Quantifying the impact of bottom trawling on soft-bottom megafauna communities using video and scanning-sonar data on the continental slope off Vancouver Island, British Columbia

by

Maeva Gauthier
B.Sc., Université du Québec à Montréal, 2007

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of School of Earth and Ocean Sciences

Supervisory Committee

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Departmental Member

Dr. Rosaline R. Canessa, Department of Geography
Outside Member

Abstract

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The purpose of this study was to develop a methodology to analyse ROV video and scanning-sonar data to document the abundance and distribution of epi-benthic megafauna on the continental slope off Vancouver Island and to quantify the impact of trawling on these megafaunal assemblages. Impacts of bottom trawling on deep-sea ecosystems vary depending on habitat types and species present. Environmental factors such as depth, dissolved oxygen concentration, substratum type, and bottom roughness also affect the diversity and composition of benthic communities. We studied two transects (30km and 12km long) on the upper continental slope off Vancouver Island, BC, Canada, that included areas of seafloor with visible trawl marks. Our study area was also located in an oxygen minimum zone with very low bottom water dissolved oxygen concentrations in its core (600m-1000m). The main target for bottom trawling fisheries in this area is the longspine thornyhead (*Sebastolobus altivelis*). Field data were collected using the ROV ROPOS equipped with a 3CCD video camera and high-resolution scanning sonar. Megafaunal composition/abundance and bottom characteristic information were extracted from video imagery and assembled using a custom-designed *MS Access* database. The same database was used to compile information on trawl-door marks detected in recorded sonar imagery. The sonar surveyed a 50m radius around the submersible during transects, providing a broader view of evidence of trawling in the area than video.

This thesis reports on relationships between environmental variables and faunal abundance, diversity and species distribution. Following the video and sonar analysis, diversity patterns and general species distribution for both transects were determined.

Relationships of community structure to depth and trawling intensity were investigated using the hierarchical clusters technique to identify similarities in the megafauna assemblages between stations . Finally, spatial structures in the megafaunal community and their associated environmental variables were examined using the Principal Coordinates Neighbour Matrices (PCNM) and redundancy analysis tests.

Differences in total abundance, species composition and distribution, and species diversity were detected between the high and low trawling intensity areas. One of the main highlights of our results was the dominance of ophiuroids and holothurians along most of the transect, except for the highly trawled area. Spatial structures were identified in the megafaunal community, showing a strong influence of bottom trawling intensity and, to a lesser extent, depth. Nearby water column measurements of dissolved oxygen concentrations suggest that depth might be associated with dissolved oxygen levels, but *in situ* oxygen data were not available during the ROV surveys. A deeper understanding of *in situ* oxygen levels would help clarify the role of this factor in shaping megafauna assemblages and its interaction with trawling.

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Acknowledgments

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Dedication

I would like to dedicate my thesis to people who supported me to take this endeavour, to move to a different province, in a different language, to study what I love. All my gratitude goes to Dr. Yves Mauffette at the Université du Québec à Montréal for his time and mentorship. He motivated me to undertake a masters in marine ecology, which was a rare field at this university during my undergraduate studies. His humour and enthusiasm was greatly appreciated! Another supporter of my endeavours, Erick Beaulieu, friend and supervisor during my undergraduate studies, helped me to see the underlying values behind graduate studies and to help me make the right decisions adapted to my interests. Finally, without Dr. S. Kim Juniper, who accepted to give me the opportunity of a summer internship in 2006, I would not be where I am today.

Chapter 1

1.0 Introduction/Literature review

1.1 Anthropogenic impacts on benthos

There are no areas in the world where marine ecosystems remain unaffected by anthropogenic impact (Halpern et al. 2008). These impacts can be caused directly (resource extraction, fishing, pollution, etc) or indirectly (climate change, ocean acidification, etc). One widespread and important human activity that affects marine ecosystems is bottom trawling, a fishing method using heavy weighted nets to drag for benthic species such as cod, flatfish and shrimp. It is considered to be a non-selective type of fishery, causing high turbidity and reducing the multidimensional relief of the seabed by dragging the sediment over long distances. By-catch of sponges and corals is particularly concerning because these organisms provide important habitat for many species (Kaiser et al. 2002).

In British Columbia, deep-sea bottom trawling started in the 1990s and the target species have been the shortspine thornyhead (*Sebastolobus alascanus*) and the longspine thornyhead (*Sebastolobus altivelis*) for the Japanese market. *S. altivelis* is found between 500 and 1,600 metres depth while *S. alascanus* has a broader depth distribution (90-1,460 metres) . The two species co-occur between 600 and 1,200 metres depth (Haigh & Schnute 2003). Hypoxia and extreme hypoxia occur along the continental slope off Vancouver Island in that depth range (Crawford & Peña, in preparation). The consensus definition for hypoxia is when oxygen levels are below 1.4 ml/l, affecting marine benthic

organisms (Tyson & Pearson 1991). The definition of extreme hypoxia or oxygen minimum zone is where dissolved oxygen levels persists below 0.5ml/l over geological time (Levin et al. 2001). Both thornyhead species tend to be evenly distributed on the muddy/sandy sediment and are frequently observed close to rocks. Jacobson and Vetter (1996) studied the bathymetric demography and niche separation of thornyhead rockfish off Oregon and California. Most of the spawning biomass occurred between 600-1000m, in the oxygen minimum zone. Younger shortspine thornyheads were found shallower (200-600m) but migrated in deeper waters when older. Longspine thornyhead, a specialist of the oxygen minimum zone, was found only between 600 and 1400m. Jacobson and Vetter (1996) suggested that interspecific competition was partially avoided because the two species had similar body sizes at different water depths. Both species have slow growth rates and late sexual maturity (25 years old). Because of the uniform distribution of these species on the continental slope, trawl tows last between four and twelve hours (COSEWIC 2007) at an average speed of 4.48 km/h (Schnute et al. 2004). *S. altivelis* has been listed as a special concern species under the Species at Risk Act (SARA) since 2007 (COSEWIC 2007). Species co-occurring with the longspine thornyhead include the shortspine thornyhead, Grenadiers (Macrouridae), sablefish (*Anoplopoma fimbria*), dover sole (*Microstomus pacificus*), deep-sea sole (*Embassichthys bathybius*), and the grooved tanner crab (*Chionoecetes* spp.) (Haigh & Schnute 2003). Bottom trawling has raised concerns from scientists and the public in the past few years in relation to its impact of seafloor habitat as well as high by-catch, but remains a very important part of the fisheries economy in Canada. Governmental bottom trawling data

from 1996 to 2005 show that the footprint is over 38,000 km^2 along Canada's Pacific coast (Sinclair 2007). The map of the footprint of bottom trawling in British Columbia shown on Figure 1 suggests that there are extensive areas of benthic ecosystems that are disturbed from trawling. A recent report by Fuller *et al.* (2008) considered the different types of fishing gear used in Canada, their various impacts and the economic importance of these fisheries. Bottom trawling had the highest catch volume in 2005 with 296,992 tons of fish accounting for $377 million of the fisheries economy. However, pot and trap gear types had a higher economic value with $1,117 million. Fuller *et al.* (2008) report that bottom trawling was found to have the most severe impact, mainly on habitat (and habitat forming organisms). Larger, epibenthic invertebrates are particularly vulnerable to unintended effects of bottom trawling because of their location on soft and hard substrata on the seafloor. These megafaunal organisms compose much of the by-catch of the trawl fishery.

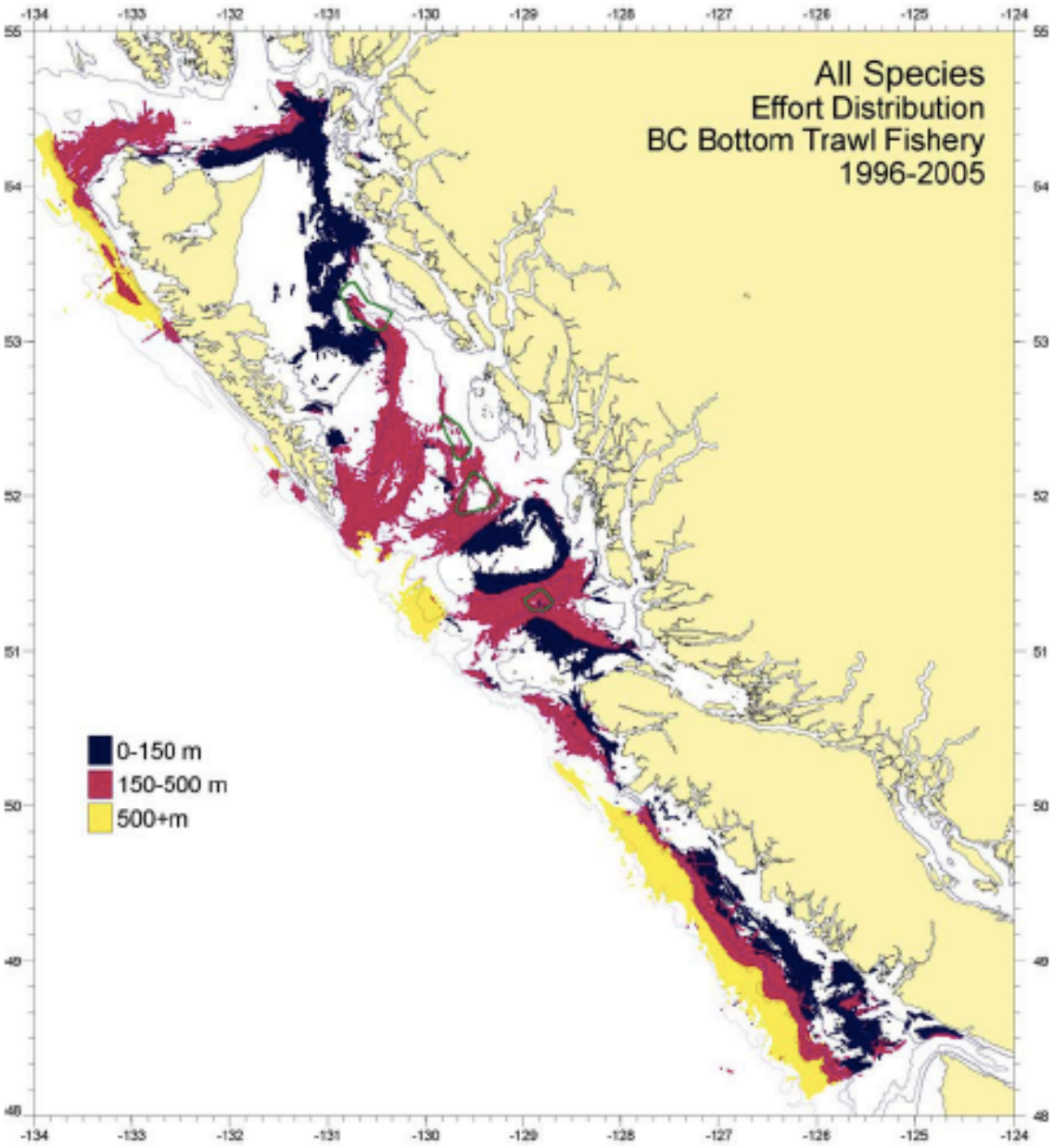


Figure 1: The footprint of the BC groundfish bottom trawl fishery totals over 38,000km^2. Three depth zones were used in this analysis and areas of sponge reef closures which were in place in 2006/2007 are outline in green. Figure from Sinclair report (2007).

1.2 The epibenthic megafauna in deep-sea ecosystems

The epibenthic mega fauna are an important component of deep-sea benthic ecosystems. Their composition is influenced by environmental features such as depth, substratum type, temperature, and organic matter availability. High pressure, cold temperature, darkness and stable salinity usually characterize deep-sea ecosystems, defined here below 200 metres (Etter & Mullineaux 2001). Photosynthesis does not occur at these depths; the small quantity of organic matter reaching the seabed helps to sustain life adapted to this environment. The bottom is usually muddy, because of the long-term sediment accumulation, making this environment favorable to some species. The presence of rocks, sponges and corals also provides habitat for many species and contributes to ecosystem variability. Along continental margins, food availability, oxygen levels, substratum variability, grain size, bottom current and size of benthos generally decrease with depth (Levin, 2001).

Habitat forming organisms are an important feature of the continental margin benthos. Krieger and Wing (2002) have shown that gorgonians (sea fans) provide food, habitat or shelter for a variety of species including brittlestars, seastars, anemones, fishes, and crabs. Beaulieu (2001) found 139 associated species with glass sponges, and Rogers (1999) has found 866 species associated with *Lophelia pertusa* (deep-sea corals) beds in the North-East Atlantic. Buhl-Mortensen (2010) described the influence of structure-forming species on habitat complexity and diversity on continental margins. Their study examined deep-sea scleractinian corals and sponges, solitary corals (gorgonians and sea pens) as well as large foraminifera.

A diminishing food supply with increasing depth makes near-bottom transport important to accessing particulate food. This transport occurs above the benthic boundary layer (BBL)(Boudreau & Jorgensen 2001), a thin layer at the surface of the seabed where friction reduces currents and particle transport to near zero. Organisms that are associated with structure-forming species have enhanced access to water currents above this layer and therefore more food particles than if they were directly on the seabed. The structure-forming species can also provide shelter and produce microenvironments bringing different resources for various types of fauna.

A progress report from Sinclair (2007) at the Department of Fisheries and Oceans Canada stated that little was known about the species composition, the demographic profiles and the habitat forming biota along the British Columbia coast, more specifically in rough bottom areas. The Geological Survey of Canada has undertaken habitat mapping on the west coast, with a particular interest in sponges and corals. Siliceous sponges (glass sponges) are predominant along British Columbia's coast and many sponge reefs have been described (Conway et al. 2005). Among others, *Heterochone calyx, Aphrocallistes vastus, Farrea occa* are reef builders in the order Hexactinosan and *Rabdocalyptus dawsoni, Acanthascus platei, Acanthascus cactus,* and *Staurocalyptus dowlingi* are non-reef builders in the Order *Lyssacinosa*.

1.3 Measuring the impact of trawling on benthic ecosystems

The impact of trawling varies depending on the seabed environment and ecosystem present (Collie et al. 2000a, Collie et al. 2000b, Kaiser et al. 2002, Kaiser et al. 2006). It has been found that high levels of trawling can decrease bottom habitat

complexity and biodiversity (Engel & Kvitek 1998, Kaiser et al. 2002). Bottom trawling can also enhance the abundance of opportunistic species; for example a surprisingly high number of ophiuroids was found in trawled areas in Monterey Bay, California (Engel & Kvitek 1998). The authors of this latter study suggested that small, motile suspension/deposit feeders are possibly not affected by trawling and perhaps even favored by being small and flexible, and able to take advantage of newly exposed sediments.

Hixon and Tissot (2007) undertook a quantitative study comparing benthic communities of trawled and untrawled areas off Oregon, USA. They found that the dominant megafauna in the trawled area were mobile scavengers that tend to aggregate along trawl-door marks. Sea pens, that are sessile, slow-growing and long-lived species, dominated untrawled seabeds. Clark and Rowden (2009) also found a significant difference in macro-invertebrate assemblage composition between fished and unfished seamounts. Live habitat-forming corals rarely occurred on the fished seamounts, but were observed regularly on the unfished seamounts (Clark & Rowden 2009).

Other studies of trawling found in the literature indicate that trawling also has a significant negative impact on soft-sediment bioturbator composition and nutrient flux rates (Olsgard et al. 2008). Tillin *et al.*, (2006) also found that chronic bottom trawling can lead to large-scale shifts in the functional composition of benthic communities.

1.4 Field methods used in trawl impact studies

Two basic approaches are commonly used to study the impact of trawling on marine ecosystems: by carrying out experimental trawls and comparing community assemblages before/after the trawl (Kenchington et al. 2001) or, more commonly, by

comparing assemblages between trawled and untrawled (or less trawled) areas (Hixon & Tissot 2007). A variation of the latter method was used in this study. Seafloor faunal assemblages can be compared between trawled and untrawled areas by carrying out video surveys using a remotely operated vehicles (ROV) or manned submersibles and by collecting samples. Video surveys usually limit fauna community comparisons to the epibenthic megafauna, the larger organisms that are visible on or near the seafloor. Compared to experimental trawls, surveying trawled and untrawled areas of seabed usually has the advantage of permitting broader scale studies of trawling impacts and does not add further impact on the benthic communities under study. Both experimental and comparative studies make use of seafloor video recordings. Subsequent video analysis allows the determination of species composition and abundance in the surveyed area. Species are identified at the lowest taxonomic level possible depending on visibility, camera angle, speed and distance from the seabed. Underwater video camera quality and recording equipment are improving with changes in technology, which will improve our ability to identify organisms from imagery and accurately describe deep-sea ecosystems.

Methods used to acquire seafloor video imagery have an importance influence on the quality of the information that is available for comparative studies. Stone (2006) has used ROV video transects for many studies in Alaska to examine the distribution of corals and species association as well as the interaction with fisheries. By having a camera looking directly down from the ROV to the seafloor and two parallel lasers 20 centimetres apart, he is able to know the width of the image area. Lundsten *et al.* (2009) examined benthic invertebrate communities on three seamounts off California, USA, using a remotely operated vehicle and videos. They examined the abundance and

distribution of organisms in over 134,000 observations of 202 identified invertebrate taxa. Efforts were made to identify the species to the lowest level of taxonomy. Two parallel laser beams were used to estimate transect width. After the video analysis, some new categories were assigned to all observed taxa to determine their functional roles of the seamount communities: motility and feeding mode. Brown *et al.*(2004) examined the accuracy and statistical power of different survey methods used in marine benthic ecology to detect change, in their assessments of coral reefs. More particularly, they wanted to determine the appropriate transect length, number of transects, and number of samples per transect. They found that longer transects (25-50 metres) had higher inconsistency than shorter transects (10 metres), suggesting that smaller sampling units were more suitable for the habitats sampled. These habitats consist more of coral cover and are not necessarily applicable to soft-bottom continental slope surveys found in this study. In general, the accuracy of transect surveys is still an issue in terms of camera orientation and frame selection.

Information on the location and frequency of commercial trawls are usually confidential and held by government management agencies, so that access for researchers is often limited. Comparative studies therefore require an independent means of quantifying trawling intensity in a given area. Trawl door marks (or trawl scars) can be seen in video imagery and appear as depressions (5cm-25cm deep) on the seabed and often have a different colour, revealing the mud from a deeper layer. Smith *et al.* (2007) used side-scan sonar combined with underwater towed video camera to quantify the impact of trawling. Side-scan sonar helped to determine the direction and density of trawl marks. Videos were used to estimate density of trawl marks, the level of bioturbation and

the density of crinoids. Most submersibles and ROVs are equipped with sector-scanning sonars that can provide a broader view of seabed characteristics (and trawl scars) than can be seen in video imagery alone. Recorded sonar scans can thus be used to quantify the abundance, direction, and distribution of trawl marks along ROV transects.

It is important to mention that using the term ‘untrawled area’ does not necessarily refer to pristine habitat. In a review on fisheries, Pinnegar and Engelhard (2008) acknowledged the largely altered state of marine ecosystems, commonly called the ‘shifting baseline phenomenon’. Maps of trawling activities on the continental shelves and slopes of most countries show few accessible areas where trawling has never taken place. The term ‘untrawled recently’ or ‘without visible trawl marks’ is more appropriate, although an effort should be made to confirm the absence of trawling at the scale of the study. Nevertheless, the benthic ecosystems studied are probably in alternative states already because of various driving forces. The information provided in Sinclair (2007) makes it clear that untrawled areas are rather rare in the area surveyed in the study presented here.

1.5 Methods used for imagery analysis

Different methods are used for seafloor video analysis, but these are often not described in detail in the literature and vary greatly between regions, researchers and studies. The basic approach, whether for trawl studies or general habitat surveys, involves reviewing video records and extracting information on the composition and abundance of benthic organisms and habitat characteristics. Linking individual observations to submersible navigation data enables accurate positioning of observations and improves the spatial resolution of the data set. Analysis and exploitation of data resulting from

video observations can range from simple characterization of transect properties in maps to the entry of all observations and navigational information into a database or Geographic Information System for statistical analysis and the mapping and classification of habitats. Different databases and software applications are used, such as *MS Access*, *Excel*, *ClassAct Mapper*, developed by Fisheries and Oceans Canada (J. Pegg, personal communication) and *VARS*, a Video Annotation and Reference System, developed by the Monterey Bay Aquarium Research Institute (N. Jacobsen, Personal communications).

1.6 Classification of marine habitat and ecosystems

Different types of classification schemes are used worldwide to map marine habitats and ecosystems (Harper et al. 1998, Connor et al. 2003, Davies et al. 2004, Valentine et al. 2005, Greene et al. 2007). Most authors agree about the need for a standardized approach to enable comparison and repeating of work being done by different researchers in different countries and habitats. In Europe, the European Nature Information System (EUNIS) is widely used (Davies et al. 2004). Valentine *et al.* (2005) focused on the description and classification of habitats, more specifically in terms of geological, biological, and oceanographic attributes for the region of northeast North America. The effects of natural and anthropogenic processes on these attributes are also described. Greene *et al.* (2007) focused on the importance of scale and physiography. They produced attribute codes associated with a classification scheme, which are based on physiography, depth, substrate hardness, geomorphology, texture, and biology. Both of these classification schemes can be expanded and adapted to the specificity of other areas. Harper *et al.* (1998) developed a biotope classification system using the

combination of sidescan sonar and video surveys for nearshore mapping and monitoring. Finally, Sameoto *et al.* (2008) combined and adapted two classification schemes from Greene *et al.* (2007) and Valentine *et al.* (2005) to analyze benthic videos surveys using a database to be imported in GIS. The method chosen for this study is adapted from Sameoto *et al.* (2008) because of the similarity between the survey methods and objectives, habitat types and benthic ecosystems found.

1.7 Research objectives

The goal of this study was to develop a toolbox of video analysis and statistical approaches for studying the relationship between megafaunal distribution and habitat characteristics. Bottom trawling is a widespread anthropogenic disturbance in that area, so developing a tool to quantify trawling intensity and its impact on megafauna was a second goal. This work was carried out on the continental slope off Vancouver Island using post-cruise exploitation of ROV video and sector-scanning sonar data from a cable route survey undertaken in 2007 for the NEPTUNE Canada undersea observatory network.

This study was designed to answer several basic questions. How do species abundances and distributions vary on the continental slope? Is species composition different in heavily versus lightly trawled areas? What spatial scales are present in the community structure and which environmental variables explain these spatial scales? To address these questions my research had four principal objectives:

1. Develop a methodology for extracting geo-referenced information from videos, using species abundance and composition, as well as quantifying trawl-door marks. Create a database and system of attributes to structure this information.
2. Develop a methodology for quantifying bottom trawling from high-resolution scanning-sonar data.
3. Characterize soft-bottom assemblages and visualize distribution and abundance using a GIS (Geographic Information System).
4. Determine the relationships of megafaunal abundance, composition and diversity with various environmental variables (substratum, depth/oxygen gradient, trawling intensity) using multivariate statistics.

This thesis will take you through these four steps. *Chapter 2* contains the methodology development, *Chapter 3* the results, *Chapter 4* the discussion and *Chapter 5* the summary of findings and conclusion.

Chapter 2

2.0 Methodology

2.1 Study area and field work

The study area was located on the continental shelf approximately 60 nautical miles off the west coast of Vancouver Island, British Columbia (Figure 2). Video transects for this study were carried out with the ROV ROPOS from August 3-5, 2007 during a NEPTUNE Canada cable route survey. The submersible surveyed a prescribed route along the seafloor, at an altitude of approximately 1.0 m. Video was recorded continuously during dives from a 3-CCD DXC 990 Sony standard definition video camera, equipped with a VCL 716 BXEA lens that was mounted on ROPOS on a pan and tilt mechanism. During transects the video camera was aimed forward and down at an oblique angle. Imagery from a high-resolution scanning-sonar (Kongsberg Simrad 1081 fully digital) was also recorded during the dives.

Two transects were analyzed for this survey. The first transect (dive R1075) covered 12 km on the continental slope near Barkley Canyon, at depths ranging from 340m to 650m (Figure 3). The second transect (dive R1074) lasted approximately 32 hours and covered 30.8 km, climbing the continental slope from 1,300m to 300m (Figure 4). These dives provided a rare opportunity to directly observe faunal and habitat distribution on the continental slope. The primary geotechnical mission of the cruise– cable route observations- limited optimization of dive logistics and imaging to suite the requirements of an ecological study.

Figure 2: The survey area is located on the upper continental slope, about 60 miles off the West coast of Vancouver Island, Canada.

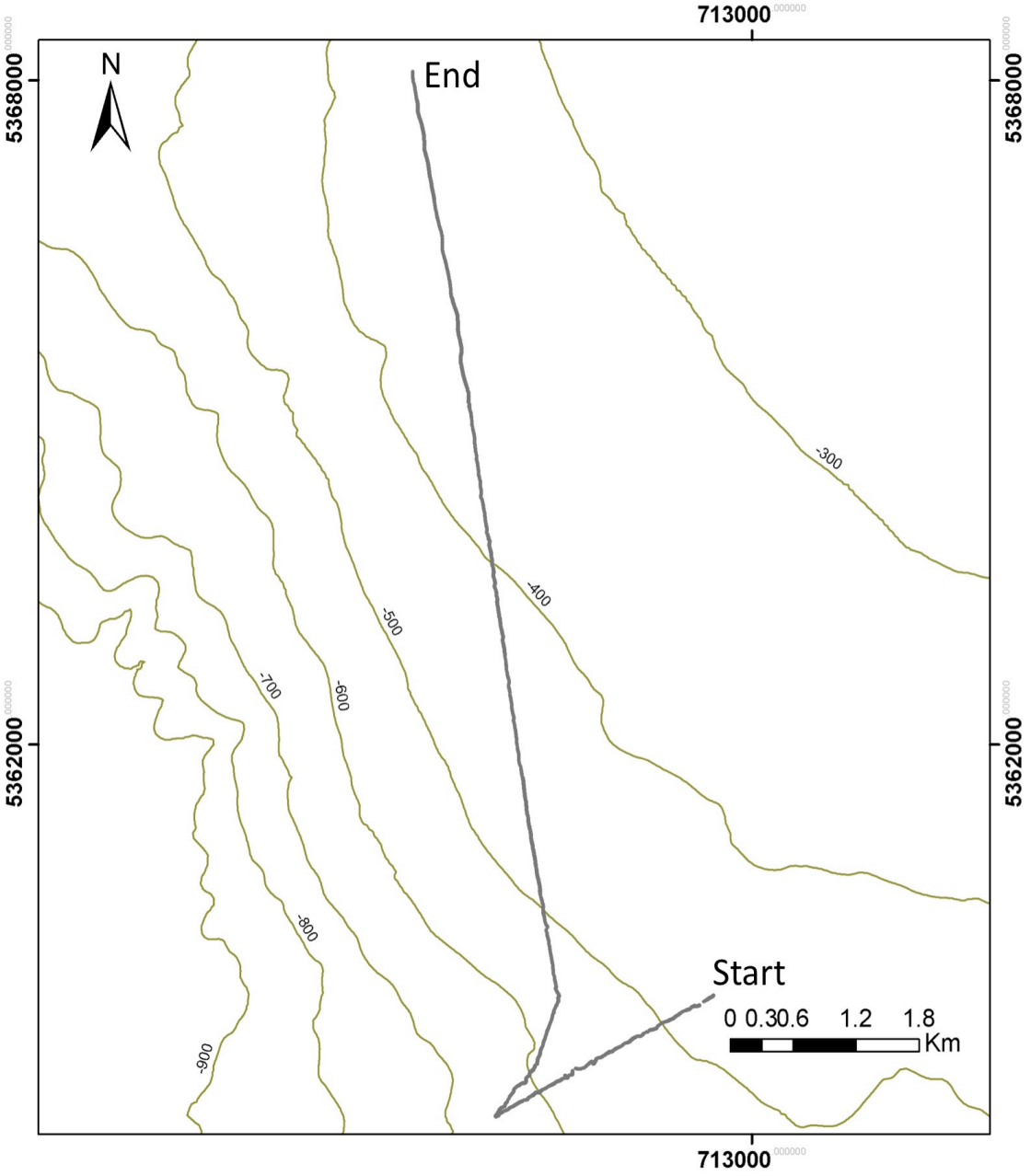


Figure 3: Map showing transect R1075 with a depth ranging from 340m-650m.

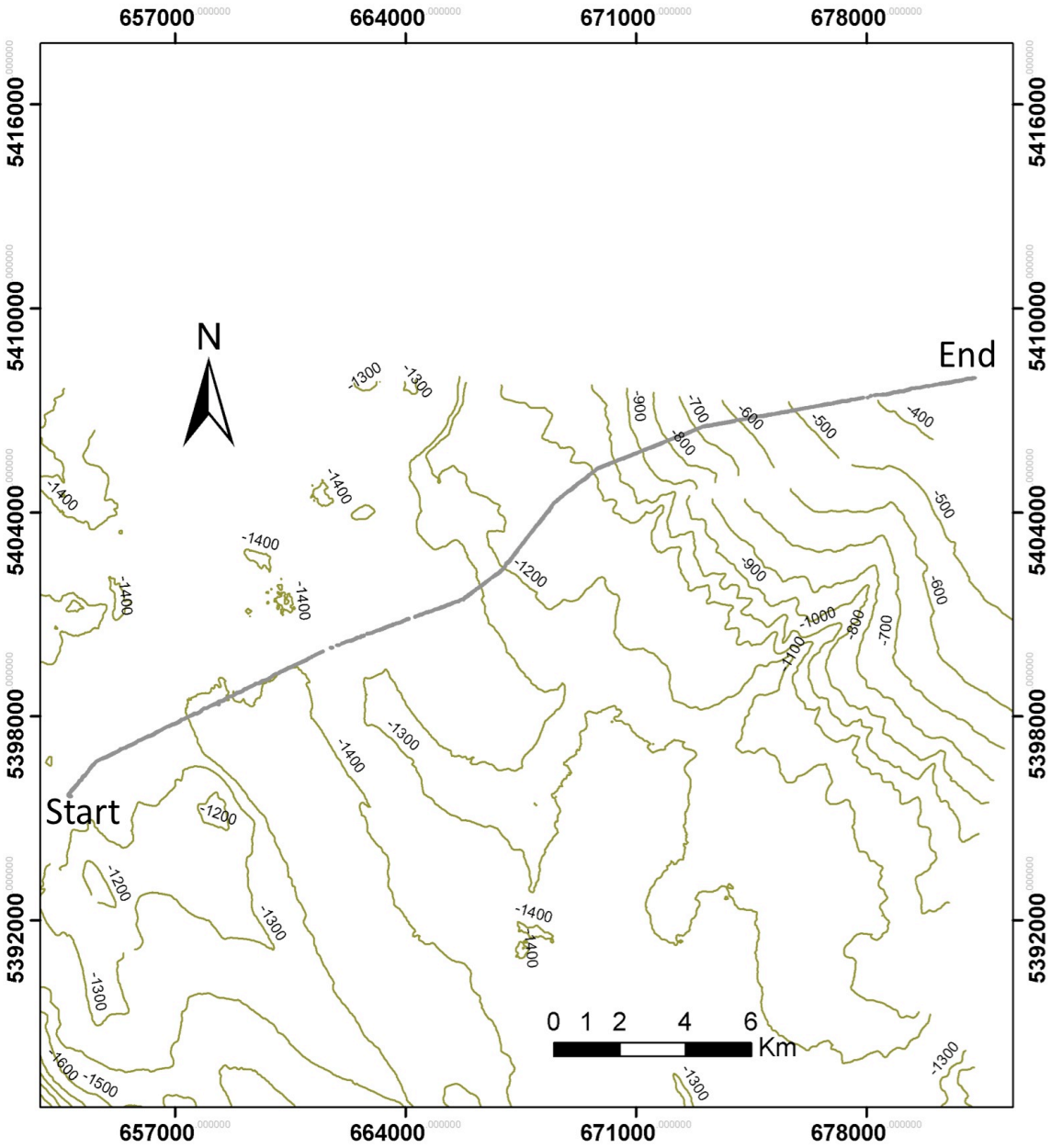


Figure 4: Map showing transect R1074 with a depth ranging from 300m-1,300m.

2.1.2 Video recording

Video was recorded on MiniDV tapes and transferred on DVDs following the survey. Information about the position (latitude/longitude), depth, time (UTC), and heading was visible on the screen. Throughout the dives, loggers took frame grabs and entered general information on seabed characteristics, indication of species, and general comments/events. Digital still pictures were also taken during the dives to have better image quality of species and close ups. This data was made available on DVD by ROPOS including logs of the dives and navigation data of the ROV,

2.2 Video/image analysis

2.2.1 Viewing and video analysis

Faunal and habitat information was extracted from video records by playing back recordings and analyzing continuously, pausing when species were visible to identify and calculate the abundance, as well as noting change of habitat. Animals were noted as they crossed the centre-line of the image, marked by two lasers dots projected by parallel lasers mounted on the camera. The laser dots were separated by 10 cm. An imaginary line joining the two lasers and perpendicular to the direction of motion of the submersible was extended to the left and right of the lasers to count organisms at two scales: a 50 cm swath and an extended swath (total width of the image of 1-2 m^2). In addition, occasional zooms provided close up imagery of species when the submersible was stationary (Figure 5).

