the threshold were identified as suitable, while values below the threshold were considered unsuitable. 10000 background points were used to assess the relationship between the binary areas of suitable habitat and binary maps of fishing occurrence, using a Chi-squared analysis.

## 4. Results

### 4.1 Variable Production and Selection

Initial analysis was carried out to ensure the available data collected from online sources supported results collected from field experiments. Depth values recorded on location for bycatch samples were found to be highly correlated with the produced 3.5x3.5km depth layer, demonstrating the modelling layers produced were suitably accurate for the study ( $r_s$ = 0.9291, n=115, p<0.001). The correlation analysis found that Ruggedness Index was highly correlated with the Fine Slope scale ( $r_s$ =0.9736, n=10000, p<0.001), resulting in the ruggedness variable being excluded from the modelling process. No other layers were sufficiently correlated (>0.7) to warrant exclusion.

### 4.2 Family Data Profiles

The number of occurrence records for each coral group varied considerably (Table 4.1). The majority of records were from bycatch from research expeditions, although benthic photographs and other literature sources both contributed to the final data sets. The data cleaning process resulted in many records being excluded from the study. All of these excluded records were from the bycatch dataset, and were excluded either due to being outside the study range, or recorded at the same location as another record of the same group.

Table 4.1 - Breakdown of occurrence record sources. All records excluded from analysis were from the bycatch dataset. Final numbers used in Maxent modelling process are in red.

Coral Group	Species	Total	Source			Excluded	Records
	Recorded within Datasets	Records	Bycatch	Camera Station	Literature	records	used for Modelling
P. arborea	Paragorgia arborea	12	9	0	3	6	6
Nephtheidae	Duva florida, Gersemia rubiformis, Capnella glomerata, C. groenlandica	172	159	13	0	96	76
Pennatulacea	Pennatula aculeata, P. phosphorea, P.borealis., Umbellula sp.	35	24	1	10	14	21

The distributions of the remaining data records after the cleaning process can be seen in Figure 4.1, alongside the raster layer of the number of hours fished used within the study. *P. arborea* samples were very rare across the study site, but were located at 3 regions. The largest of these had 3 sample locations and was found towards the continental shelf edge in the Northern region of the study site. Occurrence records of Nephtheidae were found across much of the extent of the fishing grounds. Two major areas of common occurrence were to the very North of the study region and also just off the coast from the town of Nuuk. Samples were also regularly found towards the Southern tip of Greenland, with one sample across on the Eastern coast. Samples were rarer in the more central locations of the study site, off the coast between Ilulissat and Nuuk. The Pennatulacea data records were far more common in Northern regions, although two samples were found as far South as Nuuk. These samples were generally collected further from the Greenland coast, and therefore, closer to the continental shelf than the other two coral groups.



Figure 4.1 - Trawling activity for the West Greenland Shrimp Fishery and locations of occurrence records used in habitat suitability modelling.

Variable data was extracted from occurrence record locations and analysed (Table 4.2). Analysis of this data found that Nephtheidae had the shallowest depth range, from -74m to -748m, compared to *P. arborea* which had a far wider range of -197m to -1249m. This is further supported by the mean depths for these groups, with Nephtheidae at -275.79m compared to *P. arborea* at -655.16m. Box

plots for each variable were produced to aid comparison between each coral group. Depth and Fine Slope were the two variables displaying the greatest visual difference between different groups, and can be seen in Figure 4.2. All remaining box plots can be seen in Appendix 1.

Variable	Data	Р.	Nephtheidae	Pennatulacea
	Туре	arborea		
Denth	Mean	-655.167	-275.789	-573.905
(m)	Max	-197	-74	248
(11)	Min	-1249	-748	-1136
	Mean	2.264823	1.2841	0.940006
Fine Slope	Max	3.00275	14.92892	2.73271
	Min	1.13371	0.02026	0.08103
	Mean	1.12376	0.839789	0.904919
Coarse Slope	Max	2.08653	5.69553	1.87994
	Min	0.15938	0.01666	0.007305
Temperature	Mean	1.81498	2.738151	1.385245
(°C)	Max	3.91623	5.93208	5.31704
	Min	0.85255	0.29434	0.65125
Salinity (PSU)	Mean	37.73938	37.65734	37.70671
	Max	37.92527	38.11405	38.08772
	Min	37.6062	37.22282	37.44006
	Mean	0.0005	-0.00922	0.001107
(m/s)	Max	0.00317	0.01245	0.02467
(, .)	Min	-0.00174	-0.08165	-0.01062
v	Mean	0.00267	0.01061	0.003142
(m/s)	Max	0.01127	0.07205	0.01272
(11/5)	Min	-0.0044	-0.07262	-0.01426
	Mean	5.716882	5.03088	3.880622
Log Fishing	Max	12.13363	12.18556	12.63557
	Min	0	0	0

