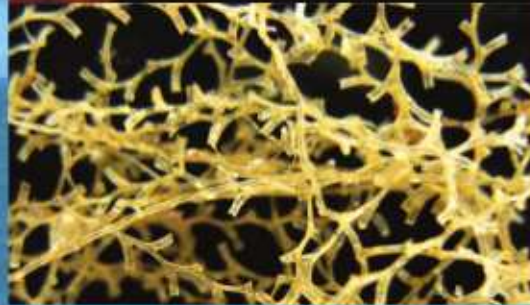




Australian Government  
Department of the Environment  
Australian Antarctic Division



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DEMERSAL FISHING INTERACTIONS WITH  
MARINE BENTHOS IN THE AUSTRALIAN EEZ  
OF THE SOUTHERN OCEAN

AN ASSESSMENT OF THE VULNERABILITY  
OF BENTHIC HABITATS TO IMPACT  
BY DEMERSAL GEARS

**FINAL REPORT**  
**FRDC project 2006/042**  
June 2014

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**Demersal fishing interactions with marine benthos in the  
Australian EEZ of the southern ocean:**

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impact by demersal gears**

FINAL REPORT FRDC PROJECT 2006/042

2014

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The Department of the Environment, Australian Antarctic Division and the  
Fisheries Research and Development Corporation



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2006/042 Demersal fishing interactions with marine benthos in the Australian EEZ of the Southern Ocean: An assessment of the vulnerability of benthic habitats to impact by demersal gears

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### Objectives

1. To develop deep-sea camera technologies that can be easily deployed during fishing operations, to facilitate widespread observations of demersal fishing activities (trawl, longline and trap) and their interactions with benthic environments.
2. To assess the vulnerability of benthic communities in Subantarctic (Australian AFZ) and high latitude areas of the Southern Ocean (Australian EEZ) to demersal fishing using trawls, longlines or traps, using video and still camera technologies.
3. To assess the risk of demersal fishing to long-term sustainability of benthic communities in these areas, based on the assessment of vulnerability and information from the literature on potential recovery of benthic species and habitats.
4. To recommend mitigation strategies by avoidance or gear modification, where identified to be needed, and practical guidelines to minimise fishing impacts on benthic communities.

## Non-Technical Summary

Australia's domestic legislation and obligations under international agreements such as the Convention for the Conservation of Antarctic Marine living Resources (CCAMLR) requires that Australia's fishing activities in the Subantarctic and Antarctic Southern Ocean avoids unsustainable impacts to the ecosystem and biodiversity. As Australia uses bottom fishing methods, including demersal trawls and longlines to target Patagonian toothfish and mackerel icefish in this region there is the potential to impact upon benthic habitats. However, understanding the scale of disturbance caused by Australia's bottom fishing activities in the deep Southern Ocean is hampered by a paucity of data, theory and procedures. This project set out to address these issues by developing tools to allow such an assessment, with a focus on the fishery that has operating since 1997 targeting Patagonian toothfish and mackerel icefish in the EEZ around Heard Island and the McDonald Islands (HIMI).

A significant output of this project was the development of a versatile camera system which was successfully deployed on trawls and longlines during commercial and research fishing activities in the EEZ at HIMI, BANZARE Bank and East Antarctica. It revealed for the first time the *in situ* nature and extent of demersal longline interactions in the deep ocean, as well as revealing the types of habitats and organisms on the seafloor where fishing takes place. This information, combined with comprehensive effort data from the fishery and scientific sampling of the types and abundance of organisms living on the seafloor across a range of depths and seafloor features, enabled the development of an assessment model to estimate the amount of disturbance caused by the fishery.

This assessment indicates that the great majority of vulnerable organisms live on the seafloor in depths less than 1200 m. This range overlaps with the depths targeted by the trawl fishery, and to a lesser extent by the longline fishery. However due to the fact that the majority of trawling has focussed on a few relatively small fishing grounds, less than 1.5% of all the biomass in waters less than 1200 m are estimated to have been damaged or destroyed. Furthermore, the HIMI Marine Reserve, established in 2003, is estimated to contain over 40% of the biomass of the groups of benthic organisms considered as most vulnerable to bottom fishing at HIMI. Overall, an estimated 0.7% of the seafloor area within the EEZ at HIMI has had some level of interaction with bottom fishing gear between 1997 and 2013.

The results of this project provide a process for assessing the levels of disturbance by bottom fishing which complements the existing processes that have been developed recently to conduct the Ecological Risk Assessment for the Effects of Fishing (ERA-EF) in other Commonwealth fisheries, as well as measures being developed by CCAMLR to avoid significant adverse impacts to vulnerable marine ecosystems.

**Keywords**

Bottom fishing, benthic invertebrates, impact assessment, risk assessment, Heard Island and McDonald Islands, Southern Ocean

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## **Glossary**

As a field of research develops there is often a proliferation of new and/or appropriation of existing terms to describe the important objects and processes involved. There is also frequently a desire to define these terms. Striking a balance in these definitions, so they are not so broad as to be ambiguous, or so constrained as to be only applicable in a few narrow instances can be difficult. In this report we have tried to avoid coining new terms where possible. Where we use a term that is new or may have multiple meanings, we have tried to make it as clear as possible, through the sense in which it is used and its context as to what we intend by its use, and have tried to be consistent in our use of these terms throughout this report. The following is a list of terms that are used many times throughout the report, and therefore we consider them worthy of expanding on here.

**Assemblage** Organisms that occur at the same location. We have chosen to describe groups of organisms sampled in this study as an assemblage, rather than communities or some other ecological grouping, as these imply that these organisms interact. While it is likely that the organisms in an assemblage do interact, we do not know the nature of these interactions for the majority of deep-sea organisms discussed in this report.

**Benthos** The collective name given to the seafloor and the organisms living in or on it. The adjective for an object, organism or process associated with the benthos is described as benthic.

**Disturbance** A discrete event that disrupts the physical, biological or ecological processes occurring at a location. Disturbance could be caused by humans, such as cutting down a forest or a 'natural' event such as an earthquake or a disease epidemic. Disturbances may also vary in their spatial and/or temporal scales.

**Fishing footprint** The area of the seafloor that is likely to have had one or more interactions with fishing gear.

**Habitat** A place in the environment where particular organisms can live. Habitats can be formed by organisms, for example reefs formed by corals create places for other organisms to live.

**Impact** The longer term and/or wider consequences of a disturbance or a number of disturbances on biological and ecological processes. Any disturbance is likely to have some impact; however the scale of consequences will vary, as will the imperative for a management intervention where there is need to mitigate the risk of an impact reaching an unacceptable level.

**Mortality** Death; permanent cessation of the biological processes performed by an organism when alive.

**Resilience** A property of a thing that makes it more or less able to recover to its pre-disturbed state after it has been disturbed.

**Seascape** The marine domain across encompassing the physical and biological environment and fisheries activities across which an assessment is applied.

**Status** A summary of the state of the seascape at a point in time (e.g. after disturbance by fishing) with reference to its undisturbed state; e.g. 90% of unfished biomass of a taxon remains after 10 years of fishing.

**Structure-forming benthic taxa** Organisms that live on the seafloor that increase the amount of structure present relative to the substrate. For example branching corals growing on a flat rock seafloor can be considered structure forming. Such structure can also form habitats for other organism, and hence can be important for the productivity and diversity of the benthos.

**Vulnerability** Related to resistance; a property of a thing that makes it more likely to be changed by a disturbance in the short term. In our report, we consider that vulnerability is not a universal property of a thing, but can only be considered with respect to a particular disturbance. For example a wooden house may not be changed consequentially by rain falling on it, but may be by fire, and therefore could be considered vulnerable to fire but not to rain.

## **Background<sup>1</sup>**

### **The Heard Island and McDonald Islands fishery**

Demersal fishing comprises a large proportion of Australian fisheries activities, both domestically and internationally, with the impacts of demersal fishing receiving increasing attention in Australia and globally. The Heard Island and McDonald Islands fisheries (HIMI) fishery comprise demersal fishing (trawl, longlining and traps) targeting Patagonian toothfish (*Dissostichus eleginoides*) and demersal and pelagic trawling for mackerel icefish (*Champtocephalus gunnari*). The fishery has been in operation since 1997 when the exploratory fishery commenced (EA, 2002). Demersal longlining was introduced in 2003, but prior to this project no work had been undertaken on the degree to which such fishing poses a threat to benthic habitats. Demersal trapping has also been used to a limited extent in the region since late 2005. Also, there have been a number of proposals by Australian fishers to further develop their distant water fishing capability with longlines in the waters of the Exclusive Economic Zone (EEZ) off the Australian Antarctic Territory in East Antarctica. The HIMI fisheries represent a substantial value to the Australian economy, with its export value likely to be in excess of \$40 million per annum (e.g. Catarci 2004).

### **Relevance of this project**

An analysis, therefore, is needed to evaluate whether the performance of the HIMI Marine Reserve and management strategies outside the Marine Reserve are sufficient to ensure conservation of benthic habitats in the HIMI area. Such work is also pertinent to considering whether the existing Conservation Zone at HIMI needs to be included within the marine reserve for providing protection of vulnerable habitats or for inclusion in the National Representative System of Marine Protected Areas.

Therefore studies of the interactions of demersal fishing gears (trawls, longlines and traps) with the benthic environment are needed to assess whether special management or mitigation measures are required for these fishing gears in order to conserve benthic habitats. To date, direct assessment of these interactions through deployment of cameras on fishing gear has occurred only in well controlled experiments on trawls and mostly outside Australia. This project was designed to produce the necessary technology and applications in order to demonstrate the nature of demersal fishing interactions (trawls, longlines and traps) with benthic habitats and species during commercial fishing operations in Australia. The technology was developed for easy deployment by observers on commercial vessels during normal operations without the need for intrusive hardware or difficult protocols on the vessels.

With respect to the HIMI Marine Reserve, these technologies will be used in areas where habitats and macrofauna are not well understood. An outstanding question in

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<sup>1</sup> First part is taken as required from the original proposal in 2006

the original analysis that led to the establishment of the HIMI Marine Reserve for the region was to what degree measures are needed to conserve deep-water benthic habitats in the face of direct anthropogenic impacts. This project will provide understanding as to the degree to which the existing marine reserve is comprehensive, adequate and representative of the region.

This project will assess the degree to which demersal gears interact with and possibly damage benthic habitats. It will also assess the degree to which these habitats might be damaged within the Australian Fishing Zone (AFZ) in the HIMI region. The project is not intended to estimate rates of recovery of benthic habitats following damage by demersal gears. However, information from the literature on rates of recovery of different benthic species and habitats will be used to assess the risks of long-term sustainability of these habitats. Overall, this work will contribute to an evaluation of the potential impacts of longline, trap and trawl fishing on benthic communities in the HIMI region, which is currently a priority area of research identified by Environment Australia in its strategic assessment of HIMI fisheries (EA, 2002) and a proposed outcome of the 2003 Bycatch Action Plan for Antarctic Fisheries (AFMA, 2003). The commercial-in-confidence report on the “Effects of Longlining” considered by the Subantarctic Fisheries Management Advisory Committee (SouthMAC) and the Subantarctic Resource Assessment Group (SARAG) in May 2005 highlighted the limited data available and subsequent uncertainty persisting in regard to the impacts of longlining on marine benthos in the HIMI fishery and other demersal longline fisheries worldwide. This report has identified further research into the impacts of longlining as a high priority for the HIMI fishery (SouthMAC, 2005). In addition, a recommendation of the Marine Stewardship Council (MSC) for certifying the mackerel icefish fishery is to show the MSC that appropriate work will be undertaken to confirm that the fishery poses a low risk to benthic communities.

The trialling of trap fishing techniques that has recently commenced for the HIMI fishery also requires an evaluation of vulnerability of and potential impacts on benthic communities before recommendations can be made on the sustainability of this fishing practice for the region’s marine resources and environments (SouthMAC, 2005).

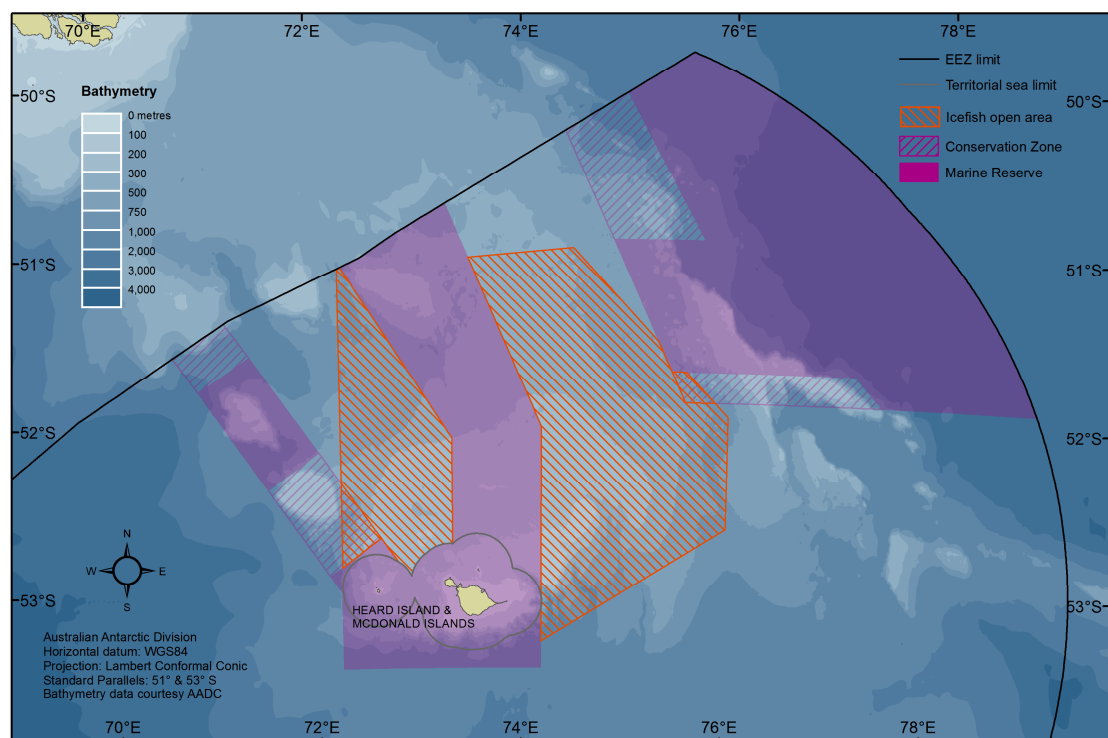
The project will inform management strategies to ensure the sustainability of demersal fishing practices in the Australian EEZ, including strategies that might assist in mitigating benthic impacts and improve the sustainability of natural marine resources in the Southern Ocean (meets FRDC Strategic Challenge 1 - Improve the sustainability of natural resources supporting wild-catch and aquaculture). The replication of sampling strategies in high latitude areas will determine the transferability of the sampling techniques and technologies developed to other locations and fisheries. The transferability of outputs will enable comparisons to be made between marine habitats



and fisheries in areas north and south of the Antarctic convergence as well as other cold and deep water fisheries.

### Recent developments in Australia's Southern Ocean fisheries

As noted above, a key element of the management strategy for mitigating the impact of bottom fishing in Australia's Southern Ocean fisheries are the extensive marine reserves established around HIMI and Macquarie Island. The HIMI Marine Reserve was established in 2003 and includes 64 000 km<sup>2</sup> of area classified as no-take (Welsford *et al.* 2011), as well as four areas making up a Conservation Zone (Figure 1). No additional regulations relating to conserving benthic biodiversity have been implemented by Australia since the commencement of this project in 2007. However, a process to review the status of benthic biodiversity in the Conservation Zone adjacent to the Marine Reserve has progressed since 2006, utilising datasets collected during this project (Hibberd *et al.* 2009). This has resulted in the identification of highly diverse assemblages in parts of the Conservation Zone, in particular, areas with high densities of benthic invertebrates or high levels of endemic taxa leading to the recommendation that these areas be added to the Marine Reserve.



**Figure 1. The Australian EEZ at Heard Island and McDonald Islands, showing arrangements constraining bottom fishing activities, including the no-take Marine Reserve, Conservation Zone and the area open to trawling for mackerel icefish. Note no commercial trawling has occurred in the Conservation Zone since it was established with the Marine Reserve in 2003.**

Since 2007, the dominance of Australian bottom fisheries activity in the subantarctic and Antarctic has changed from bottom trawling to longlining for Patagonian toothfish (Patterson & Skirtun 2012a, Patterson & Skirtun 2012b, SC-CAMLR 2012a). The Macquarie Island toothfish fishery has become exclusively a longline fishery, following experimental longlining in 2007-2010 seasons (Patterson & Skirtun 2012a). Similarly, longline toothfish catches at HIMI have grown since the experimental phase (2003-2007) to exceed trawl catches in 2010 (Table 1). Potting has been trialled several times over this period, but has not contributed significantly to commercial catches. Fishing for mackerel icefish has been relatively limited due to a combination of variable stock abundance and operational difficulties. It is expected that 2013/14 will be the last season that commercial trawling is a regular feature of the HIMI fishery with the planned retirement of the FV *Southern Champion*.

**Table 1. Bottom fishing catch in the Heard Island and McDonald Islands fisheries. Seasons run from 1 December to the 30 November in the following year. Note that the figures for mackerel icefish exclude catch and effort using midwater gear.**

Season	Patagonian Toothfish			Mackerel Icefish
	Trawl (t)	Longline (t)	Pots (t)	Trawl (t)
1996/97	1927	-	-	29
1997/98	3765	-	-	87
1998/99	3547	-	-	2
1999/00	3566	-	-	137
2000/01	2980	-	-	1098
2001/02	2756	-	-	703
2002/03	2574	270	-	2332
2003/04	2296	567	-	77
2004/05	2122	621	-	1154
2005/06	1801	659	68	359
2006/07	1787	601	-	1
2007/08	1445	835	-	193
2008/09	1287	1168	10	94
2009/10	1215	1213	30	362
2010/11	1148	1383	34	1
2011/12	1361	1356	-	4
2012/13	556	2123	39	644

Fishing by Australian vessels outside of Australia's subantarctic EEZs has also been minimal over this period. With the exception of a research longline survey by the FV *Janas* in 2008 on BANZARE Bank (Welsford *et al.* 2008), no Australian vessels have fished in the CCAMLR exploratory toothfish fisheries in the Australian EEZ along the coast of East Antarctica, or elsewhere in the CCAMLR Convention area.

### **Recent developments in conserving Southern Ocean benthic biodiversity**

Concurrent with the development of the proposal of this project, the international community has also been responding to the potential for demersal fishing to cause unsustainable damage to the organisms that live on the seafloor and form habitats for other species.

In 2006, the United Nations General Assembly passed resolution 105/61 which:

*“Calls upon States to take action immediately, individually and through regional fisheries management organizations and arrangements, and consistent with the precautionary approach and ecosystem approaches, to sustainably manage fish stocks and protect vulnerable marine ecosystems, including seamounts, hydrothermal vents and cold water corals, from destructive fishing practices, recognizing the immense importance and value of deep-sea ecosystems and the biodiversity they contain” (UNGA 2007)*

In response to this resolution, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the body responsible for managing fishing activities in the Southern Ocean, committed to avoiding significant adverse impacts on vulnerable marine ecosystems (VMEs) and has subsequently conducted technical workshops to develop methods to assess the impact of bottom fishing in the Southern Ocean, and develop management measures to maximise the likelihood that the UNGA resolution will be achieved (e.g. CCAMLR 2008, Constable & Holt 2007, SC-CAMLR 2009, SC-CAMLR 2012b). These include a suite of Conservation Measures aimed at assessing likely bottom fishing impacts, restricting destructive fishing practices and requiring CCAMLR Members to report evidence of VMEs encountered in the course of fishing or research activities (CCAMLR 2012a) (Table 2).

**Table 2. Summary of Conservation Measures implemented by CCAMLR to mitigate the impact of bottom fishing in the Southern Ocean.**

Conservation Measure	Year first adopted	Effect
22-05	2008	Prohibits bottom trawling outside of areas with existing bottom trawling regulations.
22-06	2009	Requires Members to provide information on known or anticipated impact of their bottom fishing activities, and the locations of VMEs, and provides the Commission with ability to limit bottom fishing activities to avoid significant adverse impact to VMEs
22-07	2009	Requires Members to report bycatch of VME indicator species, and provides for the designation and closing of Risk Areas where large amounts of bycatch have been recorded.
22-08	2009	Prevents exploratory bottom fishing activities in exploratory fisheries in waters less than 550m.
22-09	2011	Provides for registration and protection of VMEs identified in the CCAMLR area

During this period, CCAMLR has also been working towards the implementation of a representative system of Marine Protected Areas to address a range of objectives including conserving benthic biodiversity, providing refugia for species as they respond to climate change, and to better understand and distinguish the effects of fishing and climate change on the ecosystem. In 2009, the first CCAMLR Marine Protected Area was established on the shelf south of the South Orkney Islands, and proposals for East Antarctica and in the Ross Sea are currently being considered (CCAMLR 2012b).

## **Need<sup>2</sup>**

This project was designed to address policy objectives identified under Australia's Fisheries Management Act (FMA, 1991) and the Environmental Protection and Biodiversity Conservation Act (EPBC, 1999) relating to long-term ecological sustainability of marine resources and environments in the Australian Fishing Zone (AFZ). It also addresses the need to identify impacts of fishing activities on target and non-target species (FMA, 1991, Section 3, Part 1b) and how potential impacts might be mitigated to ensure the continued ecological viability of natural marine resources including benthic habitats in the Australian Exclusive Economic Zone (EEZ) (EA, 2002). As such, the project proposal specifically addresses objectives relevant to the strategic assessment of the HIMI fishery (EA 2002) and is also directly relevant to Program 2 (ecosystem-based fisheries management) outlined in AFMA's strategic research plan, to base management decisions on a knowledge of impacts on fisheries ecosystems and minimize impacts arising from fishing activities (AFMA 2005). The project was also designed to provide information that will help satisfy the requirements of the Marine Stewardship Council (MSC) for certifying the mackerel icefish<sup>3</sup> and Patagonian toothfish<sup>4</sup> fisheries at Heard Island and McDonald Islands (HIMI). These requirements include undertaking an assessment of risks to benthic systems and identifying a strategy to mitigate moderate to high risks. The outputs are also intended to be used to help understand the role and adequacy of the HIMI Marine Reserve and Conservation Zones.

The ecological assessment of fishery impacts in the Southern Ocean has also been identified by SARAG as a priority research area (SouthMAC 2005). The project addresses three priority projects identified in 2005 as part of the ecological assessment of the fishery research plan, which were:

- The effects of trawling on benthic ecosystems in the HIMI region,
- The effects of longline fishing on benthic ecosystems, and
- The effects of trap fishing on benthic ecosystems.

This project was developed as a collaborative initiative between the Australian Antarctic Division (AAD), the Australian Fisheries Management Authority (AFMA), industry and research partners. It has been undertaken in order to resolve outstanding questions relating to the potential impacts and sustainability of demersal fishing practices in the AFZ at Heard Island and the McDonald Islands (HIMI). It is also intended to help resolve similar outstanding questions for other fisheries in the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) in

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<sup>2</sup> Taken as required from the original proposal in 2006

<sup>3</sup> First certified in 2006

<sup>4</sup> Certified in 2012

which Australian industry participates and provide technology for use in other fisheries to address similar questions.

## **Objectives**

1. To develop deep-sea camera technologies that can be easily deployed during fishing operations, to facilitate widespread observations of demersal fishing activities (trawl, longline and trap) and their interactions with benthic environments.
2. To assess the vulnerability of benthic communities in Subantarctic (Australian AFZ) and high latitude areas of the Southern Ocean (Australian EEZ) to demersal fishing using trawls, longlines or traps, using video and still camera technologies.
3. To assess the risk of demersal fishing to long-term sustainability of benthic communities in these areas, based on the assessment of vulnerability and information from the literature on potential recovery of benthic species and habitats.
4. To recommend mitigation strategies by avoidance or gear modification, where identified to be needed, and practical guidelines to minimise fishing impacts on benthic communities.

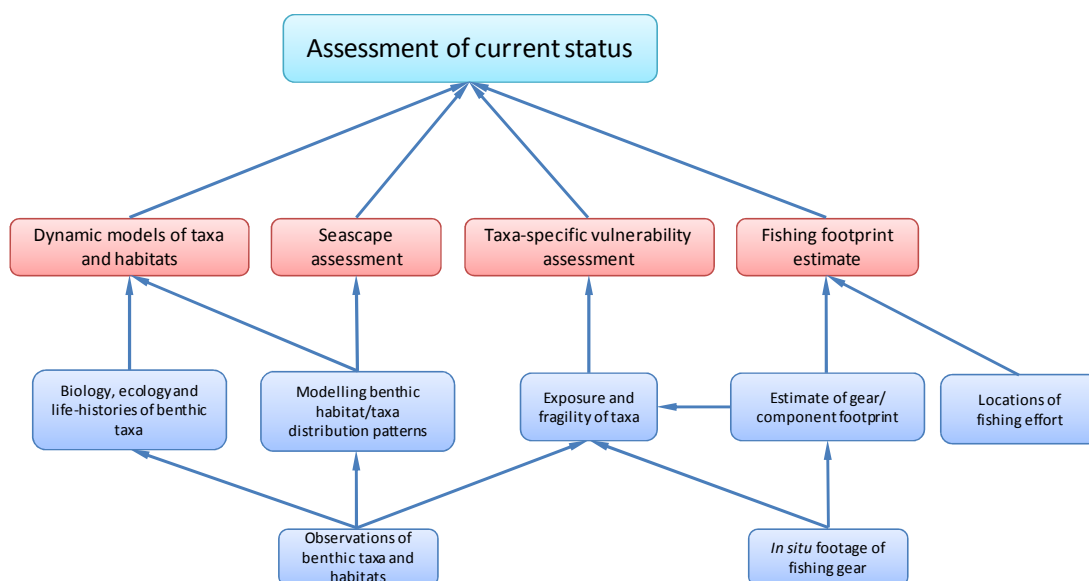
## Methods

### Assessment methodology

To evaluate the risk that demersal fishing is having an unsustainable impact on the structure and function of benthic habitats and biodiversity, the following components are required:

- Assessment of the fishing footprint including what fishing gear and gear components interact with the seafloor, where this occurs, how often and the degree of interaction,
- Assessment of the seascape where fishing has occurred and/or may occur in the future, including what types of organisms may occur there and be exposed to interactions with fishing gear,
- Assessment of the taxon-specific vulnerabilities taking into account key differences in taxa such as their ability to avoid interactions, or be damaged or killed if contacted by the different components of fishing gear, such as their body composition and brittleness, and
- Assessment of the dynamics of benthic taxa and the habitats they form, including natural mortality, recruitment, growth and other processes that may allow recovery after damage

The assessment of status at any location then derives from what quantities of benthic taxa occur there, the extent to which fishing gear has interacted with that location, and what mortality and sub-lethal damage may have occurred as a result. The components of such an assessment can be represented as a workflow, which forms the structure of this report (Figure 2).



**Figure 2. The components of an assessment of the current status of benthic habitats detailed in this report.**



Addressing all of these components in a comprehensive way is likely to be beyond the scope of any single study, particularly in a region as large and remote as the Southern Ocean, and where studies of the impacts of demersal fishing are a relatively recent development.

Despite these challenges, we have endeavoured to address the problem in a theoretical manner, which enables these components and tools to be readily generalised for any bottom fishery, as well as providing an assessment at HIMI which is the focus of the great majority of Australian fishing activity in the Southern Ocean. We also recognise that, for any given fishery, not all details may be necessary to achieve successful conservation outcomes. We have written this report in such a way that the necessary components for an assessment are readily identifiable, and the decisions made about the data and/or models required are explicit, so that the results presented here can be interpreted in that light, as well as facilitating adapting these approaches to assessments in other seascapes.

Due to the potentially unwieldy volume of technical details included in these analyses, we have chosen to provide a summary of methods and key results here, and provide more details in a series of papers appended to this report, as well as providing supplementary information on a DVD included with the report. Tables and figures in the main report are numbered conventionally while those in the appendices include a prefix identifying which appendix they are in e.g. Table A9.9 is the ninth table in Appendix 9.

### **Biology, ecology and life histories of benthic taxa**

There are very few studies of taxa in the Southern Ocean that enable a determination of their relative vulnerability to damage from demersal trawling, or their ability to recover or recolonise an area after being killed. Consequently a review was conducted of life-history characteristics, including growth rate, age, maximum size and reproductive parameters, that are related to the resistance and resilience of deep-sea invertebrates from groups known to occur in the Southern Ocean.