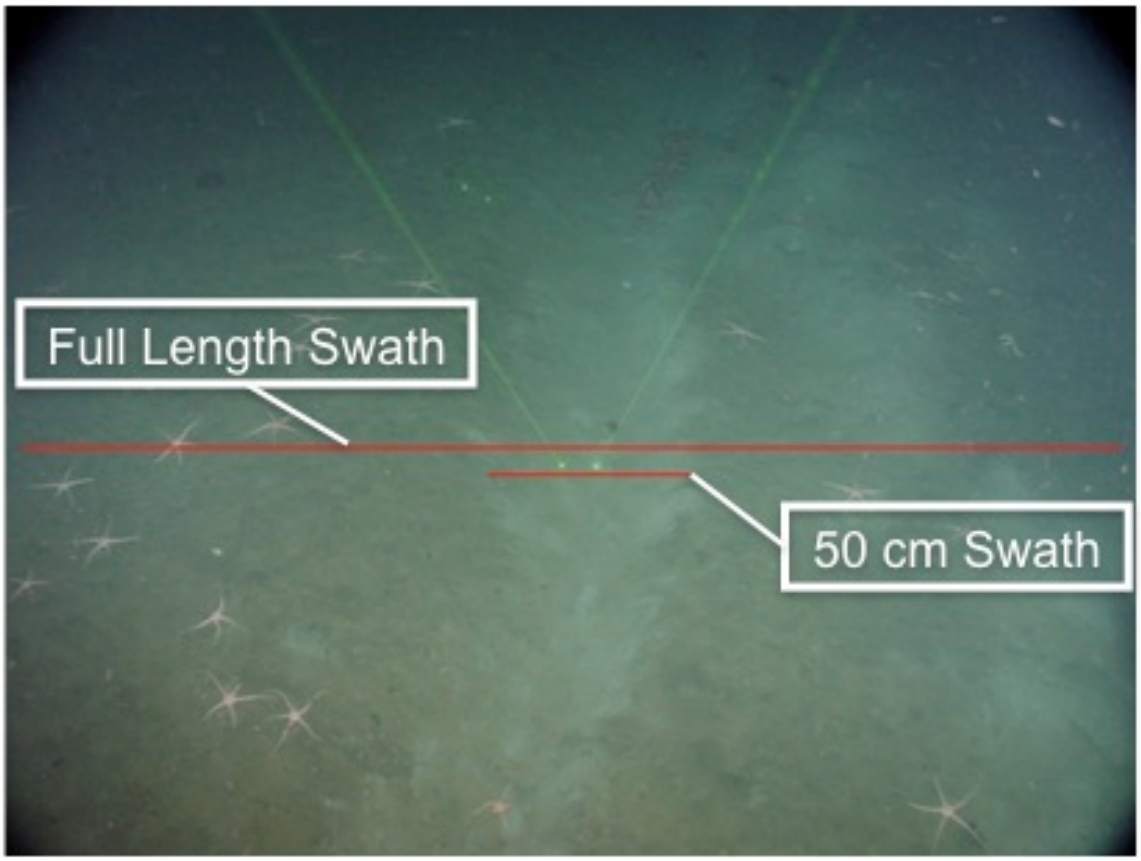


Figure 5: The video analysis followed three scales: swath (50cm length), full length swath and zoom in (ROV stopped to close up on species).

These swaths could not be directly converted to along-transect areas because the altitude of the ROV above the seabed and the angle of the camera were not always constant during transecting. This variation affects both the area encompassed by each image, as explained by Wildish *et al.* (2008) and the visibility of megafaunal organisms. The relationship between submersible altitude and observed megafauna for transect R1075 is shown in Figure 6. The mean altitude was 1.4m with a standard deviation of 0.4m. The mean altitude for transect R1074 was 1.7m with a standard deviation of 0.4m (figure not shown). Using Kinovea, a video analysis software, the average speed of the ROV over the seabed is about 0.5m/second and that 1-2 second of transect is equivalent to 1-2 m^2 of seabed. ROPOS speed over the seabed and video area covered were also observed by Du Preez & Tunnicliffe (2011).

2.2.2 Database and attributes description

Faunal and habitat information were entered directly into a relational database that was created in *Windows MS Access,* following the method of Sameoto *et al*. (2008) for benthic habitat surveys. A first viewing of dive R1075 was used to complete the menu with standard and developed attributes (Figure 7). Standard attributes included attributes already expected such as substratum description, boulders abundance, trawl mark presence, and species already known to be present from the dive logs. Developed attributes were added during the viewing process and included new species found, certainty index, and biogenic roughness categories. Attributes included abundances of species at the lowest taxonomy level, substratum category, physical and biological roughness, survey mode, visibility, scale, certainty, etc. The classification system was

modified from Valentine *et al*. (2005) and Sameoto *et al*. (2008). Attributes were divided into three main sections: time/location, substrata/habitat description, and fauna abundance/composition.

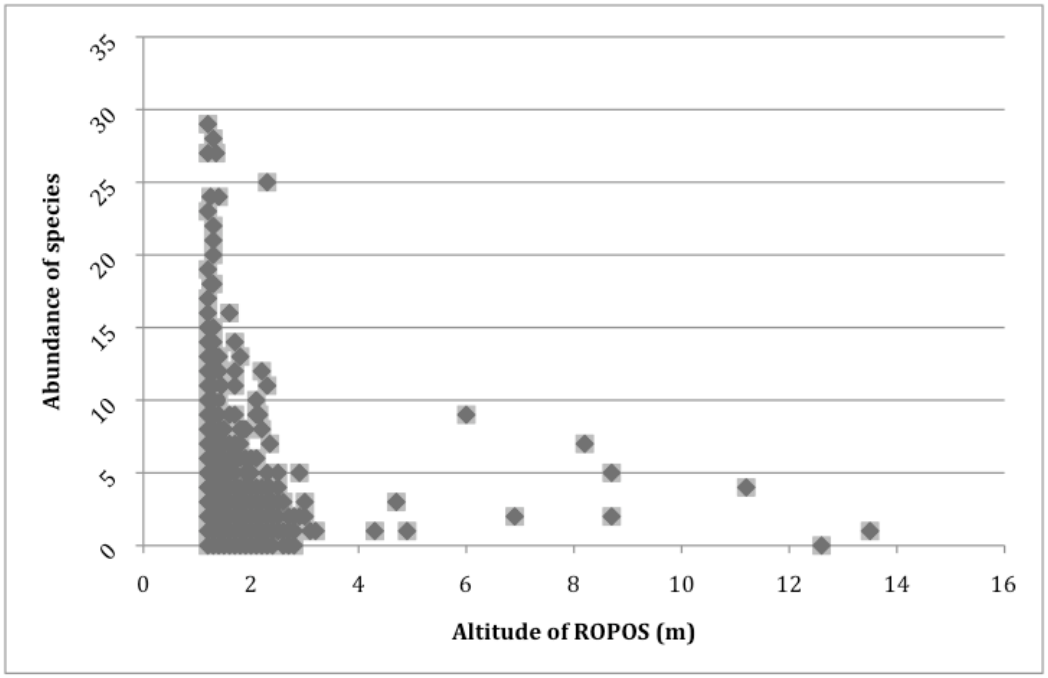


Figure 6: Total abundance of species in relation to altitude of ROPOS above the seabed during transect R1075.

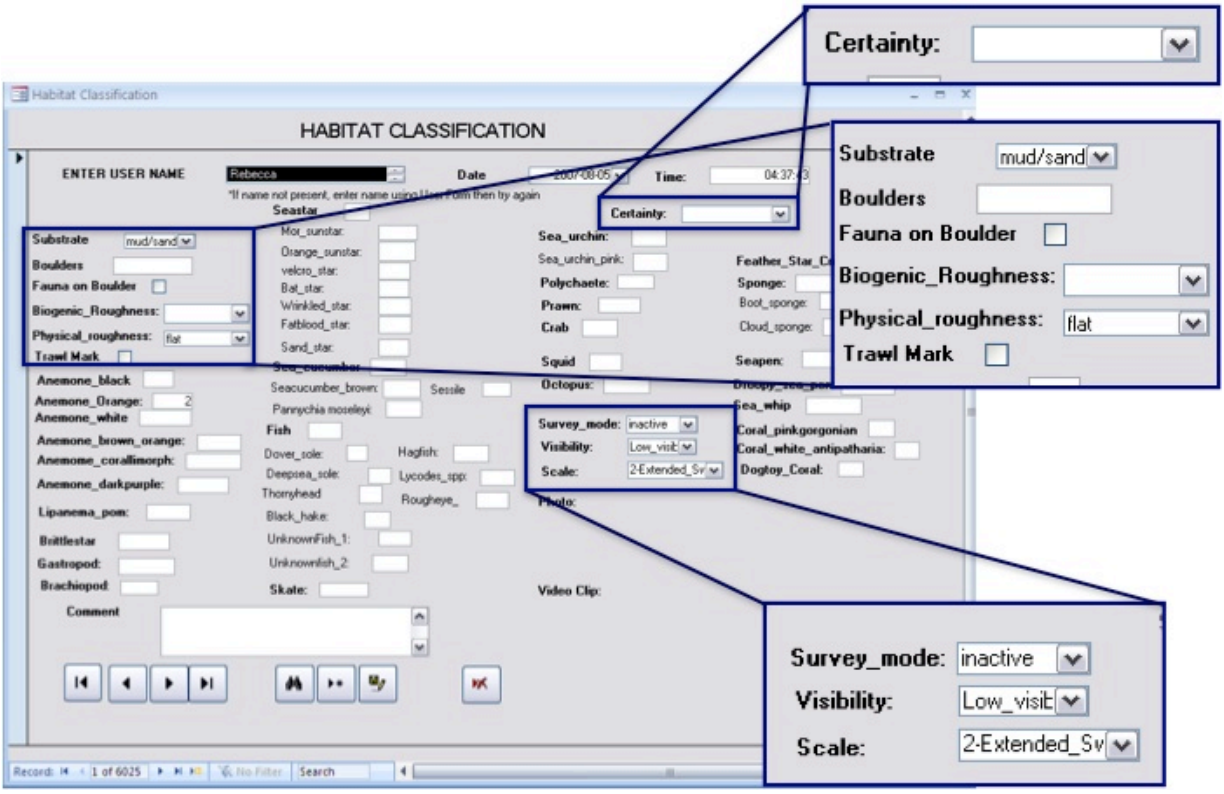


Figure 7: Screenshot from the habitat classification database in Microsoft Access and the various attributes developed.

Table 1 shows most attributes developed for analyses of transect R1075 and **Error! Reference source not found.** shows the species diversity index for the two dives combined. The database used for R1074 analysis was slightly different, including new biogenic roughness categories and different faunal species. The diversity index table lists species found throughout the dive using the 'zoom in' scale or samples (ophiuroids), however the ROV speed and altitude above the seabed during transects made it difficult to identify species at the lowest taxonomic level with 100% certainty. Species with very low detectability (size <5cm) were removed from further analysis. New developed attributes were also added during the detailed video analysis process if new species were detected. Biogenic roughness categories were used when abundances of certain taxa were very high, occupying more than 25% of the screen (Sameoto et al. 2008), knowing that this will vary by the altitude. Biogenic roughness for individual taxa were converted to average densities by counting individuals in 10-15 screen grabs of each roughness category, for each taxon (Figure 8).

Table 1: Attribute description for video analysis

General
Username : name of the person analyzing **Date :** Date of the research cruise analyzed **Time :** Time of the data entry from the video (UTM)
Habitat
Substratum:
1-Mud/Sand (if muddy/sandy bottom visible) 2-Pebbles/cobbles (if covers most of the screen) 3-Mixed (if presence of > 25% pebbles/cobbles on sandy/muddy bottom)
Boulder: number of boulders if present
Fauna on boulder (checkbox): check only if present
Biogenic roughness (if a species dominates >25% of the seabed):
1-Brittlestar; 2-sea cucumber; 3-bioturbation; if dominates the seabed 4-sea urchin; 5-white. This category has been added to describe small white species that may be sponges, anemones, or gastropods at times. They are too small to identify during transect and only if we stop and zoom in, we may see the difference. The category has been added for information for potential future studies. 6-no
Physical roughness:
1-flat; 2-slope; 3-crevasses; 4-pits
Additional Information
Certainty:
1-Uncertain_Vis: visibility is affecting the identification 2-Uncertain_ID: species unknown to the video analyst (to be described) 3-Pretty certain 4-Certain
Visibility:
1-Good_visibility 2-Low_visibility

3-No_visibility
Scale:
1-Swath (50cm) 2-Extended Swath (full width at the laser level) 3-Zoom in (close up on species)
Trawl mark (checkbox):
Check when present
Biology
Taxons have been created and abundance is indicated (see diversity index in Table 2 for complete list of species)

Table 2: Diversity index described from zoom in images or samples for both transects R1074 and R1075 as a list of species present in this area. Species were identified to the lowest taxonomy level possible during video analysis, but often did not go as far as this table. Sometimes only class was described because of the video speed or quality. cf abbreviation indicates uncertainty of the species with the video or photo available (Bengtson 1988). To avoid confusion, 'Sea Whips' are described as the long, rigid white pennatulacea (*Funiculina* spp.), in contrast to Sea pens that are shorter and soft (orange sea pen. Taxonomy following the World Register of Marine Species (WoRMS).

Database name	**Taxon common name**	**Species**	**Genus**	**Family**	**Order**	**Class**
Brachiopod	Brachiopod	*Vancouveriensis*	*Laqueus*	Laqueidae	Terebratulida	Rhynchonellata
Crustaceans						
Prawn			*Pandalus*	Pandalidae	Decapoda	Malacostraca
Crab	Tanner crab		*Chionoecetes*	Oregoniidae	Decapoda	Malacostraca
Fish						
Fish	Fish					Actinopterygii
Hagfish	Pacific hagfish	*stoutii*	*Eptatretus*	Myxinidae	Myxiniformes	Myxini
Thorny_rockfish	Shortspine thornyhead	*alascanus*	*Sebastolobus*	Sebastidae	Scorpaeniformes	Actinopterygii
Thorny_rockfish	Longspine thornyhead	*altivelis*	*Sebastolobus*	Sebastidae	Scorpaeniformes	Actinopterygii
Hake	Black cod/sablefish	*fimbria*	*Anoplopoma*	Anoplopomatidae	Scorpaeniformes	Actinopterygii
Pacific Cod	Pacific Cod	*macrocephalus*	*Gadus*	Gadidae	Gadiformes	Actinopterygii
Pacific hake	Pacific hake	*productus*	*Merluccius*	Merlucciidae	Gadiformes	Actinopterygii
Psychrolutes phrictus	Blob sculpin	*phrictus*	*Psychrolutes*	Psychrolutidae	Scorpaeniformes	Actinopterygii
B. brunneum	Twoline eelpout	*brunneum*	*Bothrocara*	Zoarcidae	Perciformes	Actinopterygii
Lycodes	Lycodes		*Lycodes*	Zoarcidae	Perciformes	Actinopterygii
Dover_sole	Dover_sole	*pacificus*	*Microstomus*	Pleuronectidae	Pleuronectiformes	Actinopterygii
Pacific_halibut	Pacific halibut	*stenolepis*	*Hippoglossus*	Pleuronectidae	Pleuronectiformes	Actinopterygii
Deepsea_sole	Deepsea_sole	*bathybius*	*Embassichthys*	Pleuronectidae	Pleuronectiformes	Actinopterygii

PinkSnailfish	Blacktail Snailfish	*melanurus*	*Careproctus*	Cyclopteridae	Scorpaeniformes	Actinopterygii
FinescaleMora	Pacific flatnose	*microlepis*	*Antimora*	Moridae	Gadiformes	Actinopterygii
Skate	Longnose skate	*rhina*	*Raja*	Rajidae	Rajiformes	Elasmobranchii
Skate	Sandpaper skate	*interrupta*	*Bathyraja*	Rajidae	Rajiformes	Elasmobranchii
Ratfish	Spotted ratfish	*colliei*	*Hydrolagus*	Chimaeridae	Chimaeriformes	Elasmobranchii
Cat shark	CatShark			Scyliorhinidae	Carcharhiniformes	Elasmobranchii
Cnidaria						
Anemone	Anemone					Anthozoa
Ane_Orange				Actinostolidae	Actiniaria	Anthozoa
Ane_black				Cerianthidae	Ceriantharia	Anthozoa
Ane_white					Actiniaria	Anthozoa
Ane_darkpurple	Sand Rose anemone	*columbiana*	*Urticina*	Actiniidae	Actiniaria	Anthozoa
Ane_brown_orange	Venus fly-trap		*Actinoscyphia*	Actinoscyphiidae	Actiniaria	Anthozoa
Ane_corallimorph	Corallimorph	*pilatus*	*Corallimorphus*	Corallimorphidae	Corallimorpharia	Anthozoa
Liponema_pom	Pom-Pom anemone	*brevicorne*	*Liponema*	Liponematidae	Actiniaria	Anthozoa
Seapen	Orange sea pen	*gurneyi*	*Ptilosarcus*	Pennatulidae	Pennatulacea	Anthozoa
Droopy_sea_pen	Droopy_sea_pen	*lindahli*	*Umbellula*	Umbellulidae	Pennatulacea	Anthozoa
Sea_whip	Sea whip (described as rigid, tall, white)		*Funiculina*	Funiculinidae	Pennatulacea	Anthozoa
Dogtoy_Coral	Dogtoy Octocoral	*ritteri*	*Anthomastus*	Alcyoniidae	Alcyonacea	Anthozoa
Coral_pinkgorgonian	Gorgonians	*longispina cf*	*Plumarella*	Paragorgidae	Gorgonacea	Anthozoa
Coral_antipatharia	Black Coral		*Antipathes*	Antipathidae	Antipatharia	Anthozoa
Echinodermata						
Sea_urch	Sea urchin				Echinoida	Echinoidea
Sea_urch_pink	Fragile pink sea urchin	*fragilis*	*Strongylocentrotus*	Strongylocentrotidae	Camarodonta	Echinoidea
Seacuc_white	White deep-sea sea cucumber	*moseleyi*	*Pannychia*	Laetmogonidae	Elasipodida	Holothuroidae
Sessile_Seacuc	Sessile Sea cucumber	*squamatus*	*Psolus*	Psolidae	Dendrochirotida	Holothuroidae
Seacuc_brown	Dirty sea cucumber	*mollis*	*Pseudostichopus*	Synallactidae	Aspidochirotida	Holothuroidae
Sea_cucumber	Sea cucumber					Holothuroidae
Feath_Star_Crino	Crinoid	*serratissima*	*Florometra*	Antedonidae	Comatulida	Crinoidea

Brittlestar	Lonspine brittlestar	*longispina*	*Ophiopholis*	Ophiactidae	Ophiurida	Ophiuroidea
Brittlestar	Tile brittlestar	*jolliense*	*Ophiosphalma*	Ophiolepididae	Ophiurida	Ophiuroidea
Brittlestar	Orange brittlestar	*cataleimmoidus*	*Ophiophthalmus*	Ophiacanthidae	Ophiurida	Ophiuroidea
Brittlestar	Scaly brittlestar	*ponderosa*	*Stegophiura*	Ophiuridae	Ophiurida	Ophiuroidea
Seastar	Seastar					Asteroidea
Mor_sunstar	Morning sunstar	*dawsoni*	*Solaster*	Solasteridae	Valvatida	Asteroidea
Oran_sunstar	Orange sunstar	*exiguus*	*Solaster*	Solasteridae	Valvatida	Asteroidea
Fatblood_star	Fat blood star	*sanguinolenta*	*Henricia*	Echinasteridae	Spinulosida	Asteroidea
velcro_star	Velcro star	*forreri*	*Stylasterias*	Asteriidae	Forcipulatida	Asteroidea
Wrinkled_star	Wrinkled star		*Pteraster*	Pterasteridae	Velatida	Asteroidea
Sand_star	Sand star	*foliolata*	*Luidia*	Luidiidae	Paxillosida	Asteroidea
Bat_star	Bat star	*miniata*	*Patiria*	Asterinidae	Valvatida	Asteroidea
O.koehleri	Rainbow star	*koehleri*	*Orthasteria*	Asteriidae	Forcipulatida	Asteroidea
Skinny sunstar		*cf pusilla*	*Hymenodiscus*	Brisingidae	Brisingida	Asteroidea
Fat sunstar	Northern Sun star	*endeca*	*Solaster*	Solasteridae	Valvatida	Asteroidea
C. patagonicus	Cookie star	*patagonicus*	*Ceramaster*	Goniasteridae	Valvatida	Asteroidea
C. crispatus	Mud star	*crispatus*	*Ctenodiscus*	Ctenodiscidae	Paxillosida	Asteroidea
Seastar Cushion	Cushion star		*Pteraster*	Pterasteridae	Velatida	Asteroidea
Mollusca						
Bivalvia	Bivalvia					Bivalvia
Octopus	Octopus		*Octopus*	Octopodidae	Octopoda	Cephalopoda
Squid	Squid	*gigas*	*Dosidicus*	Ommastrephidae	Oegopsida	Cephalopoda
Gastropod	Gastropod		*Neptunea*	Buccinidae	Neogastropoda	Gastropoda
Porifera						
Boot_sponge	Boot sponge		*Acanthascus*	Rossellidae	Lyssacinosida	Hexactinellida
Sponge	Glass Sponge		*Acanthascus*	Rossellidae	Lyssacinosida	Hexactinellida

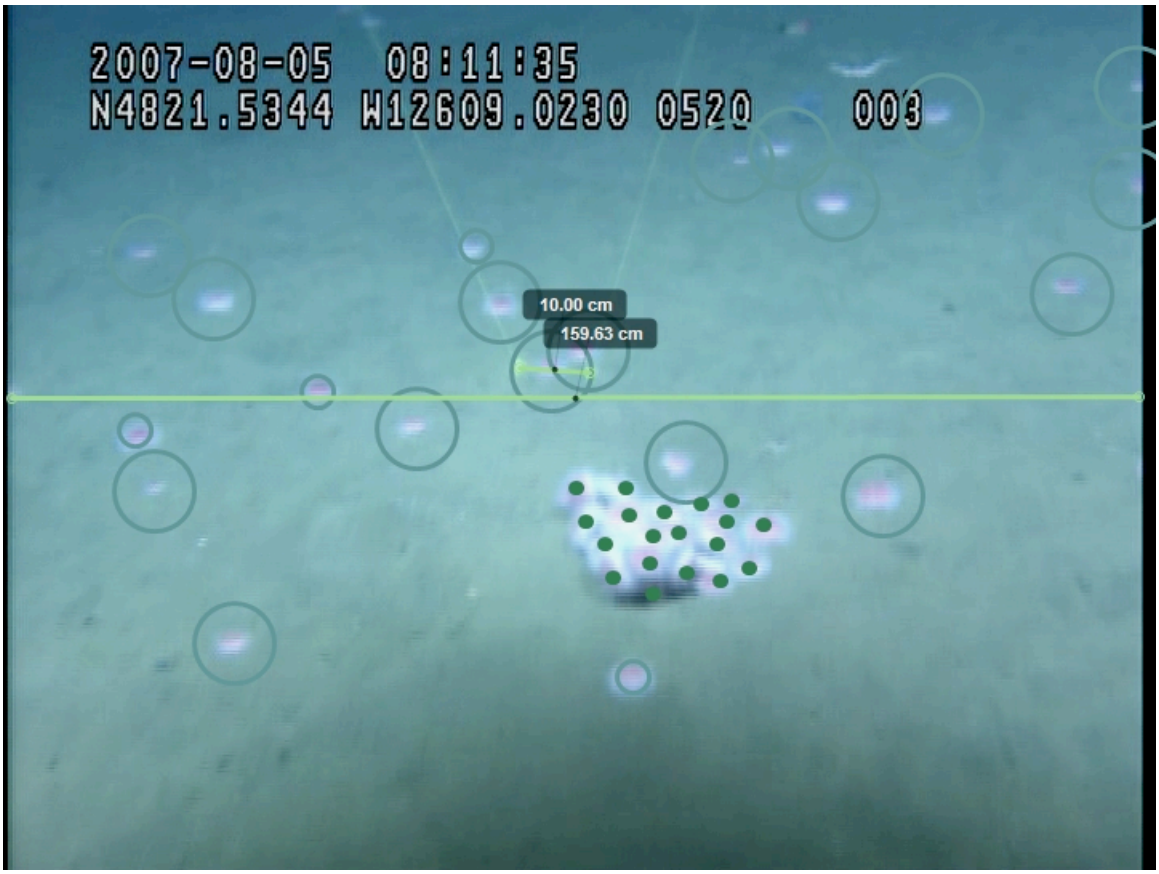


Figure 8: Using Kinovea, screengrabs were selected to calculate the average abundances of biogenic roughness categories. This shows an example for the fragile pink sea urchin (*Allocentrotus fragilis*) found sometimes in high densities.

2.3 Sector Scanning-Sonar analysis

In addition to being occasionally visible in video imagery, trawl door marks on the seafloor were also visible in the high-resolution sector-scanning sonar recordings. Sonar is often the most accurate and sensitive tool for detecting trawl marks or other seabed features (Blondel 2009). The broader area imaged by the sonar increased the likelihood of detecting of the presence of trawling since trawl doors are not always in continuous contact with the seafloor during tows. The sonar field of view had a radius of 50m, covering a total area of approximately 7,854 m^2 when completing a 360 degrees survey. For both transects, the sonar was usually set to scan a sector of 128 degrees, which covered an area of approximately 2,793 m^2 ($128°/360°(50m)^2 \pi$) compared to 1 to 3 m^2 for video imagery depending on the scale of view. Figure 9 illustrates the difference of scale between sonar and video imagery. Using the Kongsberg *MS1000* software (http://www.kongsberg-mesotech.com/images.htm) with real-time display, sonar video files from the dives R1074 and R1075 were analyzed using the playback mode. On-screen markers were placed on trawl door traces on the screen and geo-referenced images were exported (Figure 9). Trawl marks were counted and directions were taken into account. Abundances of trawl marks were then grouped by 500m sectors along both transects to calculate intensity. Table 3 shows the trawl mark intensity scale used adapted from Smith *et al.* (2007). The trawling intensity value was added to the final habitat classification database before grouping the abundance data by 250m lengths along transects.

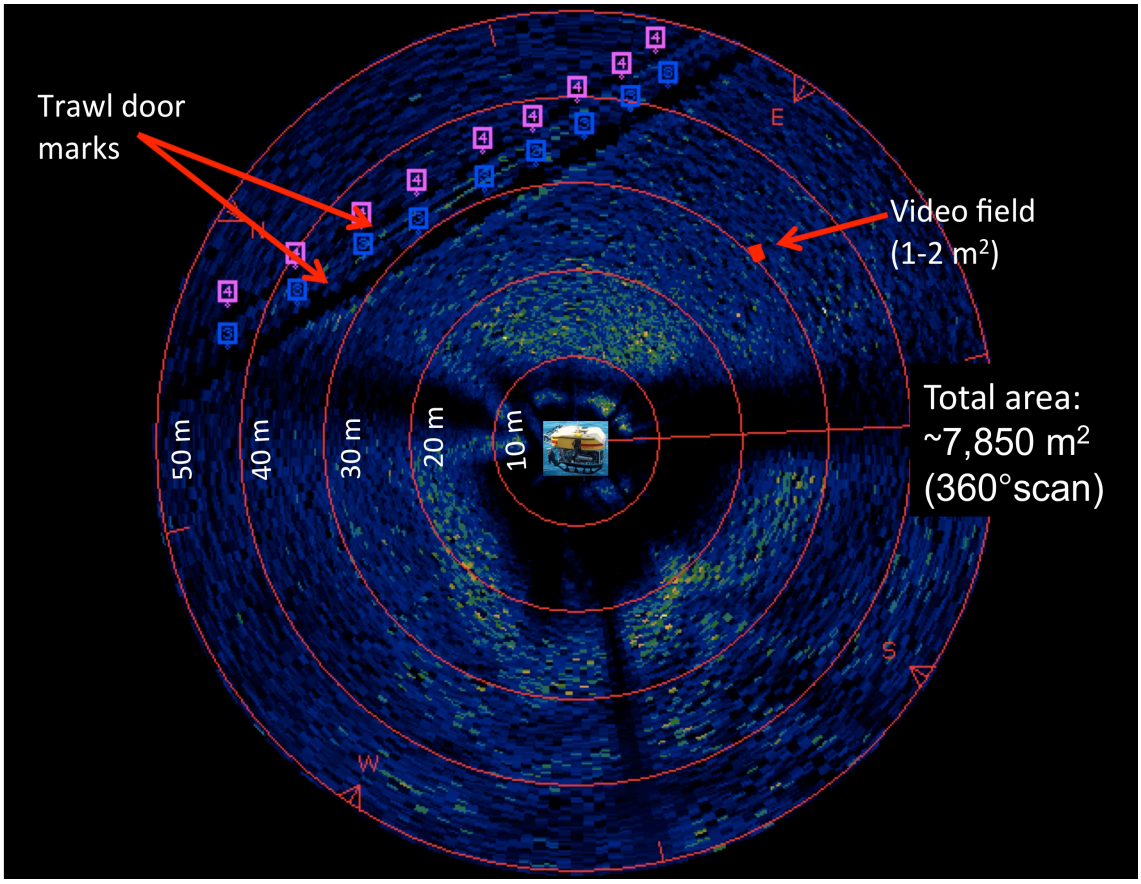


Figure 9: High-resolution scanning-sonar imagery gives a wider field of view than video. Concentric circles are separated by 10 meters. Trawl marks were counted and markers were placed on each trawl mark. Trawling intensity for each transect was compiled per 500m and added in the MS Access database along with the video data. In this screen grab, a small red square was added to represent a typical video field view (from the ROPOS video camera) of 1-2 m^2 in comparison to the 7,854m^2 area covered by a 360° sonar scan.

Trawl-door marks	Trawl Intensity
0 - 2	0
3 - 10	1
11 - 20	2
21 - 30	3
31 - 40	4
41 - 50	5
51 - 60	6
61 - 70	7
71+	8

Table 3: Trawl intensity scale used to convert trawl door mark abundances from the scanning-sonar analysis (adapted from Smith *et al.* (2007)) for each 500m section of the transect.

Comparison of trawl-door mark abundances between the scanning-sonar and the video determinations for transect R1075 showed a marked difference (3.4x) between the two methods: a total of 533 trawl marks were visible in the sonar imagery compared to 155 in the video recordings (Table 4). Uneven lighting conditions in the video and a greater sensitivity of sonar to shallow or partially-eroded trawl marks likely explain these differences. In transect R1074, a similar difference was observed between the two methods, where sonar observations were 3.6 times (1,007) the video observations (276). Both methods found trawl marks to be twice as abundant in transect R1074 compared to R1075, demonstrating that both tools provide similar relative measures of trawling intensity, albeit with different accuracies resulting from to their different sensitivities to faint marks and the size of their fields of view. The sonar data were chosen over the video data to describe trawling intensity in further analyses in this study.

2.4 Data processing

After reviewing video records and extracting biological and habitat information, observations were geo-referenced by joining the time of each data entry with the latitude/longitude field in the Access database. This required changing the HH:MM:SS time format to seconds. All categorical data were changed to integer values and absences were recorded as zero values. For all subsequent data analyses, only the 'extended swath' scale was utilized because of the rarity of data using the 50 cm 'swath' scale. For example, there were 4,930 faunal observation entries for the extended swath scale analysis compared to 1,831 entries with the 50cm-swath scale for transect R1075.

Table 4: Comparison between the total visible trawl marks using sonar and video methods in the first transect analyzed (R1075) to develop the method. For both transect, the ratio between sonar and video analysis for trawl-door marks detection is similar: 3.4 times more in R1075 and 3.6 times more in R1074.

Transect R1075	**R1075 Total Trawl Marks**	**R1074 Total Trawl Marks**
Sonar	533	1007
Video	155	276

For that reason, we did not analyze transect R1074 with the 'swath' scale, using only the 'extended swath'. Databases and navigation data of the transects were imported into the GIS, shapefiles created using the coordinate system WGS84 and then projected in Universal Transverse Mercator (UTM) system space using the NAD83 Region 9N for further analyses.

The Geospatial Modeling Environment (Hawth tools extension version 0.5.2 Beta for ArcGIS 10) was used to perform the following analyses (Beyer 2004). First, Euclidian distances between all stations were calculated and transposed into a distance triangular matrix for the two transects for future data analysis (PCNM tests). Euclidian distances between species occurrences were also calculated to identify spatial patterns and the uniformity of distribution. After video analysis, the two large databases for both transects contained a very large number of zeros, which complicated statistical analyses. In the absence of hydrothermal venting or cold seeps, such low densities and absences of visible megafauna are to be expected in deep-water, soft bottom habitats (Levin et al. 2001). In order to reduce the number of zeros in data sets used for statistical analyses, data points were grouped using grid cells in ArcGIS. Using Hawth tools extension, a grid cell vector was created using different spacings (50m, 100m, 250m and 500m). If the vector grid cell size did not include completely a row or column during the grid creation process, the tool extended it to make sure the entire space was filled. The 250m-grid was determined to provide the best resolution, reducing zeros to a manageable number for statistical calculations (Table 5), while permitting the detection of spatial patterns at a regional scale (100s to 1000s of meters). Figure 10 shows the 250m-vector grid applied over transect R1075. Using the overlay tool in the analysis tools section in ArcGIS, the 250m-

grid was intersected with the species/habitat classification database to group the data. The column containing the grid cell number now called “station” was selected and a dbf table was exported using the *summarize* function.

Table 5: Data processing involved converting the full database that was too large to analyze data and perform statistics. A vector grid of 250m was created using the Geospatial Modeling Environment (Hawth's tools version 0.5.2 Beta) and the database was summarized per grid cell number (station).