Table 4.2 - Environmental factor values at occurrence locations





#### 4.3 Habitat Suitability Models

Final model selection was based firstly on the lowest MTSST values, with tied scores for models then selected for using the test AUC values. Results for the models evaluation parameters can be seen in Table 4.3. The regularization value of 0.5 was found to produce the best models for all three of the coral groups.

Table 4.3 Evaluation statistics for each model produced by the evaluation process for each coral group. Cells with red text show best performing model results.

Regularization		MTSST Valu	es		Test AUC	
Values	Р.	Nephtheidae	Pennatulacea	P. arborea	Nephtheidae	Pennatulacea
	arborea					
0.5	0.5	0.342	0.2857	0.8633	0.6568	0.8618
0.75	0.5	0.3809	0.4286	0.8574	0.6387	0.8578
1	0.5	0.5879	0.381	0.8483	0.6312	0.8539
1.25	0.5	0.5879	0.3333	0.8417	0.6247	0.8498
1.5	0.6667	0.5879	0.3333	0.8376	0.6179	0.8456
1.75	0.6667	0.5745	0.3333	0.8336	0.6136	0.8422
2	0.6667	0.5745	0.2857	0.8272	0.6094	0.839

Models excluding Log Fishing as a factor were used to produce habitat suitability maps (Figure 4.3). *P. arborea* and Pennatulacea demonstrated similar areas of suitable habitat, with most suitable regions found in the Northern regions of the study area within close proximity to the shelf edge, although areas of most suitable habitat for *P. arborea* are slightly closer to the shelf edge than Pennatulacea. They differ considerably to the Nephtheidae habitat suitability map, which displays a much larger region of suitable habitat. The predicted areas for suitable habitat for this coral group is widespread in shallower areas, with large areas of suitable habitat in both the northern and southern areas off the West Coast of Greenland, all inland of the continental shelf edge (Figure 4.3).



Figure 4.3 - Habitat suitability models of the West Greenland Shelf for the coral groups *Paragorgia arborea*, Nephtheidae and Pennatulacea respectively. Warmer colours represent areas modelled with higher habitat suitability. A depth of greater than -1500m was outside the model range, while distribution points are plotted onto the maps for reference.

#### 4.3.1 Paragorgia arborea

The AUC value for the final model excluding Log Fishing was 0.952 while the MTSS omission value was 0. Habitat suitability is most strongly determined by the current values from West to East (U), followed by Fine Slope. U had a permutation importance of over half the total importance for the model, although it was second highest for percentage contribution (Table 4.4). Four of the variables had less than 2% Permutation Importance (Depth, Coarse Slope, Temperature and Salinity). The jackknife of regularized training gain found that the variable Fine Slope contained the most information important to the model that could not be explained by other variables.

Table 4.4 Importance of variables for the construction of the *Paragorgia arborea* habitat suitability model without Log Fishing as a variable.

			Jackknife of	Jackknife of
	Percentage	Downstation	Regularized	Regularized
Variable		Permutation	Training Gain	Training Gain
	Contribution (%)	Importance (%)	with only one	without
		Variable	Variable	
Depth	5.5	0.6	0.0696	0.9139
Fine Slope	43.3	27.6	0.4417	0.5524
Coarse Slope	10.1	0	0.0742	0.9152
Temperature	0.4	0	0.0331	0.916
Salinity	0	1.1	0.0059	0.91
U	29.3	55.8	0.246	0.7215
v	11.4	14.9	0.1097	0.8544

#### 4.3.2 Nephtheidae

The final Nephtheidae model had a training AUC of 0.775, with an omission rate for MTSS of 0.145. The variable Depth had the highest percentage contribution to the model, and the highest permutation importance. The jackknife of regularized training gain found that Depth produced the highest regularized training gain when modelled in isolation, while the gain also decreased the most when Depth was the variable omitted (Table 4.5), showing that Depth has the most useful information for predicting Nephtheidae habitat, and that it also contains the most information not contained within other variables. Table 4.5 Importance of variables for the construction of the Nephtheidae habitat suitability model without Log Fishing as a variable.