Data on life-history characteristics was sourced from scientific journal articles and technical reports, and summarized in a database. A full listing of literature scrutinised, and the database is included in the supplementary materials. Data on physical and chemical parameters were also obtained from the World Oceans Atlas. Bivariate correlations were then performed amongst life-history and physico-chemical data to determine if a consistent relationship existed which could then be used to predict the likely characteristics of Southern Ocean taxa. These analyses are detailed in Appendix 3.

### **Observations of benthic habitats and taxa**

Understanding the types of structure-forming sessile taxa present in the areas where fishing occurs is a key step in assessing their relative vulnerability to damage by fishing

gears. In this project the methods used to provide this information included cameras attached to fishing gear from commercial fishing vessels, drop cameras deployed from a research vessel, cameras attached to scientific beam trawls and samples collected in beam trawls and benthic sleds.

The project team developed the Benthic Impacts Camera System (BICS) that for the first time could be attached to non-rigid fishing gears such as longlines, allowing direct observations of the habitats where commercial fishing occurs. It was successfully deployed in several locations from commercial trawls and longlines at HIMI and on BANZARE Bank. Its development and specifications are described in Appendix 4. Training videos for the camera system and footage captured from deployments are included on the supplementary materials.

As cameras become less expensive, more compact and simpler to operate, they have great potential for rapidly characterising the types of taxa and habitats present where fishing occurs. Differences in assessments of benthic habitats and taxa may arise depending on the type of camera equipment used, such as when comparing results from video cameras used in the BICS system to towed sampling gear or high resolution still cameras. The project team compared these three methods using observations acquired in a range of habitats during a research voyage to East Antarctica. This analysis is described in Appendix 5.

The project team collated and sorted beam trawl and benthic sled samples from aboard the FV *Southern Champion* at HIMI to characterise the range of benthic invertebrate taxa and assemblages present in the region. Over 150 samples were collected across a broad range of locations, topographies and depths, and analysed to determine levels of diversity, spatial distribution patterns and levels of endemism. This analysis is described in Appendix 6. This information was used to develop a field guide to the benthic invertebrates at HIMI for use by observers aboard fishing vessels (Hibberd & Moore 2009) and is provided in electronic format among the supplementary materials.

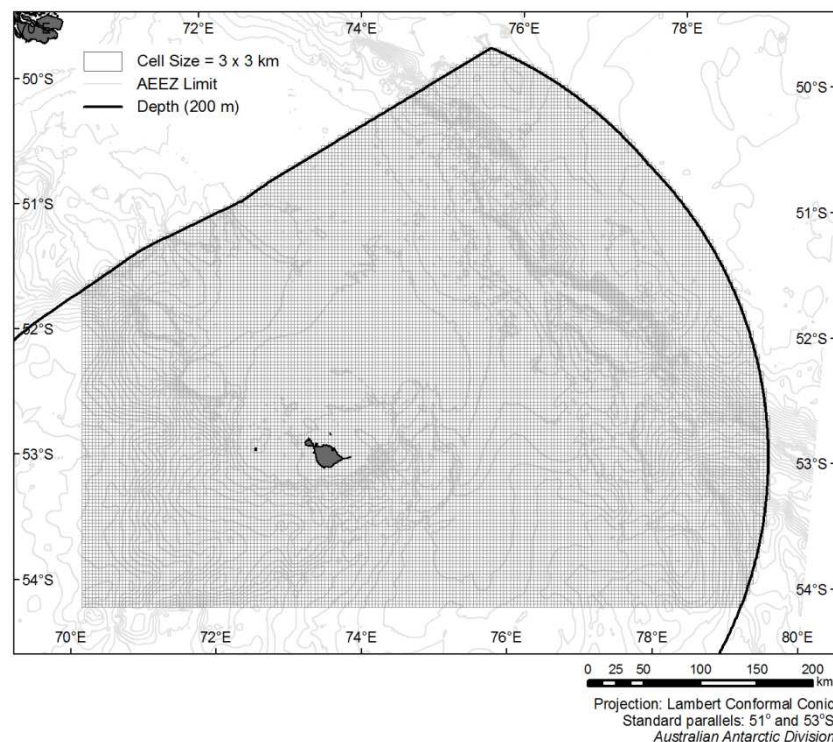
Beam trawl samples, video and camera stills of the benthos were also collected on a research voyage by the RV *Aurora Australis* to East Antarctica in the vicinity of the Shackleton Iceshelf. The analysis of these samples is detailed in Appendix 12.

### **Modelling benthic habitat and taxa distributions**

Generalised additive models were used to characterise the relationships between geophysical parameters such as depth, slope and geomorph type (e.g. bank top, bank slope, plateau etc.) based on the samples collected at HIMI described in Appendix 6, and the observations of the seafloor from the BICS. Where sufficiently well characterised relationships were found, generalised linear models were used to predict density distributions of the biomass of these taxa over a 3 x 3 km grid across the entire seascape where fishing occurs at HIMI (Figure 3).

### ***In situ* footage of fishing gear**

The BICS system was also used during deployment and retrieval of fishing gear to provide unique insights into the nature and extent of interactions between the separate components of trawl gear (footline, sweeps and trawl doors) and demersal longlines (anchors, mainline and hooks). Experimental longline deployments with cameras attached were also conducted from the RV *Aurora Australis*. A description of how *in situ* observations of gear interactions with benthos were compiled, and how this data was combined with geometric analyses to infer the types of forces exerted by each component of demersal fishing gear is described in Appendix 10.



**Figure 3. Map of the HIMI region, showing the area where distribution and abundance of taxa were modelled down to 1200 m, encompassing all scientific sampling, gridded into 3x3 km cells.**

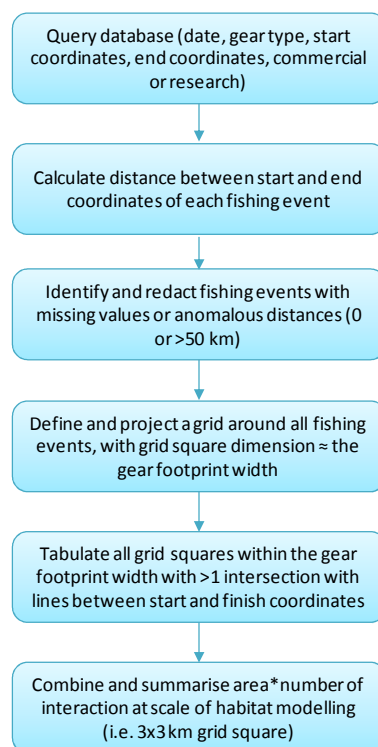
### **Locations of fishing effort**

Comprehensive data on fishing effort has been collected from all of Australian fishing activities in the Southern Ocean since it commenced in the 1990s. These data are held by the AAD and therefore were readily available for analysis by the project team. However, due to the small number of operators in the HIMI fishery, and the potential misuse of high resolution effort data by illegal fishers, under Australian legislation this data can only be presented in summary form. This data was a key input into the characterisation of the fishing footprint at HIMI described in Appendix 11.

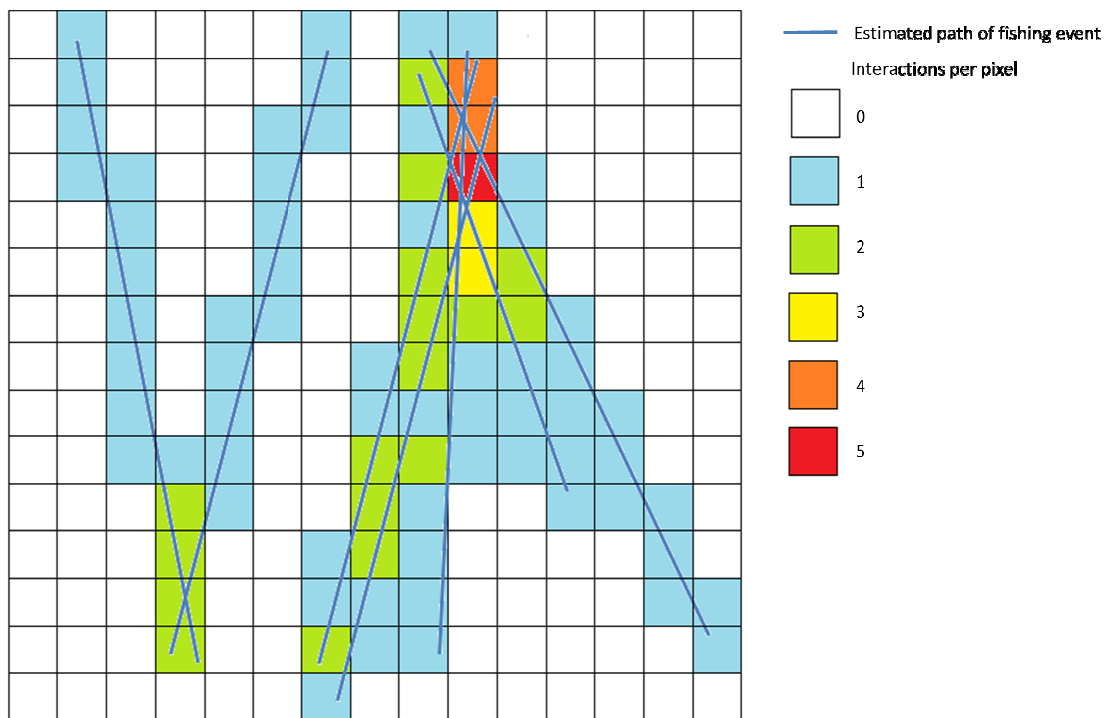
### Fishery footprint estimate

The HIMI fishery has been multi-gear throughout most of its history. Therefore, specific locations have the potential to be exposed to different interactions from gear components of trawls, longlines or pots. We have concentrated on trawling and longlining because of the relatively limited use of pots since the project commenced.

Spatial location and cumulative fishing effort of all demersal fishing at HIMI up to 2013 was calculated, and then summarised across the same 3 x 3 km grid as habitat modelling (Figure 4), taking into account overlapping fishing events (Figure 5). The different forces exerted by different gear components (Appendix 10) were differentiated in this assessment of the fishing footprint. These methods are detailed in Appendix 11.



**Figure 4. Key steps in the method to calculate the location and area affected by the multi-gear fishing footprint at HIMI.**



**Figure 5. Illustration of the method of calculating number of interactions per pixel based on intersections with the estimated path of fishing events, for a hypothetical location with seven fishing events. Note the pixel size approximates that of the gear specific footprint, i.e. ~10m for longline, or ~100-160m for the different trawl gear configurations used at HIMI (see Appendices 10 and 11).**

### Exposure and fragility of taxa

Demersal fishing gears such as trawls or integrated weight longlines are designed to be in contact with the seafloor when fishing. Consequently, we assumed that all sessile benthic invertebrates are exposed to interactions with this gear; if fishing effort overlaps with the area of seafloor where those organisms reside, they were regarded to have a very high probability of interacting with that fishing gear. This is also the case for certain other motile invertebrates that are large or have many arms or spines that make entanglement likely, such as some echinoderms. In this study we identified a range of taxa likely to be exposed to fishing gear at HIMI from those taxa most common in bycatch or video footage, as well as those present in scientific samples. These taxa included all groups identified by CCAMLR as habitat forming (SC-CAMLR 2009) that are known to occur at HIMI.

The relative fragility of these taxa was estimated using published data, preserved and fresh specimens, and footage of *in situ* interactions. A model was developed to enable the estimation of the cumulative probability of death, sub-lethal damage or remaining unscathed after exposure to different components of fishing gear, including trawls, the mainline of longlines and longline hooks, all of which have the potential to have

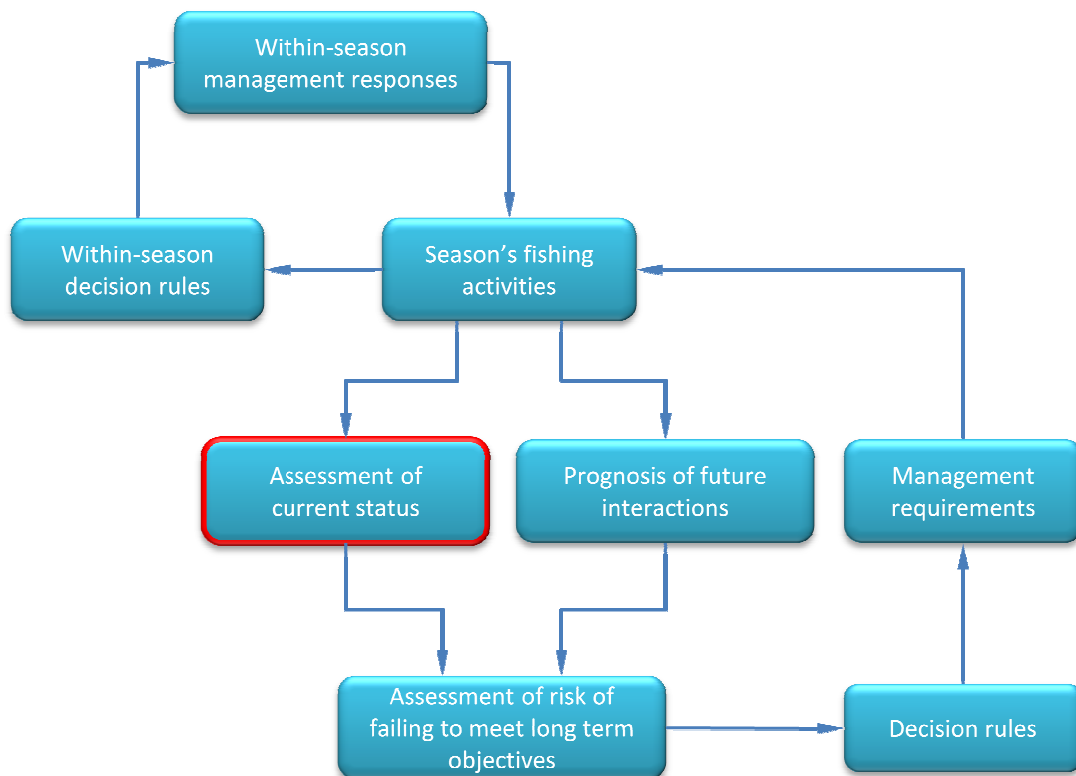
different effects on different morphologies of taxa. This analysis is presented in Appendix 13.

### **Management strategy evaluation**

An assessment of the current status of benthic habitats will ultimately need to include the assessment of interactions within the fishing along with the potential for recovery of the different taxa, taking account of errors and uncertainties in these models. Combined, these will provide an assessment of risk of the current fishing activities to benthic assemblages. A management strategy will include the management response to the results of this assessment along with the prognoses for future status of the benthic system under the expected fishing regime. Hence the assessment components shown above (Figure 2) can be seen as nested within a generic management strategy, similar to that articulated for harvest strategies for fish stocks. Such a strategy can be visualised as a management cycle (Figure 6), whereby data arising from fishing activities within a season, such as bycatch or other data collection may result in a management action, such as requiring a vessel to move away from the area where a bycatch threshold is exceeded as in CCAMLR Conservation Measure 22-07.

This data, as well as information such as historical fishing effort data, or future fishing plans, would then be used to regularly refine the assessment of current status, which in turn feeds into an assessment of the risk that the historical and future fishing activities may fail to achieve the long term objective (e.g. conserving benthic habitats or avoiding significant adverse impacts to VMEs *sensu* UNGA (2007)). Based on this risk assessment, managers can then decide if fishing can proceed as planned or may need to be regulated so as to mitigate risk to an acceptable level.

While this report is focussed on developing methods to enable the assessment of current status (outlined in red in Figure 6) of benthic habitats at Heard Island and the McDonald Islands, it also provides tools and data to facilitate the other processes shown, which could be applied to other fisheries.



**Figure 6. The components of a generalised management strategy similar to that implemented to manage finfish bycatch in the HIMI fishery. This report is focussed on the components that lead to an assessment of current status (red outline).**

The project team has developed tools to assist with the evaluation of alternative management strategies, detailed in Appendix 14. This includes the software package *Patch*, which is able to simulate the impact of fishing on the quality of benthic habitats, as well as processes such as growth, natural mortality and recruitment of benthic organisms which attempt to capture crucial characteristics such as their limited motility, potential longevity and competition for space on the seafloor. This software can also include layers representing the fishery's target species and its correlation with different habitats. Further, it represents the various data collection, decision rules and management responses currently used to conserve benthic habitats (e.g. closed areas, bycatch trigger limits and move-on rules).

## Results

### Assessment of HIMI seascape

Biomass ( $\text{kg}\cdot\text{m}^{-2}$ ) of benthic invertebrates was quantified from 129 benthic sled and beam trawl samples conducted in the HIMI region in 2003 and 2006, over a range of depths and geomorphic features as well as the HIMI Marine Reserve, Conservation Zone and areas where commercial fishing is permitted (Figure 7 and Figure 8). Footage from deployment of the BICS during commercial fishing operations was also scrutinized for biota and physical attributes of the seafloor.

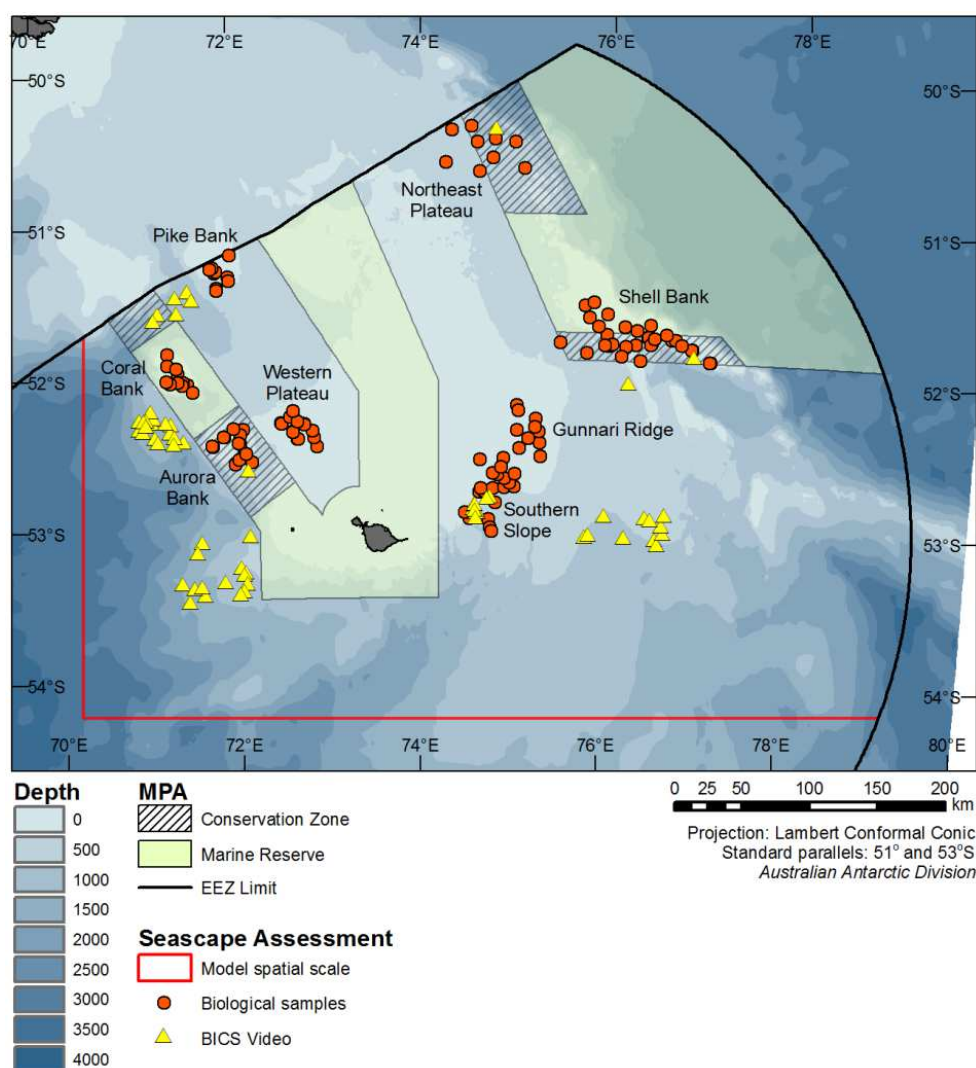
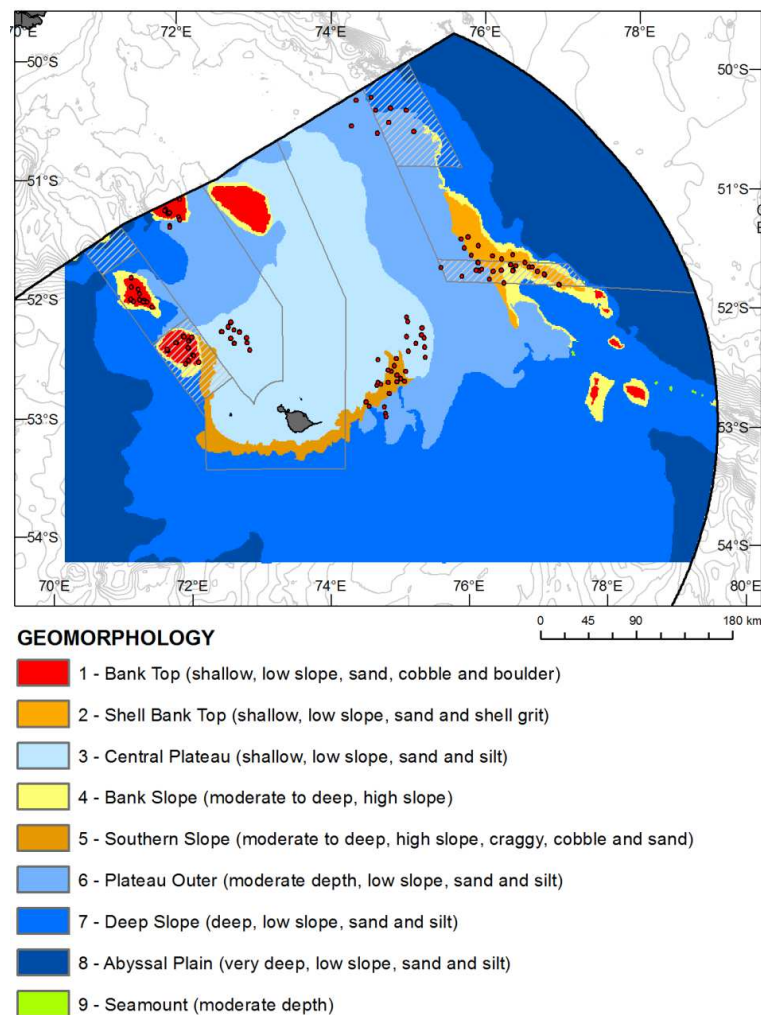


Figure 7. The model study area (red line) across which predictions were made, encompassing biological samples, video footage, and the majority of Australian fishing effort in the region between 1997 and 2010.





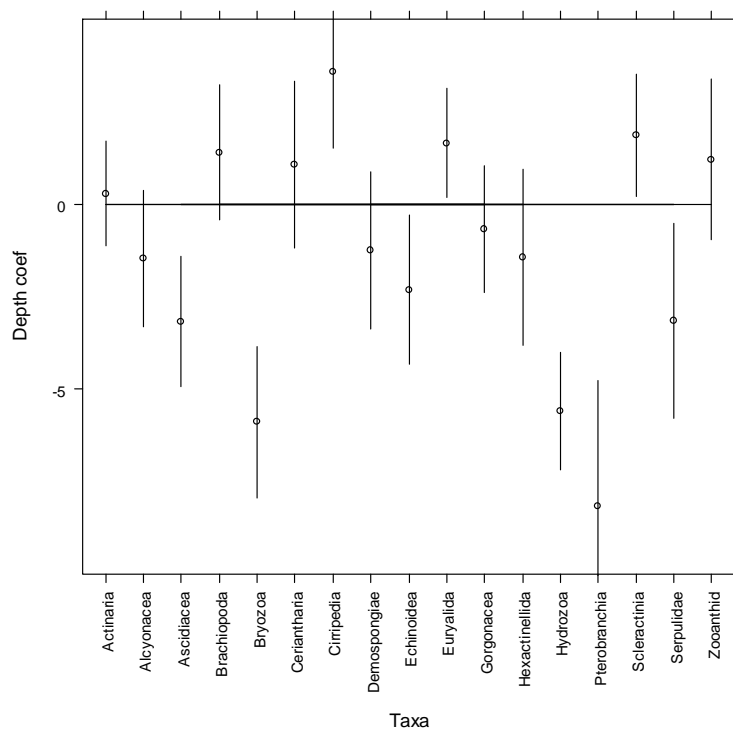
**Figure 8. Geomorphic units across the model study area characterised depth, slope and broad-scale substratum types. Biological sample or video data was available for all geomorphs except the abyssal plain (8) and the small seamounts southeast of Shell Bank (9).**

Of the taxa present in these samples, 17 groups considered structure-forming (*sensu* SC-CAMLR 2009) and vulnerable to demersal fishing gears and sufficiently common in samples to attempt modelling their distribution across the HIMI region (Table 3). Generalized additive models showed significant relationships between biomass and environmental data for 12 taxa, with depth (Figure 9) and geomorphology (Figure 10) being the most effective predictors of biomass.

Generalised linear model predictions across the depth and geomorphology combinations for all 3 x 3 km grid cells across the seascape showed taxa-specific distribution patterns (Figure A9.9). However there was overall tendency for predicted biomass to be highest above 300 m on bank tops and on the shallow central plateau, increasing in extent towards Heard Island. The biomass of most groups thereafter decreased from the periphery of the central plateau geomorph to the abyssal plain; reducing in biomass and increasing in patchiness below 600 m (Figure 11, Table 4).