	Transect R1075		**Transect R1074**	
	Full database	**Grouped data grid cell 250m**	**Full database**	**Grouped grid cell 250m**
# cells containing zero	206,238	1,855	1,815,470	7,170
# of Stations /observations	4,357	58	32,643	161

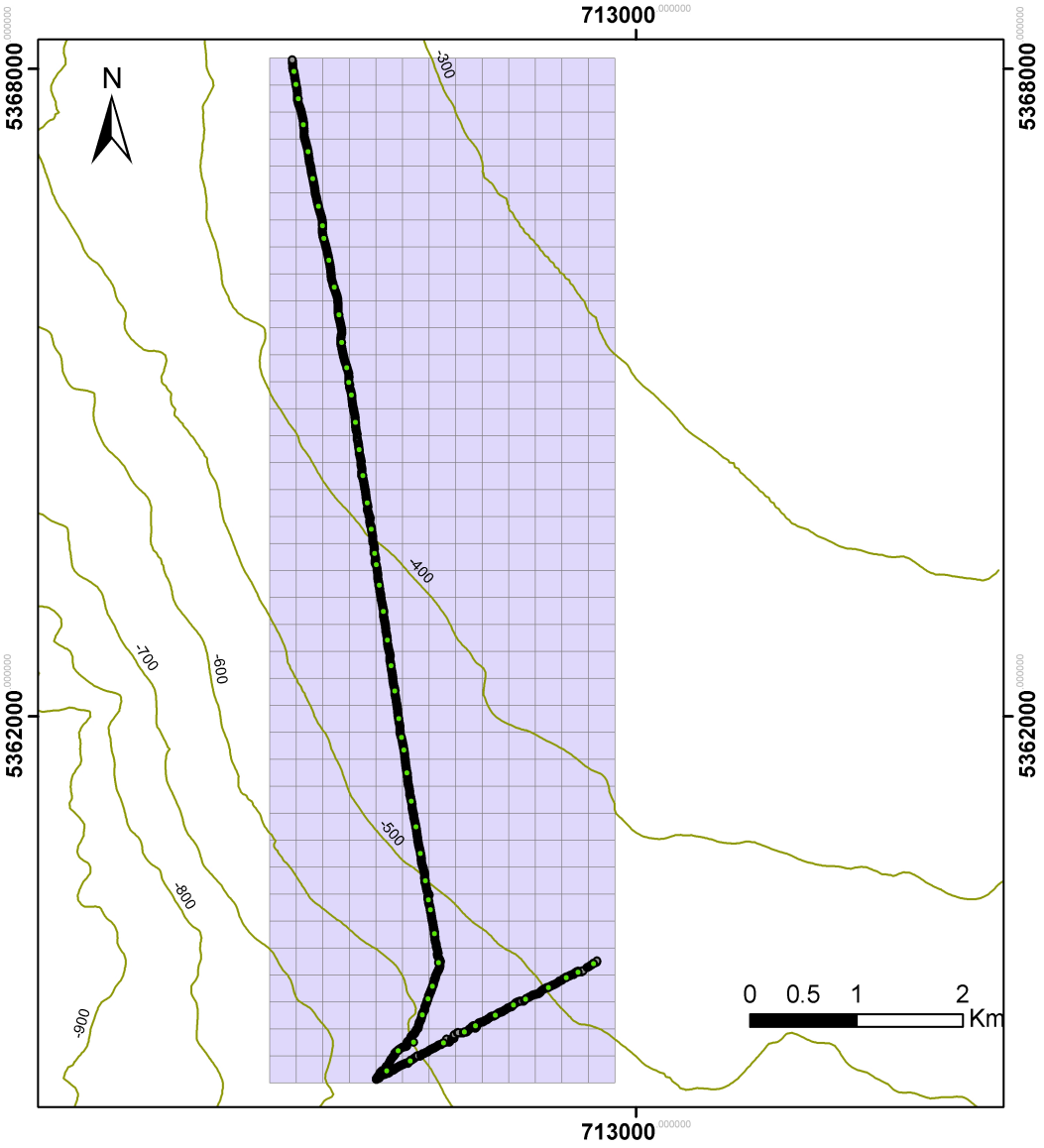


Figure 10: Hawth's tool was used to create a 250m vector grid and apply it over transect R1075 to group data for statistical purposes.

Biogenic roughness categories were transformed into average abundances by creating new fields for each corresponding taxa in the GIS. All species abundances were summarized and environmental factors averaged per grid cell by exporting a dbf table from ArcGIS that could be used in Excel. Table 6, Table 7, and 8 show the steps taken to add the total abundance for each biogenic roughness categories into the final database. The new table containing grouped data per 250m was then useable for statistical analysis. The final database manipulation integrated the biogenic roughness abundances to the corresponding average abundance of the species it described in an Excel spreadsheet. Even after grouping data, the transect R1074 had two grid cells or stations with zero abundance for all visible megafauna (#3713 and #5046), which were incompatible with statistical tests in PRIMER. These two stations were excluded from these analyses.

2.5 Data Analyses

The two transects were treated separately for data analysis. Trawling intensity maps were created using ArcGIS to evaluate the extent of trawling. A Variance Inflation Factor (VIF) test was carried out in R to evaluate the importance of multi-co-linearity between variables. When the VIF factor exceeds 5, a decision has to be made to delete a variable from the tests. Two environmental variables had a VIF of 50. The ‘presence of fauna on boulders’ variable was deleted from further statistical analysis while the ‘number of boulders’ was retained.

Table 6: Biogenic roughness categories for the transect R1075 and their average abundances calculated.

Biogenic roughness entries for R1075		**Average abundance**	**Total abundance**
1-Brittlestar	674	27	18,198
2-Sea cucumber	68	25	1,700
3-Sea urchin	9	63	567

Table 7: Biogenic roughness categories for the transect R1074 and their average abundances calculated. Some entries were monospecific and some had mixed species. The category "white" was not taken into account, as it was a species too small to document.

Biogenic Roughness entries for R1074		**Average abundance calculated**	**Total abundance**
1- Brittlestar	9651	3	28,953
2- Brittlestar cover	5550	24	133,200
3- Sea urchin / brittlestar	34	69/2	2,346/68
4- Sea cucumber (*S. globosa*)	85	36	3,060
5- White	610	-	0
6- Sea cucumber / white	76	15/64	1,140/5,120
7- Sea cucumber / brittlestar	45	24/19	1,080/855
8- White / brittlestar	411	13/0	0
9- None	16,271	0	0

Table 8: Example of calculation of total abundance to add to the final database. Biogenic roughness categories for R1074 with their total abundances obtained by the product of biogenic roughness entries and the average abundance of their respective species shown in table 5. Each species abundance calculated from the biogenic roughness were then added to their respective species abundance.

Category/Taxon	**Ophiuroids**	***Sglobosa***	***Afragilis***
Abundance before biogenic roughness	1227	11613	505
Biogenic roughness categories:			
Brittlestar	28,953	NA	NA
Brittlestar_cover	133,200	NA	NA
Urchin_brittle	68	NA	2,346
Sea cucumber (*S.globosa*)	NA	3,060	NA
Seacuc_white	NA	1,140	NA
Seacuc_brittle	855	1,080	NA
Total abundance after biogenic roughness added	**164,303**	**16,893**	**2,851**

2.5.1 Diversity indices

Using PRIMER-E software, diversity indices for species sample data were calculated using the number of species (S), Margalef's species richness per sample (d), Pielou's evenness (J'), the Shannon index (H') and Simpson's evenness index (1-λ').

The Margalef's index considers species richness (S) per sample, making some adjustments for the number of individuals (N) (Margalef 1958). In this equation, ln is the "natural logarithm" or log to base e (2.71828).

$$d = \frac{S - 1}{\ln N}$$

The Pielou's evenness index measures how evenly the different species are distributed relative to each other (Pielou 1966). The evenness index is calculated as follows:

$$J' = \frac{\mathrm{H}'}{\mathrm{H}'_{\max}}$$

where H' is the number derived from Shannon diversity index and $\mathrm{H}'_{\max}$ is the maximum value of H'. The Shannon diversity index (H') was calculated using $\log_e$ (Shannon & Weaver 1949). The Shannon index is calculated as follows:

$$\mathrm{H}' = -\sum_{i=1}^{S} (p_i \ln p_i)$$

where S is the total number of species present, p_i is the frequency of the species i in the sample. The index normally varies from 1.5 (low richness and evenness) to 3.5 (high richness and evenness).

The Simpson's index of diversity (Simpson 1949) was calculated using PRIMER-e, but the complemented Simpson index was chosen and calculated as follow:

$$1- \lambda' = 1 - \{\sum_i N_i (N_i - 1)\} / \{N (N - 1)\}$$

It is calculated by subtracting the Simpson's index to 1 or also known as the inverse Simpson index. It is easier to compare this index to other diversity indices because the regular Simpson's index is somewhat counterintuitive having a higher diversity when the number is lower. Peet (1974) suggests to use the reciprocal of Simpson's index for regular applications or to detect changes among the most common species. A value of 0 is interpreted as a more homogenous community with fewer species and less evenness while a value of 1 describes a community with more species and more evenness.

Diversity indices were then compared to trawling intensity and depth to detect patterns. Many diversity indices have a problematic overdependence on sampling effort (Warwick and Clarke, 2001), although the Simpson's index has been found to be particularly meaningful and robust with respect to sampling effort influences (Lande 1996, Magurran 2004).

2.5.2 Ordination methods and dendrograms

Non-parametric multivariate analysis of the community data was also performed using PRIMER-E software (Clarke & Gorley 2006) to identify patterns in the

communities, determine which species were typical in each group, to test for differences in community structures between sites (trawling intensities or depth) and to link community patterns to environmental factors (Clarke 1993). The species database was square root transformed to limit any bias caused by highly abundant species. A hierarchical clustering analysis using group-average linkage was performed on the Bray-Curtis similarity matrix and presented in a dendrogram. Bray-Curtis similarity is commonly used in ecological studies. It creates rank-order statements in a triangular matrix representing the similarity in species composition between pairs of samples. For example, sample A and B are more similar than A and C, and so on (Clarke 1993). Faith et al (1987) compared different similarity indices and found that Bray-Curtis similarity was the best similarity index to represent the ecological distance. The ecological distance here is defined by the multidimensional distance between two samples, sites or communities. Species abundance is used to construct the multidimensional coordinates that define ecological distance. Wolda's tests showed that the Bray-Curtis index can be really biaised under small sample size or low sampling effort conditions.

Group-average linking was chosen as it offers a good balance between the sensitivity of complete-link clustering to outliers and the inclination of single-linkage clustering to form long chains and not very intuitive and compact clusters (Manning et al. 2008). The group divisions were selected using 40-60% similarity. The Non-metric Multi-dimensional Scaling (MDS) technique was then applied to the transformed data to examine community relationships (Kenkel & Orloci 1986). The MDS technique is used to explore similarities or dissimilarities in data and allows exploring what environmental variables seem to structure megafauna assemblages. The triangular matrix created with the Bray-Curtis similarity helps to recreate a map of the samples where the approximate

distance between samples represents relative similitude in species composition (Clarke 1993). The MDS is an ordination method to represent, in a bi-dimensional space, the ecological distances among samples. It relies on the principle that Euclidean distances in the plot correspond to ecological distances in the similarity matrix.

A stress value indicates the quality of the representation:

- stress < 0.05 indicates an excellent representation
- stress between 0.05 and 0.1 indicates a good representation
- stress between 0.1 and 0.2 indicates and acceptable representation
- stress > 0.2 indicates a random non satisfactory representation

MDS plots were created using various environmental variables, including trawling intensity, depth, number of boulders, and substratum type. 2D bubbles were used to illustrate the abundance of species in relation to the depth, trawling intensity or other environmental factors.

2.5.3 Principal Coordinates of Neighbor Matrices (PCNM)

A principal coordinates of neighbor matrices (PCNM) procedure was used to detect spatial influences of various environmental variables. PCNM is used to detect and quantify spatial patterns at different scales (Borcard & Legendre 2002). This method allows the detection and quantification of spatial variability over a wide range of spatial scales detectable by the sampling design. Abundance data were first transformed using Hellinger transformation, in which the abundance data are divided by the site total abundance and square-root transformed (Borcard et al. 2011). This is considered to be a meaningful transformation for this type of analysis (Legendre & Gallagher 2001). Euclidian distance triangular matrices, which describe distances between all ‘stations’,

were imported in the R software (R Development Core TeamR et al. 2011). Then, the matrix was truncated at a threshold of 402m to only retain the distance among close neighbors. A principal coordinate analysis on the truncated distance matrices was computed and only the PCNM variables with positive eigenvalues were kept. The resulting principal coordinates (PCNM eigenfunctions) were irregular sinusoids describing all the spatial scales that could be observed in the sampling design. The PCNM variables were generated using the PCNM function implemented in the 'PCNM' package (R development core team, 2006).

Significant PCNM functions were then identified by a forward selection procedure (Dray, 2005) implemented in the 'packfor' package (R development core team, 2006). This procedure uses the results of a permutation test (999 random permutations) to test the significance of the explanatory variables (PCNM functions) successively entering the model and stops when the p-value of a newly included variable is higher than an alpha threshold of 0.05. The significant PCNM functions were then plotted and grouped into sub-models. Redundancy analyses (RDAs) were used to test the significance of each sub-model (i.e. spatial scale) on the biological matrix, followed by canonical analyses of variance (ANOVAs) to test the significance of each RDA axis. The significant axes were then fitted in a RDA to identify the significant contribution of environmental variables on each sub-model.

A redundancy analysis was also performed between environmental variables and (explanatory variables) and species data (response variables). RDA is a regression combined with a Principal Components Analysis (PCA). It is a constrained ordination procedure used to model multivariate response data (Borcard et al. 2011). This approach

is used to test a sequence of linear combinations of the explanatory variables that has the greatest fit to the variation of the response matrix.

Chapter 3

3.0 Results

3.1 Environmental context

Bottom trawling in the study area targets *Sebastolobus* spp., whose abundance and distribution are shown on Figure 11 and Figure 12. Abundances for the *Sebastolobus* spp. taxon reached 121 in transect R1075 and 368 in transect R1074. This area is also a low oxygen zone. Recent dissolved oxygen profiles from this area were made available by the Institute of Ocean Sciences, Department of Fisheries and Oceans (DFO). Figure 13 illustrates that most of the deeper areas of the continental slope are in an oxygen minimum zone (<0.5ml/l) (Crawford & Peña, in preparation). Transects in this study are located near Line B (LB in figure 13) and show lowest oxygen levels (between 0 and 1 m/l) starting at 500m depth. CTD measurements from stations P3 and P4 from a 2007 Line P cruise located close to both transects (Figure 14) were made available by the Marie Robert of the DFO Institute of Ocean Sciences. At Station P4, the closest station (12km distance) to transect R1074 oxygen concentrations were measured down to 1,300m. Dissolved oxygen concentration (ml/l) at station P4 in 2007 showed a strong oxygen gradient, with hypoxia (<1.4ml/l) detectable at 300m and severe hypoxia (<0.5ml/l) occurring between 640m and 1,325m depth (Figure 15).

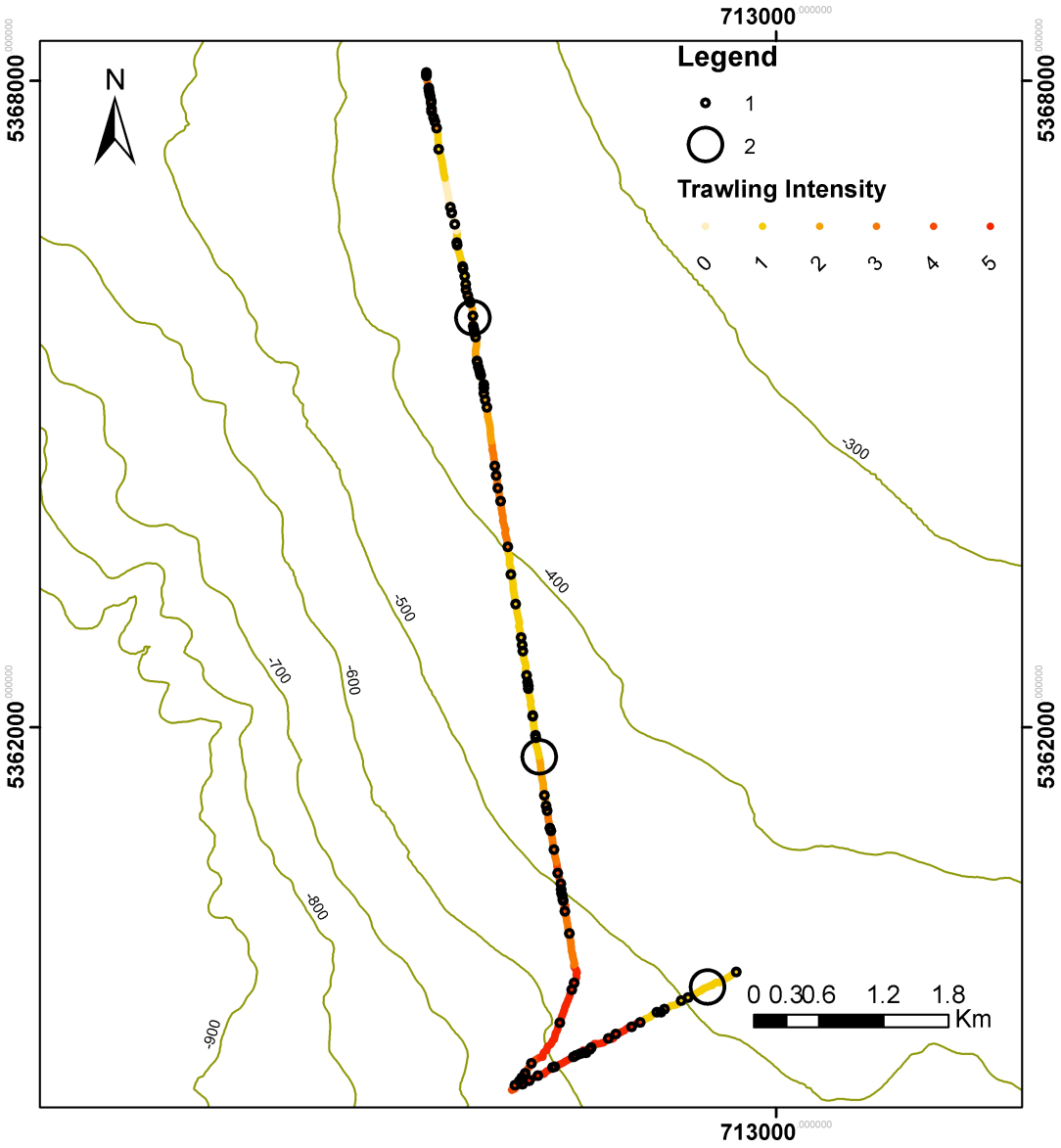


Figure 11: Abundance and distribution of *Sebastolobus* spp. along transect R1075 for a total abundance of 121.

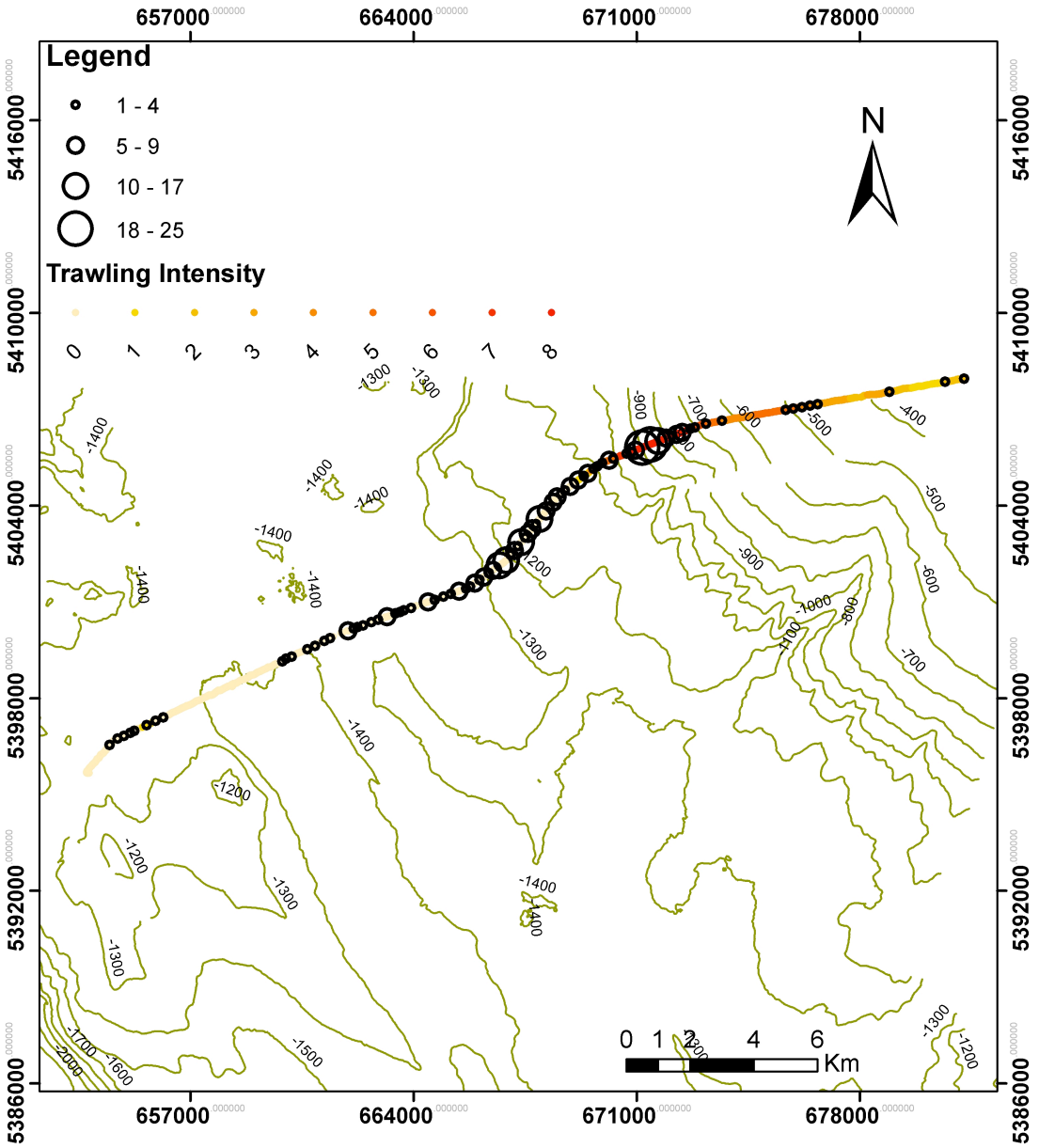


Figure 12: Abundance and distribution of *Sebastolobus* spp. along transect R1074 for a total abundance of 368.

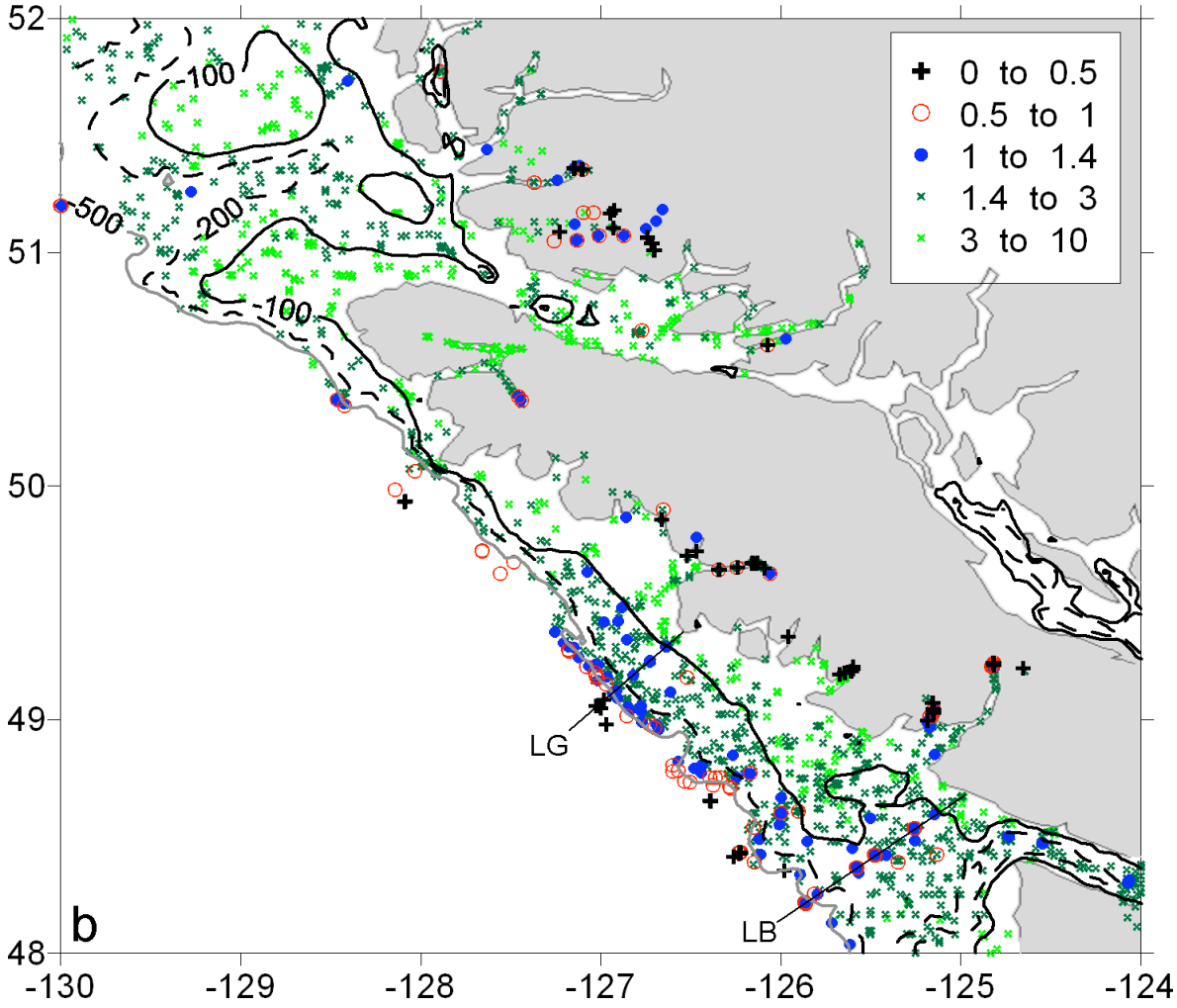


Figure 13: Dissolved oxygen concentration (ml/l) values 0-20m from bottom of the continental shelf off Vancouver Island from 2005-2009 (figure from Crawford and Peña, in preparation). Our transects are located slightly North of Line B (LB) with values from 0 to 1ml/l at 500m depth.

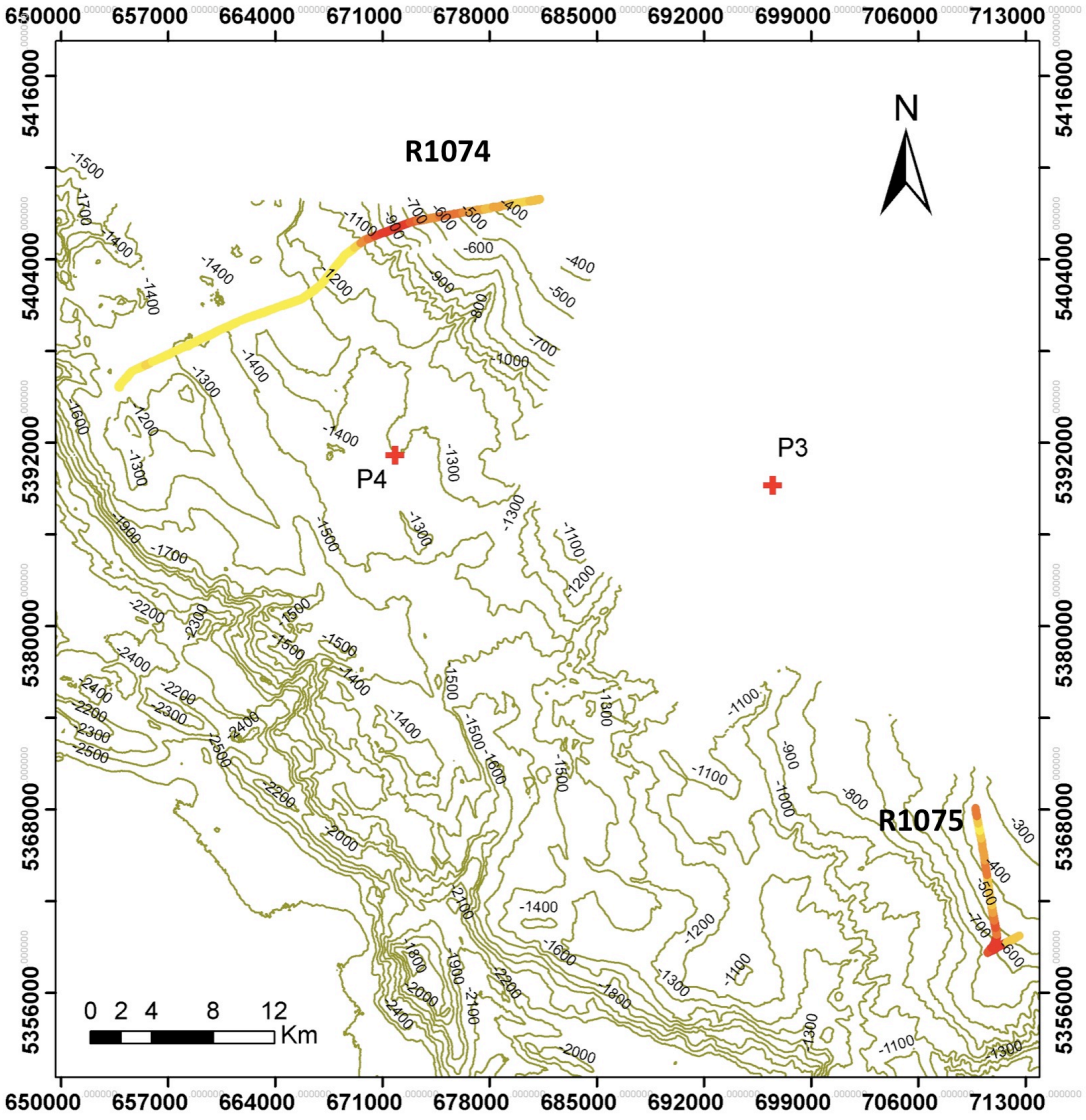


Figure 14: Oxygen, temperature and salinity data were available through Line P routine monitoring survey from February 2007. Stations P4 was the closest to our transects, in particular P4 which is located 12km from R1074 with a deeper vertical profile (1,324m) than the P3 station (756m). These data were collected and made freely available by personnel at the Institute of Ocean Sciences, Department of Fisheries and Oceans.

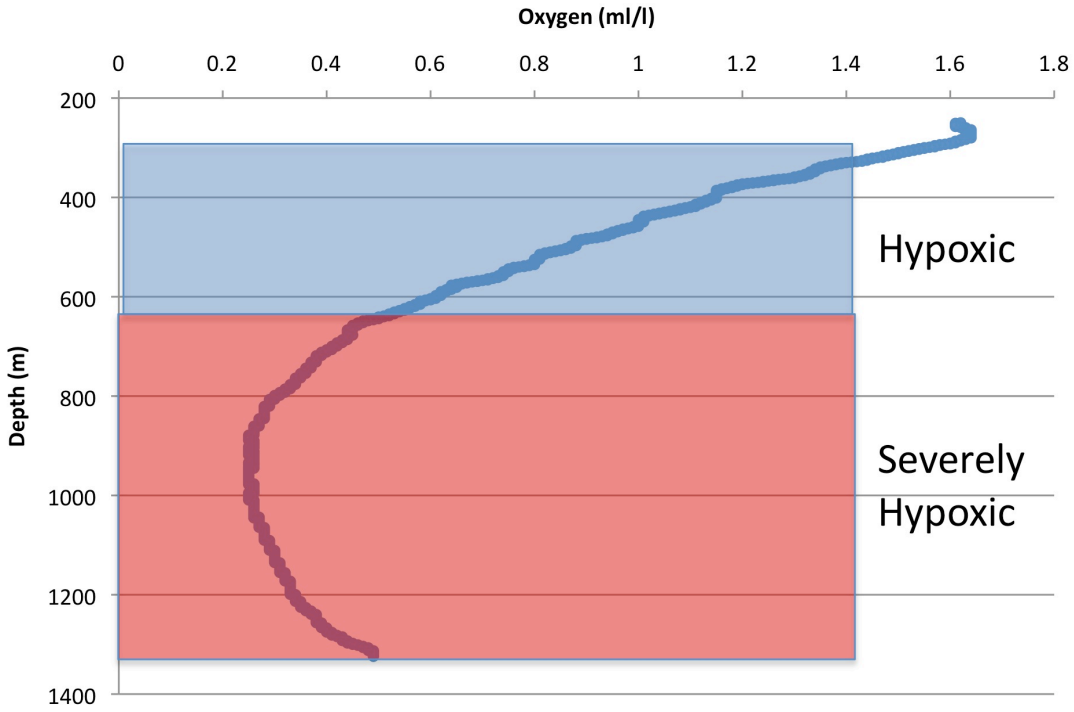


Figure 15: Dissolved oxygen measurements from a vertical profile at station P4 in February 2007, 12km from the transect R1074. Measurements of hypoxia (<1.4 ml/l) started at 300m and severe hypoxic zone (<0.5ml/l) extended from 640m to 1,325m depth.

ROV penetrometer probe measurements during dives R1074 and R1075 (1km intervals along transects) of substratum softness revealed consistently soft sediment with penetration depth varying from 30-100 cm (Table 9). Backscatter data from the surrounding area made available by the Geological Survey of Canada, also indicate widespread, fine-grained soft sediment. Textural data adjacent to these transects show a transition towards fine sand to mud, so we anticipate that most of the sediment is mud. CTD profiles from 2011 are typical for this area of the ocean, with gradual temperature decrease and increase in salinity with depth (Figure 16).

Slope analysis performed with the GIS show the survey area to be relatively flat . R1075 had a slope ranging from 0-10 degrees, with the steeper slope (5-10deg) deeper than 500m (Figure 17). R1074 slope ranged from 0-20 degrees with the steeper area (5-20deg) between 600m and 1,100m and the flatter area between 1,100m and 1,300m (Figure 18).

Results presented in this section will focus on transect R1074, which has a broader depth and trawling intensity range. Data from R1075 will be presented to re-enforce or compare interesting patterns found in R1074.

Table 9: Probe test along transect R1075 and R1074 to determine substratum softness.