			Jackknife of	Jackknife of
	Percentage		Regularized	Regularized
Variable			Training Gain	Training Gain
	Contribution (%)	importance (%)	with Only One	without
		Variable	Variable	
Depth	47.4	40.7	0.2034	0.1897
Fine Slope	0	0	0	0.4286
Coarse Slope	9.6	0	0.0198	0.4255
Temperature	13.7	21.5	0.0878	0.3795
Salinity	7.9	24.1	0.0005	0.3923
U	0	0	0.0035	0.4286
v	21.4	13.7	0.1444	0.3458

#### 4.3.3 Pennatulacea

The AUC for the Pennatulacea model excluding Log Fishing as a variable was 0.910 while the maximum training sensitivity plus specificity omission value was 0.318. All variables contributed to the production of the habitat suitability model (Table 4.6). Temperature was the single most important variable, and the jackknife of regularized training gain without Variable demonstrated it contained the most useful information for model building not found in other variables. However, Coarse Slope had the highest gain for model building when used in isolation, suggesting it has the most useful information by itself.

Table 4.6 - Importance of variables for the construction of the Pennatulacea habitat suitability model without Log Fishing as a variable.

			Jackknife of	Jackknife of
	Percentage	Dermutetien	Regularized	Regularized
Variable		Permutation	Training Gain	Training Gain
	Contribution (%)	ribution (%) Importance (%)	with only one	without
			Variable	Variable
Depth	15.5	8.8	0.2502	0.8664
Fine Slope	2.7	0.9	0.0115	1.0887
Coarse Slope	14.9	14.7	0.2647	0.9596
Temperature	35.8	41.7	0.2372	0.7782
Salinity	22.6	23.1	0.0048	0.8777
U	5.6	9	0.1782	1.071
V	2.8	1.7	0.1017	1.0968

#### 4.4 Fishing Impact

Models were run with Log Fishing as a factor, to discover the importance of fishing pressure for suitable habitat model production for each coral group. In all models, Log Fishing was found to be one of the variables of lower permutation importance. *P. arborea* had the highest values for percentage contribution, at 10.6%, which was the 4<sup>th</sup> highest variable for this model (Table 4.7). Log Fishing had the lowest percentage contribution of any variable for model production for the Pennatulacea, while it was the 5<sup>th</sup> highest variable for Nephtheidae, only above Fine Slope and East/West current velocity (U).

Coral Group	Percent Contribution (%)	Permutation Importance (%)
Paragorgia arborea	10.6	2.9
Nephtheidae	2.4	1.6
Pennatulacea	0.3	0.5

Table 4.7 - Importance of the Log of the Number of Hours Fished 1986-2010 for model building.

To further investigate any relationship between fishing activity and habitat suitability of the coral groups, output from the models that excluded Log Fishing as a factor underwent further analysis. Smooth splines were produced to look for more complex relationships between habitat suitability

and Log Fishing using 10,000 random background points (Figure 4.4). Nephtheidae and Pennatulacea demonstrate early falls in habitat suitability alongside any level of fishing pressure, while Paragorgiidae show a fall in the relationship between habitat suitability when at the highest levels of fishing pressure. In general, all three coral groups display slight positive trends.



Paragorgia arborea

Figure 4.4 - The relationship between the Log of Fishing Hours against the suitability of habitat for each coral family using a smooth spline curve.

The output of the habitat suitability models without Log Fishing were converted into binary suitable maps using the logistic threshold value for maximum training sensitivity plus specificity (MTSS) (*P. arborea* =0.499, Nephtheidae= 0.412, Pennatulacea=0.588). The binary maps produced can be seen in Figure 4.5. The 10,000 background points were analysed to see whether they occurred at

locations of suitable habitat and fishing activity. Chi-squared tests were carried out for each coral group. *P. arborea* was found to have no relationship ( $X^2$ = 0.8863, df= 1, p= 0.3465) between binary suitable habitat and fishing distributions. However, Nephtheidae ( $X^2$ = 598.9744, df= 1, p< 0.001) and Pennatulacea ( $X^2$ = 61.2502, df= 1, p< 0.001) binary habitat suitability were both found to be highly significantly related to locations of fishing activity. Upon further comparisons of expected and observed values, it was identified that Nephtheidae suitable habitat is significantly more likely to occur alongside fishing occurrence, while Pennatulacea habitat suitability is significantly likely to occur in areas where fishing activities do not take place.