**Table 3. List of structure-forming benthic taxa vulnerable to demersal fishing assessed in the HIMI region, including their motility (S= sessile or M= motile) and total number of biological samples in which they were captured (e.g. demosponges were present in 91 out of 129 samples). \*= groups whose distributions were predicted across the seascape are indicated. Note this list includes all taxa known to occur at HIMI that are also classified VME indicator taxa by CCAMLR<sup>5</sup>.**

Phylum	Taxon	Common name	Motility	Records
PORIFERA	Demospongiae*	bath or siliceous sponges	S	91
	Hexactinellida	glass sponges	S	69
CNIDARIA	Actiniaria*	anemones	S	83
	Scleractinia*	hard corals	S	45
	Alcyonacea*	soft corals or alcyonarians	S	84
	Gorgonacea*	horny corals or gorgonians	S	80
	Zoanthidae	zoanthids	S	11
	<i>Stylasteridae</i>	hydrocorals	S	17
	<i>Hydroidolina*</i>	hydroids or sea ferns	S	102
ANNELIDA	Serpulidae*	serpulid tube worms	S	82
BRYOZOA*		lace coral	S	76
BRACHIOPODA		lamp shells	S	68
ARTHROPODA	Cirripedia*	stalked barnacles	S	67
ECHINODERMATA	Echinoidea*	pencil urchins	M	80
	Euryalida*	snake or basket stars	M	46
HEMICHORDATA	Pterobranchia*	pterobranchs	S	48
CHORDATA	Ascidiacea*	sea squirts	S	105



**Figure 9. Relationship between the coefficients of depth by taxa group estimated by the GLM ( $\pm 2 \times$  SE). A positive coefficient denotes an increase in biomass with depth and the converse for the negative. Where error bars intersect the zero line no statistically significant relationship with depth was detected.**

<sup>5</sup> Available at [www.ccamlr.org/en/system/files/VME-guide.pdf](http://www.ccamlr.org/en/system/files/VME-guide.pdf), see also SC-CAMLR (2009)

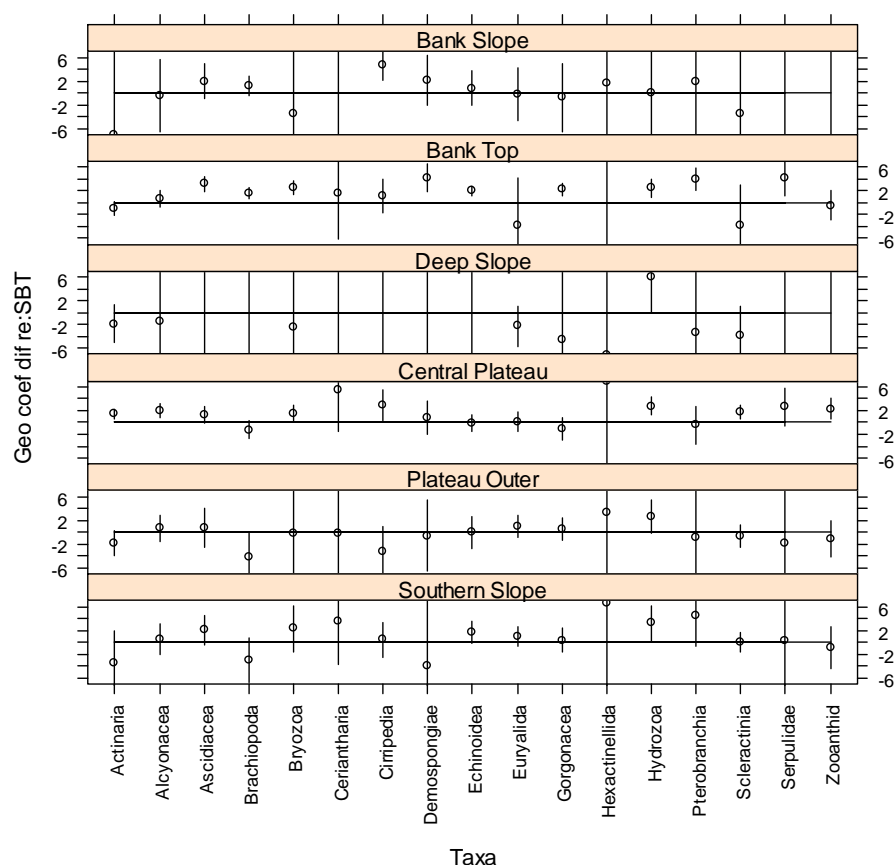
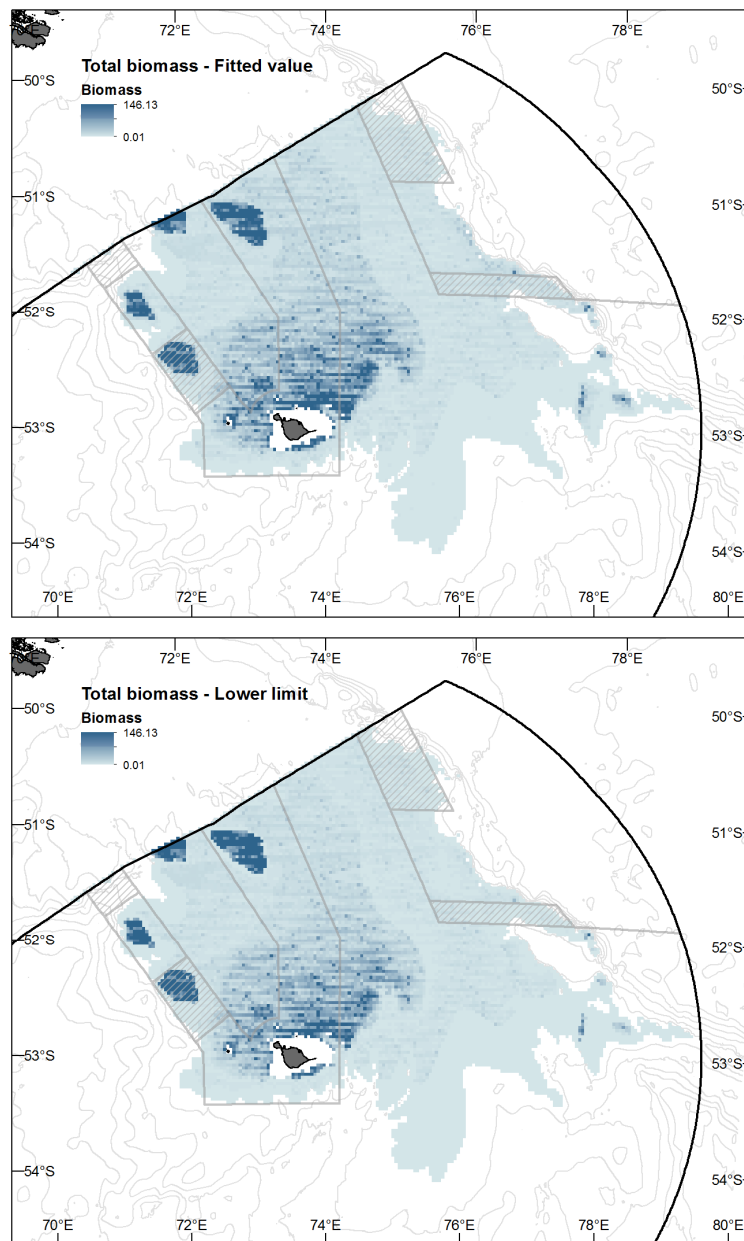


Figure 10. Relationship between the coefficient of geomorphology by taxa group estimated by the GLM ( $\pm 2 \times$  SE) using Shell Bank top (geomorphic group 2) as a reference class. A positive (negative) coefficient denotes a higher (lower) biomass by geomorphic group relative to the reference class. Where error bars intersect the zero line no statistically significant difference between geomorphological category and the reference class was detected.

Table 4. Percentage of structure-forming benthic taxa vulnerable to demersal fishing biomass by 200 m depth strata based on generalised linear model predictions based on depth and geomorphology. All= sum of all predicted taxa, POD=demosponges, ATX=actinarians, ALY=alcyonarians, GGX=gorgonians, SSX=ascidians, BZN=bryozoans, WOR=serpulids, ECH=echinoids, EUR=euryalids, PTR= pterobranchs, CSS=scleractinians, BWY=cirripedes, HYD=hydrozoans.

Depth range (m)	Percentage of predicted taxon biomass (%)													
	All	POD	ATX	ALY	GGX	SSX	BZN	WOR	ECH	EUR	PTR	CSS	BWY	HYD
0-200	13.6	3.5	5.9	13.5	1.8	16.5	42.2	19.6	10.3	0.3	41.9	1.7	0.1	43.1
201-400	46.7	83.1	53.5	62.8	47.5	74.9	56.7	75.3	70.5	5.6	57.7	29.8	3.1	54.4
401-600	11.1	10.4	34.3	18.9	23.5	7.1	1.0	5.0	13.5	25.0	0.4	45.5	12.9	1.7
601-800	7.9	2.1	2.7	4.0	23.6	1.3	0.0	0.0	4.8	52.0	0.0	17.0	14.0	0.2
801-1000	8.9	0.7	1.4	0.6	3.4	0.2	0.0	0.0	0.8	13.1	0.0	4.8	28.2	0.3
1001-1200	12.0	0.3	2.1	0.2	0.2	0.0	0.0	0.0	0.1	3.9	0.0	1.2	41.7	0.2



**Figure 11. Predicted distribution of biomass ( $\text{g}\cdot\text{m}^{-2}$ ) of vulnerable taxa across the HIMI seascape. Biomass is displayed as the mean fitted value (upper panel) and lower bound (i.e. 95% of cells are predicted to have biomass above these values). These values were predicted on the joint coefficients of depth and geomorphology.**

The taxa-specific predictions (Figure A9.9) therefore provided a synoptic view of the likely abundance and diversity of the thirteen most abundant benthic taxa that could be overlaid with the fishery footprint estimated at an equivalent scale and extent.

### Assessment of taxa-specific vulnerability

Bycatch quantities recorded in the HIMI fishery, despite relatively low taxonomic resolution prior to 2009, show that many of the benthic taxa recorded in scientific samples are vulnerable to damage and removal during fishing (Figure 12, Tables 5 and 6).



Figure 12. Photograph of benthic invertebrate bycatch sorted from a demersal trawl in the HIMI region, with motile taxa such as crinoids and asteroids most abundant, as well as including sessile taxa such as sponges and ascidians.

Table 5. Invertebrate bycatch composition in longline hauls in the HIMI fishery by season rounded to the nearest 0.1 tonnes; 0.0 indicates the taxon was recorded, but total catch was less than 0.1 tonnes.

Season	Taxon		
	Sea stars and allies <sup>a</sup>	Other <sup>b</sup>	Total
2002/03	0.0	0.0	0.0
2003/04	0.0	0.0	0.0
2004/05	0.0	0.0	0.0
2005/06	3.0	0.0	3.0
2006/07	0.5	0.0	0.5
2007/08	2.9	0.1	3.0
2008/09	4.2	0.1	4.3
2009/10	2.6	0.0	2.6
Total	13.2	0.2	13.4

<sup>a</sup> This group is likely to include asteroids, crinoids and ophiuroids

<sup>b</sup> This group includes a mix of sessile taxa including corals, anemones and sponges, as well as motile invertebrates such as crabs.

**Table 6. Invertebrate bycatch composition in demersal trawls in the Heard Island and McDonald Islands fishery, 1996/97-2009/10. Weights are rounded to the nearest 0.1 tonnes; 0.0 indicates the taxon was recorded, but total catch was less than 0.1 tonnes.**

Season	Taxon						Total
	Sponges	Corals <sup>a</sup>	Sea stars and allies <sup>b</sup>	Anemones	Unspecified <sup>c</sup>		
1996/97	1.1	8	1.3	0.0	8.5	18.9	
1997/98	3.3	1.9	1.2	1.4	17.2	25	
1998/99	0.3	0.2	0.1	0.1	2.2	2.9	
1999/00	1.6	0.5	1	0.4	3.2	6.7	
2000/01	4.1	0.4	0.8	0.5	1.7	7.5	
2001/02	1.5	0.6	1.6	0.6	1.1	5.4	
2002/03	1.7	0.3	2.1	3.3	2.5	9.9	
2003/04	1.4	0.1	0.8	0.1	1.7	4.1	
2004/05	1.5	1.6	0.6	0.3	1.4	5.4	
2005/06	1.5	0.5	2.1	0.5	1.6	6.2	
2006/07	1	0.2	1.8	0.1	2.6	5.7	
2007/08	3.1	0.7	2.2	0.3	6.1	12.4	
2008/09	2.5	0.3	2.9	1.6	9.2	16.5	
2009/10 <sup>d</sup>	15.7	1	7.1	10.6	12.4	46.8	
Total	40.3	16.3	25.6	19.8	71.4	173.4	

<sup>a</sup>This group is likely to include gorgonian, alcyonarian and scleractinian corals, based on improved at-sea taxonomic discrimination within this group since 2009

<sup>b</sup>This group includes asteroids, crinoids and ophiuroids

<sup>c</sup>This group includes motile and sessile invertebrate taxa that were not identified to lower taxonomic levels

<sup>d</sup>The majority of all invertebrate bycatch in this year derived from two Random Stratified Trawl Surveys conducted in April and September 2010. For example, 13.8 tonnes of sponges were caught in survey hauls.

Quantities recorded from trawls exceed those from longlines, however video footage captured during this project indicates that benthos removed by interactions with the mainline or by hooks may not reach the surface to be recorded (Figure 13 and Figure 14), and so bycatch records may underestimate the extent of interactions between longlines and the seafloor. Consequently, the same taxa modelled above were also analysed to determine the likely outcome of interactions with both of these demersal fishing gears.

The probabilities of benthic invertebrates dying, receiving damage or remaining undamaged were estimated separately for demersal trawl (comprising the footprint exerted by the footline and doors of the trawl as it is towed across the seafloor), the mainline of demersal longlines and the hooks on demersal longlines (Appendix 13). This was done in order to correctly combine cumulative effects where gears are fishing in the same location.

Applying equations 1-9 in Appendix 13 enabled the estimation of the probability of outcome for each taxon in the fishing footprint, as well as estimating the outcomes for overlapping fishing events interactions (Tables A13.6, A13.8 and A13.9). Gorgonians had the highest estimated probabilities of death or damage from all gear types because of their high exposure and brittleness. In contrast, echinoids, represented by the pencil urchin *Ctenocidaris nutrix*, were estimated to have a relatively low probability of death and moderate probability of damage (Table 7).

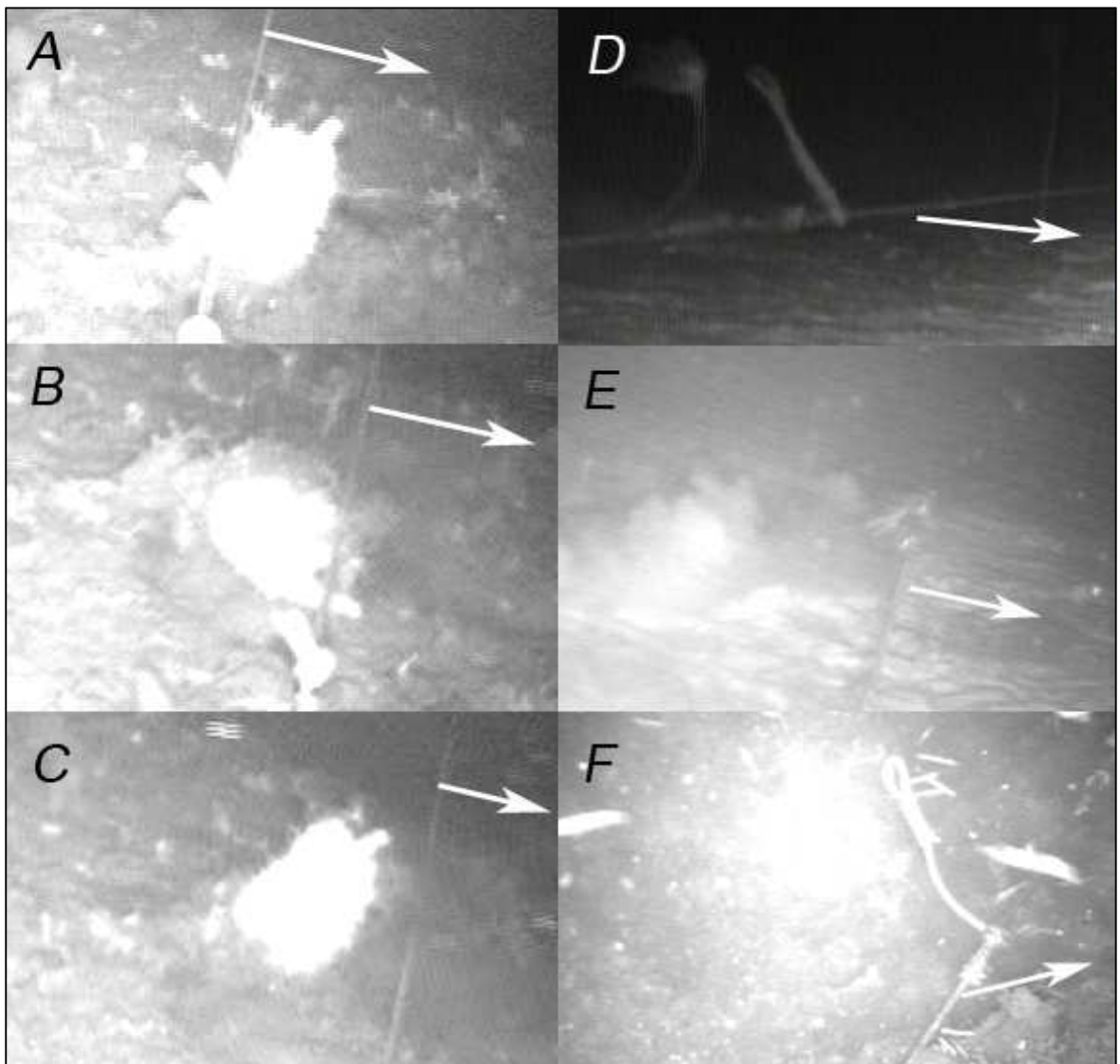
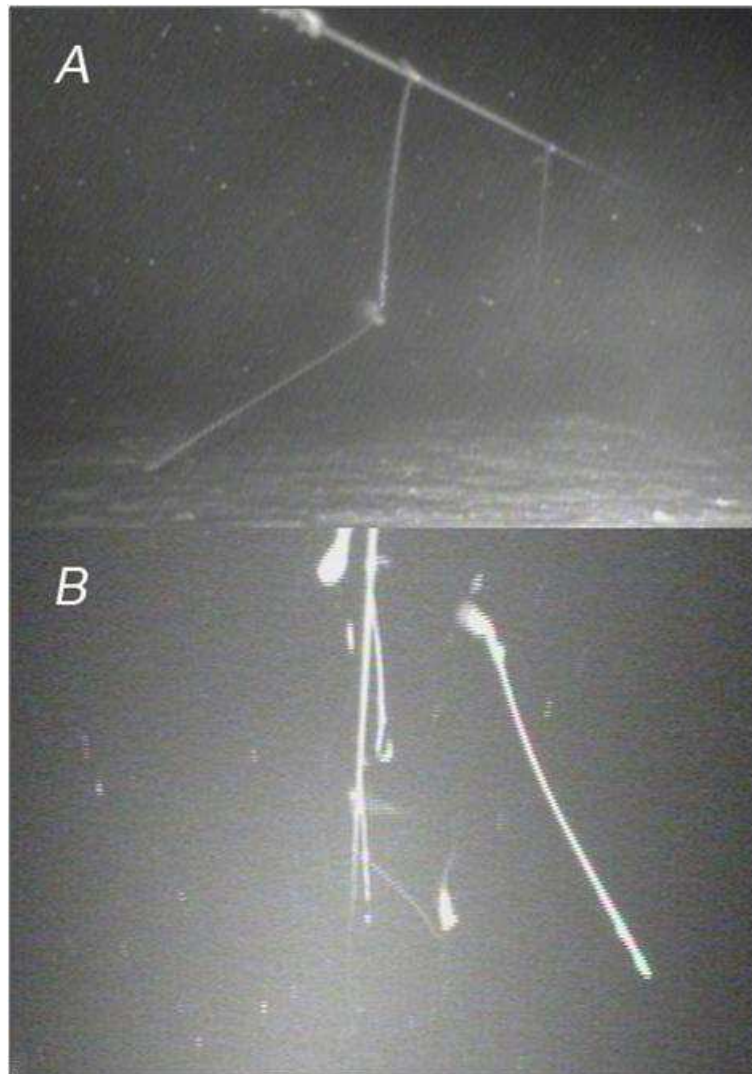


Figure 13. Frames from video footage of interactions of structure-forming taxa with a demersal longline moving across the seafloor during retrieval. White arrows indicate the direction of line movement. A, B and C depict a sponge deflecting to allow a line to pass, and then returning to a semi-upright position. D and E depict sea pens (*Umbellula* spp.) being detached by the line and F depicts an aggregation of serpulid tube worms being broken off by a passing line. In all these instances no evidence of these interactions would be observed at the surface.



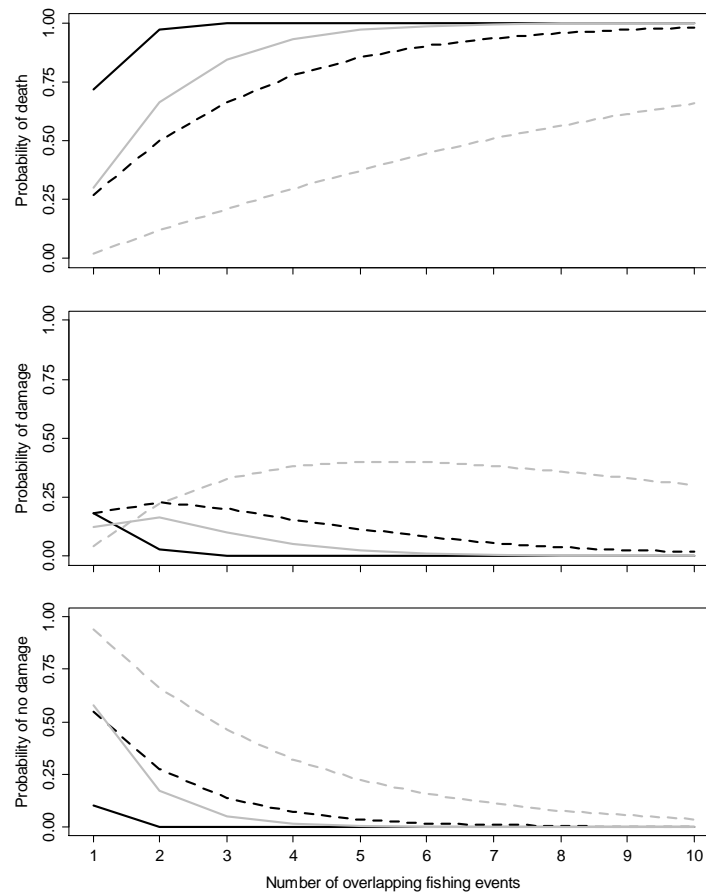
**Figure 14. Frames from video footage of a longline lifting into the water column after moving laterally across the seafloor for >20m. A) A sea pen (*Umbellula* spp.) is hooked. B) The sea pen falling from the hook around 10 minutes later as the line is being hauled to the surface.**

Longline hooking and trawl interactions are generally estimated to have a higher probability of death or damage than longline mainline interactions. Taxa with relatively low resistance, such as gorgonians, are estimated to have a greater than 99% chance of experiencing a lethal interaction from those parts of the fishing footprint with more than 2 overlapping trawl or 5 hooking events. This compares to interactions with the mainline of the longline or for species with relatively high resistance for which upwards of ten overlapping events are required to increase the probability of death to greater than 95%. Consequently, in an area with multiple overlapping fishing events, it is possible that the dominant fauna may change, as low resistance species are removed and high resistance species persist, albeit with a high probability of sub-lethal damage (Figure 15).



Table 7. Assigned probabilities relating to the resistance of vulnerable taxa that are residing in the footprint of a demersal fishing event. The superscript <sup>1</sup> identifies taxa common in trawl bycatch and <sup>2</sup> common in longline bycatch.  $a$  = the probability of being unable to evade the fishing gear;  $h$  = probability of connecting with the fishing gear due to morphological features such as height above the seafloor;  $m$  = probability of dying from an interaction with the gear;  $d$  = probability of sub-lethal damage from an interaction with the gear;  $s$  = the probability of lethal damage as a result of sub-lethal damage in a prior fishing event;  $DT$  = demersal trawl;  $LN$  = mainline component of a longline interaction;  $HK$  = hook component of longline interaction.

Taxon		Trawl				Longline				$s$				
		$a_{DT}$	$h_{DT}$	$m_{DT}$	$d_{DT}$	$a_{LN}$	$h_{LN}$	$m_{LN}$	$d_{LN}$		$a_{HK}$	$h_{HK}$	$m_{HK}$	$d_{HK}$
Porifera	Demospongiae <sup>1,2</sup>	1	0.7	0.6	0.2	1	0.7	0.2	0.2	1	0.7	0.5	0.2	1.2
Cnidaria	Actinaria <sup>1,2</sup>	1	0.5	0.7	0.2	1	0.5	0.1	0.2	1	0.5	0.5	0.2	1.2
	Scleractinia <sup>1</sup>	1	0.5	0.5	0.2	1	0.3	0.1	0.2	1	0.5	0.3	0.2	1.2
	Alcyonacea <sup>1,2</sup>	1	0.5	0.7	0.2	1	0.3	0.1	0.2	1	0.5	0.5	0.2	1.2
	Gorgonacea <sup>1,2</sup>	1	0.9	0.8	0.2	1	0.9	0.3	0.2	1	0.9	0.5	0.2	1.2
	Hydroidolina	1	0.7	0.7	0.2	1	0.7	0.2	0.2	1	0.7	0.5	0.2	1.2
Annelida	Serpulidae	1	0.3	0.9	0.1	1	0.4	0.3	0.2	1	0.3	0.6	0.2	1.2
Bryozoa		1	0.5	0.9	0.1	1	0.3	0.3	0.2	1	0.3	0.6	0.2	1.2
Arthropoda	Cirripedia	1	0.5	0.9	0.1	1	0.3	0.3	0.2	1	0.3	0.6	0.2	1.2
Echinodermata	<i>Ctenocidaris nutrix</i>	1	0.6	0.5	0.2	1	0.2	0.1	0.2	1	0.2	0.2	0.2	1.2
	Euryalida	1	0.5	0.5	0.2	1	0.2	0.1	0.2	1	0.5	0.9	0.2	1.2
Hemichordata	Pterobranchia	1	0.4	0.6	0.2	1	0.2	0.2	0.2	1	0.3	0.5	0.2	1.2
Chordata	Ascidiacea <sup>1,2</sup>	1	0.5	0.6	0.2	1	0.5	0.2	0.2	1	0.5	0.5	0.2	1.2



**Figure 15.** The estimated probability that an invertebrate with relatively high resistance (pencil urchin, *Ctenocidaris nutrix*, grey lines) or relatively low resistance (gorgonian, black lines) residing in the swept area of successive overlapping demersal trawl events (solid lines) and successive overlapping longline events (dashed lines) will die (top), survive in a damaged state (middle) or survive unharmed (bottom).

### Assessment of benthic taxa and habitat dynamics

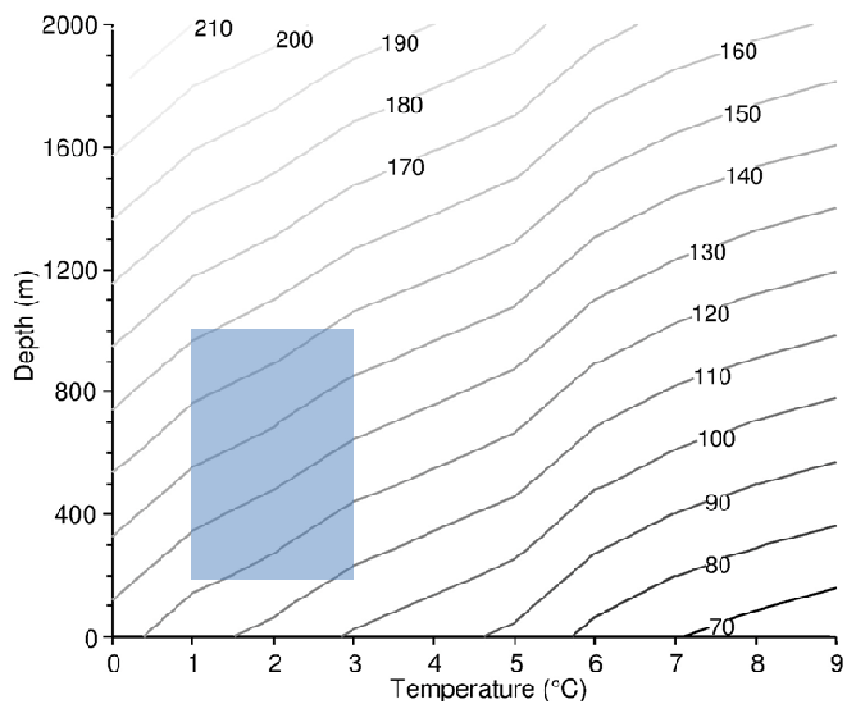
A review of the literature produced over 1200 records of life history characteristics for deep-sea benthic invertebrates in groups generally considered vulnerable to disturbance by demersal fishing (Table A3.1) (FAO 2009, SC-CAMLR 2009). Of these, gorgonians, black corals (Antipatharia), sea pens (Pennatulacea), stony corals (Scleractinia), hydrocorals (Stylasteridae) zoanthids (Zoantharia), 'other' cnidarians (including soft corals (Alcyonacea), demosponges and bryozoans had sufficient data to conduct bivariate regression analyses of life history and environmental parameters.

These analyses indicated significant relationships between growth rate and longevity. Gorgonians are generally slow growing and long lived; forms encountered in deeper, colder waters have slower growth rates and higher maximum ages (Tables A3.3-5, Figures A3.1-3). The statistical significance of these relationships made it possible to model the relationships between age, depth and temperature, indicating that the gorgonians encountered in the depth range and the temperature range at the depth

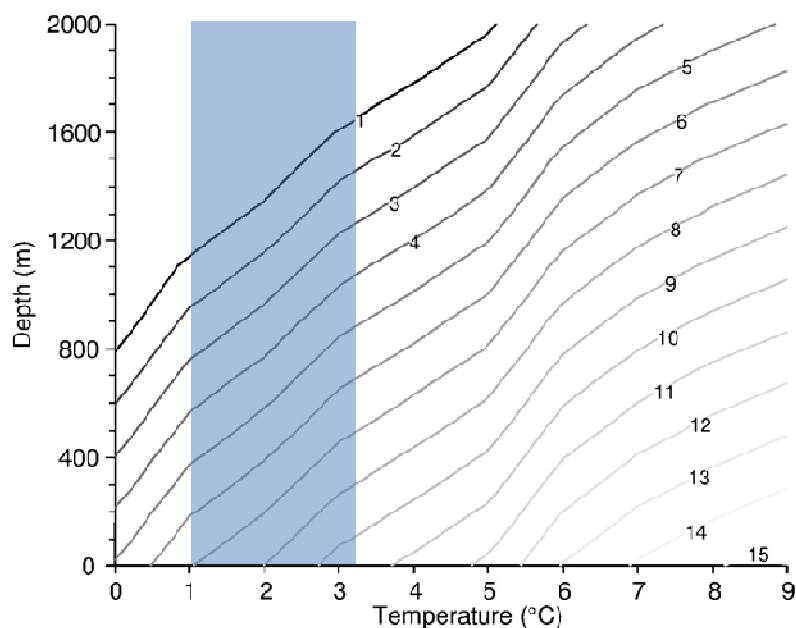
(van Wijk *et al.* 2010) where they are most likely to occur at HIMI are predicted to have maximum ages in excess of 100 years (Figure 16).