R1075		
Depth (m)	**Penetration (cm)**	**Comments**
647	40-50	
589	67	Consolidated mud
571	30	
529	40	
488	38	
431	75	Sandy
400	62	
368	63	
360	65	
349	50	
R1074		
Depth (m)	**Penetration (cm)**	**Comments**
681-1400	50-100	Soft mud, very soft, non carbonate bed
607	70	Still very soft
544	100	
450	100	
408	100	Soft
368	50	Harder sediment
332	40	
305	100	
262	50	
254	100	Stiff, slightly sandy

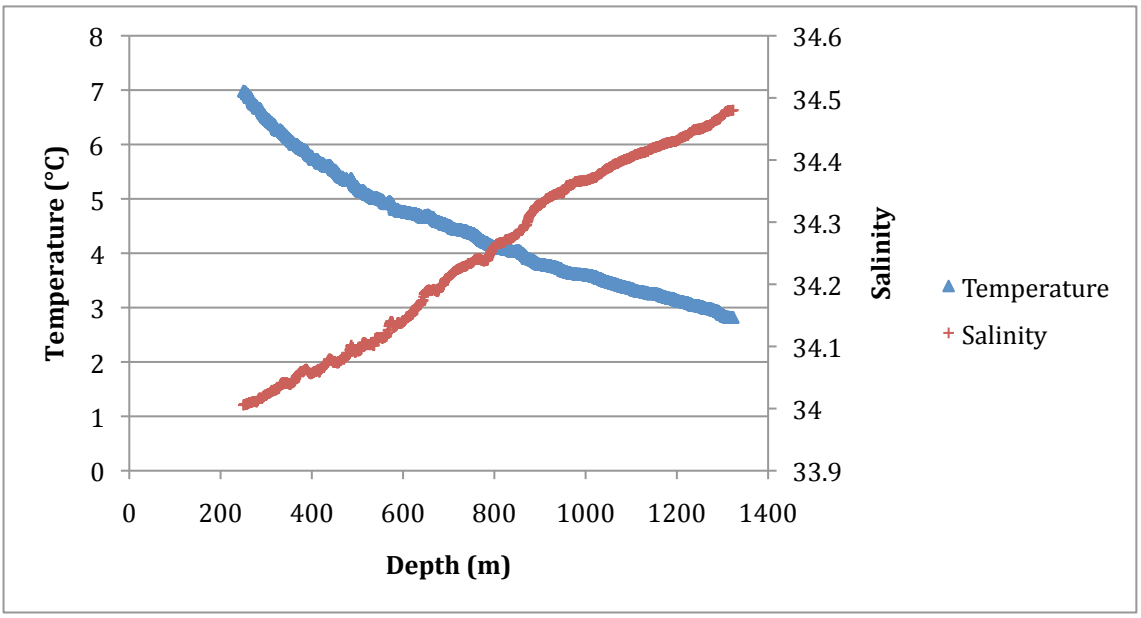


Figure 16: CTD measurements from February 2007 at station P4 show that temperature is gradually decreasing and salinity is slightly increasing as depth increases.

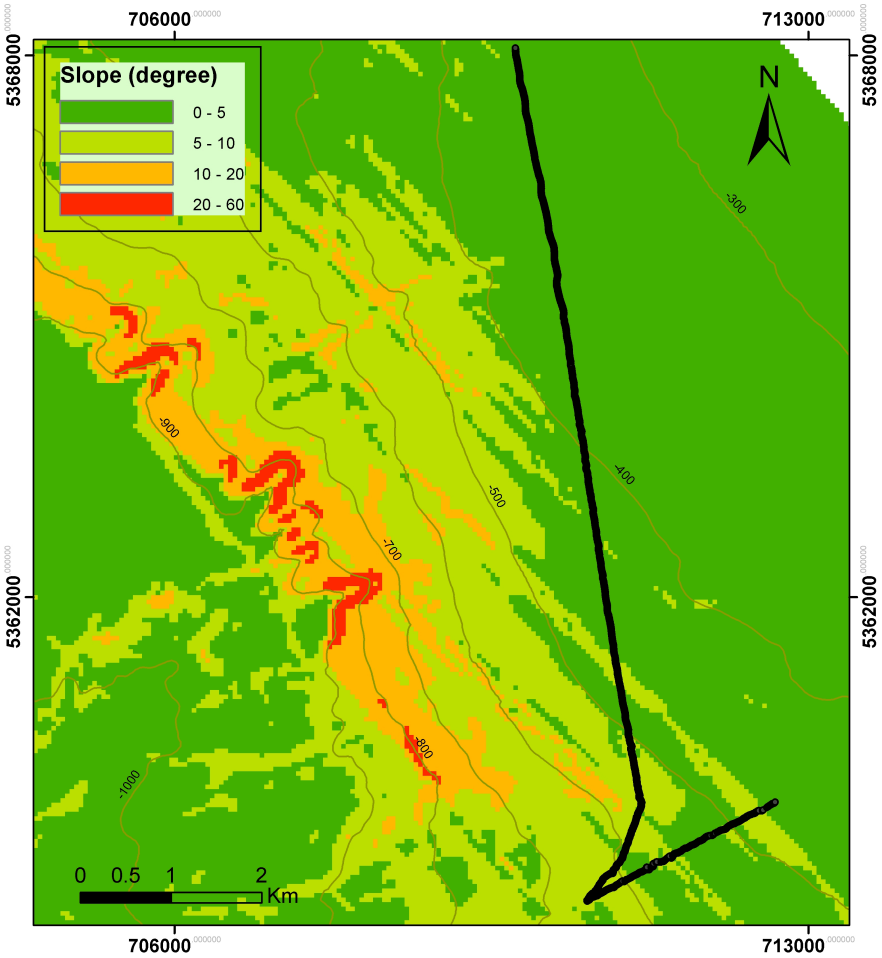


Figure 17: Slope analysis of the R1075 transect using GIS spatial tool analysis.

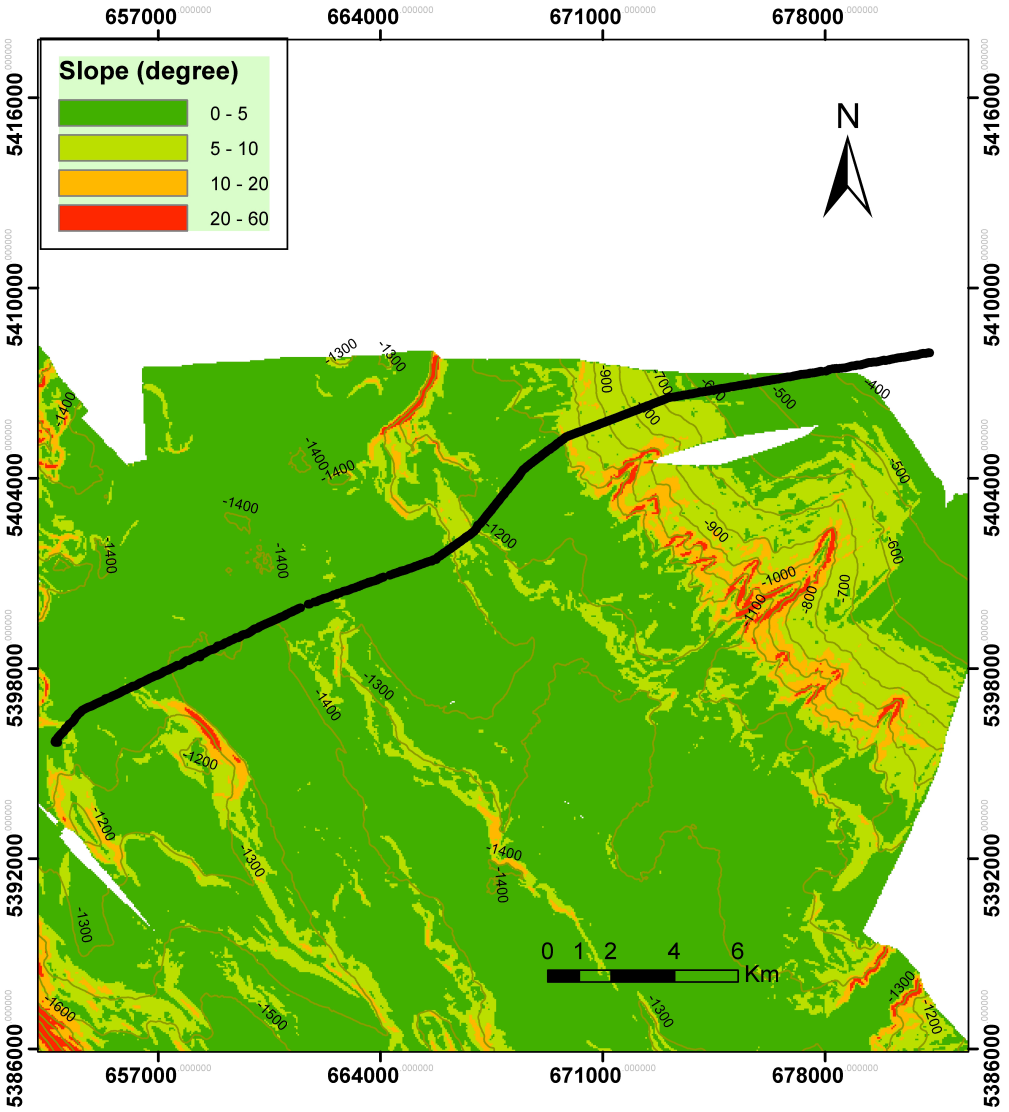


Figure 18: Slope analysis of the transect R1074 using GIS spatial tool analysis.

3.2 Bottom trawling data

3.2.1 Bottom trawling intensity with scanning-sonar

Trawling intensity was quantified from scanning-sonar data and mapped using the GIS. For transect R1075, trawling intensity was above 0 on most of the transect intensifying with depth from 450m to 650m-depth (Figure 19), but not reaching the maximum intensity found in the second transect analyzed. For transect R1074, trawl-door marks were present from 350m to 1,127m, reaching an intensity value of 5-8 at 550-1,100m, corresponding to 41-71+ marks per 500m. Trawling intensity value dropped to 0-1 (0-2 marks per 500m) below 1,127m (Figure 20).

3.2.2 Bottom trawling intensity data from Fisheries and Oceans (fishing effort)

Bottom trawling effort data from the Pacific Biological Station, Department of Fisheries and Oceans, were made available to compare our measurement method with the number of recorded tows that crossed each of our transects. The management sub-areas are 123-9 for transect R1075 and 124-2 for transect R1074 (Figure 21). Counts of fishing events crossing these transects from 1996 to August 2007 (prior to the research cruise) totalled 422 tows for R1075 and 501 tows for R1074 (Table 10). In comparison to DFO fishing events data, trawl-door marks visible in the sonar were 533 for R1075 and 1,007 for R1074. A list of the type of species caught from 1996-2007 in the sub-areas was also made available. Trawl data are derived from fisheries observers, fisher logs, and dockside monitoring.

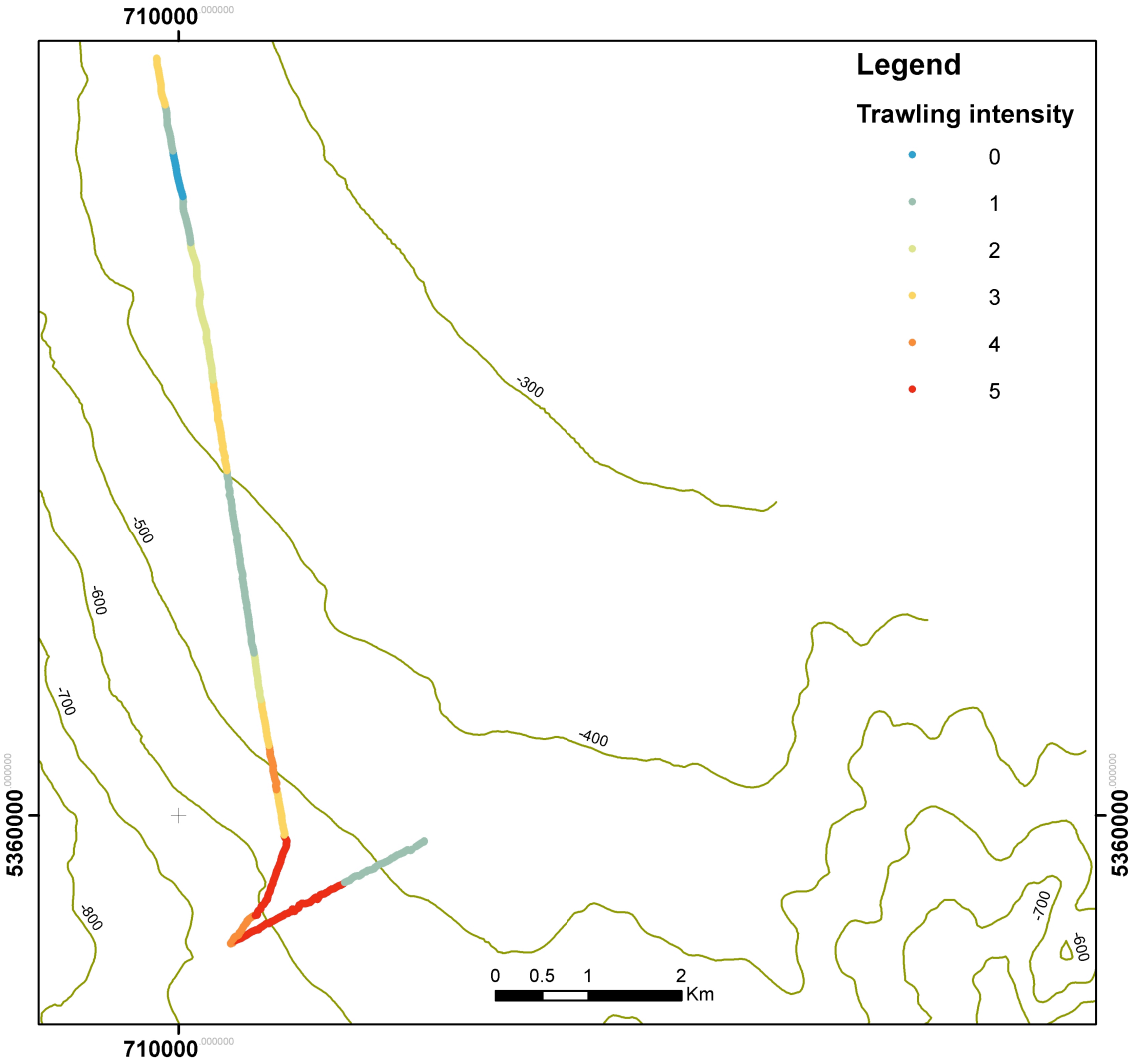


Figure 19: Trawling intensity measured with scanning-sonar along the transect R1075 (12 km) is above 0 on most of the transect intensifying as it goes deeper from 450m to 650m-depth, but not reaching the maximum intensity as seen in the second transect analyzed, R1074. The intensity ranges from 0 (0-2 marks/500m) to 5 (41-50 marks/500m).

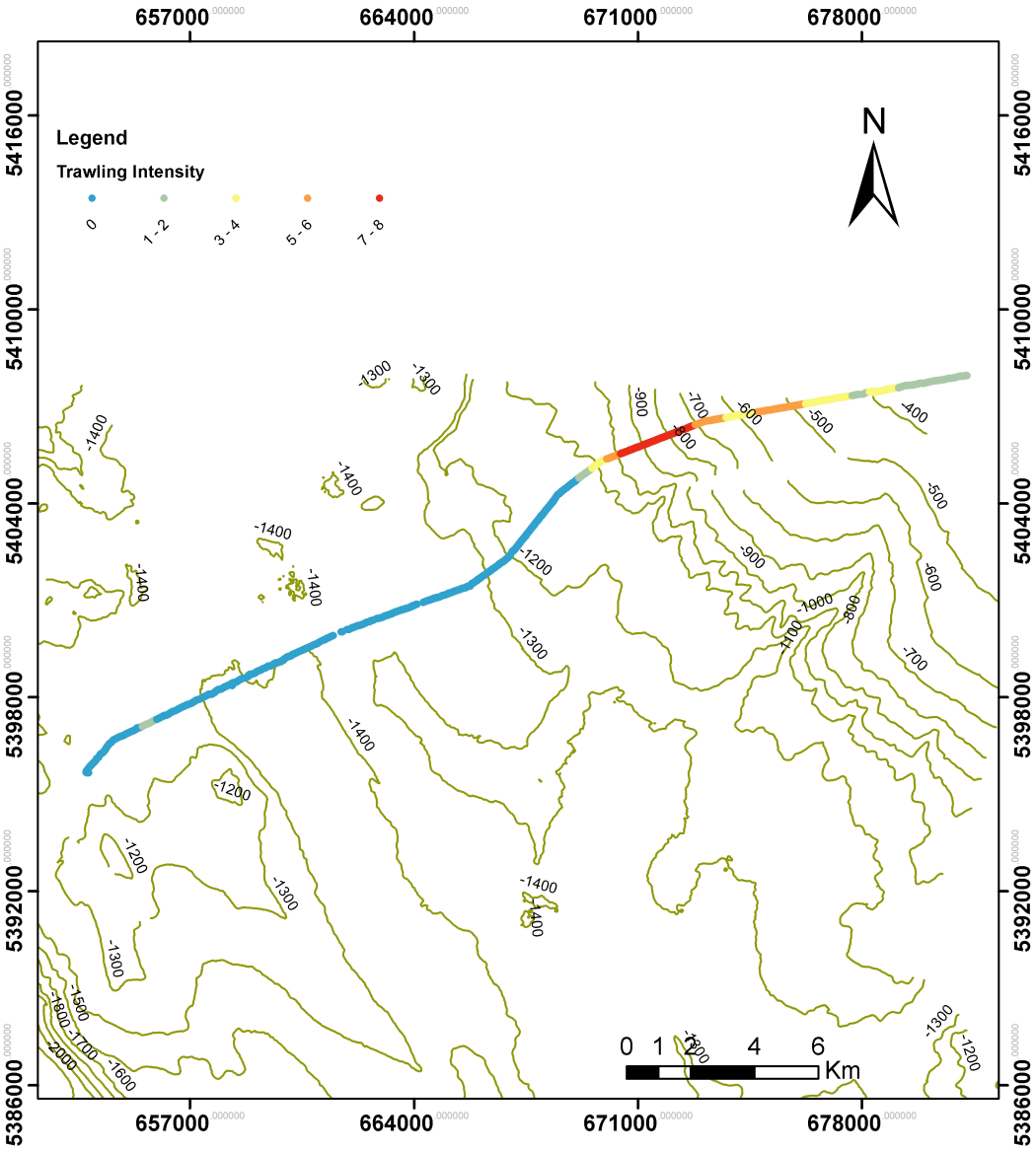


Figure 20: Trawling intensity measured with scanning-sonar along transect R1074 (30.8 km) is observed from 350m to 1,127m, with a value of intensity from 5-8 between 550-1,100m corresponding to 41 to 71+ marks per 500m. Trawling intensity drops to 0-1 (0-2 trawl marks) deeper than 1,127m.

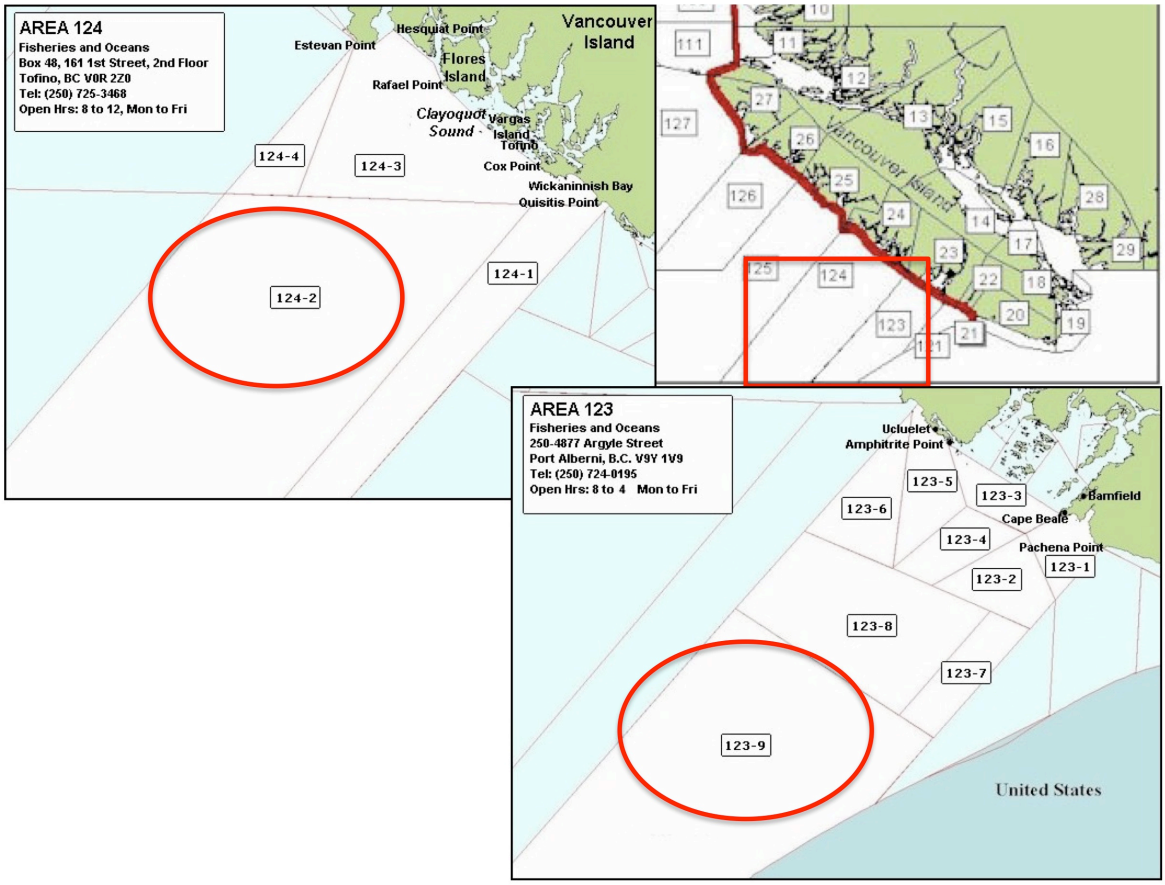


Figure 21: Department of Fisheries and Oceans Management areas on the west coast of Vancouver island. The transect R1075 is located in the management sub-area 123-9 and the transect R1074 in the sub-area 124-2.

Table 10: Count of bottom fishing events crossing both transects in selected sub-areas from 1996 to August 2007 prior to the research cruise. Trawl data are based from fisheries observers, fisher logs, and dockside monitoring. Data were made available by personnel of the Pacific Biological Station, Department of Fisheries and Oceans.

Within sub area 123-9 (R1075)		**Within sub area 124-2 (R1074)**	
Year	**CountOfFishing Events**	**Year**	**CountOfFishing Events**
1996	43	1996	105
1997	99	1997	120
1998	66	1998	67
1999	60	1999	41
2000	34	2000	25
2001	38	2001	35
2002	32	2002	24
2003	26	2003	25
2004	10	2004	18
2005	0	2005	12
2006	0	2006	21
2007	14	2007	8
Total	**422**	**Total**	**501**

3.3 Distribution and diversity patterns (both transects)

Preliminary video analyses showed a fairly flat muddy/sandy seabed with scattered boulders. Biological features present included a variety of asteroids, holothurians, echinoids, crinoids, cephalopods, actiniaria (anemones) and decapods. Corals (mainly gorgonians, sea pens and antipatharians), as well as sponges (hexactinellids) were found in some areas, but not in very high abundances except for sea whips and seapens, which were more abundant. Fish present include longspine and shortspine thornyheads (*Sebastolobus* spp.), sablefish, grenadiers, and flatfishes (deepsea, dover soles).

R1075

Table 11 shows the total abundance for each taxon found along the transect R1075 excluding biogenic roughness species. Figure 22 and Figure 23 show the proportions of groups of species along that transect without and with biogenic roughness species. The first figure (22) shows that anemones are very abundant (4,903), followed by holothurians (3,489), gastropods (886), echinoids (840), ophiuroids (628), corals (268), and asteroids (265). After biogenic roughness average abundances are added, dominant species are ophiuroids (18,198), followed by holothurians (5,189), anemones (4,903), echinoids (1907), gastropods (886), fish (511), coral (268), and asteroids (265).

R1074

Table 12 shows the total abundance for each taxon found along the transect R1074 excluding biogenic roughness species. Figure 24 and Figure 25 show the proportions of the megafauna assemblages present along that transect with and without

biogenic roughness. After adding biogenic roughness average abundances, ophiuroids are also the most dominant group along that transect (164,303), followed by holothurians (17,047), corals (3,429), echinoids (2,854), fish/sharks (2,300), asteroids (1,630), anemones (1,282), and gastropods (504).

Table 11: Total abundance for each taxon for transect R1075 without biogenic roughness.

Taxon	**Abundance**	**Taxon**	**Abundance**
Fish	60	**Ophiuroid**	628
Hagfish	2	**Crinoid**	13
Dover_sole	141	**Anemone**	3
Deepsea_sole	3	Lipanema_pom	30
Lycodes	8	Anemone white	1026
Pacific hake	122	Venus fly trap	3107
Thornyheads Rockfish	121	Corallimorph	70
Rougheye Rockfish	30	Actinostolidae	255
Skate	19	Cerianthidae	412
Ratfish	5	**Gastropod**	886
Crab	13	**Cephalopod**	
Prawn	19	Squid	11
Echinoid *A.fragilis*	840	Octopus	6
Holothurian	71	**Coral**	
P. moseleyi	1774	Seapen	52
P. mollis	750	*U.lindhali*	96
P. squamatus	894	Sea whip	108
Asteroids	174	Gorgonian	6
Morning sunstar	9	Antipatharia	2
Orange sunstar	7	Dogtoy Coral	4
Fatblood star	54	**Sponge**	19
Sand star	13	Boot_sponge	23
Bat star	8	**Brachiopod**	31

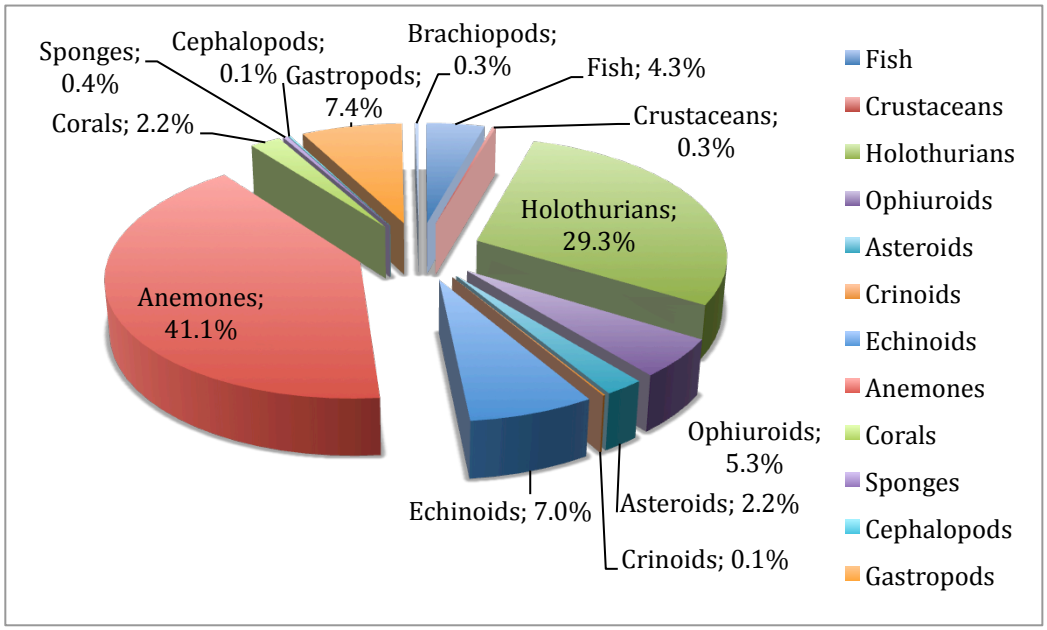


Figure 22: Total relative abundance for groups of species found along transect R1075 without biogenic roughness. Anemones are very abundant (4,903), followed by holothurians (3,489), gastropods (886), echinoids (840), ophiuroids (628), corals (268), and asteroids (265). Other groups of species were found fairly rare.

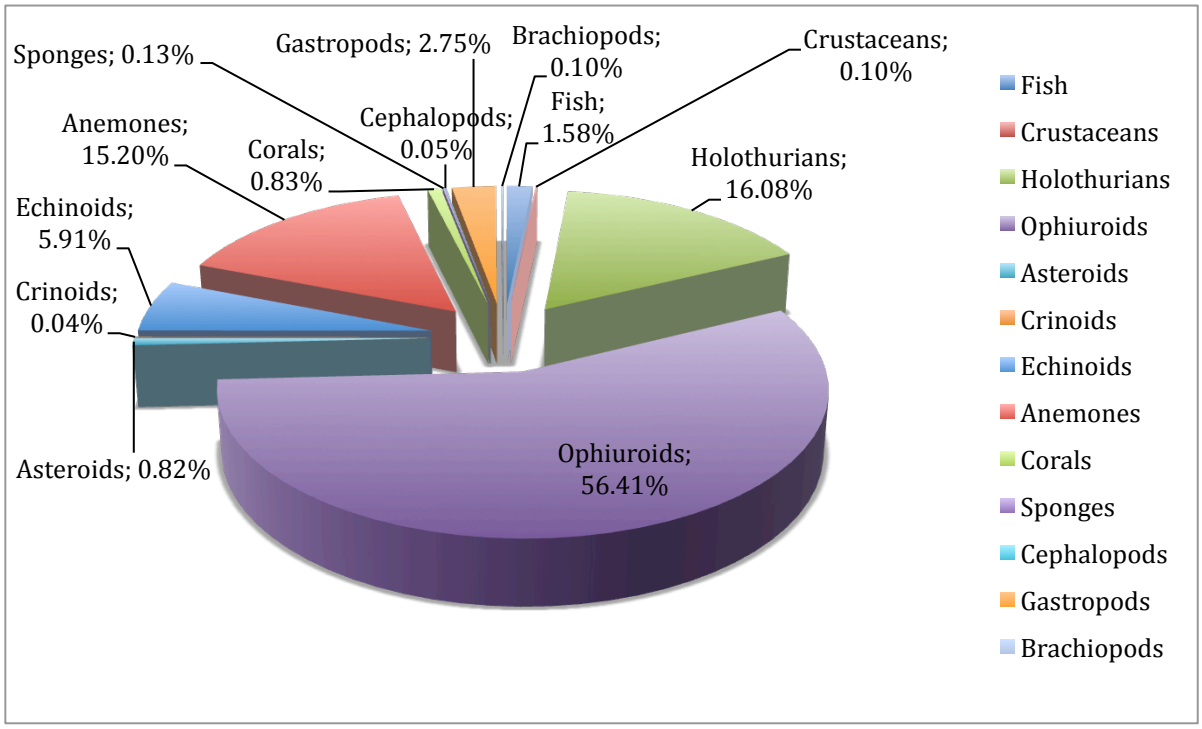


Figure 23: Total relative abundance for groups of species found along transect R1075 including biogenic roughness average abundances. Ophiuroids are the most dominant group (18,198), followed by holothurians (5,189), anemones (4,903), echinoids (1907), gastropods (886), fish (511), coral (268), and asteroids (265).

Table 12: Total abundance for each taxon for transect R1074 without biogenic roughness. If species was not identifiable, an upper taxonomy level was selected.

Taxon	Abundance	Taxon	Abundance
Fish	33	**Asteroid**	574
Rockfish	672	Blood star *(Henricia spp.)*	962
Grenadier	566	Rainbow star *(O.koehleri)*	40
Thornyhead (*Sebastolobus* spp.)	368	Mud star *(C. crispatus)*	32
Eelpout	182	Cookie star *(C. patagonicus)*	16
Pacific hake	122	Cushion seastar (*P. tesselatus*)	6
Flatfish	96	**Ophiuroid**	1,227
Brotula (B. brunneum)	88	**Crinoid**	9
Finescale Mora	60	**Anemone**	408
Pacific cod	34	Ceriantharia	384
DeepseaSole	29	Venusflytrap	245
Skate	21	Actinostolidae	85
Hagfish	18	Corallimorph	83
Sablefish (black cod)	4	Liponema	77
Cat shark	4	**Gastropod**	504
Pink Snailfish	2	**Cephalopod**	
Ratfish	1	Squid	30
Crab	6	Octopus	6
Tanner Crab	56	**Coral**	
Hermit Crab	13	SeaWhip	3,001
Echinoid		Droopy sea pen *(U.lindahli)*	304
Pink sea urchin (A.fragilis)	508	Seapen	120
Holothurian	33	Other (Paragorgia spp)	3
Sea pig *(S.globosa)*	11,613	Plumarella	1
Dirty sea cucumber *(P. mollis)*	82	**Sponge**	
Deep sea cucumber *(P.moseleyi)*	39	**Hexactinellida**	55

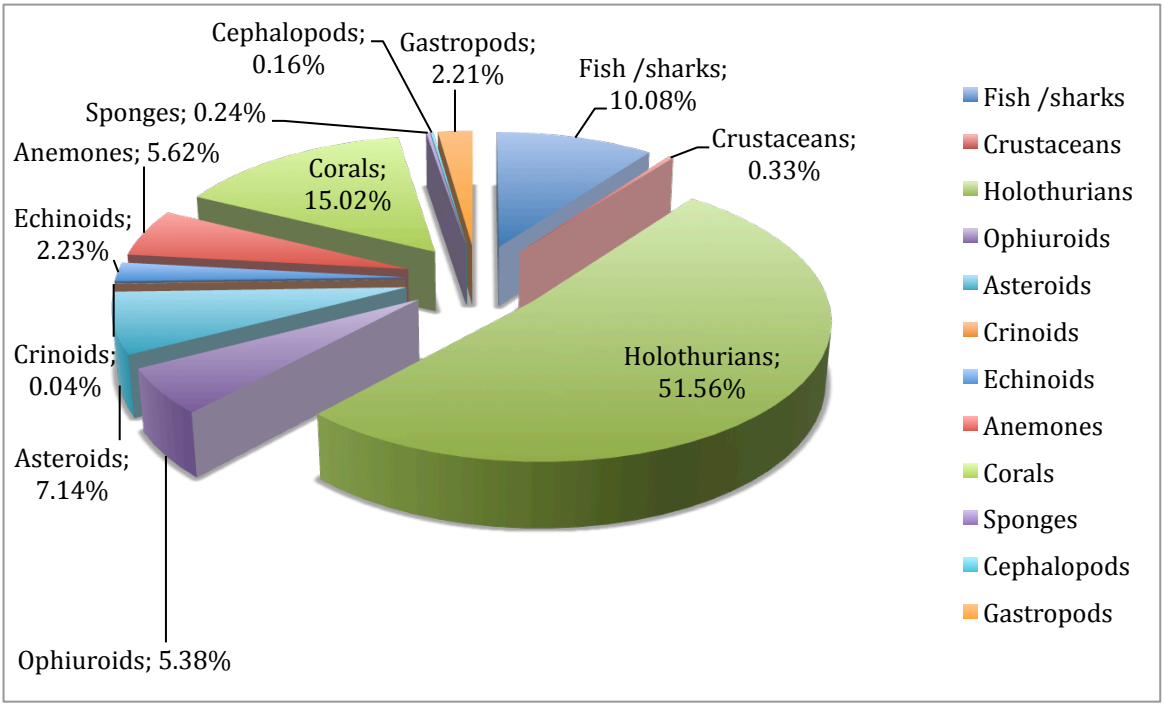


Figure 24: Total relative abundance for groups of species found along transect R1074 without biogenic roughness. Holothurians are dominant (11, 767), followed by corals (3,429), fish/sharks (2,300), Asteroids (1,630), anemones (1,282), ophiuroids (1,227), echinoids (508), and Gastropods (504). Other groups of species were all found under 100.