Figure 4.5 - Binary habitat suitability maps for each coral group across the extent of the West Greenland shrimp fishery range, alongside the binary distribution of fishing occurrence.

## 5. Discussion

This project has produced the first habitat suitability maps for three key coral groups along the West Greenland Shelf, and identified that fishing activities did not have a negative impact on the predicted areas of suitable habitat when incorporated as a variable for habitat suitability modelling. Analysis of binary distribution maps found significant differences between the locations of fishing and the distribution of suitable habitat for Pennatulacea, while suitable habitat for Nephtheidae occurred in areas that were also fished. *P. arborea* suitable habitat was not found to have a significant relationship with locations of binary suitable habitat and fishing occurrence.

#### 5.1 Habitat Suitability Modelling

The three coral groups were selected because they consist of important habitat building species, occur within different benthic environments, and are commonly caught as bycatch (Baker et al., 2011, Murillo et al., 2011, Williams, 2011, Bryan & Metaxas, 2007). Gaining an understanding of the factors that influence suitable habitat can greatly expand our knowledge on coral occurrences within the WGS region. The information within these habitat suitability models can provide greater information of deep sea corals, of which many are understudied, and can be of benefit to help inform conservation measures (Langton et al., 1990). Each coral group was found to have different variables that were of greatest importance for predicting suitable habitat. All models performed strongly, with high training AUC values (>0.75) for the final datasets, although the Nephtheidae model was noticeably lower than the other two groups. Omission values were particularly low for *P. arborea* and Nephtheidae.

#### 5.1.1 Paragorgia arborea

The results of the habitat suitability model for *P. arborea* clearly demonstrate a dependence on hard rocky substrate and currents for suitable habitat, which supports previous research on the species (Bryan & Metaxas, 2007, Leverette & Metaxas, 2005) . This highlights the continental shelf, alongside underwater valleys and depressions found inside the shelf edge, as the areas where *P. arborea* is most likely to be found. The most significant variable depicting habitat suitability was U Current, depicting East/West current velocity, which demonstrates the critical value of strong currents to the location of *P. arborea* (Genin et al., 1986). As filter feeders, access to currents ensures that individual corals can extract enough nutrients from the ocean (Mortensen & Buhl-Mortensen, 2005). Currents may be influential in bringing in a food supply to *P. arborea*, either by coming from a direction of high ocean nutrients, or due to high velocity of the current allowing a greater quantity of nutrients to travel past the coral (Genin et al., 1986).

Occurrence records used within this study were also more commonly located at highly sloping locations than other families (Figure 4.2). This can be interpreted as a preference for hard substrate; the variable Fine Slope is a proxy for substrate type, as highly sloped areas demonstrate less sediment deposition, resulting in the exposure of rocky outcrops (Bryan & Metaxas, 2007, Genin et al., 1986). The occurrence of *P. arborea* records at locations with high slope values was supported by the high permutation importance and percentage contribution values for that variable during model production. Stronger currents are often linked with more highly sloped and topographically varied areas (Mohn & Beckmann, 2002). The correlation analysis for this study found East/West current (U) and Fine Slope were not highly correlated, but over finer scales than this study allows, the influence of one factor may be concurrent with the other (Genin et al., 1986)

#### 5.1.2 Nephtheidae

The binary habitat suitability maps suggests Nephtheids have the broadest distribution of any of the coral groups studied within this project, which aligns with their higher prevalence within bycatch across the fishing grounds (Jorgensen, Tendal & Arboe, 2013). The environmental data collected at occurrence sites for the Nephtheidae demonstrate a depth limit to their distribution (Figure 4.2). This supports previous knowledge on the family, and differs to the other corals of this study which display far greater depth variability (Table 4.2) (Herrera, Shank & Sánchez, 2012, Murillo et al., 2011, Baker et al., 2011). This requirement of shallower waters is confirmed by Depth having both the highest Permutation Importance and Percentage Contribution to the model building process. The importance of depth within this study for suitable habitat aligns with previous work, which helps provide value to the accuracy of the models produced (Murillo et al., 2011).