Significant correlations were also found between life history and environmental parameters across 'other' cnidarians taxa. These indicate lower growth rates for forms in deeper and colder habitats (Tables A3.6-8, Figures A3.5-7), with linear growth rates of less than 10 mm.yr<sup>-1</sup> for these taxa predicted in the habitats where they occur at HIMI (Figure 17).

Insufficient data was available to produce equivalent predictions for bryozoans, however bivariate regressions indicate that they also tend to be slower growing (Tables A3.9-A3.11, Figure A3.8) and have maximum ages of 10-45 years in colder habitats (Barnes & Conlan 2007). Similarly, data on sponges was too sparse to detect relationships between life history and environmental parameters for this group (Tables A3.12-14, Figure A3.9). However, data for Antarctic sponges showed that their growth rate was not measurable or very slow over considerable periods (Dayton 1979) while the few studies on glass sponges suggest that they may live in excess of 200 years (Leys & Lauzon 1998).



**Figure 16. Predicted lower bound for age of gorgonians at different depth and temperature combinations based on a multiple regression model. Contour lines are marked in 10 year intervals. Shaded region indicates the depth and temperature envelope where gorgonians are encountered at HIMI.**



**Figure 17. Predicted linear growth rate for other cnidarians at different depth and temperature combinations from a multiple regression model. Contour lines are marked in  $1 \text{ mm.yr}^{-1}$  intervals. Shaded region indicates the depth and temperature envelope where alcyonarian and actiniarian cnidarians are encountered at HIMI.**

These analyses indicate that many of the taxa known to occur at HIMI, and vulnerable to death or damage from interactions with demersal fishing gear are likely to be long lived and slow growing. Consequently the recovery rates of taxa and assemblages from damage or death is likely to be in the order of decades to centuries.

### Assessment of historical fishing footprint at HIMI

A total of 21 579 individual fishing events in the HIMI region, across the period 1997-2013, were analysed (Table 8).

A comparison between the sum the length of all fishing events by the nominal width of the gear (polygon method), and the equivalent sum estimated by the pixellation of the seascape as shown in Figure 5 indicated that the pixel method over estimates the footprint area by 27-32%. Hence the total areas calculated by this method were adjusted accordingly (Table 9).

**Table 8. Summary values for fishing effort in the HIMI region, 1997-2013.**

Parameter	Gear type				
	Champion (C)	Champion (R)	Albatross	Carmen	Longline
Number of fishing events	13 952	2 439	90	674	4 424
Nominal footprint width (m)	160	100	120	160	10
Mean length of fishing events (km)	5.67	2.95	7.56	7.09	8.92
Median length of fishing events (km)	4.53	2.95	6.86	5.63	8.81
CV of length of fishing events (km)	0.72	0.23	0.56	0.72	0.40
Mean depth fished (m)	552	468	461	430	1 303
Median depth fished (m)	548	432	494	441	1269
CV of depth fished (m)	0.23	0.47	0.31	0.43	0.31

The total area of seafloor, estimated from the bathymetry in *kerf\_dem* (Beaman & O'Brien 2011) is shown in Table 10. Commercial trawl fishing in the HIMI region is conducted primarily on the upper slopes of the banks and the plateau, with a maximum of 3.1% of the 201-400 m depth band falling within the trawl footprint. Only a small proportion of trawling is undertaken in deeper slope waters, and records of hauls apparently conducted at depths greater than 1600 m are unlikely to have maintained contact with the seafloor (Table 11).

**Table 9. Summary values of estimated effort footprints in the HIMI region, 1997-2013. Total area fished with no overlaps is the sum of the area of every fishing event, as estimated by the sum of length of all fishing events by the nominal width (polygon), or the numbers of pixels intercepted (as shown in Figure 5). Total area fished - overlap is the area of the seafloor affected by fishing taking account of overlapping events, estimated by the number of pixels intercepted along the track of each fishing event, and adjusted for the relationship between the pixel and polygon method.**

Parameter	Gear type					
	Champion (C)	Champion (R)	Albatross	Carmen	All Trawl	Longline
Total area fished – no overlap (km <sup>2</sup> ) (polygon)	12 656.3	720.6	81.7	764.2	14 222.8	394.8
Total area fished – no overlap (km <sup>2</sup> ) (pixel)	16 662.4	943.8	108.1	1 012.0	18 726.3	502.3
Ratio pixel: polygon area	1.31	1.31	1.32	1.32	1.32	1.27
Total area fished – overlap (km <sup>2</sup> ) (pixels)	2 156.4	881.3	87.5	397.9	2 922.1	493.6
Total area fished – overlap (km <sup>2</sup> ) (adjusted)	1 646.1	672.7	66.3	301.4	2 213.6	388.7
Mean number of interactions within footprint	7.7	1.1	1.2	2.5	6.4	1.0

**Table 10. Total seafloor area in 200 m depth bands within the Australian EEZ at HIMI between 0 and 3000 m.**

Depth band (m)	Seafloor area (km <sup>2</sup> )	Percentage of total seafloor area <3000 m deep	Percentage of total seafloor in EEZ, all depths
0-200	4 517.5	1.6	1.1
201-400	28 844.4	10.4	7.0
401-600	26 746.0	9.7	6.5
601-800	23 665.9	8.6	5.8
801-1000	12 266.7	4.4	3.0
1001-1200	16 377.2	5.9	4.0
1201-1400	17 052.4	6.2	4.2
1401-1600	22 428.7	8.1	5.5
1601-1800	20 351.6	7.4	5.0
1801-2000	20 988.9	7.6	5.1
2001-2200	18 216.4	6.6	4.4
2201-2400	15 668.1	5.7	3.8
2401-2600	13 632.4	4.9	3.3
2601-2800	14 914.9	5.4	3.6
2801-3000	20 550.8	7.4	5.0
Total <3001	276 221.9	100	67.3
Total in EEZ all depths	410 722		100

**Table 11. Total seafloor area within the trawl-only footprint by 200 m depth bands within the Australian EEZ at HIMI, 1997-2013, estimated using the pixel method shown in Figure 5, and then adjusted as per Table 9. 0.0 = footprint area less than 0.1 but non-zero, - = no footprint area.**

Depth band (m)	Area of Footprint (km <sup>2</sup> )											Total	% of EEZ
	Number of interactions												
	1	2	3	4	5	6	7	8	9	≥10			
0-200	47.3	2.2	0.4	0.1	0.0	-	-	-	-	-	50.0	1.1	
201-400	628.5	89.3	35.0	21.8	15.9	12.6	10.8	9.2	8.4	59.2	890.5	3.1	
401-600	273.9	28.0	13.4	9.6	8.0	7.1	7.1	6.5	6.8	169.1	529.6	2.0	
601-800	317.6	34.8	17.1	11.5	9.5	7.9	6.1	5.2	4.3	41.6	455.6	1.9	
801-1000	173.8	11.7	2.6	1.2	0.7	0.6	0.4	0.3	0.2	3.2	194.8	1.6	
1001-1200	57.0	1.4	0.1	0.1	0.1	0.0	0.0	-	0.0	0.1	58.7	0.4	
1201-1400	19.1	0.1	0.1	0.0	0.0	-	0.0	-	-	0.0	19.3	0.1	
1401-1600	4.3	0.1	0.1	0.1	-	-	-	-	-	-	4.6	0.0	
1601-1800	0.2	0.0	0.0	-	-	-	-	-	-	-	0.2	0.0	
1801-2000	0.9	-	-	-	-	-	-	-	-	-	0.9	0.0	
2001-2200	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
2201-2400	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
2401-2600	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
2601-2800	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
Total	1522.9	167.6	68.8	44.2	34.2	28.2	24.4	21.2	19.8	273.2	2204.6	0.5	

Longline effort is also heterogeneously distributed, focussing mainly on deeper slopes, with a few areas of concentrated effort, with a maximum of 0.6% of the seafloor between 1601-1800m within the fishing footprint (Table 12). Most locations within the footprint have had 1 interaction, and a maximum of 17 interactions was estimated at a single 100 m<sup>2</sup> location. Taking into account overlaps reduced the estimated fished area by 6.5 km<sup>2</sup>, indicating that although longline effort tends to be focussed in some areas, as lines are generally deployed parallel or perpendicular to one another, the area of overlap is relatively small (e.g. Figure A11.6).

**Table 12. Total seafloor area within the longline-only footprint by 200 m depth bands within the Australian EEZ at HIMI, 1997-2013, estimated using the pixel method shown in Figure 5 and then adjusted as per Table 9. 0.0 = footprint area less than 0.1 but non-zero, - = no footprint area.**

Depth band (m)	Area of Footprint (km <sup>2</sup> )											Total	% of EEZ
	Number of interactions												
	1	2	3	4	5	6	7	8	9	≥10			
0-200	-	-	-	-	-	-	-	-	-	-	-	-	
201-400	0.0	-	-	-	-	-	-	-	-	-	0.0	0.0	
401-600	0.8	0.0	-	-	-	-	-	-	-	-	0.8	0.0	
601-800	14.2	0.1	-	-	-	-	-	-	-	-	14.2	0.1	
801-1000	50.6	0.4	0.0	-	-	-	-	-	-	-	51.0	0.3	
1001-1200	58.4	0.5	0.0	-	-	-	-	-	-	-	58.9	0.3	
1201-1400	56.8	0.4	0.0	-	-	-	-	-	-	-	57.2	0.2	
1401-1600	45.6	0.2	0.0	-	-	-	-	-	-	-	45.8	0.2	
1601-1800	97.6	1.3	0.0	0.0	-	-	-	-	-	-	98.9	0.5	
1801-2000	43.7	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-	44.7	0.2	
2001-2200	4.1	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	-	4.9	0.0	
2201-2400	2.4	0.4	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	
2401-2600	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.2	0.0	
Total	374.4	4.7	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	379.7	0.1	

**Table 13. Total seafloor area where longline and trawl footprints overlap by 200 m depth bands within the Australian EEZ at HIMI, 1997-2013, estimated using the pixel method shown in Figure 5, and then adjusted as per Table 9. 0.0 = footprint area less than 0.1 but non-zero, - = no footprint area.**

Depth band (m)	Area of Footprint (km <sup>2</sup> )										Total	% of EEZ
	Number of interactions											
	2	3	4	5	6	7	8	9	≥10			
0-200	-	-	-	-	-	-	-	-	-	-	0.0	-
201-400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.00
401-600	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	3.2	4.0	0.01
601-800	0.5	0.2	0.2	0.1	0.1	0.1	0.0	0.1	0.4	1.6	0.01	0.01
801-1000	2.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.02	0.02
1001-1200	0.6	0.0	0.0	-	-	-	-	-	-	0.6	0.00	0.00
1201-1400	0.2	0.0	-	-	-	-	-	-	-	0.2	0.00	0.00
1401-1600	0.0	-	-	-	-	-	-	-	-	0.0	0.00	0.00
1601-1800	-	-	-	-	-	-	-	-	-	0.0	-	-
Total	3.8	0.6	0.3	0.2	0.1	0.1	0.1	0.1	3.7	9.0	0.04	0.04

The trawl and longline fisheries are largely conducted at different depths in the HIMI region. Whilst there are areas of HIMI (e.g. the main trawl ground) where the two gears have been deployed adjacent to one another, longlining has been primarily conducted at greater than, and trawling less than, 800 m depth. However, an estimated 9 km<sup>2</sup> the seafloor has experienced overlapping longline and trawl, the majority of it between 400 and 1000 m deep (Table A11.7).

### Assessment of current status

Combining the estimate of the type, number and area of interactions in each grid cell, with the estimated taxon biomass and expected outcome for each interaction type, and assuming no growth or recovery between events, provided an expected accumulated outcome taxa within each grid cell:

$$B_{t,o} = \frac{B_t}{a} \sum_1^n \sum_g P_t A$$

Where  $B$  is the estimated total biomass in a grid cell,  $a$  is the total area of the grid cell,  $t$  is a given taxon,  $o$  is an outcome (dead, sub-lethally damaged or undamaged), and  $P$  is the probability of an outcome for a given combination of gear component  $g$ , taxon, number of interactions  $n$  and area of overlapping interactions  $A$ .

For example, in a 3 x 3 km grid cell ( $a = 9$  km<sup>2</sup>) with an estimated total biomass of 10 tonnes of demosponges ( $B_{\text{sponge}} = 10$ ), and 5 km<sup>2</sup> of which experienced one demersal trawl event and 1 km<sup>2</sup> where 2 demersal trawls had overlapped ( $P = 0.42$  for mortality after one trawl and  $P = 0.78$  for mortality after two trawls for demosponges), an estimated 1.8 tonnes of the original biomass is expected to have been killed.

Summing these estimates for all grid cells allows an estimate of the proportion of predicted biomass affected within the fishing footprint and across the entire modelled area of the HIMI seascape. Outcomes for taxa range from over 91% dead or damaged for gorgonians within the demersal trawl footprint, to more than 63% of echinoids serpulids undamaged within the longline mainline footprint (Table 14). However, overall for the modelled seascape, the amount of dead or damaged biota due to the HIMI fishing footprint is estimated to be less than 1% (Table 15).

**Table 14. Predicted outcomes for structure-forming benthic taxa vulnerable to demersal fishing within fishing footprints at HIMI based on actual effort between 1997 and 2013 in depths less than 1200 m. Percentages are calculated for dead (M), damaged (D) and undamaged (U) in each type of footprint and the footprints combined. ALY=alcyonarians, ATX=actiniarians, BZN=bryozoans, BWY=cirripedes, CSS=scleractinians, ECH=echinoids, EUR=euryalids, GGX=gorgonians, HYD=hydroids, POD=demosponges, PTR= pterobranchs, SSX=ascidians, WOR=serpulids, All = all biomass for taxa modelled.**

Taxon	Trawl			Longline mainline			Gears combined		
	M	D	U	M	D	U	M	D	U
ALY	9.3	47.4	43.3	10.0	37.9	52.1	9.3	47.4	43.3
ATX	9.2	48.0	42.8	10.0	36.2	53.8	9.2	47.8	43.0
BWY	4.6	54.3	41.1	4.9	48.3	46.8	4.7	53.0	42.4
BZN	4.6	54.4	41.0	4.7	55.5	39.8	4.6	54.4	41.0
CSS	10.6	30.9	58.5	10.1	25.6	64.3	10.6	30.8	58.5
ECH	11.9	39.0	49.1	12.2	34.6	53.2	11.9	39.0	49.1
EUR	10.4	34.3	55.3	10.1	26.0	63.9	10.3	33.0	56.6
GGX	15.3	76.3	8.4	17.2	73.3	9.5	15.3	76.3	8.4
HYD	12.4	57.4	30.1	13.9	49.8	36.3	12.4	57.4	30.1
POD	13.3	48.7	38.0	13.7	45.3	41.0	13.3	48.7	38.1
PTR	8.1	35.4	56.5	9.0	34.4	56.6	8.1	35.4	56.5
SSX	10.0	39.5	50.5	10.3	35.2	54.5	10.0	39.5	50.5
WOR	3.1	40.1	56.8	3.2	31.1	65.7	3.1	40.1	56.8
All	9.9	48.0	42.1	5.5	47.2	47.3	9.7	47.9	42.3

**Table 15. Biomass of structure-forming benthic taxa vulnerable to demersal fishing predicted to be killed or damaged across the entire seascape modelled less than 1200 m (Figure 3). Taxa abbreviations as in Table 12.**

Taxon	Predicted biomass (tonnes)	Killed or damaged					
		Trawl		Longline		Gears combined	
		(tonnes)	%	(tonnes)	%	(tonnes)	%
ALY	6 359	92.40	1.45	0.24	0.00	92.64	1.46
ATX	44 251	472.64	1.07	4.64	0.01	477.28	1.08
BWY	179 088	1575.28	0.88	407.28	0.23	1982.56	1.11
BZN	98 932	1619.20	1.64	0.24	0.00	1619.52	1.64
CSS	2 249	16.32	0.73	0.16	0.01	16.56	0.74
ECH	5 002	84.48	1.69	0.32	0.01	84.80	1.70
EUR	39 880	311.12	0.78	10.72	0.03	321.84	0.81
GGX	615	16.24	2.64	0.16	0.03	16.40	2.67
HYD	35 775	636.24	1.78	1.12	0.00	637.36	1.78
POD	120 088	2944.16	2.45	18.40	0.02	2962.64	2.47
PTR	1 924	25.60	1.33	0.00	0.00	25.60	1.33
SSX	29 229	488.80	1.67	0.80	0.00	489.60	1.68
WOR	86 119	1204.32	1.40	0.56	0.00	1204.96	1.40
All	649 509	9486.80	1.46	444.88	0.07	9931.68	1.53



## Discussion

### **Risk of current demersal fishing impacts to benthic habitats at HIMI**

We estimate that 1.5% of all benthic biota within fishable depths has been killed or damaged as a result of demersal fishing at HIMI between 1997 and 2013. The worst outcome at the level of taxa is for gorgonians, 2.7% predicted to have been killed or damaged over the same period. This relatively small amount of damage can be attributed to several factors, including the way the trawl and longline fishery operate, the spatial distribution of biota and the design of the HIMI Marine Reserve.

#### **1. The spatial distribution of trawling effort at HIMI.**

As the fishery developed at HIMI, the trawl fishery rapidly gravitated to targeting aggregations of toothfish and icefish in 5 spatially constrained fishing grounds on the southern and bank slopes of the plateau, in depths between 400 and 1000m. This fishing overlaps with important habitats for groups such as poriferans, sessile cnidarians, bryozoans and ascidians. Around 31% of the seafloor within these areas has been subjected to multiple passes by demersal trawls, and is likely that much of the biota vulnerable to such disturbance has been damaged or destroyed as result. However, the focus on a few locations has effectively constrained the trawl fishing footprint, so that large areas with similar environmental characteristics, and that beam trawl sampling indicates are likely to support many of the same groups of taxa as found within the trawl footprint, have not been trawled.

#### **2. The spatial distribution of longline effort at HIMI**

The results of this study show that the majority of benthic invertebrates at HIMI are predicted to live in depths shallower than 1000 m. This contrasts with the fishing footprint of the longline, which, while it has been able to attain commercially viable catch rates over a wider area than trawling, primarily fishes at depths >1000 m where the abundance of most vulnerable taxa is low. Hence, with the exception of the few taxa for which the deeper slopes are an important habitat such as euryalids and stalked barnacles, as well as the smaller amount of area disturbed by each longline event relative to most trawls, longline effort does not contribute greatly to the total amount of benthic taxa killed or damaged in our analysis.

#### **3. The HIMI Marine Reserve**

The HIMI Marine Reserve was established using design principles that attempted to ensure that comprehensive, adequate and representative areas of the seascape in the region were protected (Meyer *et al.* 2000, Welsford *et al.* 2011). Parts of nearly all of the geomorphs identified in the region are included within the Reserve including the tops and slopes of many of the banks and the shallow waters adjacent to the Territorial Sea, which are important locations for nearly all of the taxonomic groups vulnerable to demersal fishing. Consequently, these habitats were protected relatively early in the development of the fishery and resulted in large areas having now experienced only

minimal disturbance from commercial or research fishing or research sampling (Tables 16 and 17).

The assessments in this study show that it is unlikely that disturbance due to fishing has caused a significant impact to benthic biodiversity in the Australian EEZ at HIMI, even for the most vulnerable taxa such as sponges, corals and bryozoans.

**Table 16. Planimetric seafloor areas within fishable depth inside and outside the HIMI Marine Reserve (MR) and Conservation Zone (CZ). Areas were calculated in ArcGIS 10.1 using a Lambert Azimuthal Equal Area projection (Central Meridian 75.594°E, Latitude of Origin 51.877°S). Bathymetry courtesy of Australian Antarctic Data Centre.**

Depth range (m)	Total area in EEZ (km <sup>2</sup> )	Total area in MR (km <sup>2</sup> )	% of total area in MR	Total area in CZ (km <sup>2</sup> )	% of total area in CZ
0-200	4 517.5	3 549.2	78.6	1.7	0.0
200-400	28 844.4	12 840.8	44.5	2 278.2	7.9
400-600	26 746.0	8 704.3	32.5	1 909.2	7.1
600-800	23 665.9	2 796.2	11.8	2 343.9	9.9
800-1000	12 266.7	1 838.1	15.0	1 434.3	11.7
1000-1200	16 377.2	1 987.6	12.1	1 233.9	7.5
1200-1400	17 052.4	1 432.0	8.4	587.5	3.4
1400-1600	22 428.7	893.7	4.0	485.0	2.2
1600-1800	20 351.6	906.4	4.5	257.0	1.3
1800-2000	20 988.9	727.5	3.5	228.1	1.1
2000-2200	18 216.4	707.3	3.9	241.3	1.3
2200-2400	15 668.1	629.9	4.0	276.0	1.8
Total	227 123.8	37 013.0	16.3	11 276.1	5.0

**Table 17. Percentage of biomass of structure-forming benthic taxa vulnerable to demersal fishing estimated to be within the HIMI Marine Reserve (MR) and Conservation Zone (CZ) in depths less than 1200 m. Taxa abbreviations as in Table 12.**

Taxon	Proportion of total in the MR	Proportion of total in the CZ
ALY	41.4	4.8
ATX	39.1	3.4
BZN	55.4	5.4
BWY	25.0	22.1
CSS	32.8	4.7
ECH	45.5	16.1
EUR	15.8	11.4
GGX	32.8	18.1
HYD	55.3	2.2
POD	50.0	20.3
PTR	51.3	20.4
SSX	49.1	12.9
WOR	50.4	9.1
All	41.2	13.7

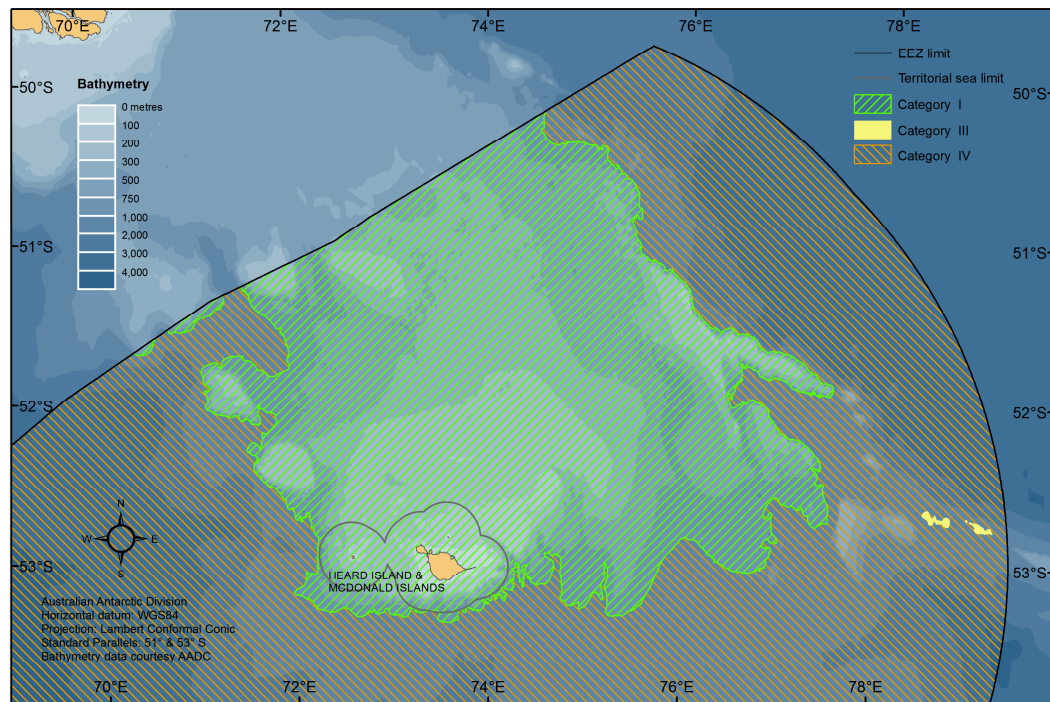
## Mitigation of demersal fishing impacts to benthic habitats in the Southern Ocean in the long term

We propose that the seascape can be categorised into one of four categories, based on the results of this study on the distribution of taxa, the relative vulnerability of those taxa and the current level of protection from disturbance due to fishing e.g. through the marine reserve (Table 18). This categorisation can be used to determine priorities for data collection in different areas as well as interim management measures. It is sufficiently generic that it could be applied in any area of the Southern Ocean, taking into account the specific distribution of spatial management measures, known or modelled distribution of benthic taxa or habitats and their vulnerability to the fishing gear used in the area.

We categorise the majority of the seascape as falling into Category I (the shallow plateau and banks, with relatively high vulnerability, but with substantial areas represented in the Marine Reserve) or Category IV (the deeper slope and abyssal plain with relatively low vulnerability) (Figure 18). In these areas, and given current fleet dynamics, the impacts to benthic biodiversity by disturbance caused by fishing are unlikely to increase dramatically in a single season. Therefore, a risk mitigation strategy involving longer-term monitoring and assessment of patterns in biodiversity is recommended, say every 5 years, as species respond to altering environmental conditions such as brought about by climate change.

**Table 18. Schema for categorisation of benthic habitats based on level of knowledge of vulnerability to demersal fishing and existing protection, and assessment approaches to assess long-term risk of impacts to benthic biodiversity.**

Category	Description	Assessment approach
I	Relatively high vulnerability, substantial areas represented in the Marine Reserve	Conduct long- term monitoring and assessment of stability or change in biodiversity
II	Relatively high vulnerability, substantial areas not represented in the Marine Reserve	Conduct regular status and risk assessments.
III	Vulnerability unknown	Obtain data on the nature and extent of habitat and gear interactions. Conduct regular status and risk assessments.
IV	Relatively low vulnerability	Conduct long term monitoring and assessment of stability or change in biodiversity



**Figure 18. Categorisation of the seascape within the EEZ at HIMI according to the distribution of vulnerable taxa, existing protection afforded by the Marine Reserve and the schema in Table 16. Note no Category II areas were identified.**

Where there are likely to be benthic taxa vulnerable to disturbance by fishing and no mechanisms such as Marine Protected Areas exist to ensure adequate protection of representative areas of benthic biodiversity (Category II), or the presence or vulnerability of taxa is unknown (Category III), it is recommended that status and risk assessments are undertaken regularly to increase the likelihood that significant impacts can be foreseen and avoided.

Furthermore, Category III areas would be a priority for data collection in order to determine the taxa present and the nature and extent of interactions that may occur in an expanded fishery, for example using targeted scientific sampling and BICS deployments during exploratory fishing in the area. This data can then be used to assess status prior to an expansion of the fishing footprint and to determine the areas where there may be increased risk to benthic biodiversity. The two groups of seamounts to the East-Southeast of HIMI represent an example of this category, as no video or biological samples have been collected from these areas. Also, the emergence of their peaks into water shallower than 1000 m and their relative isolation from the main plateau increases the likelihood that benthic biodiversity may be different to that already represented in the Marine Reserve.

## **Management Strategy Evaluation**

The assessment methodology developed here and applied to the bottom fishing activities at HIMI was able to successfully assimilate a range of empirical data (using BICS and scientific samples) on the nature and extent of interactions between fishing gear (trawls and longlines) and the benthos, and to spatially resolve estimates of the extent of disturbance caused by demersal fishing at HIMI for the period 1997-2013. Notably, the predicted quantities of biota killed or damaged by demersal trawl and longline (Table 13) are of a similar magnitude to the bycatch reported from the fishery (Tables 5 and 6), indicating that the modelling approach and parameter values used can produce realistic estimates of the scale of disturbance that may result from demersal fishing.