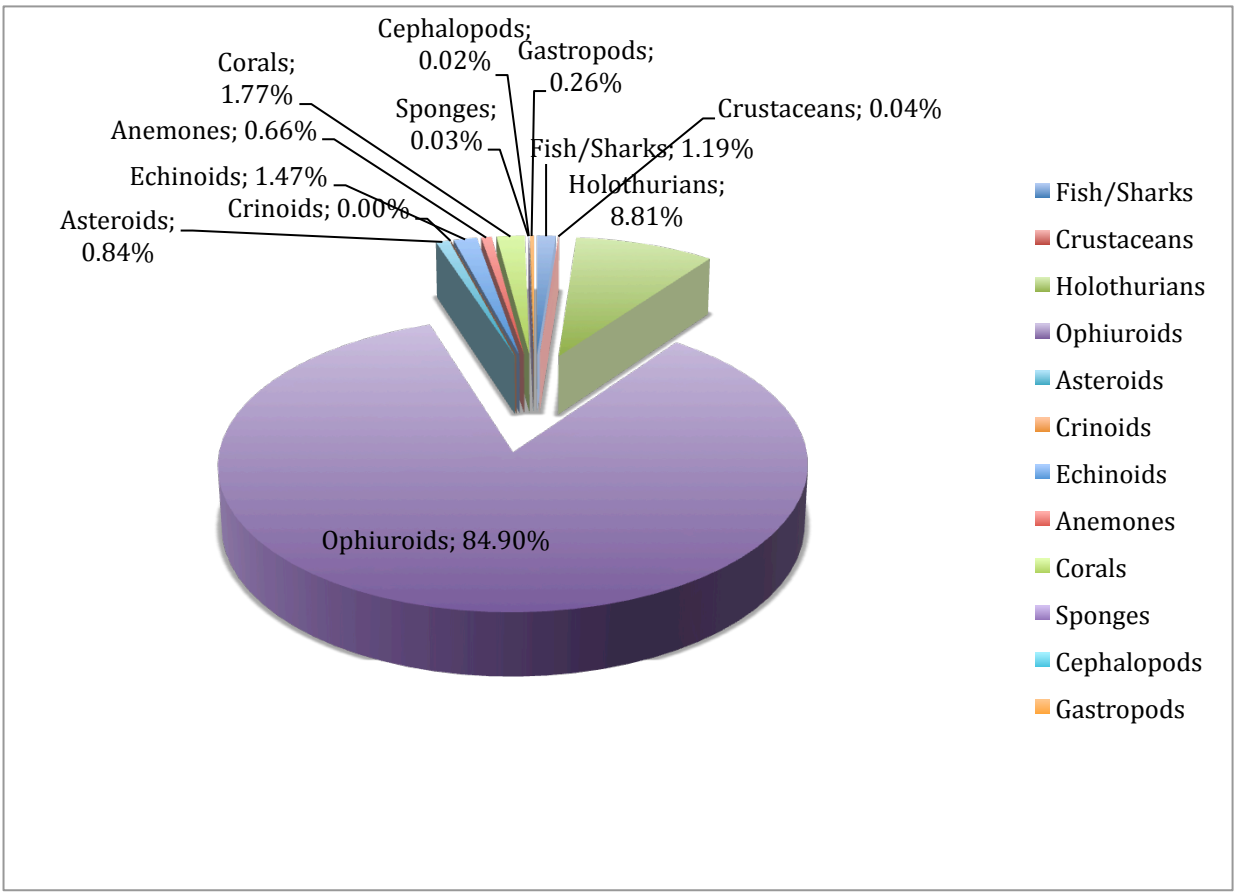


Figure 25: Total relative abundance for groups of species found along transect R1074 including biogenic roughness average abundances. Ophiuroids become the most dominant group (164,303), followed by holothurians (17,047), corals (3,429), echinoids (2,854), fish/sharks (2,300), Asteroids (1,630), anemones (1,282), and Gastropods (504). Other groups of species were all found under 100.

For both transects, the presence of echinoderms, especially ophiuroids and holothurians dominate the seabed. Soft corals are fairly abundant in the transect R1074, the majority composed of sea pens and sea whips (Pennatulacea).

For clarity and conciseness, we will focus on the analysis of transect R1074 because it has a broader depth range and is longer than R1075. It is interesting to explore how the abundance, composition and diversity vary with changes in environmental variables. Table 13 shows general characteristics (biology and habitat) for the whole transect in comparison with a range of trawling intensities and depths. Figure 26 shows the total faunal abundance and trawling intensity in relation to depth. A significant decrease in total abundance between 600m and 1,130m can be observed, corresponding to a trawling intensity of 5-8 (>40-71+ marks / 500m). With regards to the various species more or less present in that sector, the main difference in abundance is explained by the absence of faunal aggregations, especially ophiuroid and deep-sea holothurian *Scotoplanes globosa* aggregations. Figure 27 shows the distribution of ophiuroids (total abundance including faunal aggregation entries) along the transect and Figure 28 shows the distribution of *S. globosa*. Both distribution maps show a marked difference in the presence of these taxa between the high trawling intensity (5-8) and the low trawling intensity (0-4) areas.

Table 13: General characteristics (biology and habitat) for the whole R1074 transect compared to various trawling intensities and depths.

General characteristics	**Whole transect**	**Trawling intensity**		**Depth**		
		Low 0-4	**High 5-8**	**Shallower <600m**	**Medium 600-1000m**	**Deep >1000m**
Faunal aggregations	Varies	Frequent	Rare	Frequent	Rare	Frequent
Total Abundance	NA	Higher	Lower	Higher	Lower	Higher
Taxonomy diversity	NA	Lower	Higher	Lower	Higher	Lower
Muddy/sandy bottom	Frequent	Frequent	Frequent	Frequent	Frequent	Frequent
Boulders	Rare	Rare	Rare	Rare	Rare	Rare
Glass sponges	Rare	Frequent	Rare	Frequent	Rare	Frequent
Sea whips	Varies (patchy)	Frequent	Rare	Rare	Rare	Frequent
Sea pens	Varies (patchy)	Varies	Frequent	Rare	Frequent	Rare
U.Lindhali	Varies (patchy)	Dominance varies	Varies	Rare	Frequent	Rare
Ophiuroids	Abundant	Frequent	Rare	Abundant	Rare	Abundant
Holothuroids (*S.globosa*)	Abundant	Frequent	Rare	Rare	Rare	Frequent
Echinoids (*A.fragilis*)	Varies	Dominance varies	Rare	Frequent	Rare	Rare
Thornyheads (*Sebastolobus spp.*)	Abundant	Varies	Varies	Varies	Frequent	Frequent
Rockfish (may or may not include thornyheads)	Abundant	Frequent	Frequent	Varies	Frequent	Varies

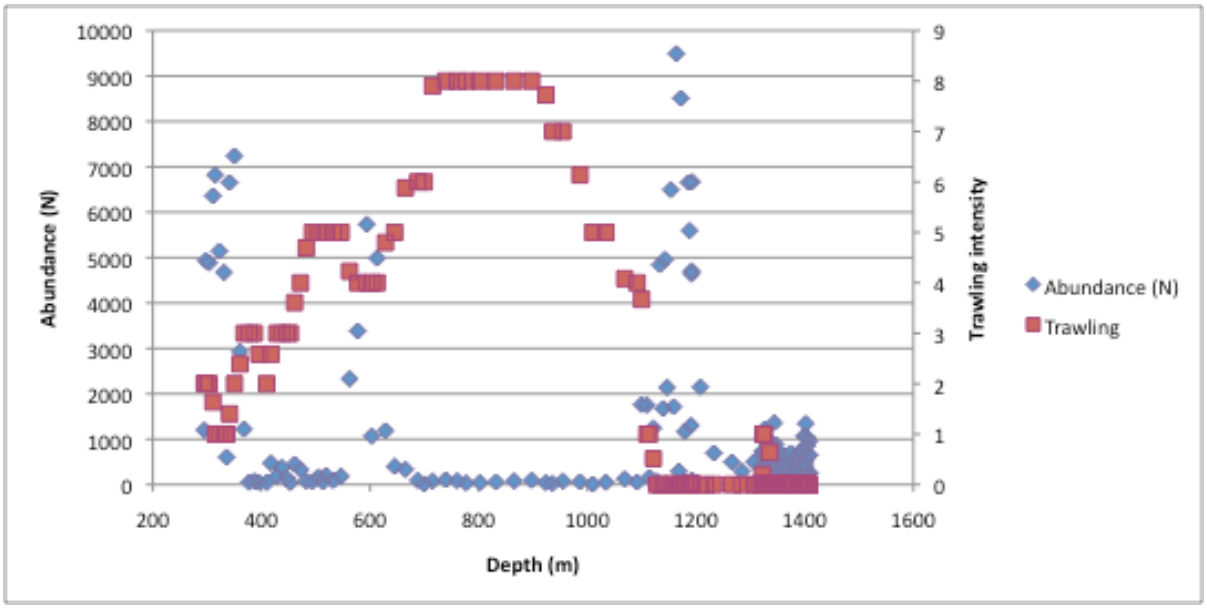


Figure 26: Total species abundance and trawling intensity in relation with depth (m) showed a marked lower abundance between 700m and 1,130m corresponding to a trawling intensity ranging from 5 to 8.

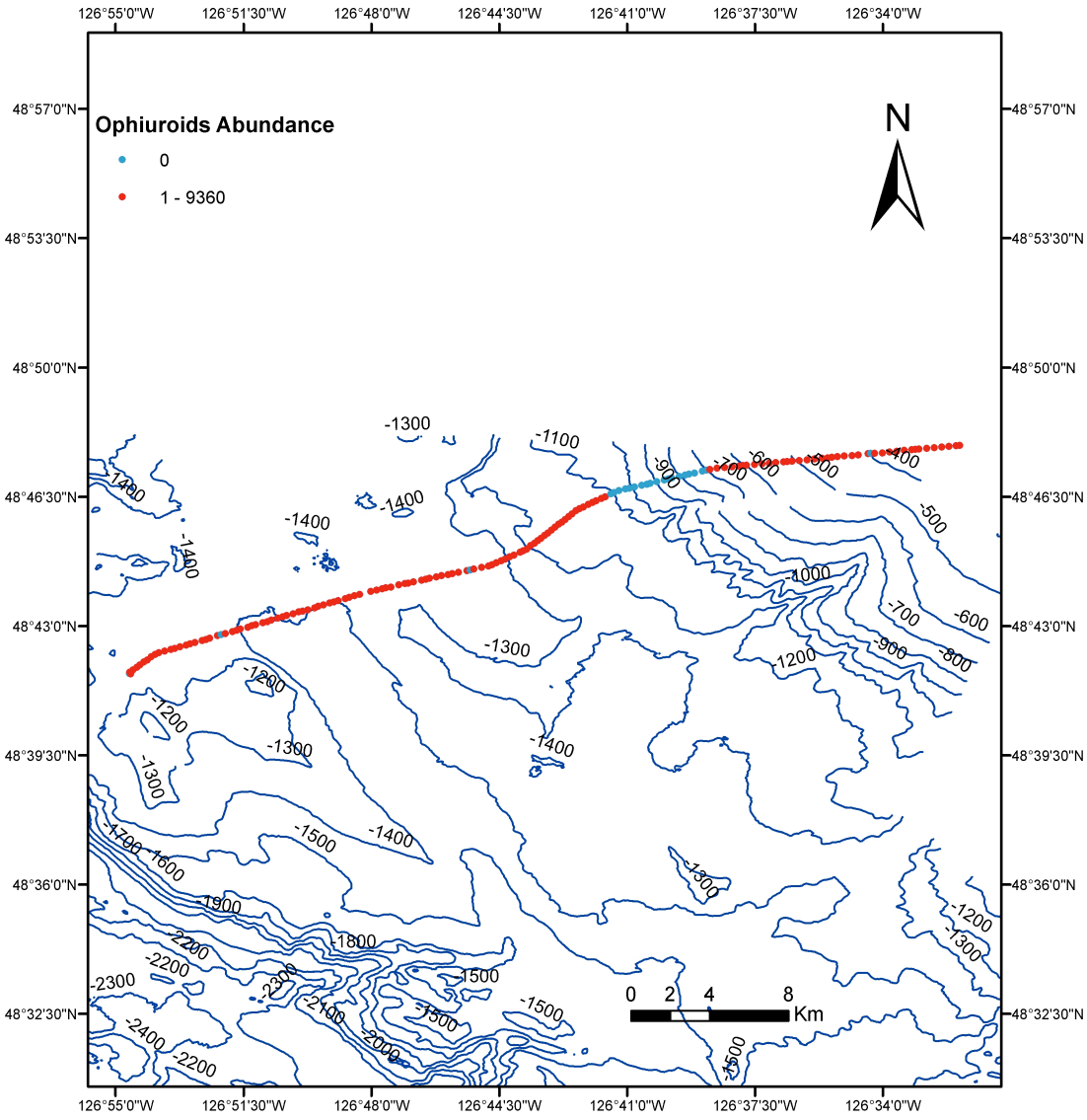


Figure 27: Ophiuroids distribution including biogenic roughness categories for transect R1074 shows that the taxon is absent from 700m to 1,130m approximately where trawling intensities are between 5 and 8 (>40 marks/500m).

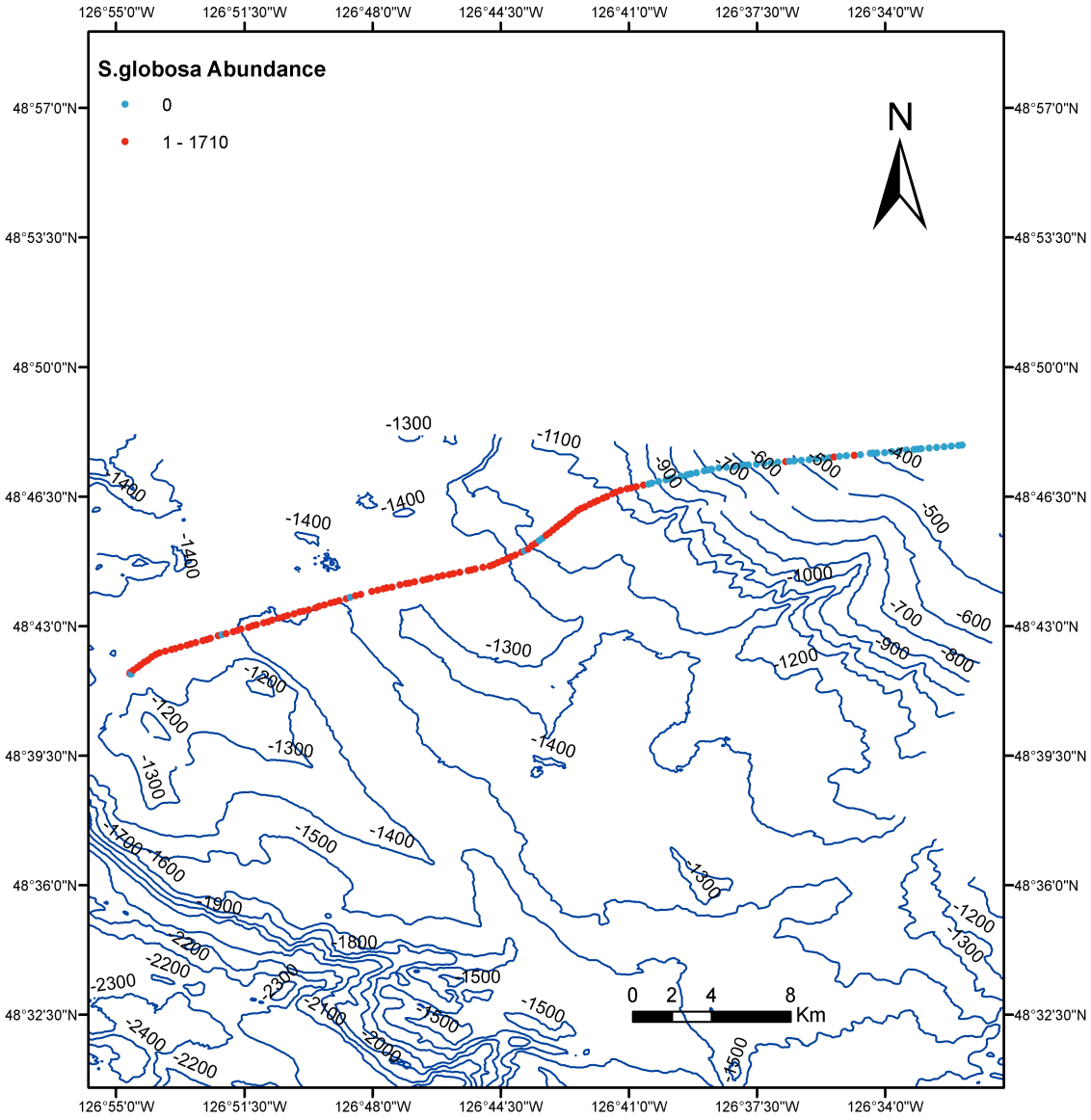


Figure 28: *S. globosa* distribution including biogenic roughness categories for transect R1074 shows that the taxon has a patchy distribution below 550m and has an extensive cover deeper than 950m). *S. globosa* is absent from 550m to 950m approximately, where trawling intensities are between 5 and 8 (>40 marks/500m) .

Diversity indices measured with PRIMER-E software provide further insight. Figure 29 illustrates the Simpson diversity index and Pielou evenness along the transect in relation to depth and trawling intensity. Species diversity and evenness increase in highly trawled areas, but diversity indices become variable in the deeper zone. Simpson and Pielou indices measured were significantly different ($P<0.0001$) between low trawling intensities (0-4) and high trawling intensities (5-8) and patterns are visible between 400-500m, 650-1,050m and around 1,400m. The Shannon diversity index (Figure 30) shows a similar pattern.

3.4 Community structure vs. depth and trawling

3.4.1 Results from hierarchical clusters and community structure associated

A group-averaged hierarchical cluster analysis was performed with PRIMER-E using square-rooted transformation and Bray-Curtis similarity resemblance on abundance data for the transect R1074. Each sample along the X-axis corresponded to grouped data along approximately 250m sections of the transect, called “stations”. The distance is approximate because of the way the vector grid was created with Hawth’s tool. The dendrogram revealed eleven groups at 45-55% similarities. Four clusters are shown here because they are groups with a high number of stations with associated environmental variables, consequently, more clear than the other clusters. Different megafauna assemblage structures associated with some stations along transect R1074 were detected (Figure 31), including three different assemblage structures in low trawled area and one assemblage structure in the highly trawled area.

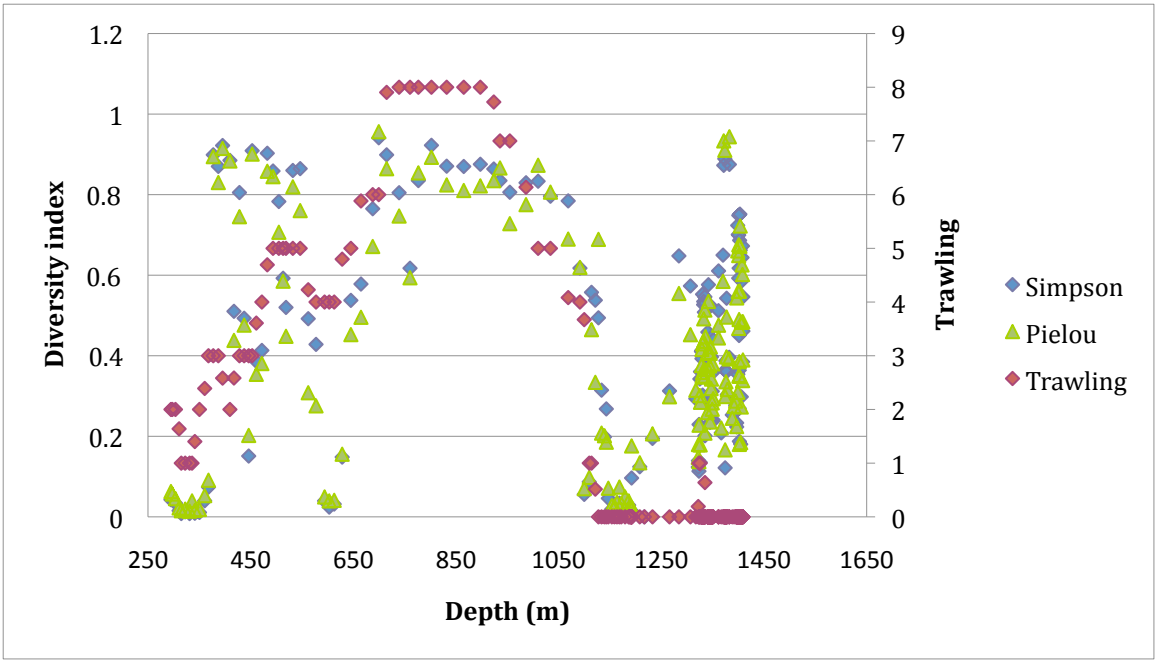


Figure 29: Simpson diversity index and Pielou evenness in relation to depth (m) and trawling intensity. Diversity and evenness indices vary greatly, but show an increase between 400-500m, 650-1,050m and around 1,400m.

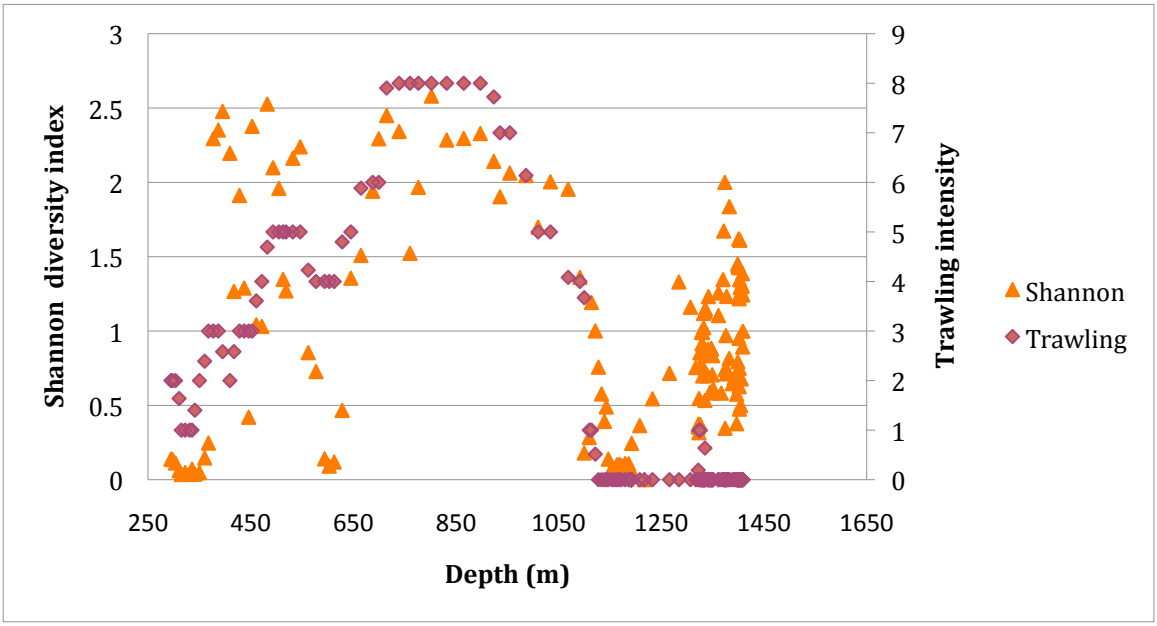


Figure 30: Shannon diversity index in relation to depth (m) and trawling intensity. Similarly as figure 12, the diversity indcx varies greatly, but shows an increase between 400-500m, 650-1,050m and around 1,400m.

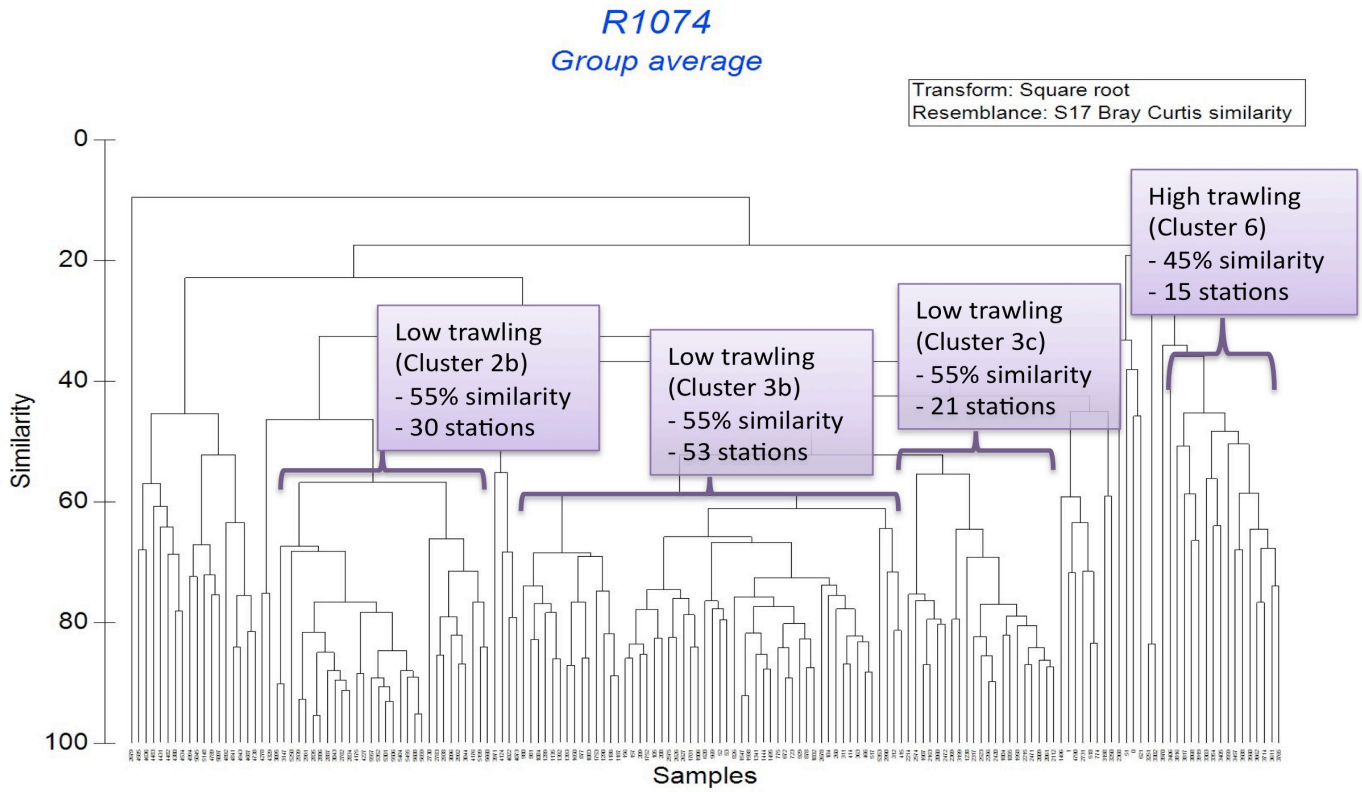


Figure 31: Group-averaged hierarchical clusters detected in megafauna assemblages along transect R1074 from the square-rooted transformed abundance data, using Bray-Curtis similarity. Each sample correspond to approximately 250m length of transect, called "station". The cutting line for similarity percentage was between 45-55%. Different assemblage structures are found in the highly trawled area (cluster 6) and low trawled areas (cluster 2b/3b/3c).

Pie charts were produced for each of the main groups detected using abundance data from these stations by grouping taxa by order, family, or species level if found in high abundances (Figures 31-35). For example, “Fish” is used to describe Osteichthyes (bony fish); “Sea pens” is used, but “droopy sea pen” is also used because this species is found in high abundance.

Highly trawled area:

Cluster 6 (Figure 32) includes 15 stations and 37 taxa with a depth range of 715-1,091m and a trawling intensity between 4 and 8 (31-71+ marks/500m). Fish are numerous (total 397) followed by droopy sea pens (*Umbellula lindhali*) and other sea pens (total 255) and Asteroids (total 107). Other groups are found at abundances below 100.

Low trawled areas:

Three hierarchical clusters were identified for low trawled areas (shallow and deep sections of the transect). They vary in terms of the dominant species identified or trawling intensity level:

Clusters 2b (Figure 33) includes 30 stations and 44 taxa along transect R1074 with a depth from 295m-613m and deeper than 1,134m with a trawling intensity ranging from 0 to 4 (0-40 marks). The megafauna assemblage is dominated by ophiuroids at 98% (total 133,164). Another pie chart was produced without ophiuroids to better illustrate the rest of the assemblage (Figure 34). *S. globosa* is highly abundant (total 1,982) together with fish (total 596). Asteroids (total 251) and the fragile pink sea urchin (*Strongylocentrotus fragilis*) (total 201) are also abundant. Other groups are found under a total abundance of 150.

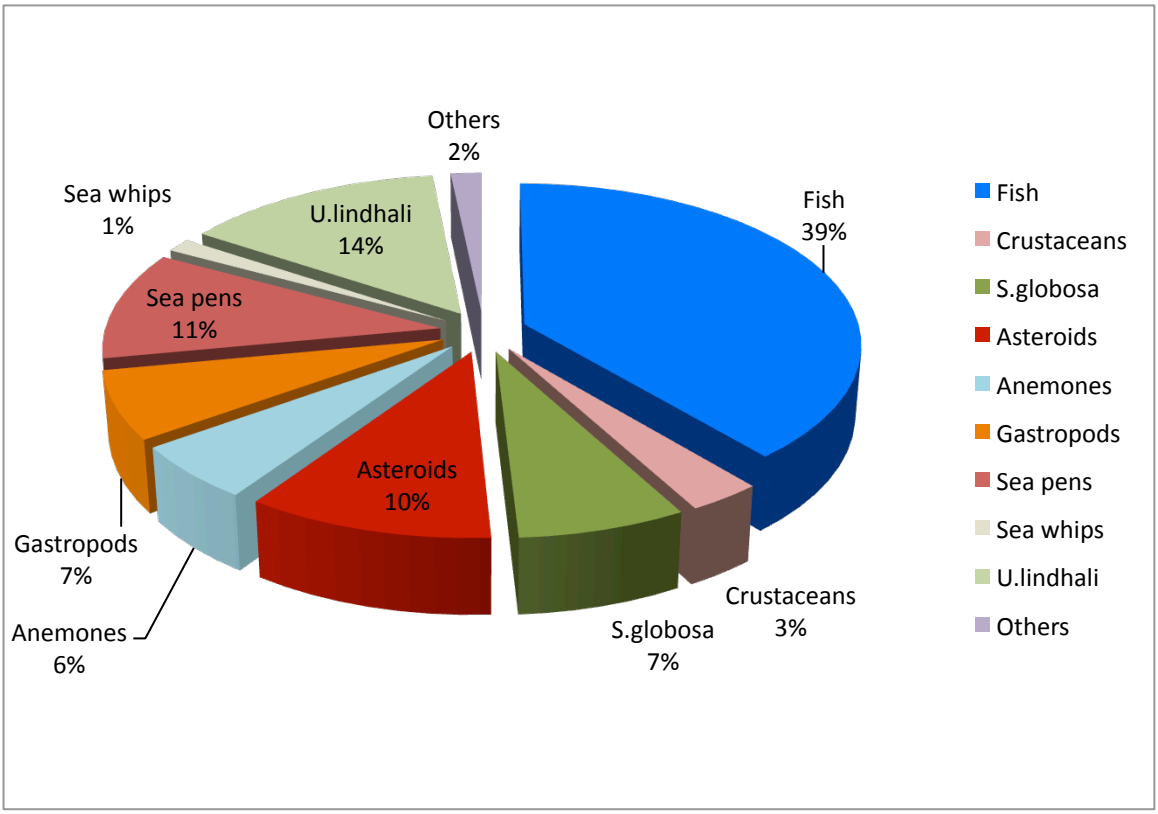


Figure 32: Cluster 6 includes 15 stations with a depth between 715-1,091m and a trawling intensity between 4 and 8 (31-71+ marks/500m). 37 taxa are present. Fish are numerous (total 397) followed by droopy sea pens (*Umbellula lindhali*) and other sea pens (total 255) and Asteroids (total 107). Other groups are found below an abundance of 100. Groupings were produced by using order, family, or species level if found in high abundances.