Nephtheids display extensive ranges for the other environmental factors used for modelling, which could indicate adaptability to different conditions, and suggest a level of resilience to environmental change (Sun, Hamel & Mercier, 2011). However, the higher variability in variable ranges could also be explained through the much larger data set for Nephtheidae compared to the other coral groups (Table 4.1). Other important factors were Temperature, Salinity and North/South currents (V). As filter feeders, currents are an expected important factor (Sherwood et al., 2008). The importance of North/South currents, compared to the favoured East/West currents for habitat suitability building for Pennatulacea and especially *P. arborea*, may reflect the differing areas of occurrence. Nephtheidae records were at shallower depths and further away from the continental shelf, where the influence of East/West currents may be diminished. Temperature and salinity are also important factors, although the broad ranges of these variables recorded at occurrence sites suggests high tolerance for variation (Sun, Hamel & Mercier, 2011). Neither slope variable was found to have any relevance for habitat suitability for the Nephtheidae. While Nephtheids rely on attaching to hard

substrates, their small size enables their presence across soft sediment areas with little to no slope, because they are capable of attaching to pebbles or other hard substrate fragments (Murillo et al., 2011).

#### 5.1.3 Pennatulacia

Every variable for Pennatulacea contributed to the construction of the habitat suitability map, which differed from the other two coral groups. Temperature was the single biggest variable that influenced the habitat suitability. This influence is reflected in the northern distribution of suitable habitat, where water temperatures are cooler. Salinity is the second most important variable, again with lower values found in the northern regions of the model map range. Interestingly, the lower salinity levels may be influenced by the closer proximity to the ice sheets. Melting ice sheets each year may impact the salinity of the surrounding water, and could explain the importance of salinity for these corals on a local scale (Aagaard & Carmack, 1989).

The jackknife of regularized training gain found that Coarse Slope was the variable that contained the most information by itself. This differs from the other two coral groups, where Coarse Slope had no permutation importance in model construction. The influence of slope over a 35km range, with preference for less sloped areas (see Appendix 2), may represent the preference of flat areas of high sediment, and would support current scientific knowledge (Tissot et al., 2006). Further evidence of this can be deduced from the habitat suitability maps of Pennatulacea and *P. arborea*. The maps share many similarities for preference of suitable habitat locations, yet Pennatulacea suitable habitat is slightly further from the shelf edge when the two maps are compared, suggesting a preference for less sloping areas that are more likely to contain soft sediment.

The two families of sea pens from which this group was composed had overlapping distributions, allowing for their combination into one dataset. However, it is highly likely that there is significant variety at the family level, and further to that the genus and species levels, which could in some part explain the influence of all variables in the production of this model (Williams 2011).

#### 5.2 Impacts of Fishing

The results of this project demonstrate that the number of fishing hours carried out within the West Greenland fishing grounds do not act as a major factor in habitat suitability predictions, based on the production of models that examined linear or unimodal (quadratic function) responses. As linear and quadratic factors could not demonstrate a strong relationship between habitat suitability and fishing pressure, it suggests that either there is no relationship with fishing pressure, or that fishing pressure is related to other features that can better explain habitat suitability. A much more

complex relationship with fishing pressure could be expected due to the variable life history traits of the studied corals.

Coral bycatch records were more commonly located along the edge of the fishing grounds, towards the continental shelf, most noticeably for Pennatulacea and *P. arborea*, but also for the Nephtheidae in the Southern regions of the fishing grounds (Figure 4.1). This lack of presence in more central fishing grounds may indicate impacts of past fishing activity, that over the many decades of fishing have removed coral populations, and as such, modern bycatch records do not provide samples in these areas (Murillo et al., 2011). This is a view reflected from anecdotes from local fishermen (Yesson, pers. comm.). Alternatively, it could simply be a reflection of areas of terrain not suitable for the models coral groups. This may be most prominent for *P. arborea*, which is known to have a preference for rocky substrate, yet the fishing grounds most commonly targeted are areas of soft sediment (Lassen et al., 2013, Baker et al., 2011)

#### 5.2.1 Paragorgia arborea

Of all the coral groups, *P. arborea* shows the largest relationship with fishing pressure for habitat suitability model production, yet surprisingly it is represented as a positive relationship. This is contradictory to much of the scientific literature, which highlights the vulnerability of *P. arborea* to fishing practices (Murillo et al., 2011, Sherwood & Edinger, 2009). However, the result of this study should be taken with an element of caution, as the small sample size can limit model accuracy (Murillo et al., 2011, Pearson et al., 2007). The results of the smooth spline analysis also suggest that for *P. arborea* there was a slight positive trend between fishing pressure and habitat suitability. There was a rapid drop of suitability at very high levels of fishing pressure, however, this was based on a small number of data points, so may be less reliable.