Currently, the assessment for HIMI does not take account of recovery of benthos following disturbance or the implications of disturbance in one area for the ecology of benthos in other areas. Many of the vulnerable taxa assessed are likely to have slow growth, be long-lived and late maturing, as well as having limited dispersal ability. We therefore consider that it is a reasonable simplifying assumption in the model that no recovery (that is no replacement of organisms that have been killed, or regrowth of damaged organisms) has occurred over the 13 year period assessed. However, some relatively resistant taxa, such as encrusting bryozoans, or other species adapted to take advantage of new patches of unoccupied habitat, may come to dominate some areas as co-occurring but less resistant taxa are removed at a higher rate. Hence the extent of change in community structure would also be useful to investigate.

The importance of indirect effects on areas outside the area of fishing disturbance is also an important question for future work. For example, while the estimate of area disturbed may be relatively small, some areas may have particular importance as a source for propagules. Therefore disturbance of these areas may have a greater impact than if the disturbed areas happened to be sinks. The development of the *Patch* management strategy evaluation tool (Appendix 14) makes it possible to investigate the impact of these assumptions on the outcome of the assessment, and we recommend that such work be done as an important extension of this project.

## **Benefits and adoption**

The beneficiaries originally identified in the proposal for this project have benefitted as follows:

### **The Australian Fishing Industry in the Heard Island and McDonald Islands Fishery**

Elements of this project have already been used to support the existing certification of the Mackerel icefish and Patagonian toothfish fisheries by the Marine Stewardship Council. Understanding the impacts by these fisheries is a key element of the assessment process for this certification. Research included in this report has also been used in a recent independent review of toothfish fisheries globally by the Monterey Bay Aquarium (MBAQ), which took into account the impact of fishing on benthic habitats and identified HIMI longline-caught toothfish as a 'best choice' species<sup>6</sup>. These outcomes have a direct benefit in terms of market access for product from these fisheries as the MSC and MBAQ have a high profile internationally and are acknowledged as involving rigorous assessment processes. Therefore many markets are moving to require product to have been reviewed by these organisations.

### **The Department of the Environment, Australian Antarctic Division and Director of National Parks**

The Director of National Parks and AAD share responsibility for administering HIMI, the World Heritage Area and the Marine Reserve and Conservation Zone under the Environmental Protection and Biodiversity Conservation Act. They have benefitted from this study through the availability of improved information on the role of the Marine Reserve and the Conservation Zone in effectively protecting biodiversity in the region. The results of this project have directly led to the recommendation for some areas of the Conservation Zone to be added to the Marine Reserve. It also confirms that the design principles used for the HIMI reserve are robust to the lack of data available when the Reserve was established, supporting the use of these principles in similar circumstances elsewhere in the Australian EEZ.

### **The Australian Fisheries Management Authority**

As a result of this study, AFMA observers who are deployed on fishing vessels now have available the *Field identification guide to Heard Island and McDonald Islands benthic invertebrates: A guide for scientific observers aboard fishing vessels* (Hibberd & Moore 2009). This has showed substantial dividends in terms of the taxonomic resolution of reporting of invertebrate bycatch at HIMI and the Macquarie Island Toothfish Fishery. AFMA will also benefit from the results of this project to update its Ecological Risk Assessments for the HIMI fisheries due in 2014.

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<sup>6</sup> [www.montereybayaquarium.org/cr/cr\\_seafoodwatch/content/media/MBA\\_SeafoodWatch\\_ChileanSeabassReport.pdf](http://www.montereybayaquarium.org/cr/cr_seafoodwatch/content/media/MBA_SeafoodWatch_ChileanSeabassReport.pdf)

### **The Commission for the Conservation of Marine Living Resources**

Data from this project has already been used by CCAMLR in its current bottom fishing risk assessment methodology, including the likelihood and extent of lateral movement by longlines. CCAMLR has also posted the Hibberd & Moore (2009) identification guide for general use by vessel crews and observers operating across the CCAMLR area. The project team has presented a number of outputs from this project to CCAMLR (e.g. Constable & Holt 2007, Constable *et al.* 2007, Constable 2009, Ewing *et al.* 2010a, Ewing *et al.* 2010b, Hibberd 2009, Hibberd *et al.* 2010, Martin-Smith 2009b, Martin-Smith 2009c, Welsford & Kilpatrick 2008) that have been influential in the development of concepts and methods that CCAMLR uses in managing the impacts of bottom fishing.

The results of the assessment at HIMI will also benefit CCAMLR in that it indicates that CCAMLR is likely to be achieving its goals under Article II of the Convention on CAMLR and the intent of UNGA resolution 106/51 in the HIMI region, which covers the majority of CCAMLR Division 58.5.2.

## **Further development**

Management of the impacts of demersal fisheries would benefit from further development on several themes that are beyond the scope or timeframe of this project. These include:

### **Comparing and evaluating alternative procedures to conserve benthic habitats in domestic and international fisheries**

Since the development of this project, several alternative methods of assessing the risks associated with fishing on benthic habitats have emerged; the Ecological Risk Assessments conducted on all Commonwealth managed fisheries in Australia (Hobday *et al.*, Williams *et al.* 2011) and assessments in regional management organisations such as the South Pacific Regional Fisheries Management Organisation (SPRFMO; <http://www.southpacificrfmo.org/benthic-impact-assessments/>) and in CCAMLR (Martin-Smith 2009a, SC-CAMLR 2012b, Sharp *et al.* 2009). A review of the differences and similarities between these approaches as well as assessment of the likely performance of these methods using management strategy evaluation techniques would be timely.

### **Upgrading video technology and collecting additional data on demersal gear interactions in deep-seas fisheries**

Less expensive, more compact and more robust camera, lighting and battery components are continually becoming available. An opportunity therefore exists for upgrading the BICS, which is already proven to be low cost to build and use as well as relatively simple and robust to deploy at sea, to make it even more straightforward to deploy from commercial fishing vessels. The routine application of such methods when fishing occurs in areas without data on benthic habitats would provide information that could be used to refine risk assessments at HIMI and other areas of the Southern Ocean, and assembling simpler and less expensive equipment will make this application easier and more likely.

### **Systematic sampling of under-represented ecoregions in the Southern Ocean**

The generalised additive modelling of taxa using data from samples from banks, plateau and upper slope at HIMI was a powerful way of predicting likely distribution of important areas for vulnerable taxa across the seascape. However, areas such as the chain of seamounts which form part of Williams Ridge to the East-Northeast of Heard Island, have not been sampled or fished extensively but are likely to support relatively high biomass benthic assemblages due to their biogeophysical attributes. Furthermore, their relatively isolated position away from the main plateau increases the likelihood that locally rare and endemic taxa occur there. Sampling such under-represented



ecoregions would provide additional data which could be used to refine predictive models for the distribution of fauna that may be vulnerable to impacts by fishing across the region as well as informing decisions as to any special management needs for the Williams Ridge seamounts at HIMI. This also applies in East Antarctica and other areas managed by CCAMLR, where opportunities exist for collecting data using the BICS from vessels engaged in exploratory fishing.

## **Planned Outcomes**

All of the outcomes originally foreseen for this project have been achieved, including:

### **1. Assessment of the vulnerability of benthic habitats and species to damage by demersal fishing, based on field observations and laboratory experiments**

Field observations including quantitative biological samples and *in situ* images of the benthos have enabled the identification of the taxa that are exposed to bottom fishing in the Southern Ocean including sponges, corals, bryozoans, pterobranchs and echinoderms. An assessment of the resistance of these taxa to the forces exerted by different components of the most prevalent bottom fishing gear types at HIMI has also enabled the estimation of the relative vulnerability of these different taxa to disturbance by fishing.

### **2. Assessment of the risks from demersal fishing to the sustainability of demersal habitats based on field work and knowledge from the literature on recovery of different types of benthic species and habitats**

The analyses in this report confirm that the demersal fishing gears used in the Southern Ocean can pose a risk to benthos, particularly where fishing effort occurs in areas that are important habitat for sessile, long-lived and slow growing species such as bryozoans, sponges and gorgonians. However, this risk can be mitigated through a management system that provides sufficient protection to representative areas, includes regular impact assessment, prioritises data collection in areas where the nature and extent of interactions between gear and benthos is uncertain, and where evaluation of management procedures occurs early in the development of a fishery.

### **3. Modifications as needed to either fishery management or fishing practices in the HIMI and/or other Southern Ocean fisheries and demersal fisheries generally**

This report indicates that the distribution of fishing relative to areas predicted to have high invertebrate biomass as well as the representation of important benthic habitats in the Marine Reserve has substantially reduced the likelihood that the current patterns of fishing at HIMI are ecologically unsustainable. Consequently, with the exception of consideration of measures to ensure the habitats on Williams Ridge Seamounts in the EEZ are adequately protected, it is not apparent that any modifications to fishery management or fishing practices at HIMI are needed if the fishery continues as it has in the past. Circumstances vary throughout the Southern Ocean and in demersal fisheries generally, particularly where Marine Reserves or MPAs do not yet exist. Nevertheless, the methods developed here have the potential to assist with assessments of these fisheries.

#### **4. Improved knowledge of the distribution and species composition of marine benthic ecosystems in the Australian EEZ.**

The sampling conducted at HIMI and the deep-sea habitats near the Shackleton Iceshelf during this project has substantially improved the data available on patterns of biodiversity in these areas. This data has contributed directly to outcomes including the review of the HIMI Conservation Zone, agreement to include additional area in the HIMI Marine Reserve and the proposal for a representative system of MPAs in East Antarctica currently being considered by CCAMLR.

A number of publications and meetings contributed to these outcomes. Results from this study were presented to government and industry stakeholders at meetings through the life of this project, notably the HIMI Stakeholder Group and the AFMA Subantarctic Resource Assessment Group (SARAG). In particular, dedicated workshops to discuss the results were held in Canberra (March 2014) and at SARAG (April 2014). Results from a number of report chapters have been presented at the CCAMLR Working Group for Ecosystem Monitoring and Management (Appendix 3 and 14) and the 2009 CCAMLR Workshop on Vulnerable Marine Ecosystems (Appendix 3), and published in peer-review journals (Appendix 4). A field identification guide of benthic invertebrates at Heard Island and the McDonald Islands was published and is used by scientific observers on commercial fishing vessels to identify benthic bycatch at HIMI. The final report will be submitted to CCAMLR's Scientific Committee and relevant components to its Working Group on Fish Stock Assessment in 2014 in support of the precautionary ecosystem-based approach to management of the marine environment at HIMI by Australia.

## Conclusions

This project has achieved all of its objectives. An important product of this project was the successful design, creation and deployment by fisheries observers of the Benthic Impacts Camera System which has provided some of the first information on the dynamics of fishing gears used in bottom fisheries in the Southern Ocean, notably demersal longlines. Footage captured by the camera revealed the extent to which these gears interact with the benthos, as well as the types of benthic megafauna present where commercial fishing operates at HIMI and is currently being successfully used at South Georgia to similar ends. The camera system was also sufficiently versatile to be used as a drop camera to reveal patterns of diversity and abundance of benthic megafauna in the Shackleton Iceshelf region, and capture the first ever footage of krill mating behaviour. We consider that such a system has great potential to be used to enhance impact assessments such as those used in the bottom fisheries in CCAMLR or the AFMA Ecological Risk Assessment, where *in situ* information on disturbances caused by bottom fishing gear is currently limited.

This project also enabled the articulation of the essential components of a management procedure to conserve benthic biodiversity, utilising data from fisheries and fisheries-independent observations and research. Further, it has developed tools to enable evaluation of management procedure to conserve benthic habitats at HIMI, and other management regimes such as CCAMLR exploratory fisheries. We recommend this evaluation take place as a priority in CCAMLR, while the impacts caused by current bottom fishing activity in the Southern Ocean is still considered relatively limited (SC-CAMLR 2012b).

Given the representation of significant areas of important benthic habitat in the Marine Reserve, the assessment of disturbance to date, and the expected pattern of fishing in the future, the risk that fishing will cause significant impacts to benthic biodiversity at HIMI is likely to continue to be low over the medium term. Evaluation of risk in the longer term may change depending on factors such as the distribution of fishing effort, the types of fishing gears used, recovery rates of taxa, additional information on the distribution of vulnerable taxa and the management procedures applied. Therefore it is difficult to provide an assessment of the long term impact of demersal fishing at HIMI. As a consequence we recommend that status and risk assessments for the fishery be updated regularly, and that simulation studies be undertaken to evaluate the likely performance of the current management approach in the long term.

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## **Appendix 1. Intellectual Property**

No intellectual property is identified as arising from this project.

The dataset generated from this project is housed in a secure database at the AAD. A metadata record describing the datasets and terms of use has been lodged with Australian Antarctic Data Centre (<http://data.aad.gov.au/>).

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### **Appendix 3. Assessing the relative vulnerability to disturbance of benthic, habitat-forming organisms in the Southern Ocean using a global database of life history characteristics and environmental correlates**

Keith Martin-Smith and Dirk Welsford

*Adapted from:*

*Martin-Smith, K., (2009). Predicting the vulnerability of benthic, habitat-forming organisms to disturbance using life-history characteristics. CCAMLR document WG-EMM-09/35, presented to the CCAMLR Working Group for Ecosystem Monitoring and Management*

*Martin-Smith, K., (2009). A database of life-history attributes for habitat-forming benthic taxa, CCAMLR Document WS-VME-09/11, presented to the CCAMLR Workshop on Vulnerable Marine Ecosystems*

*Martin-Smith, K. (2009). Predicting the vulnerability of bryozoans and sponges to disturbance using life-history characteristics. CCAMLR document WS-VME-09/12, presented to the CCAMLR Workshop on Vulnerable Marine Ecosystems*

#### **ABSTRACT**

Benthic habitats in deep water beyond the influence of surface processes such as storms or iceberg scour (i.e. greater than 500 m depth) are considered to experience low levels of physical disturbance. Increasingly, demersal fisheries in the high seas, including the Southern Ocean, are operating in these depths with consequent risk of impacts to benthic habitats. However, assessing these impacts is hampered by the paucity of information on the resistance and resilience of these ecosystems to disturbance. Both resistance and resilience of individual habitat-forming taxa are related to their life-history characteristics. A review of life-history characteristics, including growth rate, age, maximum size and reproductive parameters, showed that there were strong, consistent relationships among life-history characteristics and correlations with physical and chemical variables across a number of different phyla. For the phylum Cnidaria, an important group of habitat-forming organisms, there were significant negative correlations between growth and age, significant correlations with temperature (positive for growth, negative for age) suggesting that these taxa will show low resilience to disturbance. Similarly, bryozoans showed a strong negative relationship between growth rate and age and a strong positive relationship between growth rate and temperature, while demosponges showed a strong positive relationship between maximum size and age. Recovery trajectories in the orders of many decades or centuries are predicted.

## Introduction

Benthic invertebrates such as corals, sponges and bryozoans provide important habitat for other organisms as their complex body shapes provide substrates for epibionts and refugia for smaller organisms. However, in the deep ocean, factors such as low levels of energy input and a natural regime of disturbance that may occur over very long time scales, has led to the evolution of life history strategies where organisms may grow slowly, live for decades or centuries and have low dispersal capabilities.

Human activities such as demersal fishing (particularly trawling) have been linked to impacts on benthic habitats (Crowder *et al.* 2008, Cryer *et al.* 2002, Kaiser *et al.* 1999, Kaiser 2003, Kaiser *et al.* 2003, Kaiser *et al.* 2006) For example, changes such as destruction of benthic habitat structure (Koslow *et al.* 2001) through the local extinction of species (Hiddink *et al.* 2006) to wholesale shifts in the functioning of entire ecosystems (Jennings *et al.* 2001, Kaiser *et al.* 2000) have been attributed to demersal fishing. Consequently multi-lateral agreements have arisen in recent years to attempt to more effectively manage fishery disturbance, with a view to mitigating the risk of irreversible impacts to benthic habitats. To that end, the United Nations General Assembly resolution 106/51:

*“Calls upon States to take action immediately, individually and through regional fisheries management organizations and arrangements, and consistent with the precautionary approach and ecosystem approaches, to sustainably manage fish stocks and protect vulnerable marine ecosystems, including seamounts, hydrothermal vents and cold water corals, from destructive fishing practices, recognizing the immense importance and value of deep-sea ecosystems and the biodiversity they contain”* (UNGA 2007)

In response to this resolution, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the body responsible for managing fishing activities in the Southern Ocean, committed to avoiding significant adverse impacts on vulnerable marine ecosystems and has subsequently been involved in developing management measures (e.g. CCAMLR 2008, Constable & Holt 2007, SC-CAMLR 2009).

The vulnerability of a thing, organism or ecosystem incorporates the properties that make it more likely to be changed on exposure to a particular disturbance e.g. the interaction between fishing gear and benthic invertebrates. Any particular entity will respond differently to different kinds of disturbance. For example deep-sea corals, which stand above the seafloor, are attached, brittle and slow-growing, have been observed to be damaged or destroyed by demersal trawling (Roberts & Hirshfield 2004), and hence it can be inferred that other similar organisms are vulnerable to this activity. The concept of a ‘vulnerable marine ecosystem’ is therefore only valid when considered with respect to a particular type of disturbance. Furthermore, as noted in the text of UNGA resolution 61/105, large, structure-forming invertebrates are the primary signifier of vulnerable marine ecosystems. Therefore, we contend that managing the impacts of fishing on assemblages of such organisms is likely to make an

important contribution towards satisfying the intent of the UNGA resolution, and maintaining the productivity and biodiversity of deep-sea benthos.

The outcomes of interactions of bottom fishing gear with benthic assemblages will depend on their resistance and resilience. In this context, resistance is the ability to withstand interactions with bottom fishing gear and will be dependent on the morphological and behavioural attributes of individual taxa (Thrush & Dayton 2002). Resilience is the ability to recover structure and function following disturbance. Resilience is strongly dependent on life-history characteristics of the benthic taxa involved including regeneration from sub lethal injury, movement into disturbed areas, recolonisation from undisturbed areas and subsequent growth rate (Crowder & Norse 2008, Thrush & Dayton 2002).

Benthic marine ecosystems in the Southern Ocean harbour significant levels of biodiversity (Brandt *et al.* 2007b, Clarke *et al.* 2004, Gutt *et al.* 2004), and endemism (Barnes & Griffiths 2008, Brandt *et al.* 2007b, Rogers 2007). However, the prohibitive cost and logistic difficulties associated with working in the Southern Ocean mean that scientific research has been relatively limited and it consequently remains one of the most sparsely studied regions on the planet.

In the absence of empirical evidence on the responses of deep-sea benthic habitats in the Southern Oceans to disturbance, alternative approaches need to be considered. In this study, meta-analyses of a global database on life-history characteristics of benthic habitat-forming organisms compiled for the purpose have been used to investigate whether general relationships exist among life-history characteristics or with physical and chemical habitat parameters. These relationships are then used to predict the life-history characteristics of these organisms in the Southern Ocean from available physical and chemical data. The analyses are presented for the phyla Cnidaria, Bryozoa and Porifera since these organisms are known to be a common part of the benthic megafauna in the Southern Ocean (Barry *et al.* 2003) as well as being specifically mentioned as VME forming organisms in UNGA Resolution 61/105 and the FAO Guidelines on Management of Deep-Sea Fisheries (FAO 2009).

## Methods

### Database

Data for inclusion in the life-history database were sought on structure-forming invertebrate taxa (Table A3.1). These data were obtained from the peer-reviewed scientific literature including journal papers, government or NGO reports. Searches were undertaken using scientific indexing tools (e.g. Web of Science), internet search engines and library catalogues using key words including each of the life-history characteristics of interest in combination with various taxonomic descriptors. Over 1200 records were considered from these searches, each with as many life history data fields as possible completed (Table A3.2).

**Table A3.1. Invertebrate groups that are structure forming and/or vulnerable to disturbance by bottom-fishing considered in database of life-history characteristics. CCAMLR VME indicator= taxa are determined to be evidence of vulnerable marine ecosystems in the Southern Ocean (SC-CAMLR 2009).**

Phylum	Lower taxonomic groups (where applicable)	Common Name	Sessile/Sedentary (S) or Motile (M)	CCAMLR VME indicator
Annelida	Order Vestimentifera	Vent worms	S	-
	Family Serpulidae	Serpulid worms	S	Y
	Family Sabellidae	Sabellid worms	S	-
Brachiopoda		Lamp shells	S	Y
Cnidaria	Family Stylasteridae	Hydrocorals	S	Y
	Order Ceriantharia	Tube anemones	S	Y
	Order Antipatharia	Black corals	S	Y
	Order Alcyonacea	Soft corals	S	Y
	Order Gorgonacea	Gorgonians	S	Y
	Order Pennatulacea	Sea pens	M	Y
	Order Helioporacea	Blue corals	S	Y
	Order Actiniaria	Anemones	M	Y
	Order Zoantharia	Zoanthids	S	Y
	Order Scleractinia	Stony corals	S	Y
	Order Stauromedusae	Stalked jellyfish	S	Y
Echinodermata	Class Asteroidea	Starfish	M	-
	Class Crinoidea	Crinoids	M	Y
	Class Echinoidea	Sea urchins	M	Y
	Class Holothuroidea	Sea cucumbers	M	-
	Class Ophiuroidea	Brittle stars	M	Y
Bryozoa		Bryozoans	S	Y
Foraminifera	Xenophyophores	Forams	S	Y
Mollusca	Class Bivalvia	Bivalves	M	Y
	Class Gastropoda	Gastropods	M	-
	Class Scaphopoda	Tusk shells	M	-
Phoronida		Horseshoe worms	S	-
Porifera	Class Calcarea	Calcareous sponges	S	-
	Class Demospongiae	Sponges	S	Y
	Class Hexinactinellida	Glass sponges	S	Y

There were some issues related to data consistency when considering such a large number of different studies that may not have been performed under the same conditions or for the same reasons. For example, growth rates in some studies were measured as an increase in linear dimension whereas in other studies radial measurements were used. Some data sets consist of aggregated records for a number of

individuals whereas others provide individual measurements. In particular, estimates of age were rarely measured directly in any study, but usually inferred from radiometric methods, counts of periodic growth marks or estimated from growth curves. In most cases only a few individuals were aged from opportunistic collections. These individuals do not necessarily represent the oldest in the population and thus their ages represent a lower bound for longevity in these organisms. However, if these sources of error across the different data sets are random then any emergent patterns are likely to be robust.

In the phylum Cnidaria, a total of 150 individual records of at least 68 different species were selected, including 17 records of six species from the Southern Ocean (See supplementary materials). The majority of these records ( $n = 93$ ) were of taxa in the family Gorgonacea (gorgonians or sea fans) so the data were divided into two groups: (1) gorgonians, (2) other cnidarians which included soft corals (Alcyonacea), black corals (Antipatharia), sea pens (Pennatulacea), stony corals (Scleractinia), hydrocorals (Stylasteridae) and zoanthids (Zoantharia). In the phylum Bryozoa a total of 64 records of 45 taxa were identified while in the phylum Porifera there were 77 records of >71 demosponge taxa and 15 records of 12 hexactinellid (glass sponge) taxa. None of the records contained data in all the life-history characteristic fields and, therefore, each individual analysis was undertaken on a subset of these extracted data. Data on sessile groups other than cnidarians, poriferans or bryozoans were limited, and so we limited the analysis of these three groups.

Physical and chemical habitat parameters were obtained from the World Ocean Atlas 2005 (WOA05)<sup>7</sup> database for the one degree by one degree grid cell containing the sample location reported by the authors.

### Statistical analysis

For each group all data were checked for normality and transformed (log or arcsine) where necessary. However, some data could not be normalised, in particular some of the physical parameters. Where both variables were normally distributed, parametric bivariate correlations (Pearson's  $r$ ) were performed among biological variables and between each biological variable and each physical or chemical variable. Where one or both variables were not normally distributed non-parametric bivariate correlations (Spearman's  $\rho$ ) were performed. Similar bivariate correlations were performed among physical and chemical variables.

Where significant correlations between biological and physical or chemical variables were identified, multiple linear regression was used to construct predictive models. To avoid multiple collinearity between predictor variables, each was entered independently and rejected if the subsequent model did not produce a significant

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<sup>7</sup> [http://www.nodc.noaa.gov/OC5/WOA05/pr\\_woa05.html](http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html)

increase in the  $F$  ratio. All models were also repeated with predictor variables introduced in different orders and rejected if significantly different results were obtained.

**Table A3.2. Data fields populated for the database of life-history parameters of structure forming and/or vulnerable to disturbance by bottom-fishing benthic organisms. Note not all fields were completed for all groups.**

Data Field	Units	Description
Reference	none	Study from which data have been taken
Location	none	Geographical region of study
Latitude	°	Geographical coordinate of sample
Longitude	°	Geographical coordinate of sample
Sample depth	m	Exact depth or depth range
Median depth	m	Exact depth or median of depth range
Min depth	m	Exact depth or minimum depth of depth range
Max depth	m	Exact depth or maximum depth of depth range
Species	none	Species name or genus name where identification was problematic
Higher taxon	none	Order or family
Mean linear growth rate	mm yr <sup>-1</sup>	Mean rate of increase in individual size or branch length/colony height for colonial organisms
Min linear growth rate	mm yr <sup>-1</sup>	Minimum linear growth rate
Max linear growth rate	mm yr <sup>-1</sup>	Maximum linear growth rate
Mean specific growth rate	% mo <sup>-1</sup>	Mean specific growth rate
Min specific growth rate	% mo	Minimum specific growth rate
Max specific growth rate	% mo	Maximum specific growth rate
Mean radial growth rate	mm yr <sup>-1</sup>	Mean rate of increase in branch diameter for colonial organisms
Min radial growth rate	mm yr <sup>-1</sup>	Minimum radial growth rate
Max radial growth rate	mm yr <sup>-1</sup>	Maximum radial growth rate
Von Bertalanffy growth coefficient	yr <sup>-1</sup>	Estimated values of growth coefficient $K$ from von Bertalanffy growth equation
Age range	yr	Range of ages given in study for mature individuals or colonies from direct measurement, radiometric dating or inferred from growth marks/von Bertalanffy growth curves
Min age	yr	Minimum age from age range
Max age	yr	Maximum age from age range
Max height	mm	Maximum height of individual or colony
Max diameter	mm	Maximum diameter of individual or colony
Mating system	none	Gonochoric, simultaneous hermaphrodite, sequential hermaphrodite
Reproductive season	months	Period during which reproduction was observed or inferred from histology
Fertilisation type	none	Internal or external fertilisation
Larval dispersal type	none	Broadcast spawning, internal or external brooding
Larval competency	d	Period during which larvae can settle and metamorphose successfully
Size/age at first reproduction	mm/yr	Minimum height or age at which gametes were observed
Temperature	°C	Mean annual values for 1° grid cell containing sample location extracted from World Oceans Atlas 2005 database <a href="http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html">http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html</a>
Oxygen concentration	mg l <sup>-1</sup>	"
Oxygen saturation	%	"
Salinity	‰	"
Nitrate	µmol l <sup>-1</sup>	"
Silicate	µmol l <sup>-1</sup>	"
Phosphate	µmol l <sup>-1</sup>	"

## Results

### Gorgonians

Significant negative correlations were found between age and growth rate in gorgonians, with stronger correlations between linear growth than for radial growth (Table A3.3, Figures A3.1). There was no significant correlation between linear and radial growth rates (Table A3.3, Figure A3.1A). There were no relationships between maximum size and any other life-history variable. All of the physical and chemical habitat variables for the locations where the gorgonians were studied were highly correlated except for depth and oxygen concentration, and latitude and oxygen concentrations (Table A3.4).