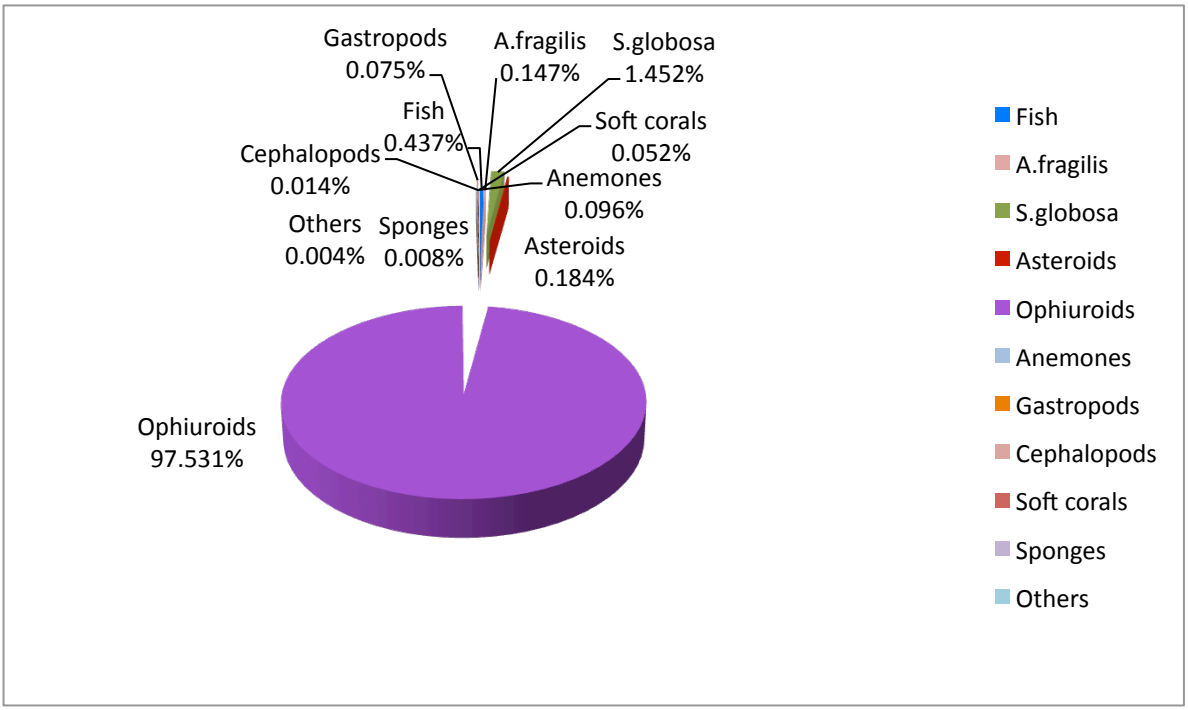


Figure 33: Cluster 2b includes 30 stations and 44 taxa along transect R1074 with a depth from 295m-613m and >1,134m with a trawling intensity ranging from 0 to 4 (0-40 marks). The assemblage has a very high dominance of ophiuroids (total 133,164). Another pie chart (Figure 33) was produced without ophiuroids to see the assemblage more clearly. Groupings were produced by using order, family, or species level if found in high abundances.

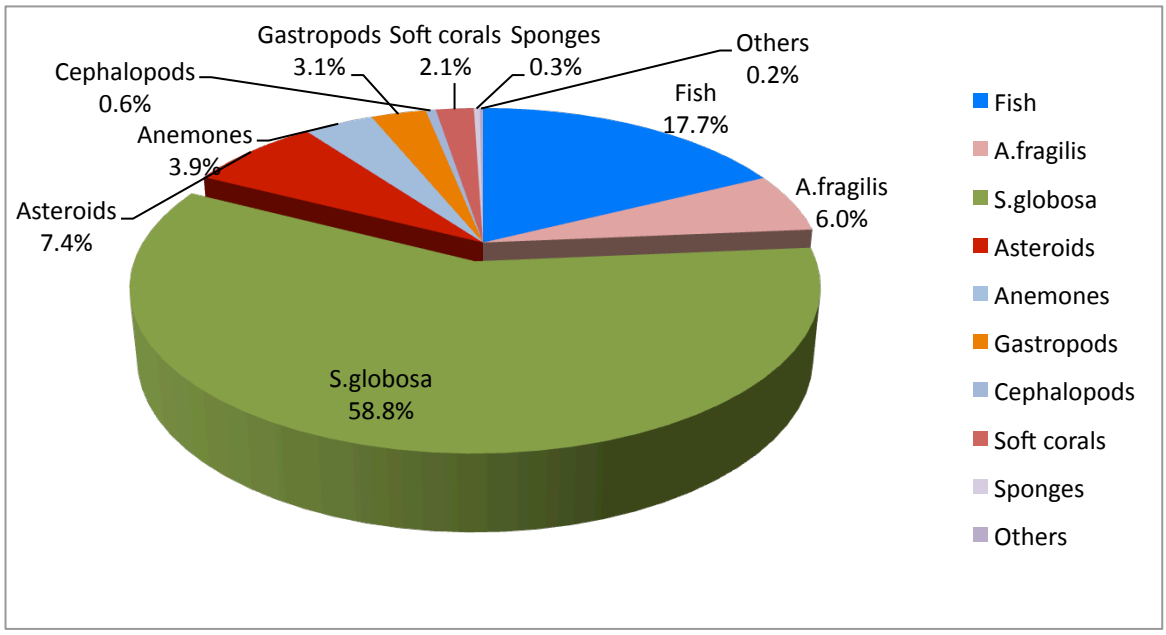


Figure 34: Cluster 2b includes 30 stations and 44 taxa along transect R1074 with a depth from 295m-613m and >1,134m with a trawling intensity ranging from 0 to 4 (0-40 marks). This chart pie is showing the megafauna assemblage without ophiuroids, which dominates this cluster. *S. globosa* taxon is highly present (total 1,982) with fish (total 596). Asteroids (total 251) and fragile pink sea urchin (*Allocentrotus fragilis*) (total 201) are also abundant. Other groups are found under a total abundance of 150. Groupings were produced by using order, family, or species level if found in high abundances.

Clusters 3b and 3c have the same depth range, but have different dominant species. Cluster 3b (Figure 35) includes 53 stations and 39 taxa along transect R1074 with a depth greater than 1,150m for most of the stations except for one station at 336m. This cluster has a very low trawling intensity: most stations have no trawling present, except four stations where trawling intensity is 1 (3-10 marks). The megafauna assemblage is dominated by ophiuroids (total 21,620) followed by *S. globosa* (total 3,044) and sea whips (2,323). Asteroids (total 911) and fish (total 581) are also fairly abundant. Cluster 3c (Figure 36) includes 21 stations and 37 taxa along transect R1074 with a depth greater than 1,120m and no trawling is visible for all stations except for one where trawling intensity is 1. *S.globosa* dominates this assemblage (total 8,246) followed by ophiuroids (total 2,512) and sea whips (total 578). Fish are also abundant (total 370) followed by asteroids (total 166).

3.4.2 Multidimensional Scaling (MDS) plots for the community structure

Multidimensional scaling plots were produced with PRIMER-E, after the abundance data were square-root transformed and Bray-Curtis similarity was calculated. Factors were created for trawling and depth, to identify patterns. A MDS plot of the megafauna assemblages with trawling intensity as a factor is shown at Figure 37. The stress value for the following plots is 0.18, which corresponds to an acceptable representation. It can only serve as an indication of relationships between megafauna assemblages structure and environmental variables.

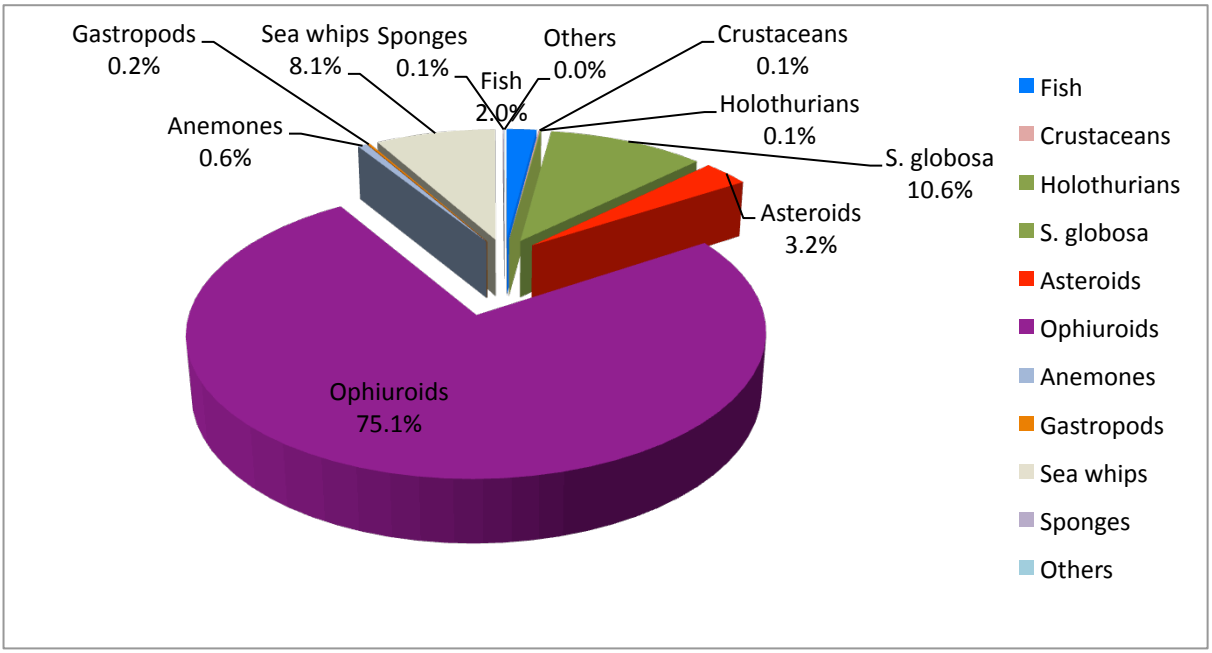


Figure 35: Cluster 3b includes 53 stations and 39 taxa along transect R1074 with a depth >1,150m for most of the stations except for one station at 336m. This cluster has a very low trawling intensity: most stations have no trawling present, except for 4 stations where trawling intensity is 1 (3-10 marks). The megafauna assemblage is dominated by ophiuroids (total 21,620) followed by *S. globosa* (total 3,044) and sea whips (2,323). Asteroids are also very abundant with a total of 911 and fish are fairly abundant with a total of 581. Groupings were produced by using order, family, or species level if found in high abundances.

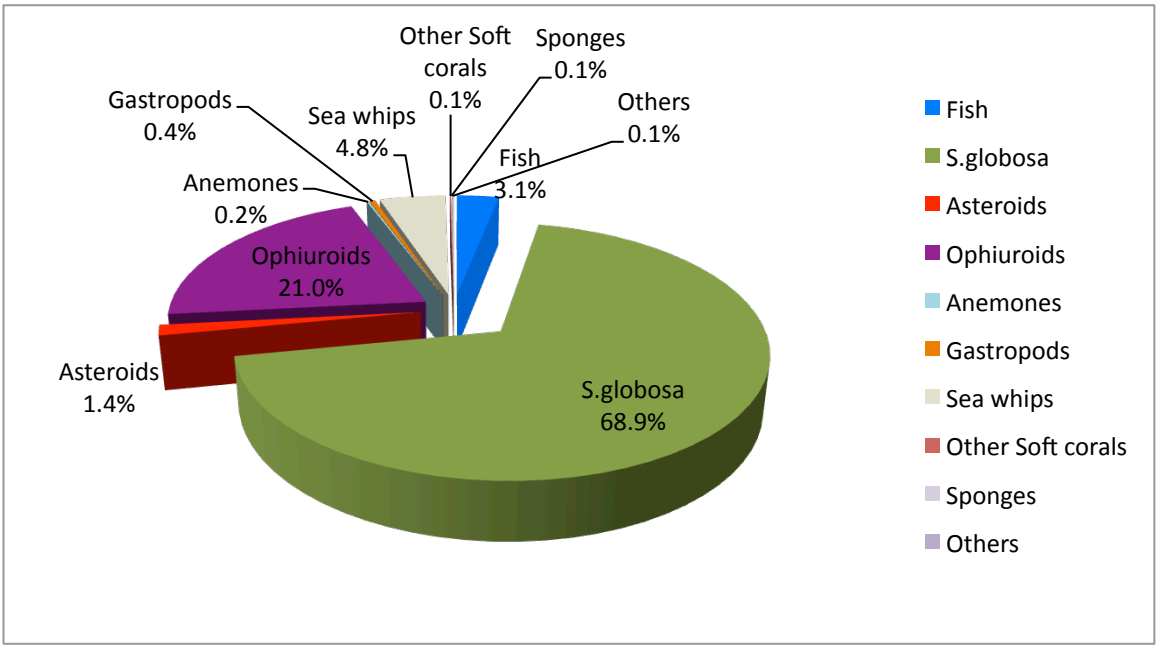


Figure 36: Cluster 3c includes 21 stations and 37 taxa along transect R1074 with a depth >1,120m and no trawling is present for all stations except for one where trawling intensity is 1. *S.globosa* dominates this assemblage (total 8,246) followed by ophiuroids (total 2,512) and sea whips (total 578). Fish are also abundant (total 370) followed by asteroids (total 166). Groupings were produced by using order, family, or species level if found in high abundances.

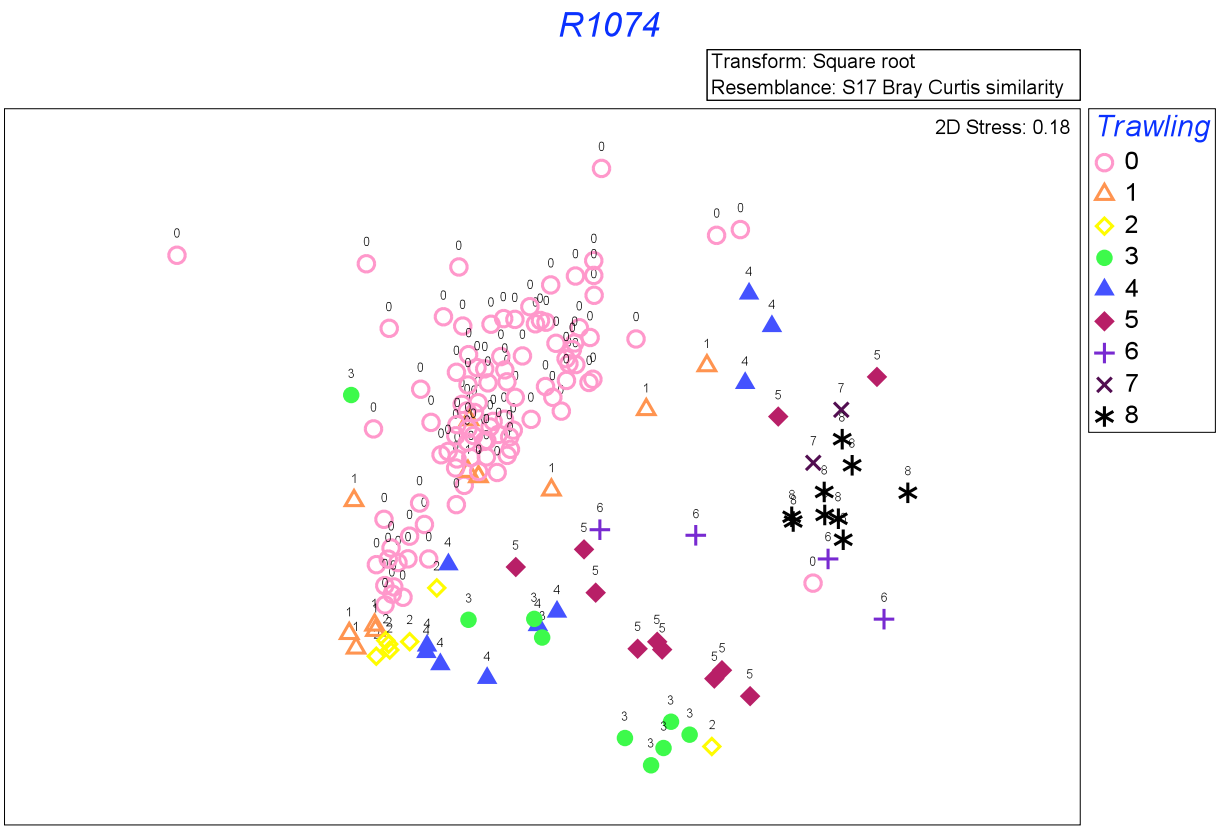


Figure 37: This MDS plot shows the megafauna assemblages using trawling intensity as a factor. Some clusters with similar assemblages are detected in the low trawled area (0-2) on the upper left side, in the medium trawled area (3-5) at the bottom and in the highly trawled area (6-8) on the right side of the graph.

Assemblages found where trawling intensities from 5-8 are clustered to the right of the graph, while lower intensities 0-1 are clustered to the left. Another MDS plot was produced to see assemblages related to depth (Figure 38). A depth factor was created in PRIMER-E with shallower depths ranging from 1-4 (295-699m), medium depths from 5-8 (700-1,099m) and deeper areas from 9-11 (>1,099m). Assemblages found in deeper areas are clustered to the left of the graph (9-11), while shallower areas tend to cluster towards the bottom (1-4) and medium depths to the right of the graph (5-8). Another MDS plot was produced to look at relief (Figure 39). The relief described mounds visible in the video analysis (1=10cm; 2=10-20cm). The cluster in blue, grouping the highest mounds, is located in the deeper area of the transect where trawling is very low or absent and the deep-sea holothurian *S. globosa* was abundant. Figure 40 shows substratum as a factor where 1 is mud/sand, 2 is mostly sandy with some gravel and 3 is muddy/sandy with scattered cobbles. No real clusters were detected.

3.4.3 MDS bubbles plots with specific taxa and environmental variables

A series of bubble plots was produced to illustrate the abundance of some specific taxa where the size of the bubble is proportional to the species abundance (Figure 40-42). Faunal aggregations (ophiuroids and holothurians) were strongly detected with MDS bubble plots and showed similar results as the abundance distribution showed above with the GIS maps. They are not included to avoid repetition. Other taxa were explored with this technique.

The two most dominant soft corals groups show different distribution patterns (Figure 41). When we examine the abundance of sea whips along transect R1074, an

abundance cluster is found in the deeper portion of the transect where trawling is low or not present. Distribution is patchy in other areas.

As for the sea pens, the highest abundance is found in the highly trawled area and shows the same taxon with an abundance cluster in medium depth (5-8), while distribution is patchy in the deeper section (9) of the transect and occasional in shallower waters (1) **(**Figure 42).

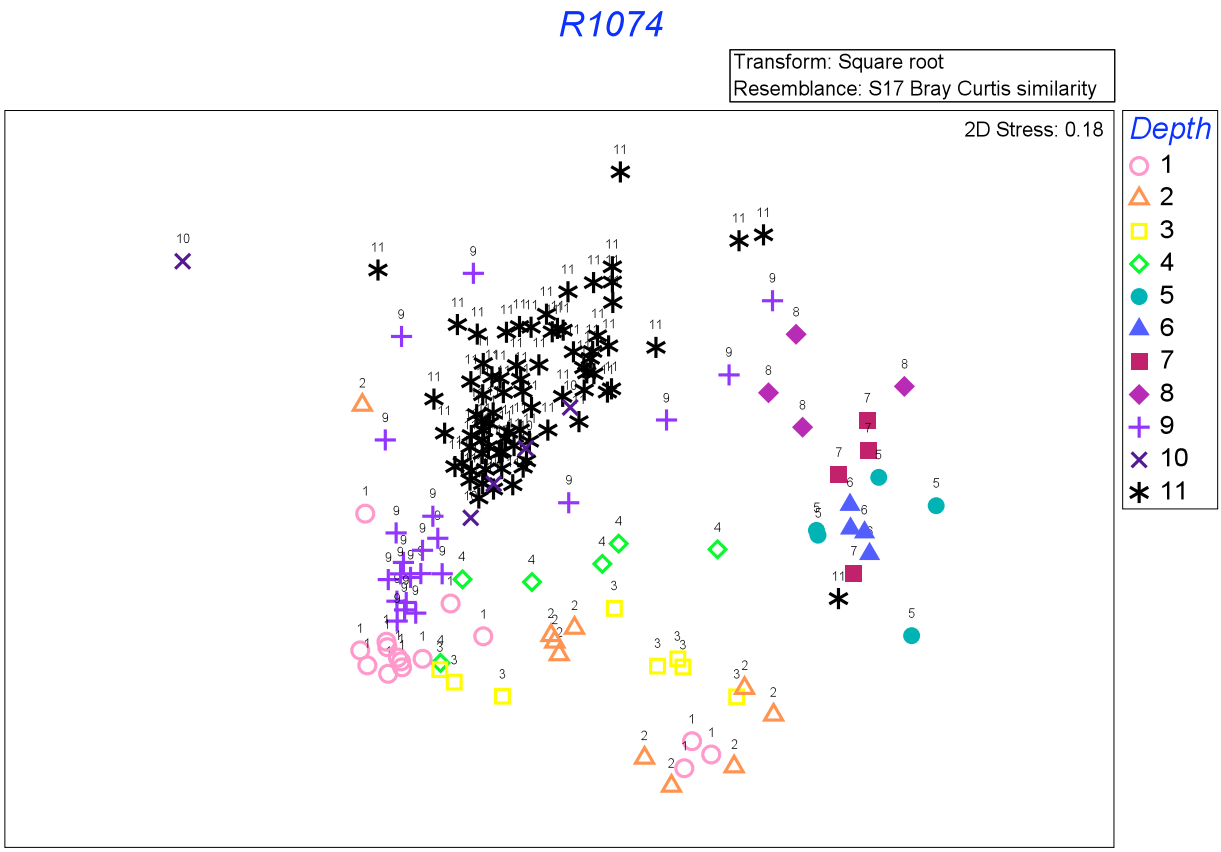


Figure 38: This MDS plot shows the megafauna assemblages with depth intensity as a factor. Shallower areas range from 1-4 (295-699m), medium depth between 5-8 (700-1,099m) and deeper areas from 9-11 (>1,099m). Assemblages found in deeper areas are clusters to the left of the graph, while shallower areas tend to cluster towards the bottom and medium water depths to the right of the graph.

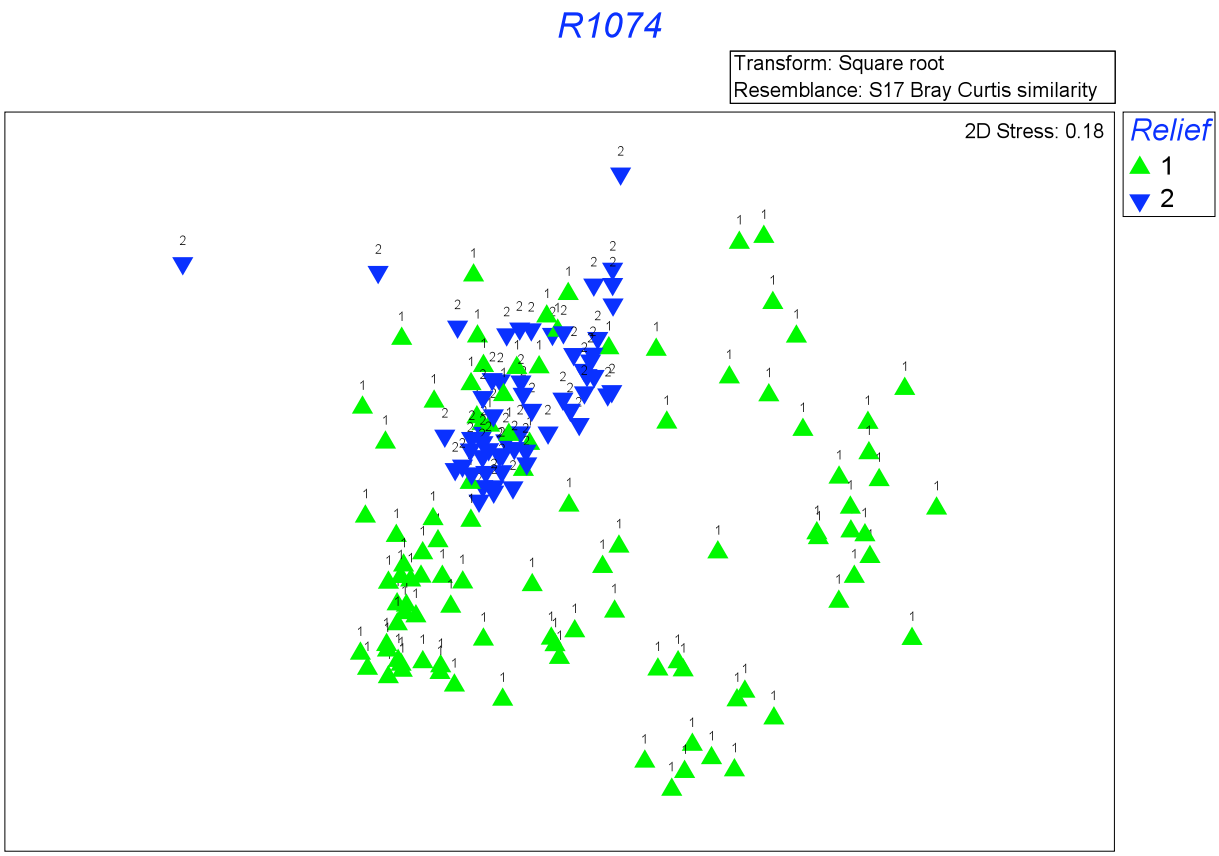


Figure 39: This MDS plot was created to look at relief as a factor, which was representative of mounds visible in the video analysis (1=10cm; 2=10-20cm). The cluster in blue comprises stations from deeper areas of the transect where there was very little trawling and where patches of deep-sea holothurians *S. globosa* occurred.

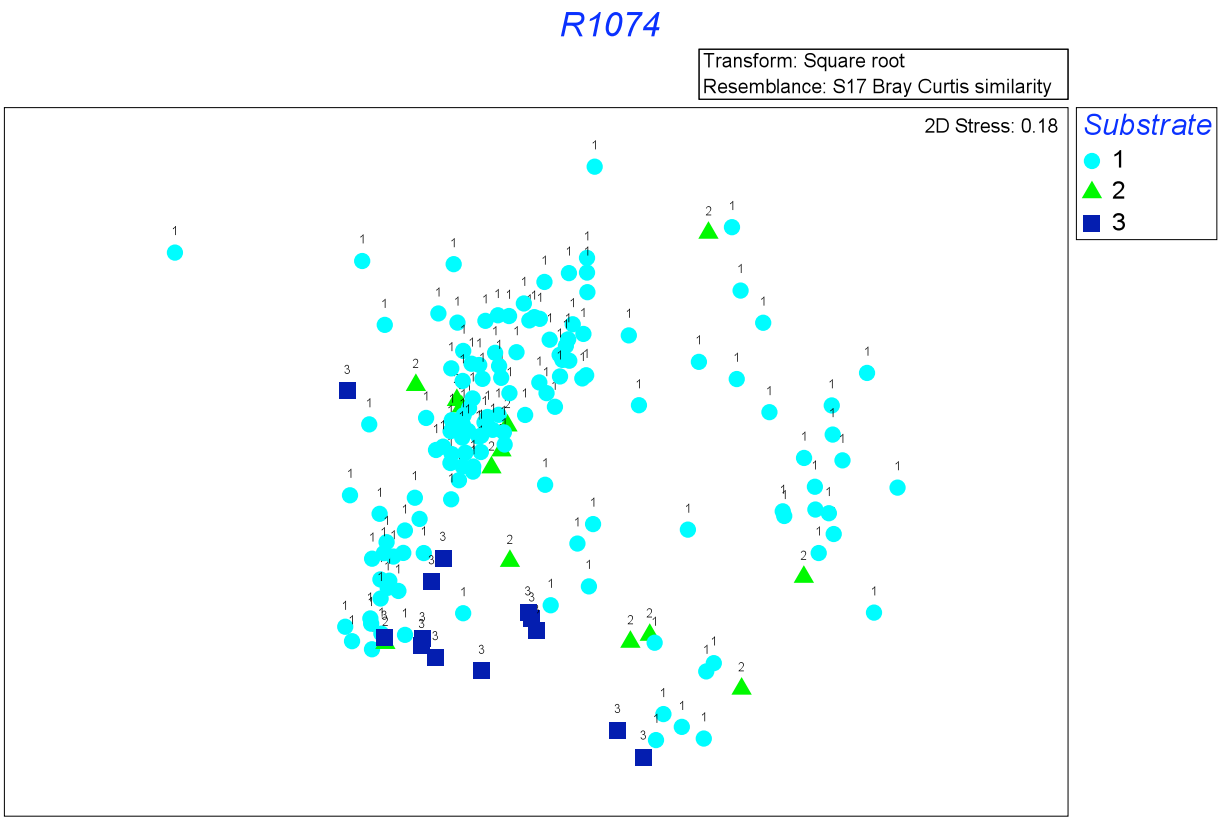


Figure 40: This MDS plot was created to look at substratum type as a factor in the video analysis (1=mud/sand; 2= sand/gravel = mostly sandy with some gravel; 3=mud/sand with scattered cobbles). No real clusters are apparent.

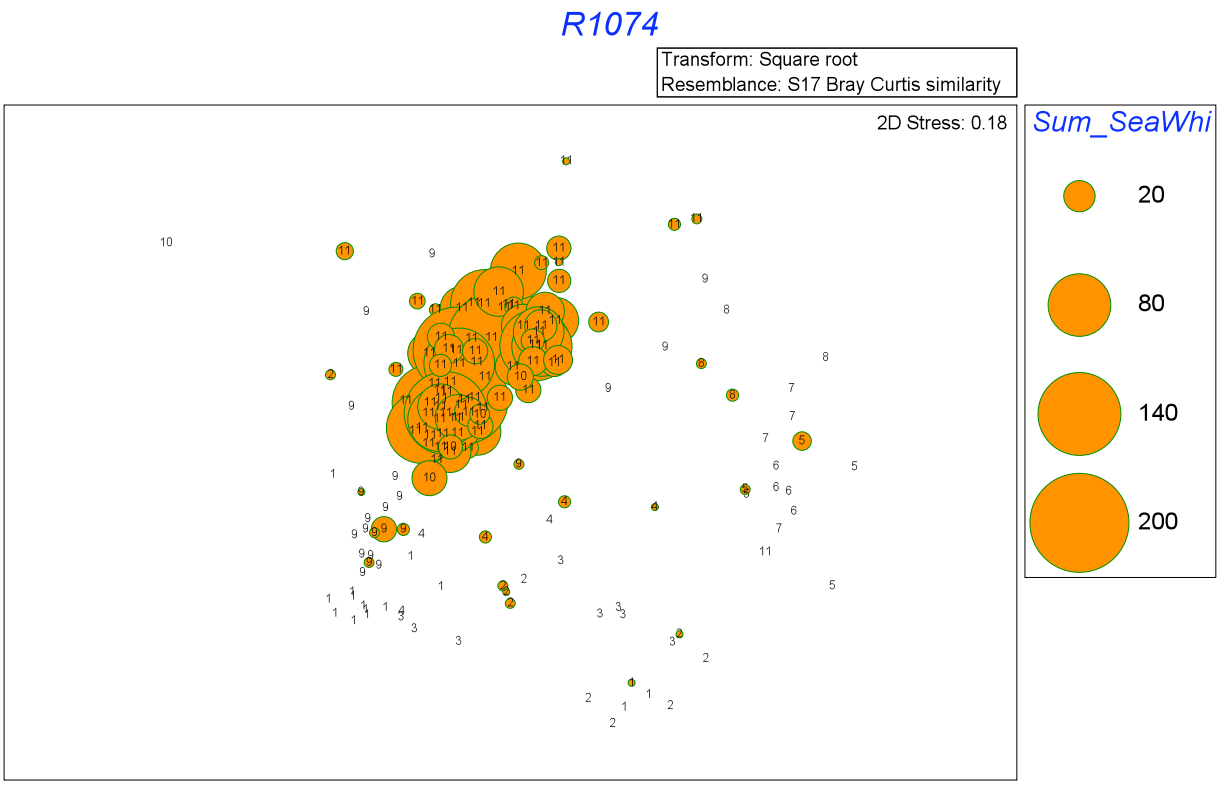
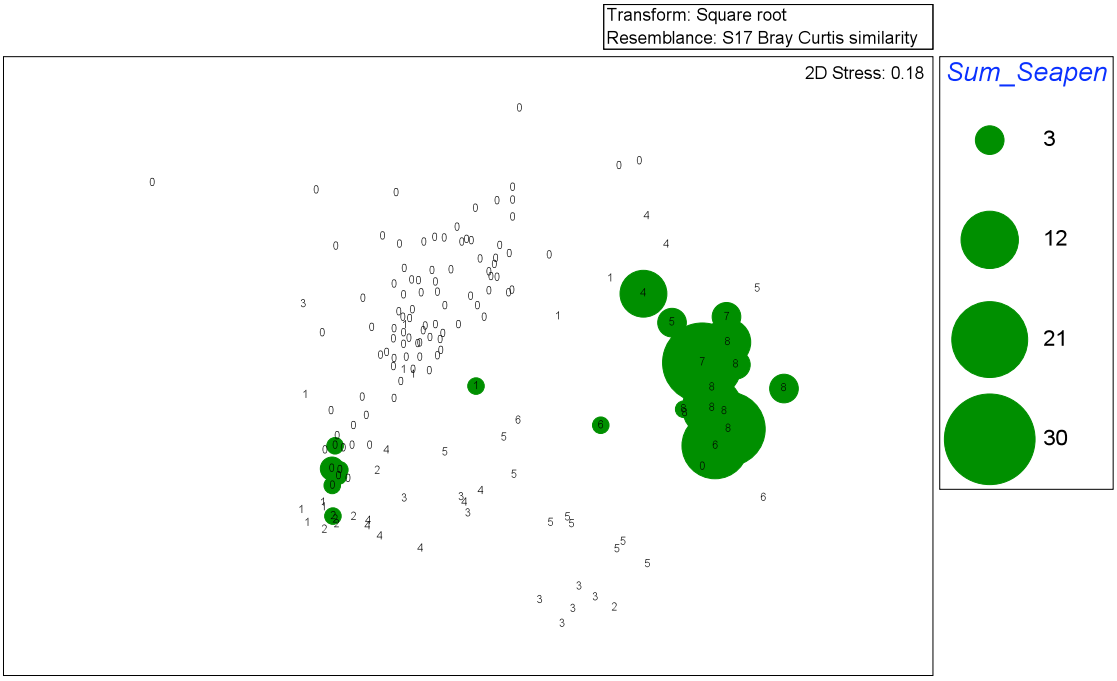


Figure 41: This MDS bubble plots shows the abundance distribution of sea whips along transect R1074 using depth as a factor. Depth factor ranges from 1-11. Shallower areas range from 1-4 (295-699m), medium depth between 5-8 (700-1,099m) and deeper areas from 9-11 (>1,099m).