The lack of a significant relationship between *P. arborea* and fishing from the Chi-Squared analysis of the binary distribution maps further indicates that there is no relationship between habitat suitability and fishing. This discovery is surprising. Potential reasons for this lack of relationship include the preference of *P. arborea* for highly sloping and rugged terrain (Baker et al., 2011). While rockhopper gear does broaden the potential range of trawling activity, these areas are still unlikely to be suitable trawling grounds (Lassen et al., 2013, Hamilton, Brown & Rasmussen, 2003). They also do not reflect the habitat where the target of the fishery, *Pandalus borealis*, is most commonly found, as they prefer soft sedimented areas (Lassen et al., 2013).

Habitat suitability modelling does not take into account the size of organisms, but only that they are present. This may be of particular importance for *P. arborea*, which is especially long lived and can grow to large sizes (Mortensen & Buhl-Mortensen 2005). As they are important for increasing

diversity and abundance of associated organisms, a reduction of the larger colonies may be particularly damaging to the wider benthic community (Bryan & Metaxas, 2007). It may be the case that average biomass of organisms in the coral groups studied is smaller in areas with high trawling pressure, compared to areas where fishing does not take place (Koslow et al., 2001).

The habitat suitability model suggests a narrow distribution, which agrees with the scientific understanding that *Paragorgia arborea* occurs in small clustered populations (Bryan & Metaxas, 2007). However, this narrow distribution is only representative of the current distribution. The anecdotes from fishermen suggest they were once far more common as bycatch, which could well imply a shrinking of population distribution that has occurred over the extensive timeline of fishing in the area (Yesson, pers. comm., Hamilton, Brown & Rasmussen, 2003). The samples used within this study, and further records from Greenland, have all been obtained through bycatch, and while extremely rare, are also more commonly found on the edges of the fishing grounds (Jorgensen, Tendal & Arboe, 2013, Tendal, 1992).

#### 5.2.2 Nephtheidae

The Nephtheidae are the family of corals most commonly caught as bycatch across Greenland, therefore understanding their relationship with fishing practices is important to ensure populations are not being damaged (Jorgensen, Tendal & Arboe, 2013). Within the production of habitat suitability models, fishing was found to have very little influence. The smooth spline demonstrated a fall in suitable habitat over the earliest levels of fishing pressure, but in general suggested a slightly positive correlation. Most interestingly, the Chi-Squared of the binary habitat suitability and fishing map demonstrated that there is a significant relationship between the two distributions. Furthermore, it is a positive relationship suggesting the two areas are highly likely to coincide. This relationship is reflected by the high occurrence of bycatch records (Table 4.1). Overall, the overlap of suitable habitat and fishing areas further suggests that there are no negative impacts for this coral family.

There is potential for other negative impacts for the Nephtheidae, such as reduced lifespan or size of an organism, which cannot be represented in habitat suitability modelling (Henry, Kenchington & Silvaggio, 2003). This may be especially prominent within the Nephtheidae community, as they are far more common as bycatch than any other coral groups (Table 4.1) (Jorgensen, Tendal & Arboe, 2013). The continued occurrence of these corals in bycatch may reflect resilience of the population to trawling, or that there is no impact (Henry, Kenchington & Silvaggio, 2003). The Nephtheidae family may not be impacted by the trawling activities of the shrimp fishery due to the small size and soft structure of most species (Kenchington et al., 2009). This may result in the trawls passing over

many of these organisms without impacting them, or if contact is made, the organism can recover from the impact (Henry, Kenchington & Silvaggio, 2003). Another possibility may be the fact that some mature Nephtheids can survive as fractured pieces, and develop into new 'offspring' (Sun, Hamel & Mercier, 2011).

#### 5.2.3 Pennatulacea

The Log Fishing variable was least important in the construction of habitat suitability models for all the coral groups. Pennatulacea, like the Nephtheidae, demonstrated a fall in suitable habitat over the earliest levels of fishing pressure. Overall, there was still a slight positive trend, although it never returned to the level of habitat suitability before any fishing occurred.

The fact Pennatulacea more commonly occur on flatter soft sediment suggests that they may be more likely to come into contact with trawling activities, as there is a preference for trawling flatter grounds compared to rockier, uneven substrate (Lassen et al., 2013, Murillo et al., 2013). However, the most suitable habitat as predicted by the habitat suitability models of this study suggest a significant difference between the areas of most suitable habitat and the areas where fishing activities have taken place. This lack of presence in more central fishing grounds may indicate impacts of past fishing activity, that over the many decades of fishing have removed coral populations, and as such, modern bycatch records do not provide samples in these areas (Murillo et al., 2011).