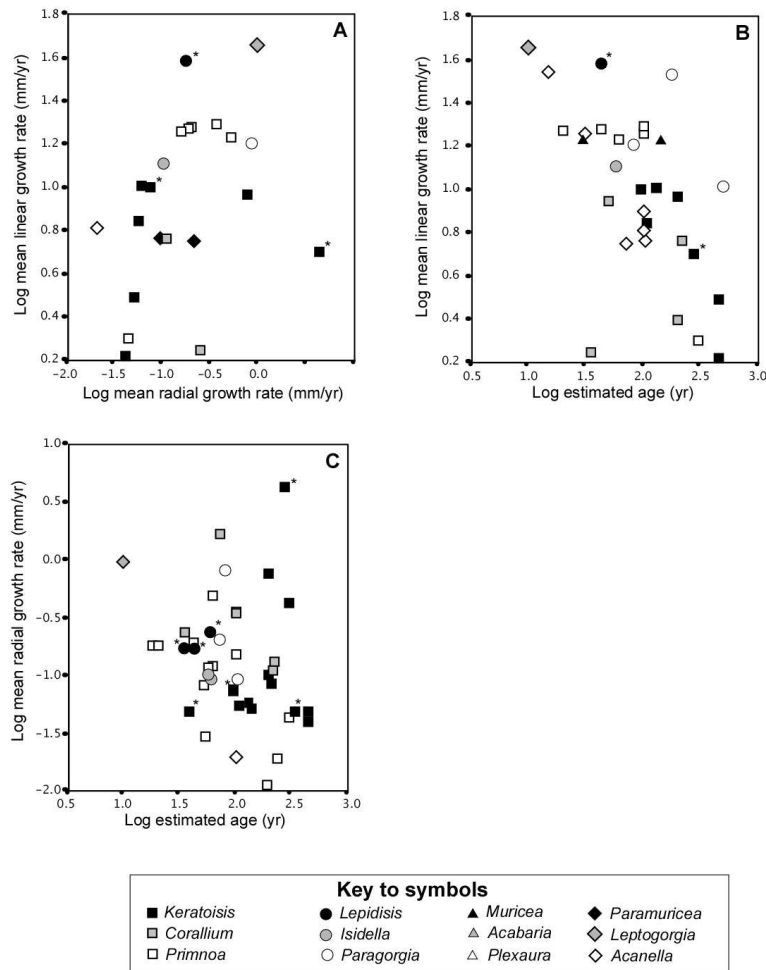
**Table A3.3. Correlations among life-history variables for gorgonians. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Linear growth rate	Radial growth rate	Minimum age	Maximum age	Maximum size
Linear growth rate	-	$r=0.380$ $p=0.081$ $n=22$	<b><math>r=-0.558</math></b> <b><math>p=0.001</math></b> <b><math>n=31</math></b>	<b><math>r=-0.591</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=31</math></b>	$\rho=-0.054$ $p=0.668$ $n=65$
Radial growth rate		-	$r=-0.251$ $p=0.109$ $n=42$	<b><math>r=-0.313</math></b> <b><math>p=0.044</math></b> <b><math>n=42</math></b>	$\rho=-0.099$ $p=0.524$ $n=44$
Minimum age			-	<b><math>r=0.910</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=55</math></b>	$\rho=0.140$ $p=0.308$ $n=55$
Maximum age				-	$\rho=0.162$ $p=0.238$ $n=55$

**Table A3.4. Correlations among physical and chemical habitat variables for gorgonians. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Latitude	Oxygen concentration	Oxygen saturation
Depth	-	<b><math>\rho=-0.862</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=86</math></b>	<b><math>\rho=0.631</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=86</math></b>	$\rho=-0.065$ $p=0.562$ $n=83$	<b><math>\rho=-0.866</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=83</math></b>
Temperature		-	<b><math>\rho=-0.820</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=87</math></b>	$\rho=-0.124$ $p=0.260$ $n=84$	<b><math>\rho=0.779</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=84</math></b>
Latitude			-	<b><math>\rho=0.477</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=84</math></b>	<b><math>\rho=-0.548</math></b> <b><math>p&lt;0.001</math></b> <b><math>n=84</math></b>
Oxygen concentration				-	<b><math>\rho=0.347</math></b> <b><math>p=0.001</math></b> <b><math>n=84</math></b>

Temperature was significantly correlated with all life-history variables; positively for both linear and radial growth rates and negatively for age and maximum size, (Table A3.5, Figure A3.2) as was oxygen saturation (Table A3.5). Similarly, depth was significantly correlated with all life-history variables; negatively for growth rate (both linear and radial) and positively for age and maximum size (Table A3.5, Figure A3.3). Linear growth rate was significantly negatively correlated with latitude, while maximum size was significantly positively correlated with latitude (Table A3.5).



**Figure A3.1.** Plot of point data for significant correlations among biological life history characteristics for gorgonians. Southern Ocean records are indicated with asterisk.



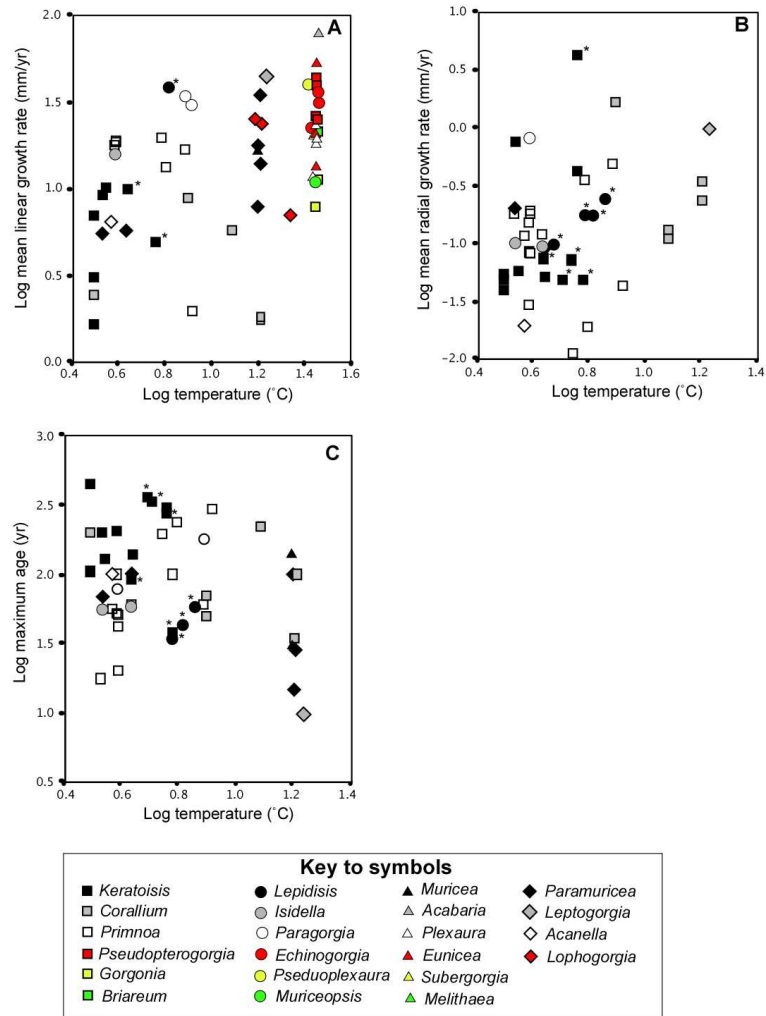
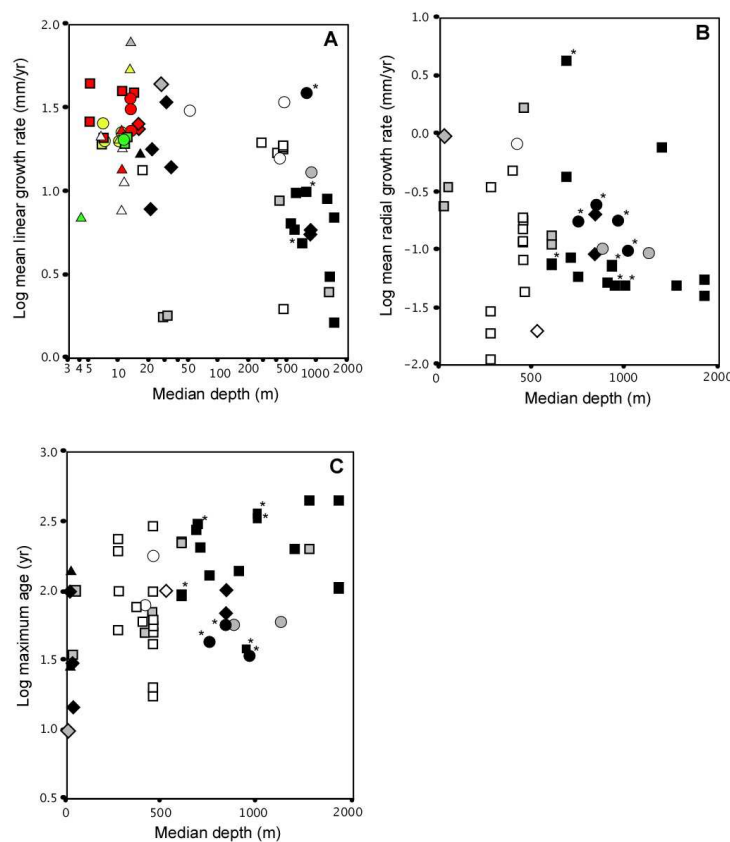


Figure A3.2. Plot of point data for significant correlations between life history characteristics and temperature for gorgonians. Southern Ocean records indicated with asterisk.

Table A3.5. Correlations between life-history variables and physical and chemical habitat variables for gorgonians. Significant correlations at the  $p < 0.05$  level shown in bold.

	Depth	Temperature	Latitude	Oxygen concentration	Oxygen saturation
Linear growth rate	$\rho = -0.521$ $p < 0.001$ $n = 63$	$r = 0.492$ $p < 0.001$ $n = 63$	$\rho = -0.470$ $p < 0.001$ $n = 63$	$\rho = -0.043$ $p = 0.743$ $n = 61$	$\rho = 0.439$ $p < 0.001$ $n = 61$
Radial growth rate	$\rho = -0.308$ $p = 0.044$ $n = 42$	$r = 0.370$ $p = 0.015$ $n = 43$	$\rho = -0.158$ $p = 0.311$ $n = 43$	$\rho = 0.245$ $p = 0.122$ $n = 41$	$\rho = 0.334$ $p = 0.033$ $n = 41$
Minimum age	$\rho = 0.434$ $p = 0.001$ $n = 51$	$r = -0.313$ $p = 0.025$ $n = 51$	$\rho = 0.071$ $p = 0.619$ $n = 51$	$\rho = -0.220$ $p = 0.128$ $n = 49$	$\rho = -0.319$ $p = 0.026$ $n = 49$
Maximum age	$\rho = 0.449$ $p = 0.001$ $n = 51$	$r = -0.312$ $p = 0.026$ $n = 51$	$\rho = -0.009$ $p = 0.952$ $n = 51$	$\rho = -0.310$ $p = 0.030$ $n = 49$	$\rho = -0.400$ $p = 0.004$ $n = 49$
Maximum size	$\rho = 0.283$ $p = 0.008$ $n = 86$	$\rho = -0.488$ $p < 0.001$ $n = 86$	$\rho = 0.478$ $p < 0.001$ $n = 86$	$\rho = 0.012$ $p = 0.915$ $n = 83$	$\rho = -0.404$ $p < 0.001$ $n = 83$

The best multiple regression model for linear growth rate in gorgonians included both temperature and depth ( $R^2=0.305$ ,  $F_{2,58}=12.70$ ,  $p<0.001$ ) while no significant model could be fitted for radial growth. Similarly for age and maximum size, the best multiple regression models included temperature and depth ( $R^2=0.242$ ,  $F_{2,45}=7.17$ ,  $p=0.002$  for age and  $R^2=0.454$ ,  $F_{2,79}=32.81$ ,  $p<0.001$  for maximum size). Using this model enabled the prediction of the lower bound for age of gorgonians at different depth and temperature combinations over a range representing the ambient conditions in the Southern Ocean (Figure A3.4), showing increasing expected ages with increasing depth and lower temperatures.



**Figure A3.3.** Plot of point data for significant correlations between life history characteristics and depth for gorgonians. Symbols as in Figure A3.2. Southern Ocean records indicated with an asterisk.

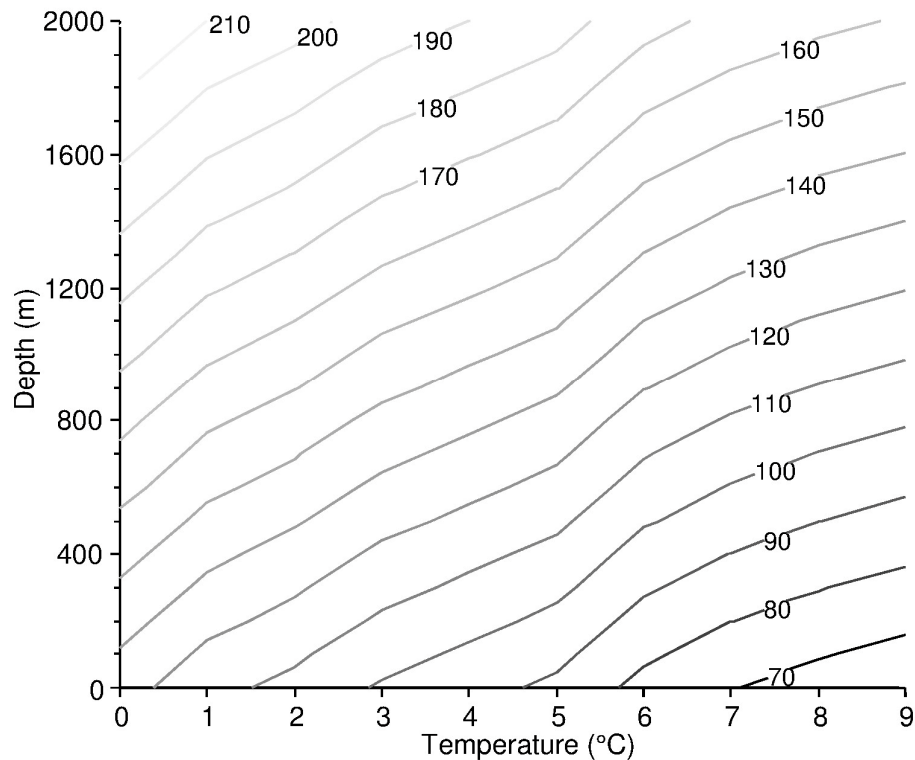


Figure A3.4. Predicted lower bound for age of gorgonians at different depth and temperature combinations based on a multiple regression model. Contour lines are marked in 10 year intervals.

### Other cnidarians

Sample sizes, and therefore power to evaluate relationships for cnidarians other than gorgonians were relatively low. The only significant correlations among life-history variables for other cnidarians were found for maximum size and linear growth, maximum size and age, and between minimum and maximum age (Table A3.6, Figure A3.5). Again, there was not a significant correlation between linear and radial growth rates (Table A3.6).

Many of the physical and chemical habitat variables were highly correlated, particularly depth and temperature, latitude and temperature, and oxygen saturation with both depth and temperature (Table A3.7).

Depth was correlated with all life-history variables except maximum size; negatively for growth rate (both linear and radial) and positively for age (Table A3.8, Figure A3.6). There were two conspicuous outliers in the relationship which were shallow-water species of *Balanophyllia* (Scleractinia) that had slow growth rates. Significant positive correlations were found between temperature and growth rate (both linear and radial) for other cnidarians (Table A3.8, Figure A3.7A-B). Oxygen concentration was significantly negatively correlated with all life-history variables except linear growth rate while oxygen saturation was significantly positively correlated with linear growth rate and significantly negatively correlated with minimum age (Table A3.8, Figure A3.7C-G).

**Table A3.6. Correlations among life-history variables for other cnidarians. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Linear growth rate	Radial growth rate	Minimum age	Maximum age	Maximum size
Linear growth rate	-	$r=0.746$ $p=0.148$ $n=5$	$r=-0.061$ $p=0.787$ $n=22$	$r=-0.083$ $p=0.715$ $n=22$	$r=0.485$ $p=0.001$ $n=41$
Radial growth rate		-	$r=-0.426$ $p=0.192$ $n=11$	$r=-0.196$ $p=0.564$ $n=11$	$r=0.022$ $p=0.950$ $n=11$
Minimum age			-	$r=0.947$ $p<0.001$ $n=32$	$r=0.365$ $p=0.040$ $n=32$
Maximum age				-	$r=0.357$ $p=0.045$ $n=32$

**Table A3.7. Correlations among physical and chemical habitat variables for other cnidarians. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Latitude	Oxygen concentration	Oxygen saturation
Depth	-	$r=-0.661$ $p<0.001$ $n=43$	$\rho=-0.092$ $p=0.526$ $n=50$	$\rho=-0.326$ $p=0.031$ $n=44$	$\rho=-0.739$ $p<0.001$ $n=44$
Temperature		-	$\rho=-0.583$ $p<0.001$ $n=44$	$\rho=-0.271$ $p=0.079$ $n=43$	$\rho=0.754$ $p<0.001$ $n=43$
Latitude			-	$\rho=0.785$ $p<0.001$ $n=45$	$\rho=-0.142$ $p=0.351$ $n=45$
Oxygen concentration				-	$\rho=0.345$ $p=0.019$ $n=46$

**Table A3.8. Correlations between life-history variables and physical and chemical habitat variables for other cnidarians. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Oxygen concentration	Oxygen saturation
Linear growth rate	$r=-0.373$ $p=0.021$ $n=38$	$r=0.486$ $p=0.003$ $n=35$	$\rho=-0.003$ $p=0.986$ $n=16$	$\rho=0.517$ $p=0.001$ $n=36$
Radial growth rate	$r=-0.750$ $p=0.020$ $n=9$	$r=0.723$ $p=0.028$ $n=9$	$\rho=-0.681$ $p=0.044$ $n=9$	$\rho=-0.008$ $p=0.983$ $n=9$
Minimum age	$r=0.455$ $p=0.012$ $n=30$	$r=-0.201$ $p=0.324$ $n=26$	$\rho=-0.427$ $p=0.024$ $n=28$	$\rho=-0.431$ $p=0.022$ $n=28$
Maximum age	$r=0.386$ $p=0.035$ $n=30$	$r=-0.110$ $p=0.592$ $n=26$	$\rho=-0.457$ $p=0.015$ $n=28$	$\rho=-0.355$ $p=0.064$ $n=28$
Maximum size	$r=0.187$ $p=0.194$ $n=50$	$r=0.221$ $p=0.144$ $n=45$	$\rho=-0.334$ $p=0.023$ $n=46$	$\rho=0.075$ $p=0.621$ $n=46$

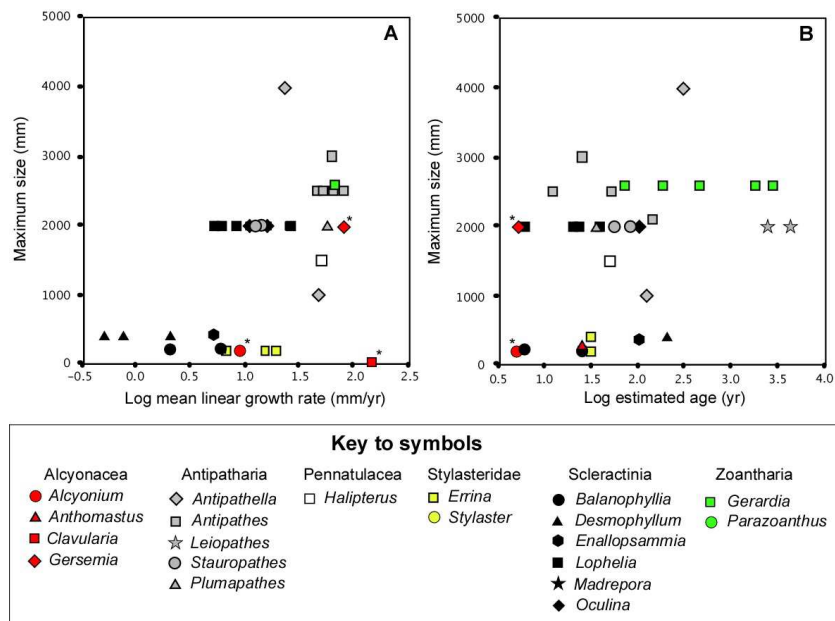


Figure A3.5. Plot of point data for significant correlations among life history characteristics for other cnidarians. Southern Ocean records indicated with an asterisk.

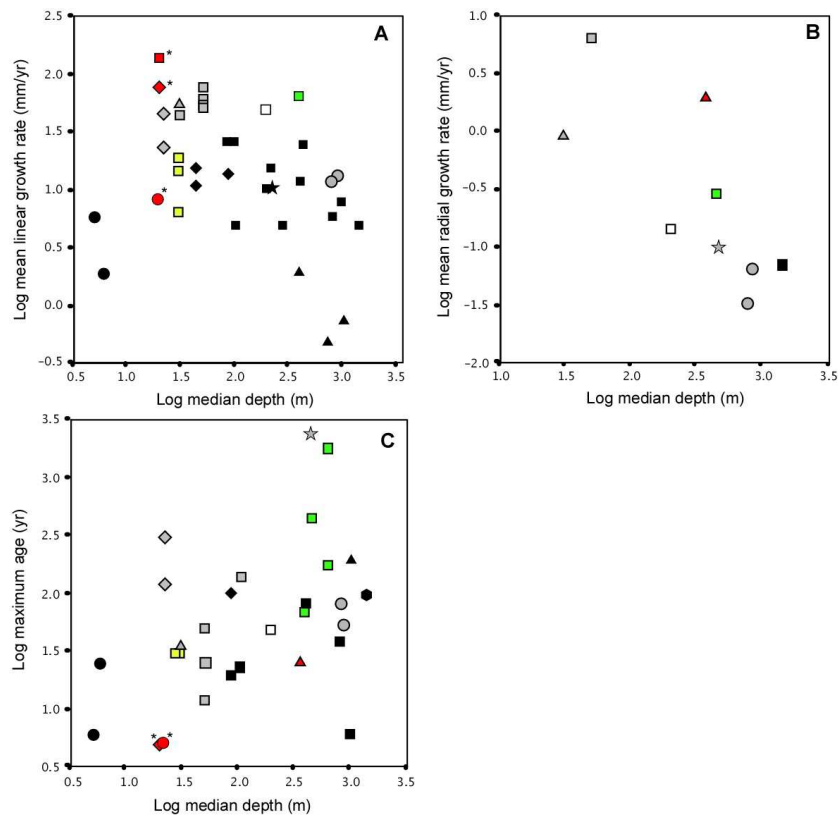
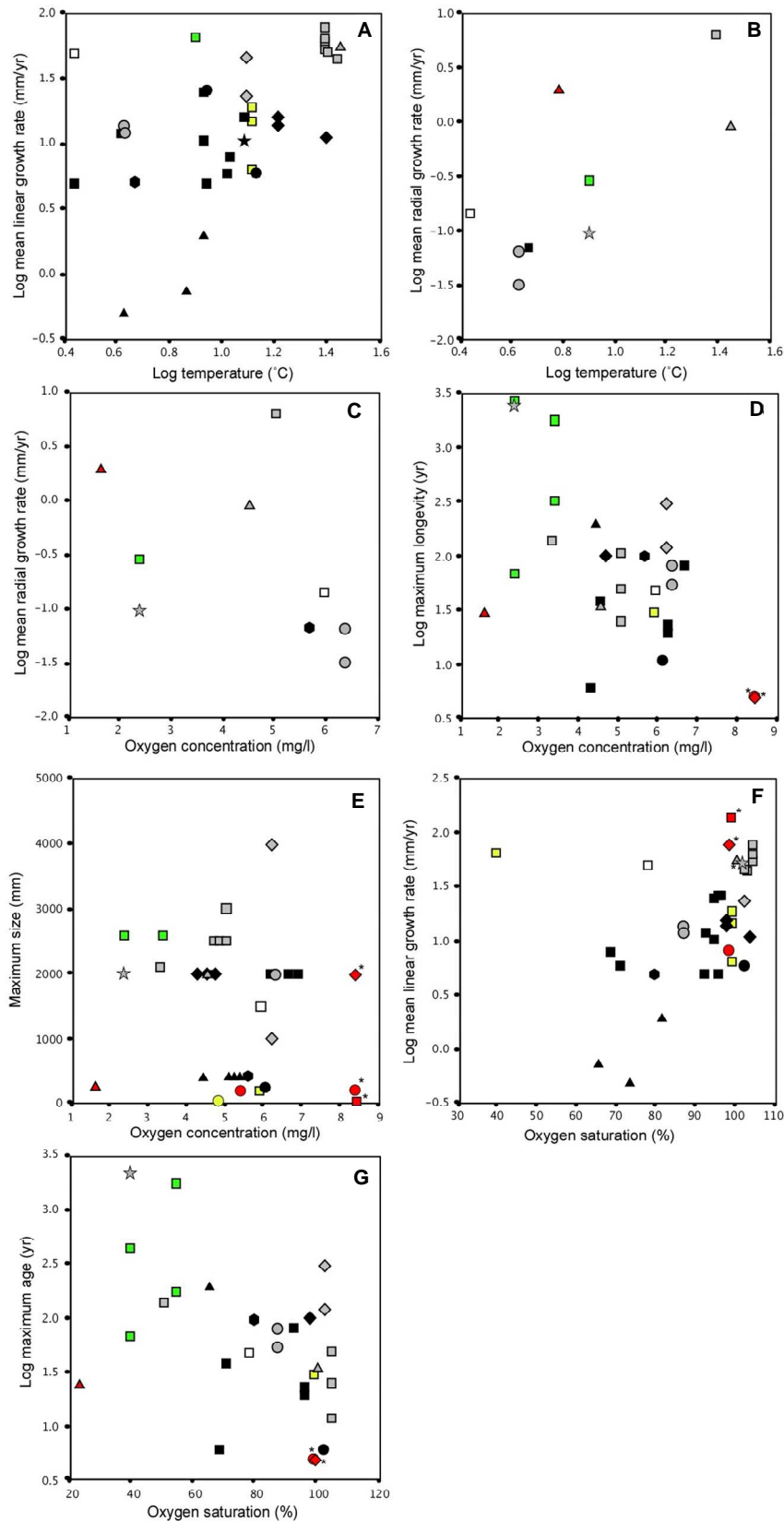


Figure A3.6. Plot of point data for significant correlations between life history characteristics and depth for other cnidarians. Symbols as in Figure A3.5. Southern Ocean records indicated with an asterisk.



**Figure A3.7.** Plot of point data for significant correlations between life history characteristics and temperature (A-B), oxygen concentration C-E) and oxygen saturation (F-G) for other cnidarians. Symbols as in Figure A3.6. Southern Ocean records indicated with asterisk.

The best multiple regression for linear growth rate of other cnidarians included depth, temperature and oxygen concentration ( $R^2=0.282$ ,  $F_{3,30}=3.53$ ,  $p=0.028$ ) while for radial growth the best model included only temperature ( $R^2=0.523$ ,  $F_{1,7}=7.66$ ,  $p=0.028$ ). No significant models could be generated for age or maximum size. Given the relationships between linear growth rate, maximum size, depth and temperature estimated growth rates of less than  $10\text{mm.yr}^{-1}$  for other cnidarians, growth to observed sizes of 1000 mm or more (Figure A3.5B) may take decades to centuries depending on depth and temperature (Figure A3.7).

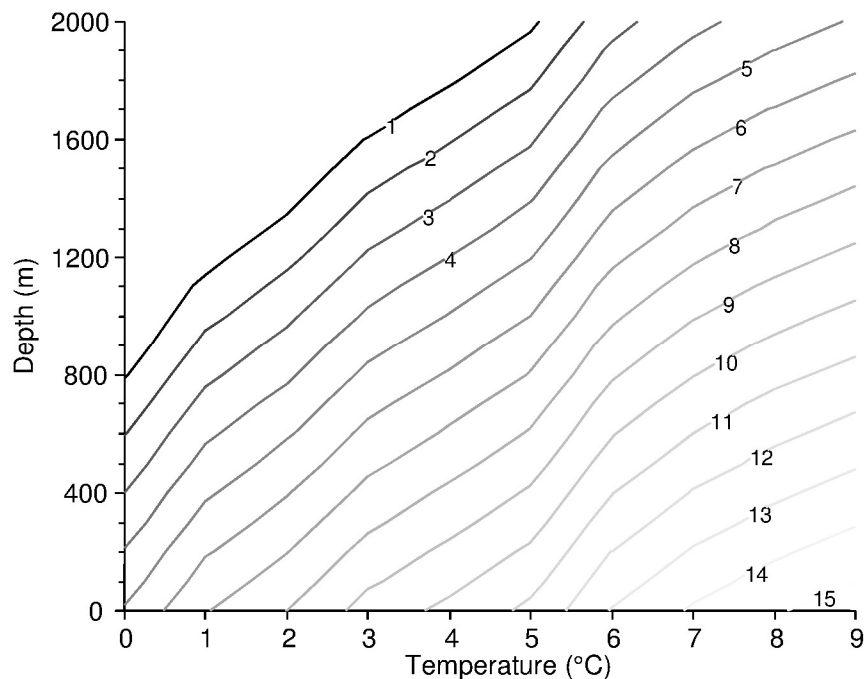


Figure A3.7. Predicted linear growth rate for other cnidarians at different depth and temperature combinations from a multiple regression model. Contour lines are marked in  $1\text{ mm.yr}^{-1}$  intervals.