A:



B:

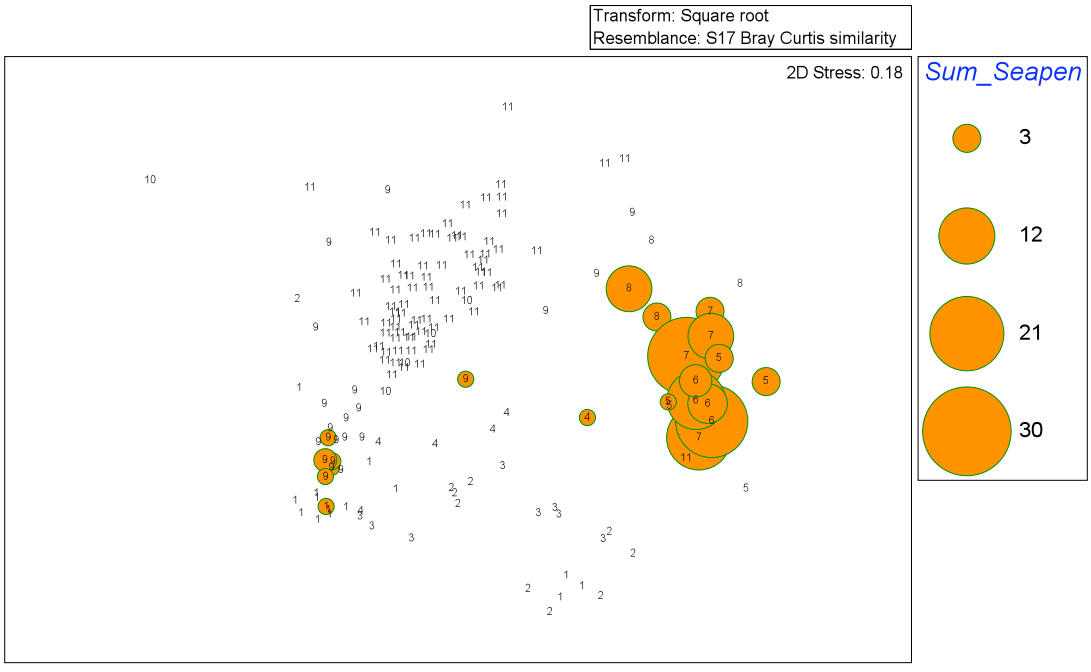


Figure 42: This MDS bubble plots shows the abundance distribution of sea pens along transect R1074 using A: trawling as a factor. B: depth as a factor.

MDS bubble plots for sponge distribution (Figure 43) show abundance to be concentrated in low trawled areas (0-4), but sometimes present in trawling intensities up to 6. Sponges were absent from the high trawling intensity area (7-8), while being present in the shallower and deeper sections of the transect.

3.4.4 MDS plots - Comparison with results from other transect (R1075)

Community assemblages

Figure 44 shows megafauna assemblages along transect R1075 using trawling as a factor. Trawling intensity varies from 1-5 in this transect. Clusters are distinguishable in low trawled areas and highly trawled areas (60% similarity). Clusters are also visible for the depth ranges (Figure 45).

Specific taxa

To compare with taxa patterns found in the transect R1074, MDS bubble plots with sea pens, sea whips and sponges were created. Figure 46 shows the abundance distribution of sea whips along transect R1075 using trawling intensity as a factor. A cluster is found where trawling is low or not present, which is the shallower area of the transect. Figure 47 shows the abundance distribution of sea pens along transect R1075 using trawling as a factor. Clusters are apparent in both low and highly trawled areas.

Figure 48 illustrates the distribution of sponges using trawling as a factor along transect R1075. Sponges were present in low trawled areas (0-3), occasionally present at trawling intensity 4 and absent from the highly trawled area (4-5).

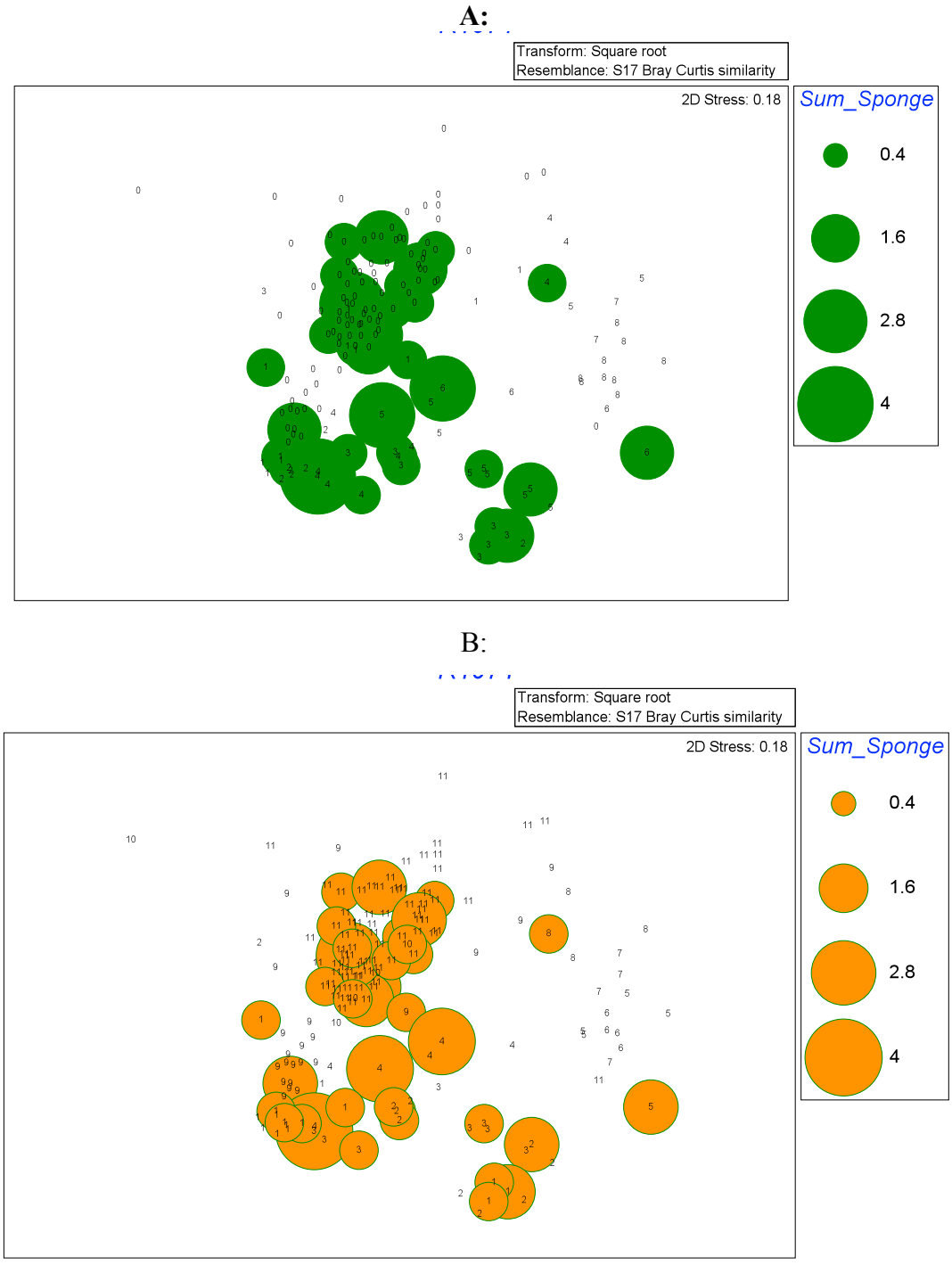


Figure 43: The MDS bubbles plots for distribution of sponges with A: trawling intensity and B: depth as a factor.

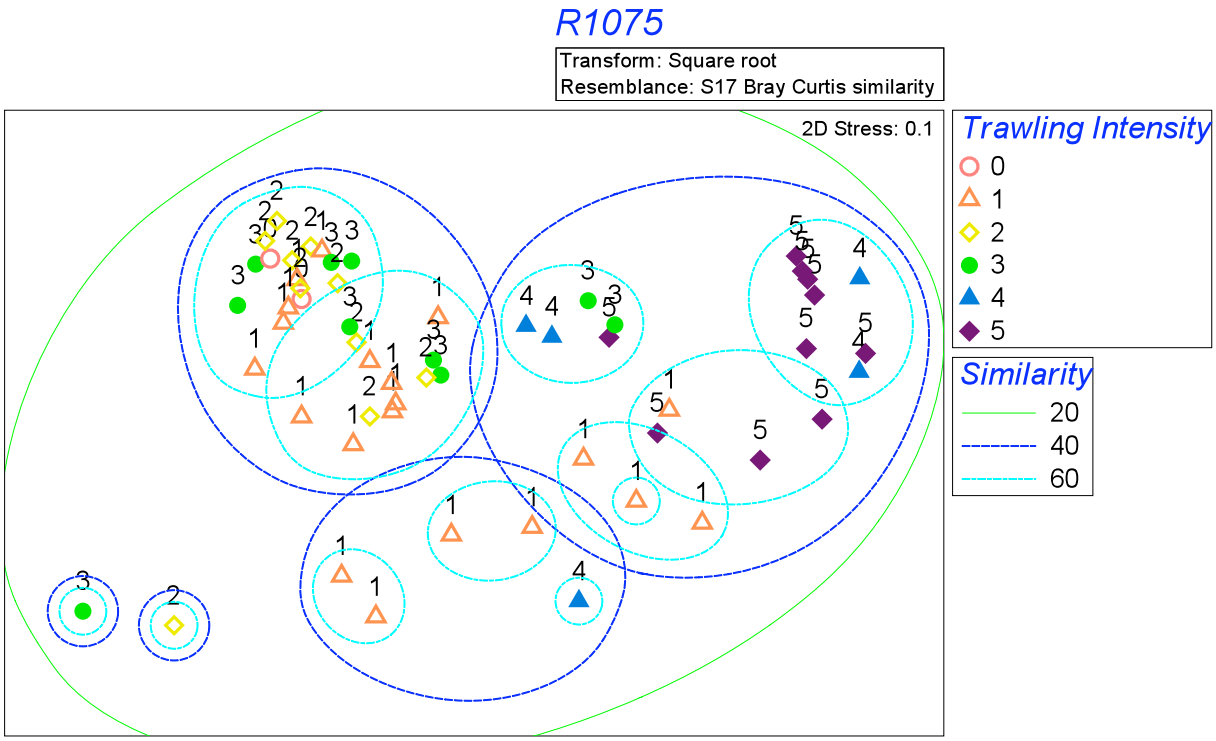


Figure 44: A MDS plot was produced with data from transect R1075 to see if patterns are also detected in community assemblages using trawling intensity as a factor (0-5:0-50 trawl marks/500m). Clusters are detected in low trawled areas and highly trawled areas. 20, 40 and 60% similarity percentages of the megafauna communities are indicated by the circles.

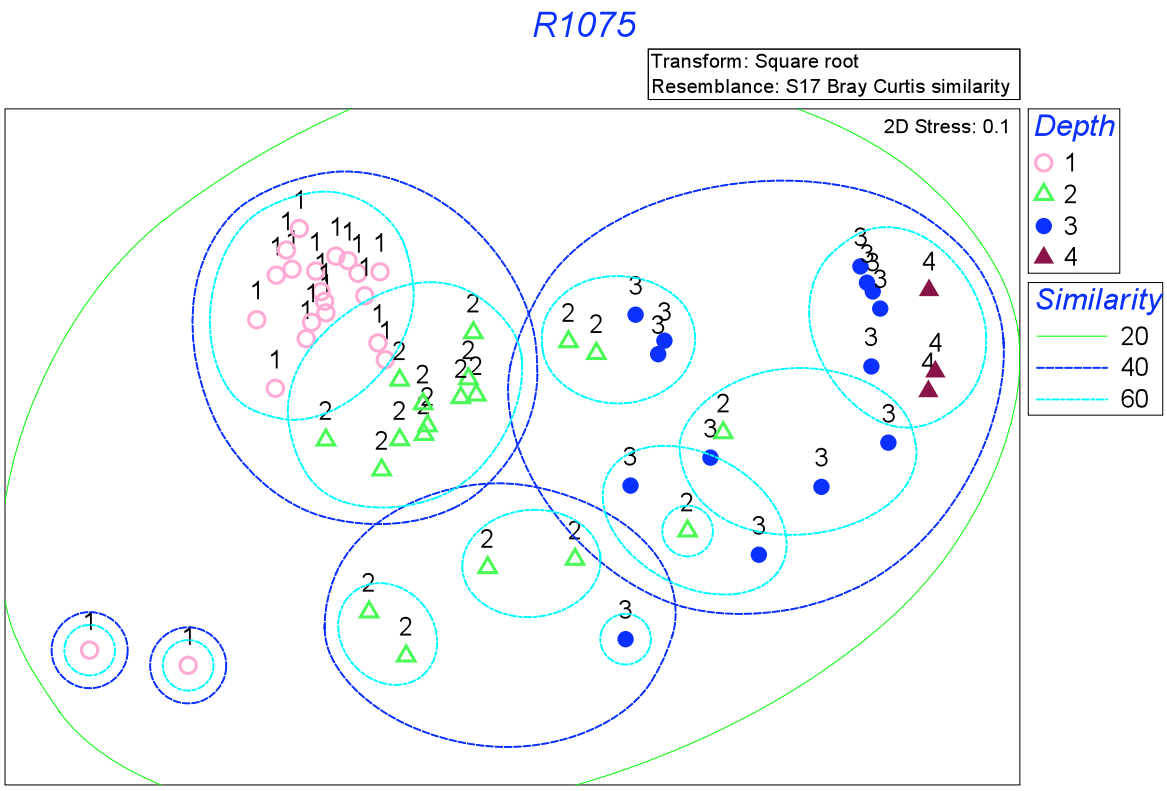


Figure 45: A MDS plot was produced with data from transect R1075 using depth as a factor. Clusters are found at the various depth sections (1:340-399m; 2:400-499m; 3:500-599m; 4:600-650m). Similary percentages of the megafauna communities are indicated by the circles.

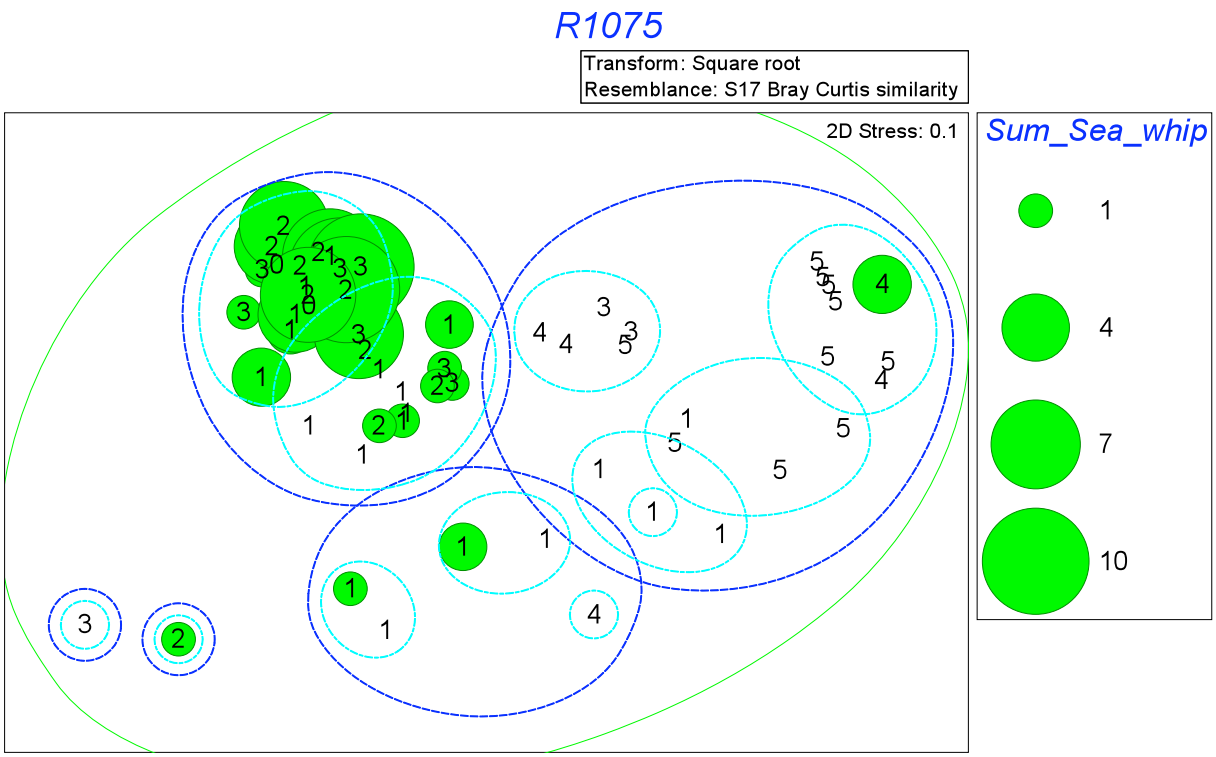


Figure 46: This MDS bubble plots shows the abundance distribution of sea whips along transect R1075 using trawling intensity as a factor. A cluster is found where trawling is low or not present (1-3), which corresponds to the shallower area of the transect).

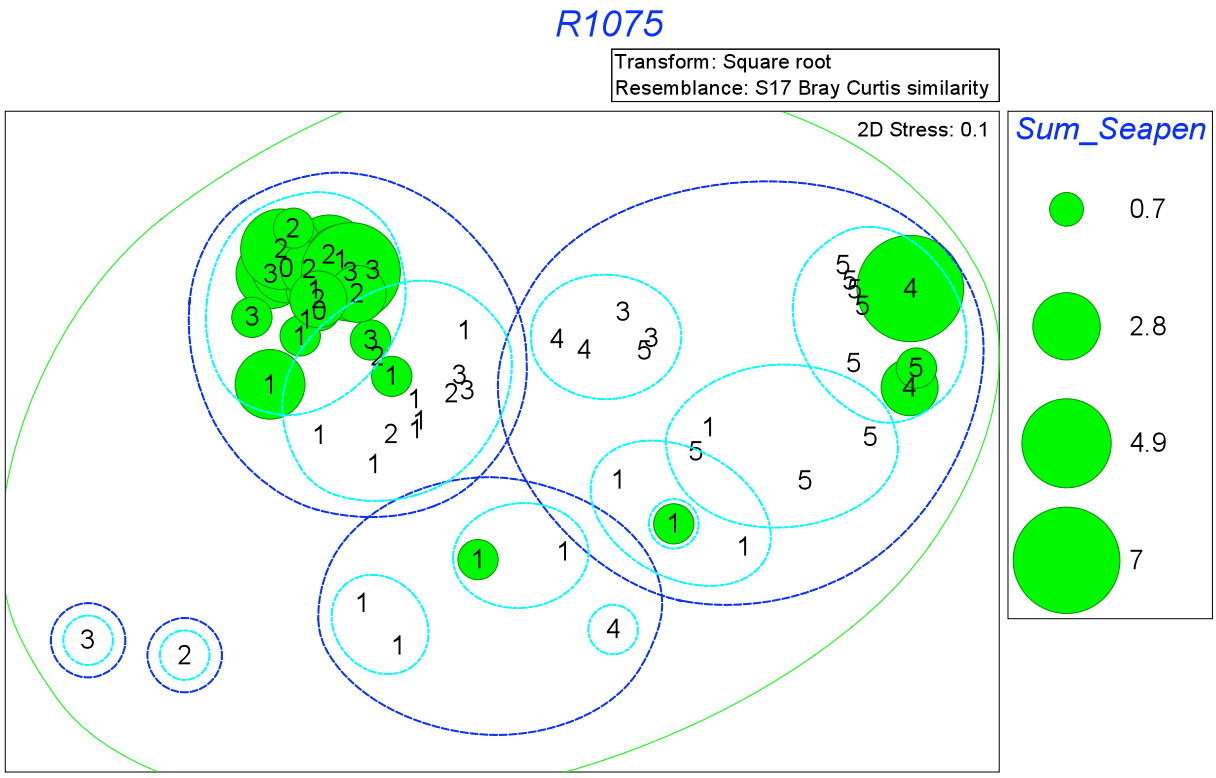


Figure 47: This MDS bubble plots shows the abundance distribution of sea pens along transect R1075 using trawling as a factor. A cluster is found in low trawled area and the highly trawled area.

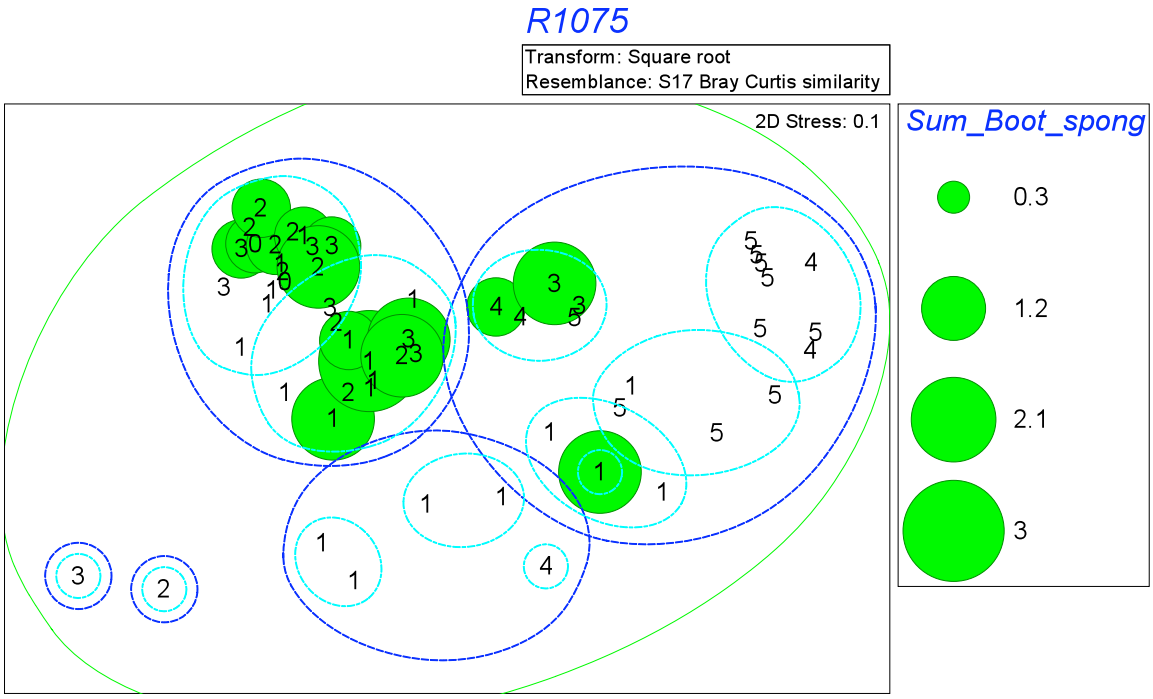


Figure 48: The MDS bubbles plots shows the distribution of hexactinellid sponges with trawling as a factor along transect R1075. Sponges are present in low trawled areas (0-3), sometimes present in trawling intensity 4 and absent from the highly trawled area (4-5).

3.5 Spatial structures in megafaunal community (transect R1074) and relation with the environment

3.5.1 Constrained ordination (redundancy analysis)

The RDA identified, after forward selection, six significant environmental variables explaining 41% (R^2) of the transformed abundance variation in the community structure (Figure 49). Trawling intensity (pvalue=0.001) and depth (pvalue=0.001) explained most of the variation with respectively 22% and 13%. Slope indicator (pvalue=0.001), oxygen (pvalue=0.032), substratum type (pvalue=0.007), and relief (pvalue=0.048) each explained less than 3% of the variation (Table 14). The first axis separates high and low trawling observations, with the high trawling stations on the left side of the graph and the low trawling observations on the right side. Deeper stations are correlated with higher abundance of sea whips and holothurian *S.globosa*. Ophiroids abundance is correlated with stations in the low trawled area.

3.5.2 Principal Coordinates Neighbour Matrices (PCNMs)

The Principal Coordinates Neighbour Matrices analysis identified spatial influences of environmental variables on ecological structures. A truncation distance was selected at 402m, as it was the longest distance between two contiguous sites. Out of 61 PCNMs with positive Moran's I values, a forward selection based on alpha 0.05 and the adjusted R^2 of the previous RDA selected 37 significant PCNMs. These significant PCNMs were divided as submodels to decompose the variance in the megafauna community (Figure 50). The broad-scale (PCNMs 1-6) had a range of 1-2 peaks per 9.6 km (4.8 km-9.6 km pattern); medium-scale (PCNMs 7-24) with 3-4 peaks per 9.6 km (2.4

km-3.2 km pattern); fine-scale (PCNMs 29, 30, 32, 33, 36, 38, 39, 41, 42, 45, 48, 50, and 53) with 5-9 peaks per 9.6 km or distance between peaks narrower than medium scale (1 km-1.9 km pattern). The broad and medium-scale submodels explained 12% and 52% of the total variation in the community structure, while fine scale explained only 0.4% (Table 15). Environmental variables that significantly contributed to each sub-model (with associated probabilities) can be found in the same table. The redundancy analyses conducted between environmental variables and the broad-scale submodel showed a significant influence of depth, trawling, slope indicator, biogenic roughness, and relief (mounds/bioturbation indicator). At medium-scale, the RDA detected a significant influence of depth, trawling, biogenic roughness and substratum type. The fine-scale submodel was not correlated to any of the environmental variables considered in this study.

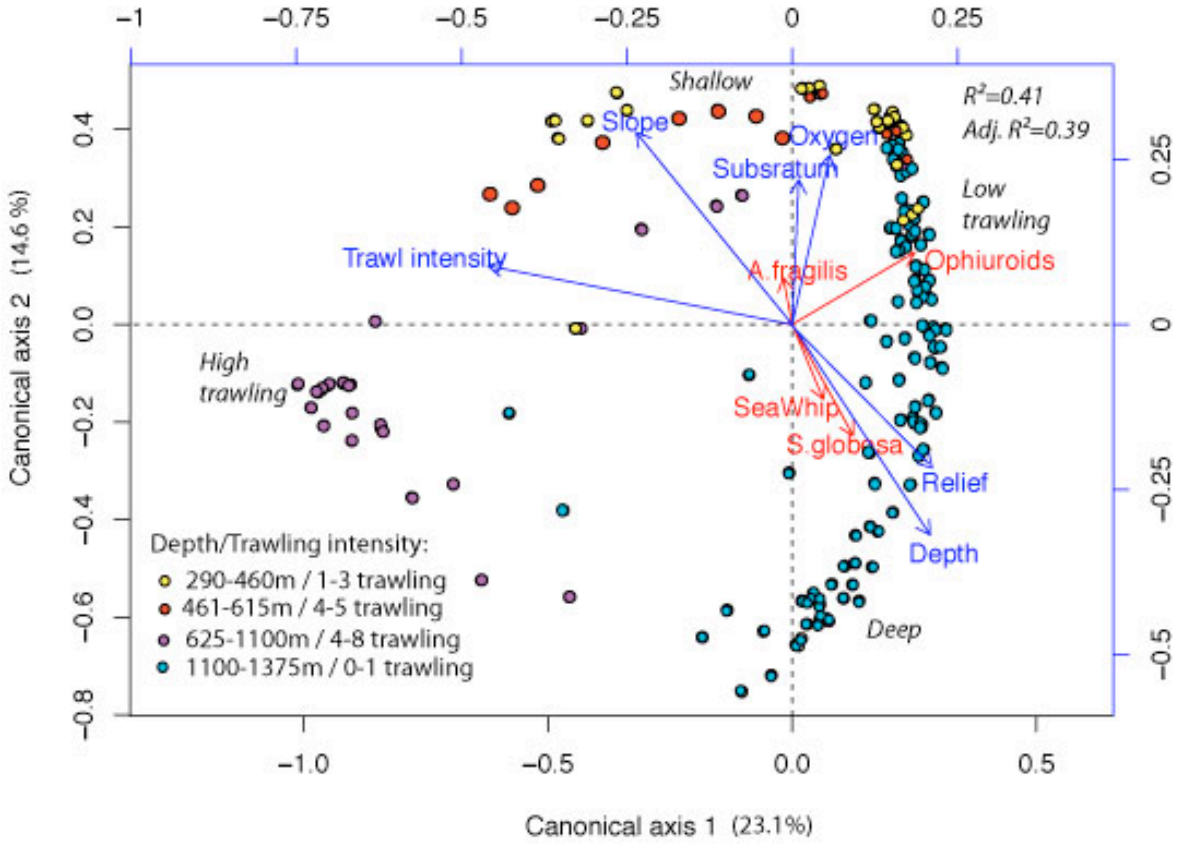


Figure 49: Canonical redundancy analysis correlation biplot, after forward selection, based on the transformed species abundance data. Significant environmental variables: depth, trawling intensity, oxygen, substratum type, small-scale relief (mounds), and slope indication on the megafauna community structure. The canonical axis explains approximatively 23% of the variation, followed by the second axis at 14%.

Table 14: Results of the redundancy analysis (RDA), after forward selection, based on abundance data (Hellinger transformed) for R1074. The six significant environmental variables detected explained 41% of the total variation in community structure.

	R2	R2Cum	AdjR2Cum	F	pval
Trawl intensity	0.2196	0.2196	0.2147	44.7525	0.001
Depth	0.1264	0.3460	0.3378	30.5360	0.001
Slope indicator	0.0326	0.3786	0.3668	8.2394	0.001
Substratum type	0.0151	0.3937	0.3782	3.8742	0.007
Oxygen	0.0113	0.4050	0.3858	2.9498	0.032
Small-scale relief (mounds)	0.0086	0.4136	0.3908	2.2607	0.048

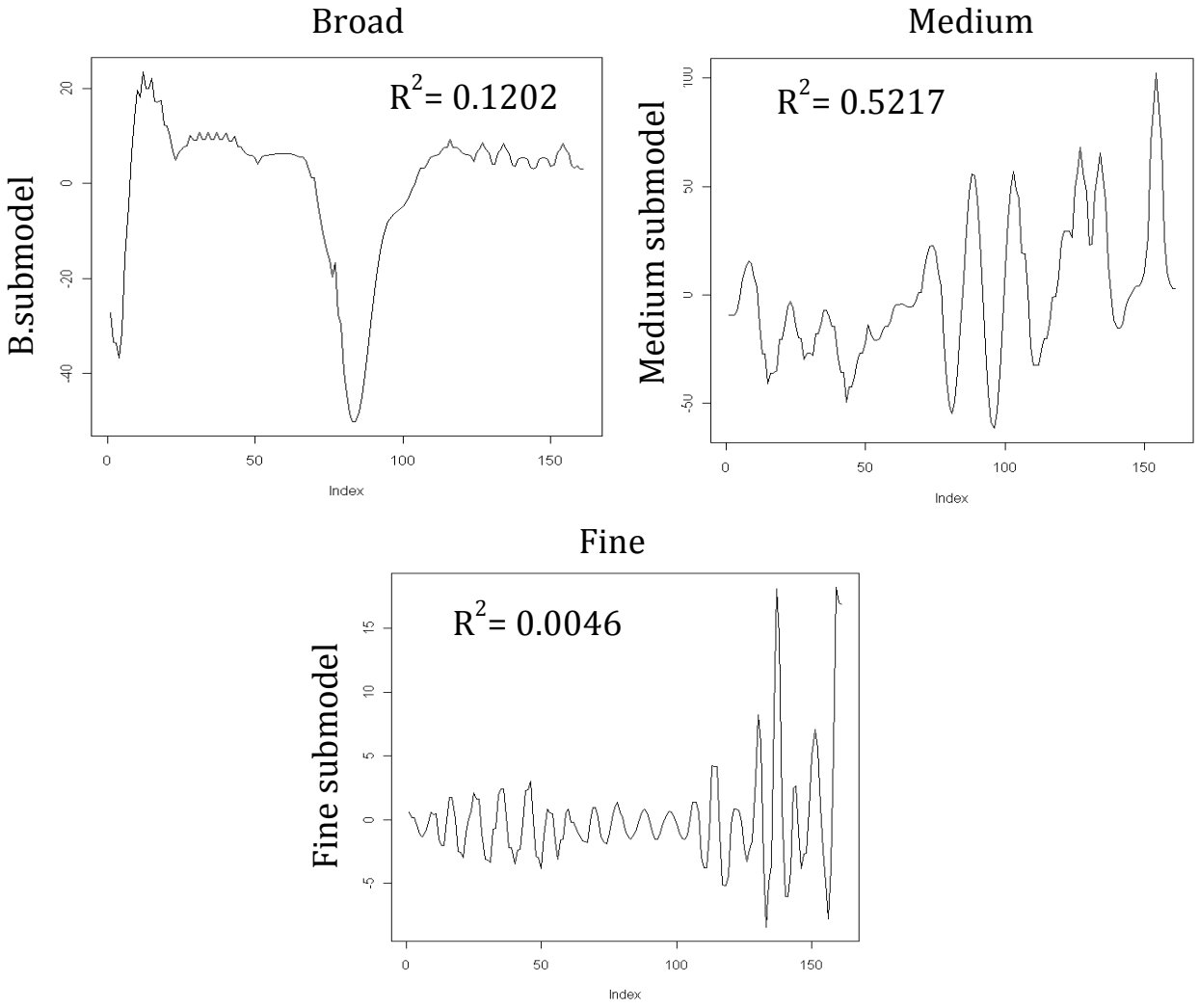


Figure 50: Spatial PCNM (Principal Coordinates Neighbour Matrices) submodels for broad, medium and fine scales for transect R1074. The PCNMs graphs represent 161 'stations' along the 30.8 km transect. The average distance between 0 and 50 on the graph is approximately 9.6 km. The broad scale shows an influence of trawling intensity, oxygen levels, and small-scale relief (mounds/bioturbation indicator) at a spatial pattern detected from 4.8 km-9.6 km. The medium scale describes an influence of depth, trawling intensity, oxygen levels, slope, and substratum type with a spatial pattern detected between 2.4 km-3.2 km. The fine scale submodel shows a pattern ranging between 1 km-1.9 km, but could not be explained by these environmental variables.