Some sea pen species have the ability to contract into the sediment within which they are anchored, while others, such as Pennatulas, can move their anchoring point after disturbance or uprooting (Williams, 2011, Eno et al., 2001). These traits could suggest a lesser impact from fishing activities, as individual colonies could withdraw into the sediment as trawling gear passes by, or could reattach to the sea floor if trawling uprooted them (Eno et al., 2001).

#### 5.4 Strengths & Limitations

#### 5.4.1 Strengths

This project was successful in producing strongly performing models for three key coral groups for the West Greenland Shelf. This is the first habitat suitability models of the region, greatly expanding previous knowledge. The model production process has overcome many limiting factors, including small datasets for occurrence records, difficulties in identifying coral species, a lack of research on life history traits for many deep water corals, and limited availability of environmental data.

Small data sets are widely considered a drawback to successful modelling, and can certainly limit the level to which a model should be believed (Bean, Stafford & Brashares, 2012). However, Maxent has

been shown to be especially effective in this role, working to sample sizes as low as 5 (Shcheglovitova & Anderson, 2013, Pearson et al., 2007). The habitat maps produced should not be regarded as explaining the full extent of the family range, but rather, they highlight areas of similar environmental conditions to the samples already collected (Pearson et al., 2007). This can be extremely useful for conservation because it can guide future surveys, potentially leading to the discovery of previously unknown populations of these organisms, which it turn could provide additional data for the model, thus making the model stronger (Pearson et al., 2007).

#### 5.4.2 Limitations

There were several limitations to the project that are important to consider, and that future work could look to improve upon. Most of these relate to the fact this project is studying an environment which impedes accurate data collection. The influence of water pressure brought about by increasing depth results in the requirement of specialist sampling equipment that is expensive to use, and that can only provide small, localised surveys (Taylor et al., 2013, Mortensen & Buhl-Mortensen 2005). The difficulty in sampling is one explanation of small sample sizes, but conversely, this difficult in obtaining data also makes habitat suitability modelling such an important method for the area (Yesson et al., 2012).

This project relied on abiotic variables produced from oceanographic models, but the data available was a coarse scale (MyOcean, 2014). Modelling, by its very nature, is a predictive tool, and therefore the environmental variables used in this study should not be considered a perfect description of the deep sea environments. Further processing of the available raster layers took place when upscaling the pixel size (Davies & Guinotte, 2011). This resulted in some data gaps within the raster grids that were a relic of the 'cookie cutting' process, and were usually found in small areas of significant depth changes, such as hollows or troughs. This is unfortunate, as it resulted in the habitat suitability models being unable to predict these areas. In one case, a *P. arborea* sample was located within a trough location that resulted in missing environmental data at this location. Maxent was adjusted to use species with missing data to combat this issue (Phillips, Anderson & Schapire, 2006). However, this missing data especially impacts *P. arborea*, where the data set available was very small, and as such, exclusion of any data could have significant impacts on model production (Pearson et al., 2007).

There is also a compromise between resolution of pixels and the speed at which models can be produced. A 12km<sup>2</sup> pixel size for this project was suitable considering the extent of the West Greenland shelf, but if greater detail was required for more localised areas, then smaller pixel sizes should be recommended to avoid missing details at finer scales (Bryan & Metaxas, 2007, Etnoyer &

Morgan, 2007). The role that resolution has on impacting habitat suitability models is difficult to identify (Bryan & Metaxas, 2007). Improvements in the resolutions of available data can only help to advance the detail contained within these models, but additionally, significant computer processing power may be required to practically take advantage of these finer grained habitat layers.