### Bryozoans

For bryozoans the only significant correlation between life history variables was a strong negative relationship between mean linear growth rate and age (Table A3.9, Figure A3.8).

All of the physical and chemical habitat variables were significantly correlated with each other; negatively for temperature with depth, latitude and oxygen concentration and positively for depth and latitude, depth and oxygen concentration, and oxygen concentration and latitude (Table A3.10). Temperature was significant; positively correlated with mean linear growth rate and significantly negatively correlated with age, while latitude was significantly negatively correlated with mean linear growth rate (Table A3.11, Figure A3.8).

**Table A3.9. Correlations among life-history variables for bryozoans. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Linear growth rate	Minimum age	Maximum age
Linear growth rate	-	<b><math>r = -0.671</math></b> <b><math>p = 0.002</math></b> <b><math>n = 18</math></b>	<b><math>r = -0.625</math></b> <b><math>p = 0.006</math></b> <b><math>n = 18</math></b>
Minimum age		-	<b><math>r = 0.952</math></b> <b><math>p &lt; 0.001</math></b> <b><math>n = 20</math></b>

**Table A3.10. Correlations among physical and chemical habitat variables for bryozoans. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Latitude	Oxygen concentration
Depth	-	<b><math>\rho = -0.462</math></b> <b><math>p &lt; 0.001</math></b> <b><math>n = 57</math></b>	<b><math>\rho = 0.498</math></b> <b><math>p &lt; 0.001</math></b> <b><math>n = 57</math></b>	<b><math>\rho = 0.277</math></b> <b><math>p = 0.037</math></b> <b><math>n = 57</math></b>
Temperature		-	<b><math>\rho = -0.961</math></b> <b><math>p &lt; 0.001</math></b> <b><math>n = 62</math></b>	<b><math>\rho = -0.600</math></b> <b><math>P &lt; 0.001</math></b> <b><math>n = 62</math></b>
Latitude			-	<b><math>\rho = 0.562</math></b> <b><math>p &lt; 0.001</math></b> <b><math>n = 62</math></b>

**Table A3.11. Correlations between life-history variables and physical and chemical habitat variables for bryozoans. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Latitude	Oxygen concentration	Oxygen saturation
Linear growth rate	$\rho = 0.046$ $p = 0.001$ $n = 21$	<b><math>r = 0.739</math></b> <b><math>p &lt; 0.001</math></b> <b><math>n = 22</math></b>	<b><math>\rho = -0.530</math></b> <b><math>p = 0.011</math></b> <b><math>n = 22</math></b>	$\rho = -0.107$ $p = 0.635$ $n = 22$	$\rho = 0.416$ $p = 0.054$ $n = 22$
Estimated age	$\rho = -0.027$ $p = 0.914$ $n = 19$	<b><math>r = -0.566</math></b> <b><math>p = 0.009</math></b> <b><math>n = 20</math></b>	$\rho = 0.333$ $p = 0.152$ $n = 20$	$\rho = -0.077$ $p = 0.748$ $n = 20$	<b><math>\rho = -0.298</math></b> $p = 0.202$ $n = 20$



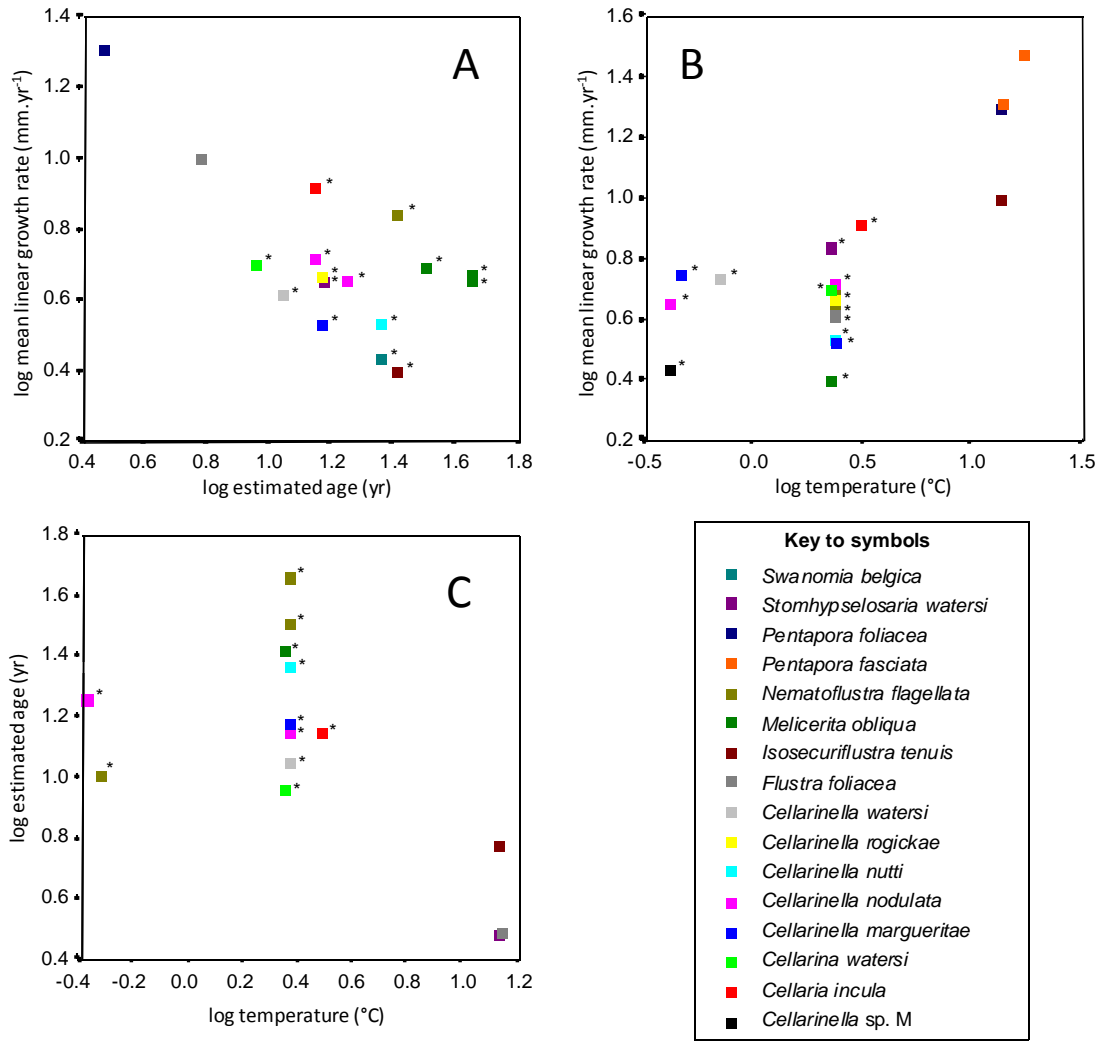


Figure A3.8. Plot of point data for significant correlations between life history characteristics (A) and temperature (B and C) for bryozoans. Southern Ocean records indicated with asterisk.

## Sponges

Data available for sponges was also relatively limited and thus, it was not possible to provide robust analyses of many of the potential relationships. The only significant correlation among life-history characteristics was a positive correlation between estimated age and maximum size (Table A3.12, Figure A3.9). Similar to cnidarians, all of the physical and chemical habitat variables were correlated with each other except for depth and oxygen concentration (Table A3.13). There were no significant relationships between life-history variables and any of the physical or chemical habitat variables although samples sizes were too small in many instances for robust analyses (Table A3.14).

Data for Antarctic sponges showed that growth rate was not measurable or very slow over considerable periods (Dayton 1979), while the few studies on glass sponges suggest that they are potentially extremely long-lived with estimated ages of more than 200 years (Leys & Lauzon 1998).

**Table A3.12. Correlations among life-history variables for demosponges. Significant correlations at the  $p < 0.05$  level shown in bold.**

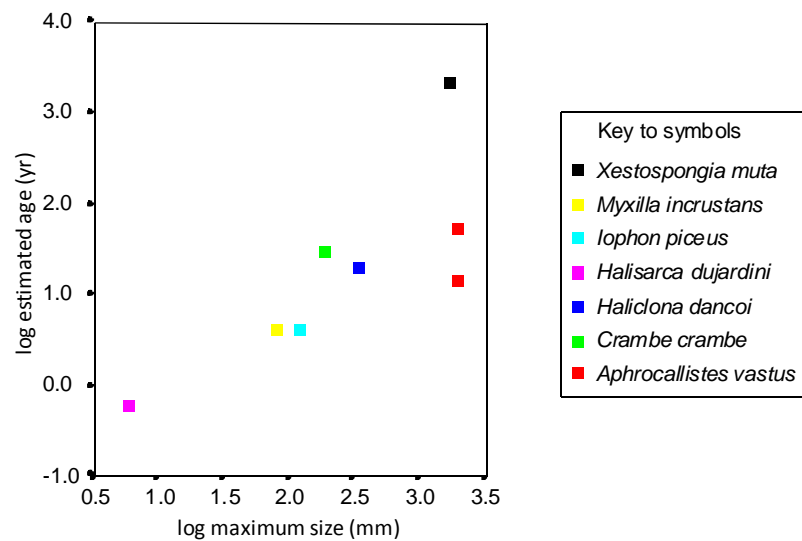
	Linear growth rate	Specific growth rate	Estimated age	Maximum size
Linear growth rate	-	$r = -0.306$ $p = 0.694$ $n = 4$	insufficient data	$\rho = 0.238$ $p = 0.480$ $n = 11$
Specific growth rate		-	insufficient data	$\rho = -0.099$ $p = 0.524$ $n = 44$
Estimated age			-	<b><math>\rho = 0.928</math></b> <b><math>p = 0.008</math></b> $n = 6$

**Table A3.13. Correlations among physical and chemical variables for demosponges. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Latitude	Oxygen concentration
Depth	-	<b><math>\rho = -0.355</math></b> <b><math>p = 0.001</math></b> $n = 64$	<b><math>\rho = 0.301</math></b> <b><math>p = 0.010</math></b> $n = 73$	$\rho = 0.126$ $p = 0.370$ $n = 53$
Temperature		-	<b><math>\rho = -0.989</math></b> <b><math>p &lt; 0.001</math></b> $n = 64$	<b><math>\rho = -0.916</math></b> <b><math>p &lt; 0.001</math></b> $n = 53$
Latitude			-	<b><math>\rho = 0.911</math></b> <b><math>p &lt; 0.001</math></b> $n = 53$

**Table A3.14. Correlations between life-history variables and physical and chemical habitat variables for demosponges. Significant correlations at the  $p < 0.05$  level shown in bold.**

	Depth	Temperature	Latitude	Oxygen concentration
Linear growth rate	$\rho=0.000$ $p=1.000$ $n=13$	$r=-0.052$ $p=0.866$ $n=13$	$\rho=0.000$ $p=1.000$ $n=13$	$\rho=0.000$ $p=1.000$ $n=13$
Specific growth rate	$\rho=0.013$ $p=0.945$ $n=31$	$r=0.314$ $p=0.097$ $n=29$	$\rho=-0.046$ $p=0.806$ $n=31$	$\rho=-0.096$ $p=0.622$ $n=29$
Estimated age	$\rho=0.471$ $p=0.346$ $n=6$	insufficient data	$\rho=-0.585$ $p=0.222$ $n=6$	insufficient data
Maximum size	$\rho=0.171$ $p=0.383$ $n=31$	$\rho=-0.189$ $p=0.367$ $n=25$	$\rho=0.204$ $p=0.299$ $n=28$	$\rho=0.003$ $p=0.987$ $n=25$



**Figure A3.9. Plot of point data for significant correlations between life history characteristics for demosponges. Note no Southern Ocean species were available to include in the analysis.**

## Discussion

Where disturbance causes partial or complete mortality of benthic organisms in a location, then a return to the undisturbed state will depend on growth of remaining individuals or recruitment of new individuals. In the absence of direct evidence of recovery processes, life-history parameters of organisms in the ecosystem can be used as a relative measure of the time course of recovery (Teixidó *et al.* 2007). For example, for a given level of disturbance, the recovery period will be positively correlated with growth rate and probably longevity of the taxa involved.

This study has demonstrated that there are consistent empirical relationships among life-history characteristics and between life-history characteristics and physical or chemical parameters across a wide range of benthic taxa. These relationships can therefore be used to bound plausible values for life-history parameters where very few data are available, as in the Southern Ocean, and hence indicate the likely time frames for recovery following disturbance. Given the immediacy of the issue of managing bottom fishing to conserve benthic habitats and the practical difficulties associated with obtaining empirical data from the Southern Ocean, predictive approaches are useful to characterise the likely life histories of these taxa in relation to the physical environment.

Where records for Southern Ocean taxa exist they fall within the range of variability of other taxa from throughout the world's oceans. Although there are too few data to test statistically, it is indicated that the relationships presented are general and that it is unlikely that Southern Ocean organisms represent special cases when considering the life-history characteristics examined here.

For the best characterised group and important habitat-forming organisms, the gorgonians, there were strong relationships between growth and age and both of these life-history characteristics were correlated with temperature and depth. For ambient Southern Ocean conditions, it is predicted that the lower bound to recovery of an undisturbed age structure would be 130-200 years depending on the depth at which fishing occurs. This value is predicated on immediate recruitment which could occur if there are surviving colonies nearby. However, if an entire habitat patch was destroyed or reproduction only occurred periodically then these lower bounds for recovery would be increased.

Where data were available, similar relationships were found for other cnidarians. Deep- and cold-water members of other groups of cnidarians, in particular stony corals, black corals and the zoanthid *Gerardia*, showed very slow growth rates and extremely high maximum ages of more than 2500 years (Parrish & Roark 2009, Roark *et al.* 2005, Roark *et al.* 2006, Roark *et al.* 2009). Recovery times after disturbance may therefore be considerably greater for these taxa than for gorgonians.

Although also restricted by the relative paucity of data available, analyses showed bryozoans and sponges also have similar life history characteristics to the cnidarians, such as the negative correlation between growth rate and age in bryozoans or size and age in sponges. Hence, many of the habitat-forming benthic invertebrates found within the range of demersal fishing in the high latitudes of the Southern Ocean, which generally occur deeper than 500 m, are likely to be characterised by slow growth and longevity in a time frame of decades to centuries, with slower growth and longer life in deeper and colder areas.

Estimates of decades to centuries for recovery also concur with the limited number of direct studies of natural disturbance in the Southern Ocean. These estimates range from 65 years for a community at 9 m depth at Signy Island (Peck *et al.* 1999) to 340 years for sponge communities at 114-315 m in the Weddell Sea (Gutt & Starman 2001) for iceberg scour and over 30 years after volcanic eruptions at Deception Island (Cranmer *et al.* 2003). Hence, we conclude that management strategies for conserving benthic habitats need to consider time frames that may exceed 100 years when evaluating the risks from disturbance and the impacts that may result from demersal fishing activities in the Southern Ocean.

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## **Appendix 4. An autonomous video camera system for monitoring impacts to benthic habitats from demersal fishing gear, including longlines.**

Robert Kilpatrick, Graeme Ewing, Tim Lamb, Dirk Welsford and Andrew Constable

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Autonomous video camera system for monitoring impacts to benthic habitats from demersal fishing gear including longlines. Deep-Sea Research Part I: Oceanographic Research Papers, 58: 486-491*

### **ABSTRACT**

Studies of the interactions of demersal fishing gear with the benthic environment are needed in order to manage conservation of benthic habitats. There has been limited direct assessment of these interactions through deployment of cameras on commercial fishing gear, especially on demersal longlines. A compact, autonomous deep-sea video system was designed and constructed by the Australian Antarctic Division (AAD) for deployment on commercial fishing gear to observe interactions with benthos in the Southern Ocean finfish fisheries (targeting toothfish, *Dissostichus* spp). The Benthic Impacts Camera System (BICS) is capable of withstanding depths to 2500 m, has been successfully fitted to both longline and demersal trawl fishing gear, and is suitable for routine deployment by non-experts such as fisheries observers or crew. The system is entirely autonomous, robust, compact, easy to operate, and has minimal effect on the performance of the fishing gear it is attached to. To date, the system has successfully captured footage that demonstrates the interactions between demersal fishing gear and the benthos during routine commercial operations. It provides the first footage demonstrating the nature of the interaction between demersal longlines and benthic habitats in the Southern Ocean, as well as showing potential as a tool for rapidly assessing habitat types and presence of mobile biota such as krill (*Euphausia superba*).

## Introduction

It is now well recognised that demersal fishing gear has the potential to impact benthic habitats (Kaiser *et al.* 2006). As a consequence, considerable research effort has been applied to this issue, albeit almost entirely focused on the impacts of towed demersal gear such as trawl and dredge rather than on longlines (Allen & Clarke 2007, Cryer *et al.* 2002, Hiddink *et al.* 2007, Jenkins *et al.* 2001, Jones 1992, Reed *et al.* 2007, Wassenberg *et al.* 2002). Deep-sea biogenic habitats have been recognized as being particularly vulnerable to impacts from fishing and are considered a high priority for management (UNGA 2007). Video footage of the seafloor is a useful tool for assessing the impact of demersal fishing gears on benthic habitats and for surveying the distribution of these habitats. It has been used in a number of recent studies (e.g. Althaus *et al.* 2009, Clark & Rowden 2009, Heifetz *et al.* 2009, Jones *et al.* 2006, Rodrigues *et al.* 2001, Williams *et al.* 2010). However, due to severe environmental factors such as temperature, pressure, and the absence of ambient light, video equipment suitable for deployment into deep-sea habitats has generally been expensive, cumbersome, and has often required a connection to the surface for providing power and operator control. These limitations have led to most deep-sea observations being collected from dedicated research vessels deploying specialised equipment, such as towed sledges and remotely operated vehicles, and have generally precluded the deployment of video systems on commercial deep-sea fishing gears. Despite these limitations, the advantages of deployment of video equipment during actual commercial fishing events are clear. They include more realistic conclusions through observing commercial gear interactions rather than attempts to simulate such activity during research operations, greater potential for replication and broader habitat coverage due to the frequency of commercial fishing operations, and significant cost savings relative to dedicated research fishing (particularly if the camera system can be deployed by vessel's crew).

In shallow waters, video cameras have been deployed on large fishing gears such as demersal trawls and dredges (for example, Wassenberg *et al.* 2002), as their rigid structure has provided sufficient support for the video systems and an umbilical can be used. However, despite the widespread use of non-rigid fishing gears, such as demersal longlines, their level of interaction with the benthos is poorly understood relative to trawling (Lokkeborg 2005), and there is currently no record of observations of such interactions in the literature. This is due partly to the considerable technical challenges associated with deploying video equipment on such gears without interfering with the deployment and behaviour of the gear. To be deployed on a commercial demersal longline, a video system requires the following characteristics. It must be 1) autonomous, as lines are detached from the vessel once deployed; 2) compact, as the line is generally deployed through a small shooting window (typically 500 mm square) in the stern of the vessel and to ensure that it does not influence the behaviour of the line in strong currents or increase the risk of snags; 3) robust, as the line is deployed at around 1-2 m.s<sup>-1</sup>, during which the camera has a high likelihood of impact with the side

of the vessel; 4) provide long battery life and high image storage capacity, as a longline deployment typically exceeds 24 hours; and 5) relatively inexpensive, as longlines are routinely lost due to snags and sea ice cover. Recent advances in solid state recording media and LED lighting, digital video encoding, and miniaturisation, reduction in cost and increased accessibility of electronic components, have provided the opportunity to produce video camera systems that can meet the requirements for deployment on non-rigid detached commercial fishing gears.

The Benthic Impacts Camera System (BICS) has been developed by the Australian Antarctic Division (AAD) for the project 'Demersal fishing interactions with marine benthos in the Australian EEZ of the Southern Ocean'. The camera system was developed for deployment during commercial fishing events to assess the nature and extent of interactions between the benthos and different demersal fishing gears (trawl and longline) used to target toothfish, *Dissostichus* spp. and mackerel icefish, *Champscephalus gunnari*. The study also aimed to investigate the types and distribution of benthic habitats in the Southern Ocean. This paper describes the technical development, specifications, and deployments of the BICS. The usefulness of this apparatus for other deep-sea video applications, such as rapid habitat assessment, is also discussed.

### **Development and specifications**

The BICS takes advantage of recent advances in video, electronics and battery technologies to produce a camera system capable of meeting the difficult technical challenges involved in deploying a camera system on a range of deep-sea fishing gear, including demersal longlines and trawl nets, and capable of being deployed with minimal interruption to routine fishing operations.

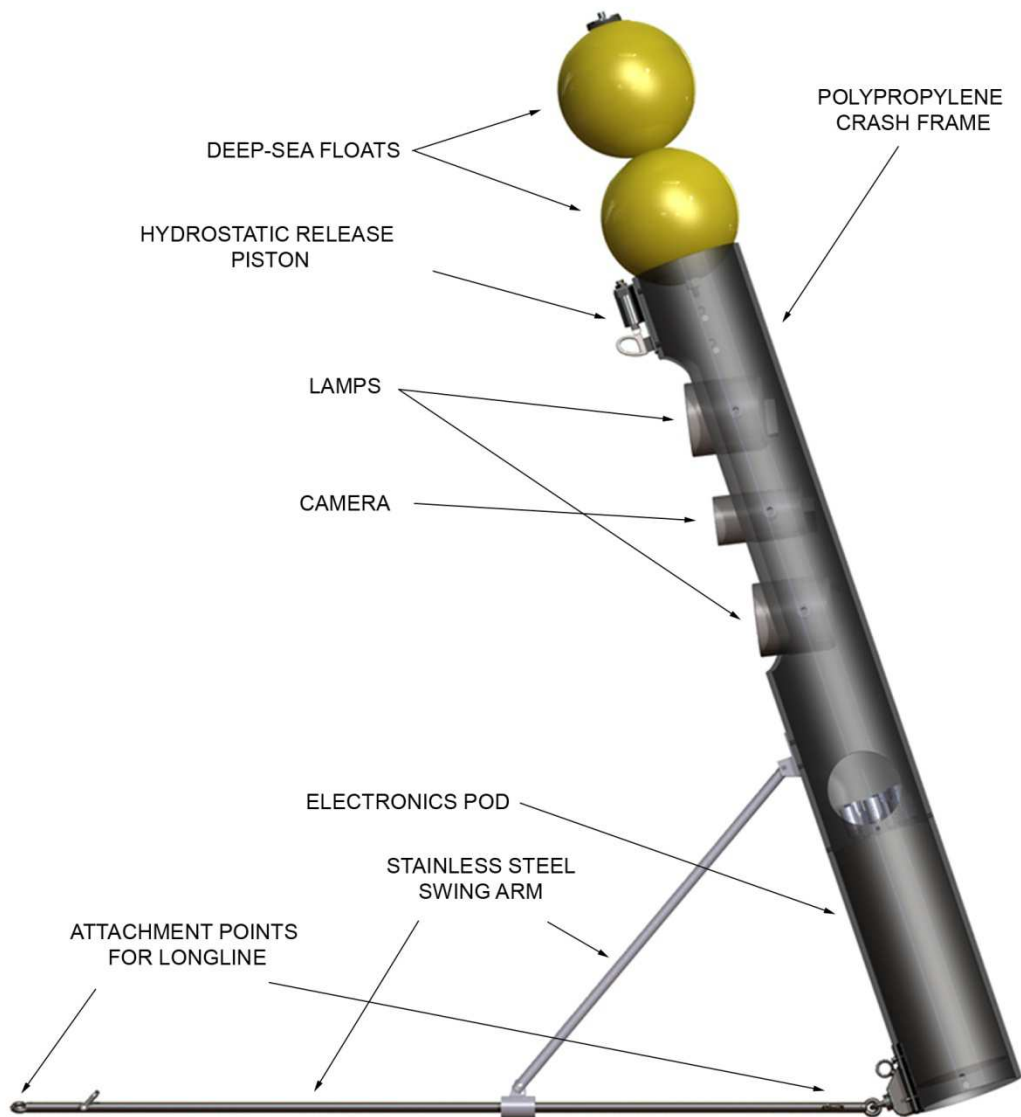
### **System components**

The BICS is modular, comprising a video camera, solid state lighting, an electronics pod (containing controlling electronics, a portable video recorder, and a battery pack), and a pressure switch. These components are housed in individual pressure casings connected by waterproof cables. This component design enables the system to be assembled in a range of configurations to suit different applications and facilitates replacement of individual components. Two different robust polypropylene crash frames to house the BICS for deployment, with either trawl or longline fishing gears, have been developed (Figures A4.1 and A4.2 respectively). The cost of materials for a complete camera system is approximately 13, 000 AUD\$ depending on the type of crash frame that is used.





**Figure A4.1. Benthic Impacts Camera System (BICS) mounted in the trawl net crash frame (with extra mounting hardware for attachment to trawl warp).**



**Figure A4.2. Benthic Impacts Camera System (BICS) mounted in the longline crash frame.** The narrow cylindrical shape of the longline housing allows it to be deployed through a narrow shooting window, the stainless steel swing arm on the left side is attached to the longline and folds open after deployment (as shown). The floats keep the unit upright and filming down the longline during fishing and retrieval.

### Pressure housings

Lamp, camera and pressure switch housings are all machined from poloxymethylene (DuPont™ Delrin®), a type of high-density plastic, and have 12-19 mm transparent acrylic lenses. Poloxymethylene is relatively inexpensive, machines well, is robust, and does not corrode. The electronics pod housing is machined from aluminium (6061, hard anodised for corrosion protection) and has a pressure relief valve fitted to the end cap to facilitate internal battery charging. All housings are rated to at least 2500 m.

### **Illumination**

Each LED light pod is fitted with two, triple LED, aluminium clad printed circuit boards (PCB), equipped with a secondary optical collimator and a diffuser, and mounted on an aluminium heat-sink. Luminous output is over 500 lumens per lamp and intensity can be manipulated from 40-110% of rated DC-DC output. LED lighting is capable of withstanding the high impacts and vibration likely to be experienced during commercial fishing deployments, is highly energy efficient extending battery life and therefore filming duration, and can easily be upgraded to accommodate the rapid advances in LED lighting technology.

### **Video camera**

For trawl-net applications, the system utilises an analogue colour Bosch Dinion<sup>XF</sup> camera (1/2" CCD, 0.018 Lux, 540TVL) coupled to a Bosch 1/2", 4-12 mm Vari-focus lens. The external housing is fitted with a 25 mm, optically-corrected glass view port. For longline applications, 1/3" CCD colour and monochrome bullet cameras (520 TVL, 0.001 Lux) have been housed in poloxymethylene pressure vessels with 12 mm acrylic lenses. Bullet cameras are compact and very robust due to the lack of moving parts. Bullet cameras are also compatible with trawl net deployments.

### **Controlling electronics and battery**

Video footage is converted to digital format (MPEG2), broken down into 2 or 4 GB files (using the FAT32 file system), and saved to a high density compact flash card using a miniaturised Digital Video Recorder (DVR, Flashback II by *Ovation Systems Ltd.*). The recording parameters of the DVR, such as file compression ratio and the time & date character are programmable. A 32 GB card will hold approximately 8.5 hours of continuous footage at broadcast quality resolution. Digital video allows for ease of archiving and analysis, and is time and date stamped to assist in annotating footage and matching with fishing event records.

A separate PCB contains a re-settable real-time clock and microcontroller (Wilke Tiny-Tiger, model ENN 4/4), which triggers the lamps, camera, and DVR. This allows the user to specify how the system utilises the 8.5 hours of recordable time. For example, it can be programmed to record continuously until the memory is expended or to record separate clips at set intervals.

A custom-built 14.4V Lithium-ion battery pack supplies power to the lamps, camera, and recording electronics. The overall capacity of the pack is estimated to have a minimum nominal capacity of 36Ah at 14.4V (23°C), which can power the BICS for 8-10 hours (at 1-2°C). Charging current is supplied by a mains powered adaptor and can be achieved without opening the pressure housing. A full charge takes approximately 8-10 hours.

### **Pressure switch**

This unit consists of a miniature stainless steel pressure switch attached to the main electronics housing via a 2-pin wet connector and enables the system to remain in standby mode until it reaches a pre-specified activation depth. At this point the DVR controller is activated and will commence the programmed recording sequence. On retrieval, when the system comes above the activation depth, the pressure switch deactivates the DVR controller. As the unit will not commence its programmed recording sequence until the activation depth is exceeded, the BICS can be fitted to the fishing gear well in advance of its deployment, improving safety and reducing the likelihood of interference with routine fishing operations.