Table 15: R^2 and p-values associated with the spatial analysis describing the ecological structures of the megafauna assemblages along transect R1074. The first line represents the R^2 of the significant PCNM for each submodel (broad, medium, fine). The second line represents the R^2 of the regression of the submodel on a subset of forward-selected environmental variables. The third line represents the product of the two R^2 above, showing the variation of the communities data explained by the environmental variable at the specified scale. P-values of the regression coefficient of the environmental variables are found below for each submodel.

	Megafauna assemblages	Broad	Medium	Fine
R^2 of PCNM submodel on megafauna assemblages		0.1202	0.5217	0.0046
R^2 of envir. on submodel		0.2364	0.5201	
R^2 of envir. on megafauna assemblages	0.3951	0.0284	0.2713	
Depth (m)	0.001*	0.13	0.01*	
Trawling intensity	0.001*	0.005*	0.005*	
Substratum type	0.007*	0.33	0.049*	
Slope description	0.001*	0.105	0.035*	
Oxygen	0.032*	0.013*	0.037*	
Relief (mounds)	0.048*	0.017*	0.74	

Chapter 4

4.0 Discussion

4.1 Trawling intensity quantification and limitations on interpretation

This study quantified trawling intensity by counting trawl-door marks in video and scanning-sonar imagery. We ultimately used only the sonar data because of its apparent higher sensitivity and larger field of view. It is unlikely that our quantification method was substantially biased by along-transect variations in the resistance of the seafloor to detectable scouring by trawl doors or the rate at which trawl scars are eroded by bottom currents. Penetrometer measurements during submersible transects and Geological Survey of Canada maps show the substratum to be mostly uniformly muddy and soft throughout the survey area.

Vessel Monitoring System (VMS) data are often used to quantify trawling intensity and in studies of the impact of trawling on benthic ecosystems (Tillin et al. 2006, Hiddink et al. 2007, Mills et al. 2007, Lee et al. 2010, Lambert et al. 2011), but VMS data are not always available, as was the case here. Other studies have used video or sonar methods to quantify trawling. Smith et al (2007) combined sidescan sonar and video data to quantify trawling and concluded that this combined method provided a suitable tool for ground-truthing VMS data or for quick assessments. Malik and Mayer (2007) assessed the combination of multibeam, sidescan sonar and video for seabed fishing impacts. Another study of bottom trawling impacts (Engel & Kvitek 1998) found

a semi-quantitative relationship between VMS data and video surveys wherein areas for which VMS data showed high trawling intensity had significantly more visible trawl marks in seafloor imagery than did lightly trawled areas.

One important dimension to consider in interpreting the results of trawl impact surveys is the time interval between the survey and the most recent trawls in an area. Depending on the length of this recovery interval, observed seafloor faunal attributes (eg. composition, abundance) may have been influenced by post-trawling recolonization. In this study, neither VMS records nor shipboard log information were available for individual trawls, so that it was not possible to date any of the trawl marks observed along the two transects. Our data therefore record the cumulative impact since deep-water bottom trawling began in this area in the 1990s. Data obtained from the Canadian Department of Fisheries and Oceans (hereafter DFO) show a relatively constant level of trawling activity in the area since record keeping began in 1996, with a total of 400-500 detectable 'events' for each of our transects, where (confidential) navigation records show our transects crossing over previous (1996-2007) trawls. Considering that the two trawl-doors from the bottom nets would be visible in the sonar, the number of trawl-door marks counted for R1074 correlates well with the fishing events data, suggesting that trawl marks remain visible on the seabed for at least 10 years in that environment. These navigation records from DFO show no obvious year-to-year trends in the location of trawls along our transects. In the absence of information that would allow the dating of trawling activity in each of the 250-m-long transect sections that were the spatial units in our analysis, the observed faunal characteristics must be assumed to be an unknown mixture of three possibly different faunal assemblages:

1. Virgin assemblages on fragments of seafloor area untouched by trawling.
2. Survivor assemblages of species that resisted the passage of the trawl.
3. Recolonizing assemblages consisting of species best adapted for rapid recolonization of disturbed areas of the seafloor.

4.2 Challenges for megafauna identification

Video transects and subsequent analysis permitted the acquisition of a spatially continuous record of the distribution and abundance of megafaunal organisms with relatively little impact on the ecosystems studied. However, the identification of species in video imagery can be challenging. Identification confidence levels can vary as can the taxonomic level of identification. Challenges for video analysis include variations of the height of the ROV over the seabed, the angle of the video camera and the light intensity.

Where there is no historical baseline or comparable unfished areas, evaluation of the impact of trawling is probably best approached by comparing areas that have been subjected to different levels of trawling activity (McConnaughey et al. 2000, Atkinson et al. 2011). Despite the fact that our observations come from the opportunistic exploitation of seafloor surveys undertaken for another purpose (cable route surveys), they do meet this basic requirement of encompassing a wide range of trawling activity levels. The broader depth and trawling intensity range of R1074 makes this transect particularly interesting for identifying patterns or differences in the communities, in relation to these two important environmental variables. R1075 likely captured only part of the pattern present in the area because it is a shorter transect with an oblique direction along the depth contours. Confidential trawl location maps data show that both transects are

representative of larger, surrounding areas that were subjected to bottom trawling over the decade preceding the 2007 surveys.

4.3 General faunal composition

Sebastolobus spp. tends to be evenly distributed (Haigh & Schnute 2003). In our survey area, most of the *Sebastolobus* spp. distribution is located in their expected depth range distribution, which also corresponds to the high trawling intensity area. As found in the literature (Haigh & Schnute 2003), our data showed that sablefish, grenadiers, and flat fishes (deep-sea sole and dover sole) are often found in association with thornyheads. For both transects, echinoderms, especially ophiuroids and holothurians dominated the seabed. Levin and Gage (1998) found that oxygen minimum zones typically have lower macrofauna diversity with high dominance of a species, which constitute often 40-85% of the community. Megafauna diversity is likely to have a similar trend. Faunal aggregations is a category that was transformed in average abundance and might not reflect the exact number of species, but do represent a high number of dominant species covering the seabed in too large densities to count manually.

The generally muddy seabed and very gentle slope made it difficult to associate changes in the community structure with visible substratum properties. The relationship between sediment descriptors and faunal distribution is complex and can be affected by grain size, microbial abundance and composition, pore-water chemistry, and organic matter content (Snelgrove & Butman 1994), none of which can be determined from video observations. Measured environmental variables such as substratum softness, adjacent substratum texture/type, temperature, and salinity appear to be constant or to change

gradually along the soft-bottom slope. These add complexity to interpreting the influence of trawling on faunal distribution. For example, in the North Sea, Callaway et al. (2002) results showed that sediment properties, bottom temperature and beam trawling were strongly correlated with species richness and diversity, community patterns and possibly community composition.

4.4 Faunal Aggregations patterns

4.4.1 Faunal aggregations detected

We observed faunal aggregations in the shallow and deep zones of the transect where trawling intensities were the lowest (0-4 intensity). These aggregations were mainly monospecific or mixed between the holothurian *Scotoplanes globosa*, the echinoid *Allocentrotus fragilis* and/or the ophiuroid taxon. Faunal aggregations caused peaks in total abundance of species along the transect R1074. Ophiuroids can be considered opportunistic species because of their feeding versatility and their resistance to disturbance. Smale (2007) observed a similar "absence pattern" in Antarctica where pioneer species decreased in abundance with increasing disturbance intensity and were absent from an area highly disturbed by iceberg scours. Invertebrate biomass reductions are also detected after disturbance as shown by Gerdes et al. (2008), Jennings et al. (2001), Pranovi et al. (1998), Prena et al. (1999), and Svane et al. (2009).

Faunal aggregations found in the lightly trawled areas are mainly deposit feeders or omnivores. Opportunistic species are often the first ones to recolonize after a disturbance. Although our study was not a time series, it is expected that part of the assemblages found are colonizers after a decade of disturbance. Many studies have documented a tendency of faunal aggregations composed of opportunistic species in

different environmental conditions. Iceberg scours impact studies have detected that trend (Gutt & Piepenburg 2003, Smale et al. 2008), as well as bottom trawling impact (Engel & Kvitek 1998, Pranovi et al. 1998, Prena et al. 1999, Collie et al. 2000b, Tillin et al. 2006, Vergnon & Blanchard 2006, Demestre et al. 2008) and aggregate dredging impact (Kenny & Rees 1996, Desprez 2000, Van Dalfsen et al. 2000).

4.4.2 Recolonization patterns observed elsewhere

Recolonization patterns could help to create scenarios for recovery in our survey area, although disturbance continues and varies from year to year. Following disturbances, benthic communities are often dominated by r-selected species that reproduce often, have short lives, and are highly mobile (Rhoads et al. 1978). Recovery from disturbance is usually defined as the establishment of a community that is comparable in terms of species composition, population density and biomass to what previously existed or to a similar but undisturbed site (C-CORE 1996). Reported rates of recovery by marine benthos in sand and gravel habitats after dredging vary from two years to around 5-10 years where deposits are coarser. Dernie et al. (2003) found that sand communities recover faster than stable muddy sand communities. Recovery times for benthic communities can depend on factors such as substratum, stability, intensity and frequency of the disturbance (Newell et al. 1998).

4.5 Ecosystem state evaluation

Some studies have found that more frequently disturbed benthic communities remain in a transitional or altered state. Collie et al. (2000b) observed that seabed areas trawled more than three times a year in the North Sea remain in a permanently altered

state dominated by opportunistic species. Gutt and Starmans (2001) also found that communities in Antarctica disturbed by icebergs scours were not reaching maturity because of the intensity of the disturbance.

Evaluating the state of disturbance or recovery of the benthic communities in this study is complicated by the added stress of hypoxia in the sections of the transects where trawling activity was most intense. The 'aggregation hole' is the most dominant feature in our faunal data that can be associated with the zone of intense trawling. In this zone, the absence of aggregations formed by dominant echinoderm taxa could be caused by the high intensity of trawling, altering the high, often single-species dominance that would normally be present in an oxygen minimum zone benthos (Levin & Gage 1998). Alternatively, the aggregations may represent a community that is re-adjusting after moderate levels of disturbance by trawling, as found by Blume (2001). In that study, the "not directly" impacted sites showed a higher density of the total megafauna than the adjacent impacted sites after three and seven years. Blume (2001) speculates that the sediment plume that resettled after an experimental ploughing event may have an initial negative effect, but after a few years, it could attract opportunistic species. In such a scenario, the observed echinoderm aggregations would be representative of a community recovering from trawling, while the 'aggregation hole' would represent an area where trawling was too intensive for this recovery process to begin. Clark and Rowden (2009) identify a positive effect of trawling on populations of the ophiuroid *Ophiacantha brachygnatha,* which were larger and nearly twice as abundant in fished areas compared to unfished area on deep-sea seamounts off New Zealand. In contrast, in a meta-analysis of 39 publications on the impact of fisheries, Collie et al (2000b) found that populations

most seriously affected among the echinoderms were ophiuroids and holothurians, while asteroids and echinoids were less affected.

4.6 Species richness and diversity

In the identified hierarchical clusters, species richness in the heavily trawled area (37 taxa) was similar to lightly trawled areas (37-44 taxa), but diversity indices, including evenness, were higher in the heavily trawled area. This may be explained by the absence of the dominant aggregate-forming species in the heavily trawled area, where diversities indices would be skewed by high numbers of single types of echinoderms. In addition, these faunal aggregations may also have a direct effect on the use of seafloor habitat by other species. For example, Ambrose Jr. (1993) found that experimental removal of ophiuroids increased diversity (Shannon-Wiener index) after 12 weeks of experiment compared to high density of ophiuroids. Studies of areas of seafloor impacted by iceberg scouring provide insight into changes in abundances, composition and diversity caused by a natural disturbance that resembles bottom trawling in its physical impact on the epibenthos. Gutt and Piepenburg (2003) found a scale-dependent impact in diversity. At a regional scale (1-100km), they found an increase in diversity in area scoured by icebergs that was mainly explained by the resulting seabed heterogeneity and the co-existence of different recovery stages. However, at a local scale (1-100m), levels of diversity would be lower in disturbed areas than undisturbed by iceberg scouring because of the loss of sponges and their associated assemblages (Gutt and Piepenberg, 2003).

It the case of our study, it is more likely that higher diversity indices in the high trawling zone are statistical manifestations of the absence of single-species faunal aggregations.

4.7 Spatial structures in megafaunal community and relation with the environment

Ecological processes occur at multiple scales and converge into multiscale patterns affecting a community. Identifying which environmental variables affect the community at which scale is an important step in understanding its ecology. Scale patterns with environmental variables associated were detected in the biological response structure using a recent method, the Principal Coordinates of Neighbour Matrices (PCNMs) procedure. This test which belongs to a group of methods called Moran's Eigenvector Maps (MEM) has been shown to be a robust and flexible analytical tool for studying spatial patterns in ecological data (Dray et al. 2006). Compared to other kinds of trend analysis, PCNM allows modeling over a very wide range of spatial structures (Borcard & Legendre 2002), with the exception of finer scale structure, which is not often explained by environmental variables because of the presence of autocorrelation and biotic influences (Borcard et al. 2004).

The redundancy analysis (RDA) indicated a strong influence of trawling intensity and depth on the community structure. Slope, dissolved oxygen concentration (measured ex situ), relief, and substratum also influenced community structure in the RDA, but to a lesser extent than trawling and depth. The influence of oxygen data may have been masked by their co-variation with depth or the fact that matching *in situ* oxygen data were not available. PCNM results showed that most of the variation in the ecological structures were detectable by the broad and medium scale models, and to a lesser extent the fine scale (patterns <1km). This variation captured by the PCNM was explained by

most of the environmental variables used, especially by trawling intensity and secondly by depth.

4.8 Hypoxia and its effect on the community structure

In situ dissolved oxygen data were not available for our study, but dissolved oxygen concentration data from regular surveys by DFO indicate a persistent hypoxia/oxygen minimum zone along the continental slope off Vancouver Island. A closer look at oxygen concentration levels show a low oxygen core zone that ranges from approximately 450m to 1,100m depth, where the lowest levels are around 0.2ml/l. Then, an increase of oxygen level follows from 1,100m to 1,300m, which is the maximum depth for which data are available. Our data showed faunal aggregations to be most prominent at the threshold of the hypoxia zone, near both the upslope and downslope boundaries. Is this an 'edge effect'? Very high densities of megafauna at the upper and lower edges of the low oxygen zones have been observed elsewhere (Diaz & Rosenberg 1995, Levin 2003). Boundaries can also be more biologically productive and experience organic enrichment, which may cause these abundance peaks in megafauna as well (Gowing & Silver 1983, Diaz & Rosenberg 1995). A study of ophiuroid distribution and population densities on the continental slope off California showed a similar pattern to our data: the absence of ophiuroids in the oxygen-minimum core zone and peaks at the edges (Summers & Nybakken 2000). Seafloor sediments overlain by oxygen-poor water tend to be more enriched in organic matter than adjacent sediments, because aerobic decomposition is reduced in the overlying water column, allowing the sedimentation of more organic matter. Organisms able to tolerate the edges of this zone would have access to a richer food supply. Mobile organisms would tend to aggregate where they encounter

a low-oxygen barrier to their movements. This aggregation could be enhanced by the availability of a richer food supply near this barrier, as described above.

The hypoxic zone on the continental slope off Vancouver Island is caused by a mixing of the North Pacific oxygen minimum zone (Karstensen et al. 2008) and the California undercurrent (Krassovski 2008), both of which bring low oxygen waters to the area. Mullins et al. (1985) found a strong edge effect at the oxygen minimum zone (OMZ) off California and found an increase in biogeochemical activity at the boundaries. However, reduced benthic diversity tends to be the norm in OMZ, with megafaunal abundance also decreasing as dissolved oxygen decreases (Gallardo et al. 2004). This contrasts with what was observed in this study where diversity indices were slightly higher in the low oxygen core zone, despite lower overall abundances. Species groups have different tolerance levels to hypoxia. Echinoderms and crustaceans are less tolerant, in comparison to polychaetes and bivalves (Diaz & Rosenberg 1995). Because persistent hypoxia slows growth and lowers reproductive success, it should also act to reduce rates of recolonization following disturbance by trawling. One would therefore predict that intense trawling tend to even further reduce faunal diversity in area with severe hypoxia. Few studies have examined deep-sea trawling impacts in hypoxic zones. Our statistical analysis indicates that trawling intensity had a greater influence on faunal community attributes than did depth or dissolved oxygen levels.

There is no pre-trawling ecosystem baseline for this area, but data on species caught and the proportion of ophiuroids in the total catch were made available by DFO to determine if ophiuroids were present in the core of the oxygen minimum zone during the early years of trawling, and thus possibly eliminated as a result. Ophiuroids were indeed

present in the management sub-areas, but not present in the dataset every year. Catches of ophiuroids were twice as high in the 700-1000m depth range (peaking in 1998) as in the 200-500m range, in the 1996-2006 interval. This contrasts with our data that show aggregations of ophiuroids to be absent in the 700-1000m depth range. Keeping in mind that natural communities have a dynamic structure and are spatially heterogeneous (Sousa 1984), this suggests that ophiuroids were also present in the lowest oxygen concentration area. Exploring differences in species distribution and composition between the low and high trawling intensity areas might be a helpful tool to detect patterns that were detected and clarify the relationships with environmental variables.

4.9 Species distribution differences between high and low trawling intensities

Some species distributions showed differences between high and low trawling intensity areas. Trawling is known to create patchiness in benthic ecosystems (Kaiser et al. 2002), although spatial differences in species distributions can also be explained by depth, oxygen or other environmental factors.

Although Ophiuroids are often found in trawled areas as Tissot et al. (2006) observed, they were entirely absent from the high trawling intensity zone studied here, suggesting that there is a limit to their tolerance. *S. globosa* aggregations were mainly found in the deeper section of the transect, greater than 900m. In other studies, their abundances have been found to be higher at mid-slope depths, from 1,000-3,000m (Grassle et al. 1975, Sibuet & Segonzac 1985). Interestingly, the presence of *S.globosa* does not seem to influence the presence ophuiroids, through possible competition, as shown in Summers and Nybakken (2000). Elasipodid holothurians are opportunistic

deposit feeders often found in high density "herds" in areas rich in organic matter or close to submarine canyon systems. A possible explanation of their presence is also the low energy current flow regimes, as mentioned by Gage and Tyler (1991). Their aggregation behavior has been well documented (Billett 1991, Gutt & Piepenburg 1991) and may have some advantages for synchronized reproduction or exploitation of patchy food enrichments. Hydrographic factors that influence the deposition and concentration of organic matter are likely to be the main elements determining holothurian distribution (Billett 1991).

The echinoid *Strongylocentrotus fragilis* was concentrated in the shallower part of the transect down to 650m and was very scarce deeper than 800m. Sea whips mainly occurred in the deeper section of the transect R1074 with low trawling intensity (>1,150m), but these organisms were also found elsewhere except for the 800-1,000m depth interval where trawling intensity was most pronounced. In transect R1075, the same trend was found with a cluster of abundance in the low trawling intensity, corresponding to 340-499m. These results suggest a vulnerability to trawling. Taxa described as sea whips in this study are rigid and tall, which makes them more vulnerable to trawling than other sea pens, which are softer and shorter.

Sea pens in R1074 are concentrated at 700-1,100m and then patchy from 1,100-1,200m. The slope is a bit steeper between 700-1,000m, which may create more energy locally at the bottom. Sea pens can be indicators of a moderately high-energy seabed, have a patchy distribution, and are associated with more eutrophic conditions (Gage & Tyler 1991). A study of the recovery of a pennatulacea species showed that uprooted individuals can re-root themselves in up to 144 hours if present on a muddy substratum

and if the peduncle can be in contact with the substrate (Eno et al. 2001). This might explain their presence even in areas of high trawling intensity. In the shorter transect (R1075), a similar trend was observed, as they seem to be more clustered in the low trawling intensity area, but still present in the high trawling intensity area. This suggests that they are not as vulnerable to trawling than sea whips.

Sponges were clearly present in low trawling areas and absent from the high trawling areas in both transects, which does not come as a surprise, as they are vulnerable to bottom trawling (Collie et al. 2000a, Kaiser et al. 2000, Clark & Rowden 2009).

The main species of interest to the groundfish fisheries, *Sebastolobus* spp., had their peak density from 600m and 1300m (including the heavily trawled area). This distribution can be explained by the fact that its habitat, with muddy bottom at depths between 500 and 1600m, is where dissolved oxygen concentrations are the lowest (Jacobson & Vetter 1996).

Chapter 5

5.0 Conclusion

This study developed a quantitative method for documenting the distribution of epi-benthic communities on the upper continental slope from remotely-operated vehicle surveys conducted for another purpose. This approach, which is equally applicable to dedicated ROV surveys, involved extracting biological and environmental data from ROV video and sonar records, assembling a database and applying a suite of statistical tools to identify linkages between faunal attributes and environmental variables.

Analyses revealed differences in terms of diversity indices, total faunal abundance, and assemblage composition of the epibenthic megafauna, between high and low levels of trawling intensity. In the heavily trawled areas of transect R1074, diversity indices were slightly higher, total abundance was lower, epibenthic megafauna assemblages were distinct with more presence of sea pens, absence of sponges, and absence of dominating species aggregations. In the lightly trawled areas, corresponding to the shallower and deeper areas of the transect R1074, diversity indices were slightly lower, abundances were higher primarily because of holothurian and ophiuroid aggregations, sea whips and sponges were more present, while sea pens were rarer, and megafauna assemblages were dominated by holothurians and/or ophiuroids.

5.1 What is the ecological significance of losing faunal aggregations?

The absence of benthic faunal aggregations can have many implications for ecosystem function. If there is less biomass and activity at the sediment surface,

bioturbation and nutrient cycling will be reduced. Epi-benthic species can affect pore-water and circulation in the benthic boundary layer that can ultimately affect the community structure (Rhoads & Young 1970, Snelgrove & Butman 1994, Boudreau & Jorgensen 2001). Quantifying the importance of the presence or absence of faunal aggregations for ecological services will require comparative geochemical studies. Such studies would need to be supported by an understanding of how these aggregations form and progress across the seafloor, and then presumably disperse.

5.2 Management considerations

Hypoxia conditions impose a selective stress on the benthic ecosystem on the continental slope off Vancouver Island and oxygen-minimum zones are presumed to be low-productivity environments (Mullins et al. 1985). However, this is also a key spawning area for many commercial groundfish species such as dover sole, sablefish, and shortspine and longspine thornyhead (Hunter et al. 1990, Vetter et al. 1994). Widespread trawling activity is imposing an additional stress that appears to be eliminating faunal aggregations and causing notable changes in species composition and diversity. A desktop study of cumulative impacts of anthropogenic marine activities on the continental shelf and slope off Vancouver Island showed that 83-98% (depending on the scale or "buffer zone" chosen) of the seabed is being affected by various stressors (Ban & Alder 2008). The marine activity with the highest stress value at the scale of small and medium buffers was commercial bottom trawling, with shore-based industry (logging operations, pulp and paper mills, fish processing facilities, etc) becoming important when the larger buffer zone was considered (Ban and Alder 2008).

DFO has developed a framework for bottom trawling management. Identifying sensitive areas and vulnerable marine ecosystems are among the first steps for managing fisheries. The Ecologically and Biologically Sensitive Area (ESBA) framework is based on five criteria: uniqueness, aggregation, fitness consequences, resilience, and naturalness (DFO 2004).

In our study area, we have described the species composition, abundance and diversity of a soft-muddy bottom, low productivity, hypoxic habitat over a depth range of 300-1300m. Longspine thornyhead (*Sebastolobus altivelis)* is the main target species for trawling in this area and is adapted for these particular conditions. It plays most probably an important role in that ecosystem (COSEWIC 2007). *S. altivelis* is of special concern under the Species at Risk Act since 2009 and receives protection under the Fisheries Act. Following the beginning of the thornyhead fishery in 1996, the report mentions a 50% decline in catch per unit effort was observed after eight years and that fishing is the main and probably the only cause of this decline (COSEWIC 2007). If we are looking at the five criteria for the ESBA framework, the uniqueness factor for its habitat is the low oxygen zone on a continental slope setting. Longspine thornyheads are randomly distributed and the fitness consequences criteria should indicate that the area is highly crucial to their survival or reproduction (Jacobson & Vetter 1996). The likely extent of occurrence might be over 17,775 km^2 in British Columbia, but the observed occurrence would likely be closer to 11,700 km^2 (COSEWIC 2007). Fish species such as the thornyheads found in low productivity deep-sea habitats have a low resilience because their maturity is estimated to be at approximately 15-20 years old (25cm length) and most of the spawning occur, for both species, at a depth range between 600 and 1000m in the

OMZ (Ianelli et al. 1994, Jacobson & Vetter 1996). Some studies have shown that trawling could increase oxygen consumption and nutrient concentrations (Riemann & Hoffmann 1991, Pilskaln et al. 1998) in the water column, but impacts of trawling on oxygen levels in a deep-sea setting have not been studied.

DFO developed a management plan for the longspine thornyhead fishery to maintain sustainable populations and public consultations were opened from February to April 2012 (DFO 2011). At this stage, it is too early to know what actions will be implemented as the implementation is subject to availability of funding and other required resources. As a recommendation from this study, I would suggest taking the refugium management approach to this fishery on the continental shelf to maintain a pool of undisturbed areas to serve as a reference for monitoring the impacts and recovery of the thornyhead, and other species in their ecosystem. Because thornyheads tend to be evenly distributed (Haigh & Schnute 2003), areas would need to be large enough to protect an appropriate abundance level of the population to allow the species to reproduce and grow to renew the fishing stock and make this fishery more sustainable. The decision of the location and size of a refugium would need to be investigated using a tool such as MARXAN, allowing to make a decision based on specific criteria (Ball et al. 2009),

5.3 Scenarios and moving forward

Recovery of benthic communities from trawling is difficult to predict as the disturbances continue and vary in intensity from year to year, but some trends identified in this and other studies can be used to develop informative scenarios. If groundfish trawling intensifies on the continental slope off Vancouver Island, the most affected species will likely be the longspine thornyhead because of its biology and the specificity

of their habitat. The benthic community would tend to remain in an alternate state, not developing faunal aggregations or biogenic habitat such as sponges. If trawling decreases, a sustainable fishery might be possible at very low catch rates (Norse et al. 2012), although examples of sustainable deep-sea fisheries are rare. The benthic community would likely begin a recovery process with less frequent or more widely dispersed trawling impacts. Glass sponges and soft corals would likely recolonize the seabed under a reduced trawling scenario, as would be the case if trawling were to be eliminated altogether. If trawling intensity stays the same (since 1996) level, long term changes in community composition are unlikely, except for natural dynamics that might affect species abundances from year to year, or climate change affects on food supply to the benthos or the intensity of the OMZ. In a 'business as usual' scenario, sponges and sea whip abundances will continue to decrease through bycatch mortality and longspine thornyhead populations will have an uncertain commercial future, especially since recruitment rates and actual abundances of this species are so poorly known.

Many countries, including Canada, are now transitioning from single-species approach towards ecosystem-based management of fisheries. This approach takes into account sustainability, goals, complexity and connectedness, ecological models, the dynamic nature of an ecosystem, context and scale, human as part of the ecosystem, flexibility and responsibility (Christensen et al. 1996). Crowder et al (2008) stated that impacts of bycatch, artisanal or recreational, and environmental change should be taken into account and suggested a flexible model focused on food-web interrelations allowing to add complexity as data become accessible. The study presented here provides new information on the occurrence of species, abundance and diversity variability, and

community structure on the continental slope off Vancouver Island, and thereby is a first important step towards understanding the complexity and dynamics of this deep-sea assemblage, and developing an ecosystem-based management framework for the area. Although, there is a mixture of recolonizing assemblages, virgin assemblages and survivor assemblages, there is a great opportunity to study how these ecosystems will change after fishing closures.

A recent partnership has been developed involving Living Ocean Society, David Suzuki Foundation, DFO, and Canadian Groundfish Research and Conservation Society (LivingOceanSociety 2012). This partnership includes measures reducing the footprint of bottom-trawling implemented by DFO through the integrated fisheries management plan. It includes a 65% footprint reduction in the 800m-1,400m depth range and 18% reduction in the 200m-800m depth range. As of April 2012, I did not have the exact locations of these fishing closures.

5.4 Future survey design and recommendations

Dissolved oxygen levels and species aggregations seem to have an important role in this ecosystem. In order to pursue this topic further, a future survey would need to focus between 550m and 1,200m depth on the continental slope, which corresponds to the location just before and after the ophiuroids abundance peaks found in 2007. It would be interesting to have a video transect in that depth range with a CTD profile at the bottom and install sediment traps from the boundaries to the oxygen minimum core to study the difference in the organic matter input at different oxygen levels. A scanning-sonar would be important as well to quantify trawling intensity.

There is probably no need to do a transect as long as 30km, as the species accumulation curve (Figure 51) showed that most of the new species counted were found after approximately 10km of transect. Although, this decision can vary depending on the objectives of the research and questions being asked. As for the video analysis, it is important to capture the abundance peaks around the core of the oxygen minimum zone and the change between zones of high/low trawling areas.

The CTD data and scanning-sonar for trawling intensity would help determine the length of each sub-transect to analyze. For example, one could analyze 200m length of transect and document all species found, then skip the next 100m if this is not in the transition zone of trawling intensity or at the boundaries of the oxygen minimum core zone. This should allow detecting changes in abundance levels and species composition.

Using the new PCNM statistical tool will help detecting changes in the community structure and differentiate which environmental variables are associated with these changes. *In situ* oxygen levels are crucial to be able to associate changes in the community attributed to oxygen and understand how strongly oxygen and trawling intensity are influencing the community structure. This information will help to understand how bottom trawling influence oxygen levels and achieve a more complete understanding of the impacts under these conditions.

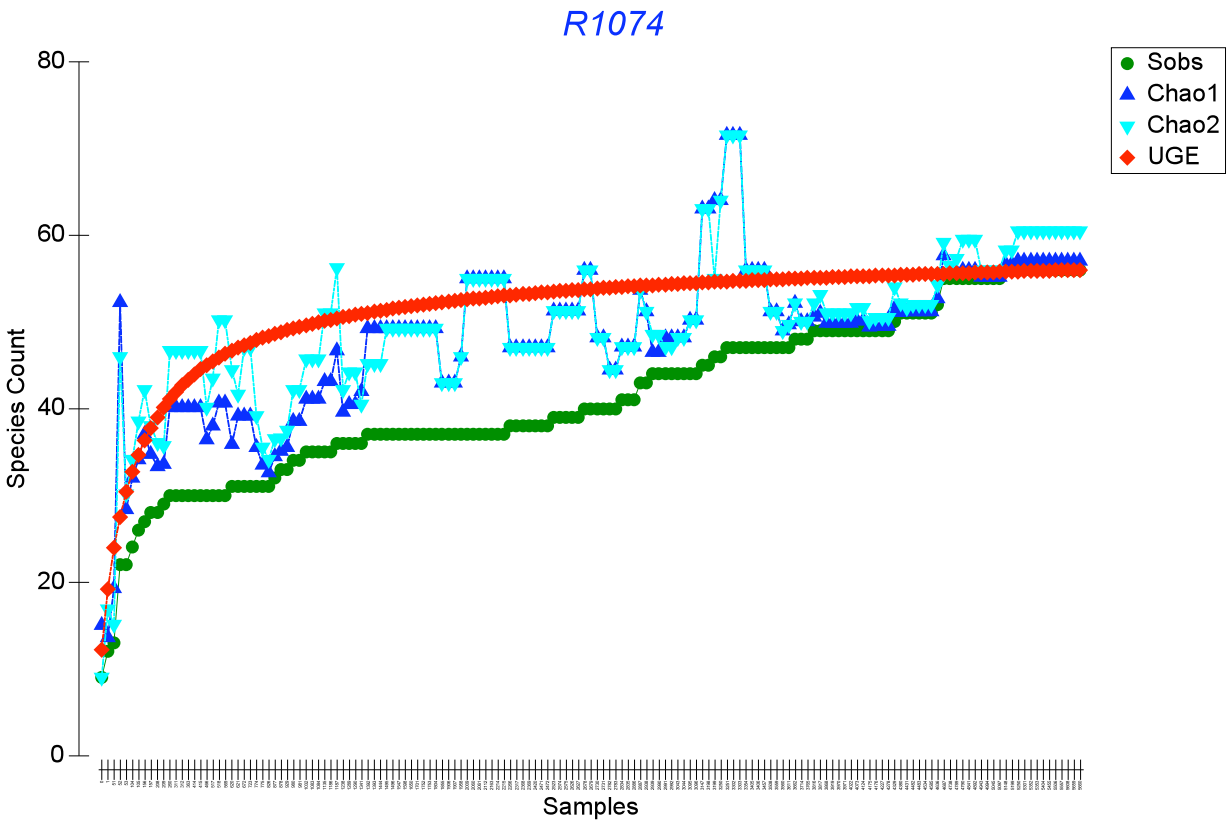


Figure 51: Species accumulation curve using PRIMER-E software. Each sample correspond to approximately 250m distance along the transect. It shows that most species identified happened in the first 10km.

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