Inevitably, there is some chance of sample bias. The research trips to Greenland are an ongoing process, so data collected from these voyages currently form part of an incomplete dataset. The research vessel M/T Paamiut is designated to assess the shrimp stock, and may have favoured trawling shallow and flat areas compared to higher sloping rocky substrate found on the shelf edge, where the shrimp stock is more commonly found (Lassen et al., 2013). This could help explain the low levels of P. arborea data, which tend to locate on hard substrate (Baker et al., 2011, Genin et al., 1986). Current data collection methods revolve around assessing bycatch, which is problematic in that it ensures that damage to the environment continues as we attempt to assess it (Baker et al., 2011). It also brings difficulties for occurrence record accuracy, as trawls pass over large extends of the sea floor before being brought up to the ship. Furthermore, unknown quantities of corals may be uprooted or damaged but not landed on the fishing vessel, so records can be missed (Taylor et al., 2013). For this project, the midpoint of a trawl was taken as the location of occurrence, but invariably there are issues with accuracy for this, which could help explain some of the anomalies in the data sets. The maximum trawl length from the M/T Paamuit, which collected bycatch records, was approximately 2.7km (Jorgensen, Tendal & Arboe, 2013). Considering each pixel was a 3.5 by 3.5km square, the potential for occurrence records being misreported is notable, but does not considerably impact the study. The difficulties in collecting data from the deep ocean ensure that habitat suitability modelling should be one of the most prominent methods to expand our knowledge.

#### 5.5 Further Work

#### 5.5.1 Future Research

The habitat suitability models are the first available for the West Coast of Greenland, and can be used to help direct future work. These habitat suitability maps can focus future *in situ* work to areas of predicted highly suitable habitat. This will allow appropriate evaluations of the model predictions, while also potentially leading to the identification of key coral populations (Etnoyer & Morgan, 2007). Using ROV's or camera traps to gain more of an understanding of the coral communities within these areas can help to provide greater information on their environmental importance (Clark & Rowden, 2009, Stone, 2006, Mortensen & Buhl-Mortensen 2005).)

The models produced can continue to be refined in the future to further improve the accuracy of the predictions made. As additional data points are added, the reliability of the model predictions will be improved. Specifically, improved numbers of data points for *P. arborea* and Pennatulacea would be of great benefit. Maxent has been shown to have a threshold of 50 data points that beyond which model improvement is less pronounced (Hernandez et al., 2006). Future models would benefit from having 50 data points within each dataset, for stronger model production, while also allowing better evaluation in the form of a masked geographical approach (Radosavljevic & Anderson, 2014). Further to this, models can be refined with more accurate identification of samples to species or genus level. The coral group containing the broadest spectrum of organisms in this study was the Pennatulacea, which contained samples from two families. Inevitably, individual species are likely to exist within different niche habitats, so the broader the scope of the group increases the chances the occurrence records display more variable environmental data (Williams, 2011).

Future production of models could also reflect seasonality, which may influence the values of environmental variables. For example, temperature has commonly been reported as a limiting factor for *P. arborea* distributions, yet was of no influence for this study. The temperature values for *P. arborea* occurrence sites were all found to be lower than those predicted in the literature (Tendal 1992). However, the production of the Temperature variable was produced using annual mean data, whereas the data collected by Tendal was from July- October, when sea temperatures are commonly warmer (MyOcean, 2014, Tendal 1992).

#### 5.5.2 Policy Implications

Deep sea benthic habitats can be especially vulnerable to fishing impacts and yet very little is known about them (Roberts, 2002). Therefore, gaining an increased understanding is essential to inform decisions on fishing practices and provide evidence to support mitigation effects (Taylor et al., 2013). The models produced in this study can directly contribute to the benthic assessment carried out by IOZ for the MSC evaluation of the West Greenland shrimp fishery. By clearly identifying locations of key suitable habitat, policy makers can ensure that fishing practices avoid these areas, which can result in reduced bycatch by the fishery, and overall lead to improved measures for sustainability (Lassen et al. 2013).

#### 5.6 Conclusion

This study has produced the first habitat suitability models for deep sea corals off the Coast of West Greenland. Furthermore, it has identified that fishing pressure is not a major factor influencing the prediction of suitable habitat. Alternatively, it has predicted that the most suitable Pennatulacea habitat occurs in areas significantly different from areas of fishing practices. The Nephtheidae,

however, has suitable habitat areas that are significantly linked to the fishing grounds, while *P. arborea* displays no relationship. These findings greatly advance our knowledge of benthic environments across the West Greenland shelf and the relationships of corals with the West Greenland shrimp fishery. The identification of these key areas of suitable coral habitat can help inform policy and management practices, helping the fishery to achieve sustainability.

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## Appendix 1- Box Plots of Variables at Occurrence Location



## Appendix 2- Model Outputs

#### P. arborea



#### Nephtheidae

Salinity Temperature

> U ٧

> > 0.00

0.05

0.10

0.15

0.20

regularized training gain







0.25

0.30

0.35

0.40

0.45

#### Pennatulacea