### **User interface**

The system is entirely autonomous with no umbilical and the timing of recording intervals is fully programmable prior to deployment. To simplify operation, and maximise operator safety, all routine operations such as battery charging, downloading footage, reformatting memory media, and programming the timing of recording events, are achieved without the need to open a pressure casing. Programming recording intervals, downloading footage and formatting memory media is achieved through a USB interface with a standard laptop computer. A fast, safe, and uncomplicated user interface was an important requirement for the BICS as it allows the deployment of the camera by non-research personnel (such as fishing boat crew and fisheries observers). This dramatically increases the scope for data collection and replication.

### **Trawl crash frame**

The trawl crash frame is constructed from high density polypropylene sheet and provides the BICS with impact protection and a means of attachment to a demersal trawl net (Figure A4.1). Stainless steel gimbals allow the camera and lamps to be rotated in a 120° arc in the vertical plane and a 30° arc in the horizontal plane to allow adjustment to observe different parts of the net while fishing and to optimize lighting. Buoyancy is provided by a central polypropylene tube containing a cylinder of syntactic foam. A second polypropylene tube at the rear of the crash frame contains the electronics pod. The crash frame has multiple mounting points along its upper surface and can be bolted, sewn or shackled to a trawl net. This crash frame has also been used to attach the BICS to a research beam trawl and a benthic sled.

### **Longline crash frame**

The longline crash frame is constructed from a 1.4m length of high density polypropylene pipe (Figure A4.2). Midway along the pipe, the light pods and camera are mounted in stainless steel gimbals, which allow for rotation within a 140° arc in the vertical plane to adjust the portion of the longline in frame and optimize lighting. The unit is held upright by two deep-sea floats mounted at the top end of the pipe. A

spring-loaded stainless steel arm ensures the BICS stays aligned with the direction of the longline. This is secured against the crash frame body by a custom built hydrostatic release piston and allows the unit to pass through a small line shooting window. The hydrostatic piston releases at approximately 100 m, and once that depth is exceeded a rubber bungee engages the stainless steel arm and positions the BICS so that the camera is around 1000 mm above, and looking along, the longline. The BICS and longline crash frame weighs approximately 25 kg in air, maintains slight negative buoyancy in seawater (4 kg), and had no effect on the sink-rate of a longline during initial trials.

### Camera deployments

The BICS has been deployed from commercial fishing vessels in the Australian managed toothfish fishery in the Heard Island and McDonald Islands (HIMI) region in the subantarctic during the 2007, 2008, 2009 and 2010 fishing seasons (Table A4.1). The majority of deployments were accomplished by Australian Fisheries Management Authority observers. The HIMI region is in the Southern Ocean approximately 4000 km south west from the Australian landmass and is renowned for very adverse sea conditions. Toothfish are targeted in this region using demersal trawl and integrated weight longline (IWL), at depths from around 500 to 3000 m.

### Demersal trawl deployments

The trawl crash frame was attached to a reinforced section of the mesh of the demersal trawl, in a number of positions in the proximity of the headline of the net, using sister clips (20 mm), allowing attachment and removal in under two minutes. This system allowed the orientation of the crash frame to be adjusted to look forward or aft and to starboard or port. Two 10 inch trawl floats were also tied to the crash frame to increase buoyancy. Generally, the BICS was programmed to film continuously during trawl deployments.

**Table A4.1. Benthic Impacts Camera System deployments on commercial fishing vessels across the 2007- 2010 fishing seasons at Heard Island and the McDonald Islands. Habitat assessment, line deployment and line retrieval refer to the number of longline camera deployments with clear footage of the benthos, the longline settling on the seafloor on deployment, and the longline leaving the seafloor on retrieval, respectively.**

Vessel	Trawl camera events	Longline camera events		
		Habitat assessment	Line deployment	Line retrieval
Southern Champion	12	-	-	-
Janas	-	4	0	2
Austral Leader II	-	20	10	13
Antarctic Chieftain	-	39	16	19

### **Demersal longline deployments**

Integrated weight longline (IWL) is deployed in a series of connected segments (magazines) of around 1000 m and lines can be as long as 20 km (20 magazines). The BICS longline crash frame was connected with stainless steel swivels to its own 4 m magazine of standard IWL, and could be inserted between any two magazines. Deployment entailed tying one end of the short BICS magazine to the trailing end of an outgoing magazine and tying the other end to the beginning of the next magazine to be deployed. The outgoing line then pulled the BICS from a custom launch tube out through the shooting window, which in turn deployed the following magazine. This procedure enabled the camera to be deployed with no interruption to routine fishing operations on vessels using IWL and automatic line baiters. Whilst the BICS has not been deployed on vessels that use snap-on gear (whereby hooks and snoods are periodically 'snapped on' to the mainline by hand) or fixed gear (snoods and hooks already attached to mainline and arranged in buckets or tubs prior to deployment), it is envisaged that deployment would be easier in the absence of an auto-line baiting unit. The camera was retrieved during hauling by disconnecting two quick-release stainless steel spinnaker clips as it reached the hauling window. This enabled the camera to be removed from the line being hauled in less than two minutes, presenting a minimal interruption to routine fishing operations.

Generally, the BICS was programmed to capture footage of the IWL arriving on the seafloor, then to record for 5 minutes every hour during the gear soak-time (typically 24 to 48 hrs), and finally to film continuously during the retrieval of the line. The line retrieval was of particular interest as this is when line movement across the seafloor, and consequent interaction with the benthos, is most likely to occur.

### **Research deployments**

The BICS was also deployed on a number of dedicated research gears on the shelf break of East Antarctica during an AAD marine science voyage in the summer season of 2009/10. The BICS was mounted alongside a high resolution still camera system on a research beam trawl equipped with a 10mm codend. This apparatus was deployed 32 times in depths from around 300 to 1400 m.

During this field sampling, rapid movement of sea ice precluded use of a research beam trawl to determine the extent of high-value habitats encountered in a canyon feature. This inspired the novel use of the BICS (assembled in the longline crash frame) to provide a rapid and convenient means of determining the benthic habitat type on the shelf break adjacent to the canyon. The BICS in the longline crash frame was rigged on a vertical line with a length of chain as an anchor. The BICS operated as if on a longline, coming to rest on the seafloor in its usual position and capturing video footage of the benthic habitats before it. The unit was left on the seafloor for 2 minutes and then raised to approximately 100 m from the bottom, allowing the ship to drift with the gear

clear of the bottom. This procedure was repeated for 3 replicates and then the unit was retrieved. As the ship drifted during this procedure, a different patch of substrate was sampled during each replicate. Twenty nine BICS video drops were conducted at approximately one nautical mile intervals and at three depths on the shelf break adjacent to the canyon feature.

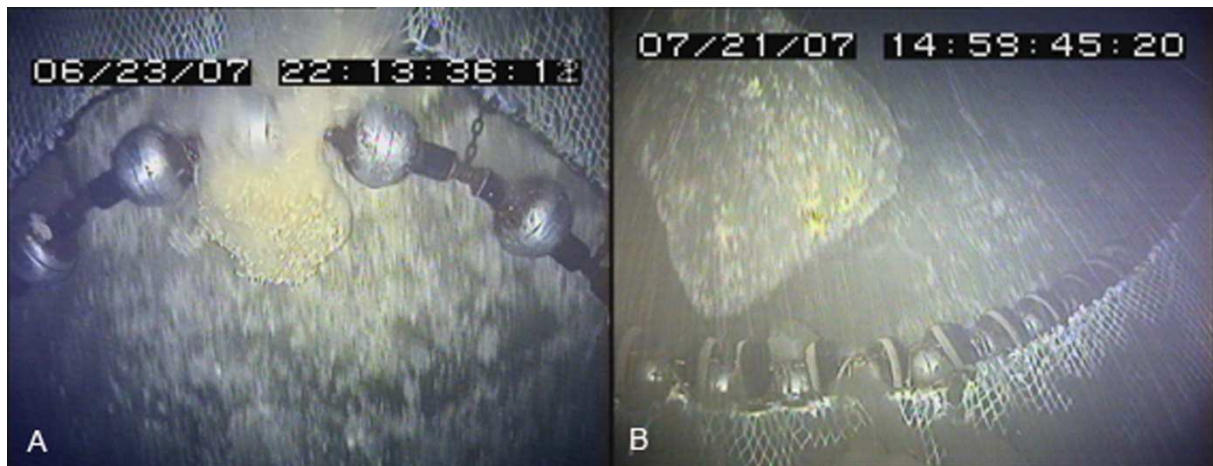
## **Results and Discussion**

Sea trials were conducted to optimize exposure, camera and lamp angles, and the position and methods of attachment of the crash frames to the fishing gears. Whilst the camera system consistently produced footage of sufficient quality for analysis of demersal gear interactions and habitat assessment, other factors such as unexpected variations in fishing gear configuration or the timing of fishing events reduced the usefulness of footage in approximately 10% of deployments.

### **Demersal trawl deployments**

Deployments of the BICS from a commercial trawler has provided over 10 hours of footage from 12 trawl events in the plateau and upper slope trawl grounds of the HIMI region. This footage provided the first ever *in situ* observations of interactions between a demersal trawl and the benthos of the HIMI region.

The trawl crash frame facilitated rapid attachment and removal from the net and also successfully protected the system from impact damage during deployment and retrieval. The compact design and flexibility of camera and lamp orientation permitted the unit to be attached in a number of positions in the net mouth without any obvious effect on net geometry. This enabled examination of the interactions that different parts of the net (e.g. ground gear, sweeps, trawl doors) had with the benthic environment. The most satisfactory field of view depicting the interaction of the ground-gear with the benthos (Figure A4.3) was obtained when the camera was positioned on the inside of the net, 1 m behind the join between the 2<sup>nd</sup> and 3<sup>rd</sup> top mesh panels, facing forward toward the ship. In this position, video resolution and illumination were sufficient to allow broad scale habitat classification and individual fish species to be identified. The system was also identified as a potential tool for examining animal interactions with the net.



**Figure A4.3.** Video stills taken from BICS deployments on a demersal trawl showing interactions between the ground-gear and the benthos at 740 m (A) and 690 m (B). The cluster of hard coral in still A was dragged for approximately 7 meters (calculated using trawl speed) before being overridden by the ground gear. The large boulder shown in still B was estimated to be over 3.5 m at its widest point (based on comparison to 300 mm trawl bobbins) and was completely rolled over once before the ground gear passed over it.

Observations of how the net behaved over different topographies, and the effectiveness of ground-gear configurations for preventing fish escaping the gear, were beneficial to the fishers. Camera gear could be left attached to the net for multiple deployments and posed no hindrance to normal deck operations. With a laptop computer, footage of a particular shot can be downloaded in less than 10 minutes from the camera system without actually removing it from the net, allowing the operators to promptly assess net behaviour, and the effectiveness of the camera field of view for observing interactions with the benthos.

### **Longline deployments**

Deployments of the BICS from 3 commercial longline vessels has provided over 30 hours of footage from 3 distinct areas within the HIMI region. In total, 53 deployments were made from 3 different vessels, all using auto-line baiters. This footage is the first ever captured of the interactions between IWL longline and the seafloor and has also contributed to the knowledge of the distribution of benthic habitats in the HIMI region.

The design of the crash frame not only facilitated relatively easy attachment to and from the line, but it also protected the system from impact damage during deployment and retrieval. Furthermore, the design allowed the unit to orientate itself along the length of the line when on the seafloor and several meters of mainline were clearly visible in front of the camera (Figure A4.4). Image resolution was sufficient to allow identification of benthic habitats based on dominant taxa, the interaction of demersal fishing gears with that habitat, and in many instances to identify individual taxa, including a number of mobile species (Figure A4.5).



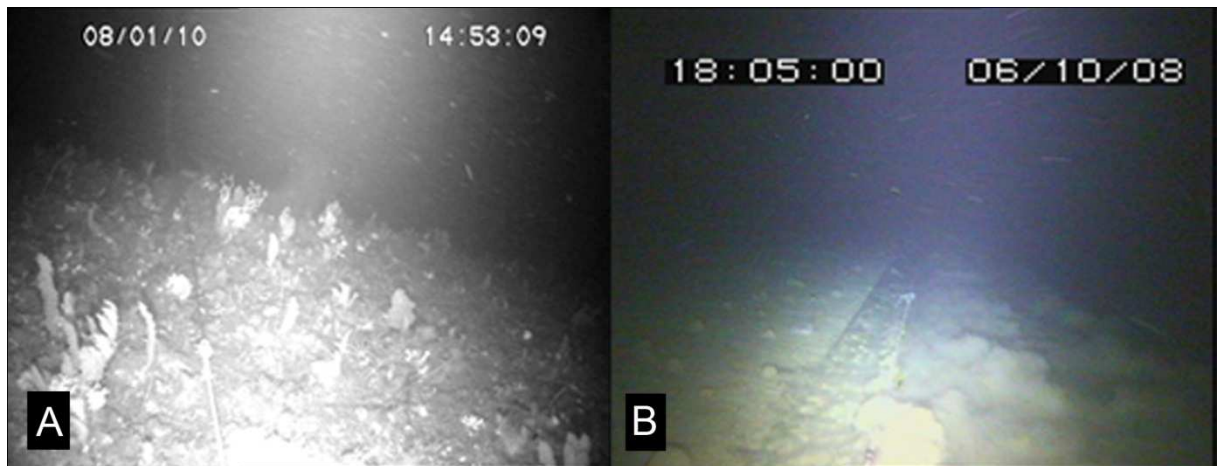


Figure A4.4. Video stills from BICS deployments during simulated demersal longline fishing showing interactions with the benthos in East Antarctica at 540 m (A) and at 720 m (B). Still A depicts the line settling in complex habitat. Still B shows a furrow created by the longline in soft sediments as hauling commences.

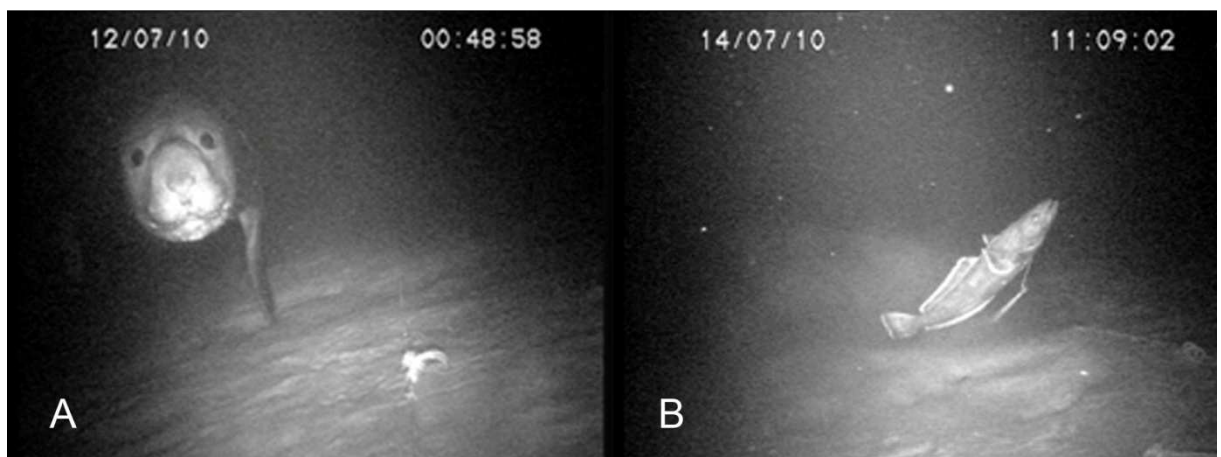


Figure A4.5. Video stills from commercial longline BICS deployments showing (A) a male elephant seal (*Mirounga leonina*) at c. 1270 m depth (note that this is the first time an elephant seal has been captured by video at this depth), and (B) a Patagonian toothfish (*Dissostichus eleginoides*) hooked on a line at c. 1500 m.

Footage revealed that the BICS did not appear to alter the way the demersal mainline behaved on the seafloor and did not increase the likelihood of line hook-ups. The camera launch tube did not hinder shooting room operations and enabled the BICS to safely and easily launch itself. The ability to program recording sequences allowed operators to match the camera's activation time with the skipper's estimate of when the line was likely to be hauled and improved the likelihood of capturing footage of any movement of the line on seafloor during retrieval.

## Research deployments

Deployments of the BICS on the research trawl on the continental shelf-break of Antarctica collected approximately 4 hours of footage, in depths ranging from 300 to 1500 m and from 4 distinct areas within East Antarctica. Comparisons of the various sources of habitat information (biological samples from the codend, high resolution photographs from the stills camera system, video footage from the BICS) will be used to evaluate their relative usefulness for characterizing benthic habitats, including the accuracy of habitat classification from commercial BICS footage.

The opportunistic deployment of the BICS on a vertical drop line on the continental shelf-break of Antarctica collected 3 hours of footage, in depths ranging from 400 to 850 m in the vicinity of a canyon feature. This footage provided data that will contribute to an understanding of the distribution of habitats on the continental shelf-break in East Antarctica. The advantages of the BICS for such habitat assessment were clear. A replicated BICS drop was typically accomplished in under one hour, including downloading and viewing the footage. This rapid turnaround was largely due to the simplification of deck operations as a result of the compact nature of the BICS and the ability to download data with a laptop computer without opening the pressure casings. The BICS could be used while the vessel was in sea-ice by deploying the unit through a small gap in the ice in the wake of the vessel.

The short turnaround time for replicated footage also provided an opportunity to cover many more sample stations than would have been possible using other sampling methods and within tight ship schedules. Another advantage of the BICS unit for this type of survey work is that it weighs only ca. 25 kg (in air) allowing it to be deployed from much smaller vessels than bulkier deep-sea video equipment, further reducing cost and increasing the flexibility of survey programs. Consequently, the BICS offers the opportunity to establish benthic habitat type and heterogeneity over a larger area for a given ship-time allocation and over a broader range of sea states, including sea ice cover.

On some occasions, when the camera was stationary on the seafloor, or in mid-water between replicates, krill swarmed around the unit. Analysis of this krill footage has contributed to an understanding of aspects of krill behaviour and life history in deep water (Kawaguchi *et al.* 2011). This highlights the potential of such camera systems for research in meso and bathy-pelagic waters. The BICS also offers advantages for the ground-truthing component of remote sensing or acoustic habitat mapping surveys.

## Conclusions

The design features of the BICS enabled it to successfully meet the significant challenges associated with deployment on commercial vessels by fisheries observers without interfering with routine fishing operations. This has produced much-needed, and unprecedented, *in situ* footage of the interaction between demersal longlines and

the benthos. The features of the BICS also allow it to be used for other research and commercial purposes, as well as deployment from a broader range of platforms, including small and/or non-research vessels, providing greater flexibility and potential cost savings.

## **Appendix 5. Evaluation of photographic methods for characterising benthic habitats for the purpose of assessing relative vulnerability to impact from disturbance**

Graeme Ewing, Ty Hibberd and Troy Robertson

### **ABSTRACT**

Advances in electronics have facilitated compact, easy to operate and cost-effective technologies for collection of digital visual footage of the benthos. Low resolution video footage collected opportunistically from deep-sea, subantarctic, commercial fishing operations using the Benthic Impacts Camera System (BICS) in the Heard Island and McDonald Islands region is particularly beneficial due to the high cost of dedicated research expeditions in such a remote and adverse region. The accuracy of BICS footage for assigning habitat types, densities and distributions, was determined by comparison with high resolution still digital images and biological samples collected simultaneously from research beam trawl deployments. An algorithm was developed to correct for perspective effects resulting from the forward facing oblique camera angle and to allow estimates of the area of seafloor in view. A Java program *Benthic Video Annotator* (BVA) was developed in-house and used to derive diversity and abundance counts on both stills and video footage, and CPCe (Coral Point Count with Excel extensions software (Kohler & Gill 2006)) was used to allocate random points to infer the relative importance of each taxa and assess habitat patchiness in stills images. Population parameters derived from digital visual data were also compared with diversity and biomass determined from biological samples. In situations where high resolution taxonomic information is required, conventional methods are likely to be superior to video. However, the ability to reliably categorise habitat and dominant biota types from low resolution video indicates this technology is a cost-effective means of rapidly acquiring such data off a diverse range of platforms including fishing vessels.

## Introduction

Deep-sea biogenic habitats have been recognized as being particularly vulnerable to impacts from disturbance and are considered a high priority for management (UNGA 2007). Consequently, increasing research effort to better understand the impacts of bottom fishing in deep-sea has been applied in recent years (Allen & Clarke 2007, Cryer *et al.* 2002, Hiddink *et al.* 2007, Jenkins *et al.* 2001, Jones 1992, Reed *et al.* 2007, Wassenberg *et al.* 2002). In deep-sea, high latitude waters, sessile colonial taxa, such as sponges and corals are generally correlated with high complexity benthic communities as they provide structural habitat for motile and epizootic taxa. However their often fragile structure also leaves them vulnerable to disturbance and their low productivity increases the risk of longer term ecological impacts from such disturbance. Consequently, understanding the taxa, growth form and distribution of structure-forming invertebrates is fundamental to assessing the relative vulnerability of benthic habitats to impact from disturbance, such as demersal fishing.

Surveys of the benthos in deep water, in remote locations, and/or in adverse sea-states such as routinely encountered in the Southern Ocean, are generally very expensive to conduct, and consequently, data on the distribution of benthic habitats is generally scant, particularly in the high latitudes. The presence of demersal fisheries, such as that for toothfish (*Dissostichus eleginoides* and *D. mawsoni*), emphasise the need for acquisition of data in areas where little or no information exists on the benthos presents a challenge for sustainable management. Knowledge of the benthos in deep-sea habitats has traditionally been gained through collection of physical samples using dredges, box corers, grabs and beam trawls (e.g. Kaiser *et al.* 2011) or from using highly sophisticated submersibles. Digital imagery of seafloor a powerful tool for assessing the substrate, biota and degree of human interaction with the seafloor (Foster *et al.* 2009, Shortis *et al.* 2008). Recent technological advances that have reduced the cost, increased the availability, reduced power consumption, increased battery life, and increased compactness of digital camera systems have facilitated the development of camera techniques in marine science (Kilpatrick *et al.* 2011).

Opportunistic sampling from vessels that are not dedicated research platforms, such as those engaged in fishing, has the potential to provide cost-effective data from a broad range of locations; however, camera systems developed for this purpose must be compact, robust, inexpensive, autonomous, and easy to operate. The Australian Antarctic Division (AAD) has developed a camera system that meets these criteria for deployment during commercial fishing events to assess the nature and extent of interactions between the benthos and different demersal fishing gears, able to be deployed up to 2500 m depth and utilises inexpensive, robust, standard resolution, surveillance video cameras (Kilpatrick *et al.* 2011).

This paper compares density estimates of structure-forming benthic taxa derived from camera footage with those derived from physical samples of the benthos to determine

the relative effectiveness of these methods for identifying the distributions of these taxa, and locations that may require management intervention to ensure they are appropriately conserved.

## Methods

Sampling was conducted over a range of habitat types on and around the continental shelf-break of East Antarctica from the 29<sup>th</sup> of December 2009 to the 8<sup>th</sup> of January 2010. A research beam trawl with still and video camera systems mounted on the beam was deployed from the *Aurora Australis* in depths ranging from 350 to 1400 m. Deployments targeted a representative range of habitat types from soft sediment, low complexity habitats to more complex rocky habitats on the shelf break of East Antarctica. The beam trawl was in contact with the seafloor for up to 10 minutes at a tow speed of around 2.5 knots. For the purposes of this study, structure-forming taxa were defined as erect, sessile invertebrates such as corals and sponges.

### Beam trawl samples

The beam trawl was 2.68 m in width and was fitted with a 10 mm mesh codend liner. Biological material collected in the codend were sieved ( $\geq 4$  mm), sorted, and weighed. Non-colonial (solitary) taxa such as asteroids or crustaceans were counted and weighed individually. Colonial taxa such as sponges, hydrozoans, bryozoans and octocorals, which could not be counted as individuals, were separated to genus or species (where possible) and a whole weight was recorded.

The swept area of each beam trawl shot in square meters was the product of the width of the beam trawl (2.68 m) and the distance travelled by the research ship whilst the beam trawl was in contact with the seafloor. Catches yielded diversity, abundance and biomass parameters. Biomass values for each structure-forming taxon at each site were normalised by transforming raw values to the power of  $2/3$  and divided by the swept area, to estimate density by taxon, assuming a catchability of 1 regardless for all taxa.

### Image processing

A Java program *Benthic Video Annotator* (BVA) was developed to relate real-time and stored ship-underway data (including depth and position). It allows estimation of the camera position and depth based on footage time-stamping and annotation of video and stills photography (such as substrate and seafloor characteristics and species identification and counts). Additionally it records the view-field coordinates of objects of interest such as measurement laser dots or individual organisms. Image identity, position, depth, annotation, and view-field coordinate data are written in CSV format.

### Stills camera analysis

The stills camera system was comprised of a Canon EOS 20D SLR set at 1/60<sup>th</sup> second shutter opening, 12 mm focal length, ISO 800 and f3.5, housed in a pressure casing and mounted on the beam of the beam trawl, facing forward and down at an angle of approximately 20 deg below horizontal. Lighting for the still system was supplied by four 1800 lumen underwater LED lamps in pressure housings with hemispherical acrylic dome lenses. Each lamp unit contained constant current drive electronics to run the 6 x 3 LED clusters. A time lapse controller and a 24V 2.5Ah Cyclon SLA battery pack were also housed within the camera housing and shots were taken every 10 seconds. The camera ran wholly from an attached NP-FH70 Li-Ion battery pack. The stills camera system included two laser units that projected parallel beams 0.5 m apart horizontally and parallel to the axis of the centre of perspective of the camera.

Up to one still was analysed from each one minute of bottom time. Images where sediment plumes obscured the seafloor, were excluded. Each stills image was analysed using BVA to ascertain the coordinates (in pixels) of the laser dots and to derive the species list/diversity and abundance by taxa. *Coral Point Count with Excel extensions* (CPCe) (Kohler & Gill 2006) was used to locate the bounding coordinates (in pixels) of the interpretable region of the seafloor in each image, and to allocate random points within that region on the image. The fauna or substrate type lying under each of 50 random points was recorded.

The relative density of each taxon in each image was inferred from the relative proportion of random points lying on individuals of that taxon and was expressed by area to facilitate comparison with biological samples and to increase the resolution of habitat assignments from still images. The area of the readable region of each image was calculated trigonometrically from the characteristics of the lens (assuming rectilinearity), the separation in pixels of the lasers marks and the size of the readable region selected in CPCe. First the distance from the lens to the seafloor along the centre axis of perspective of the lens ( $d$ ) was estimated by eq. 1:

$$d = \frac{W_L}{2 \tan \theta} \quad 1)$$

where  $W_L$  is the separation of the parallel laser beams (500 mm) and  $\theta$  is angle from the centre of perspective to one laser dot, estimated by eq. 2:

$$\theta = \tan^{-1} \left( \frac{M_L}{2f} \right) \quad 2)$$

where  $f$  is the focal length of the lens (12 mm in this instance) and  $M_L$  is the apparent separation of the laser dots in millimetres on the image, estimated by eq. 3:

$$M_L = M_H \left( \frac{P_L}{P_H} \right) \quad 3)$$

where  $M_H$  is the width of the image capture medium (22.5 mm wide sensor in this instance),  $P_L$  is the separation between the laser dots in pixels taken from the BVA coordinates and  $P_H$  is the width of the image in pixels.

The distance on the seafloor of the readable region represented vertically in images was calculated by first calculating the angle of the camera to the seafloor and then determining the distance along the seafloor from directly below the lens to the point corresponding to the nearest edge of the readable region in the image ( $V_0$ ) was estimated by eq. 4:

$$V_0 = H_C \tan(\beta) \quad 4)$$

Where  $H_C$  is the height of the camera above the substrate (assumed constant at 1.2 m) and  $\beta$  is the angle between the closest point on the seafloor in the image and the vertical line between the lens and the seafloor, estimated by eq. 5:

$$\beta = \left[ \cos^{-1} \left( \frac{H_C}{d} \right) \right] - \frac{\alpha_V}{2} \quad 5)$$

and where  $\alpha_V$  is the vertical angle of view of the lens, estimated by eq. 6:

$$\alpha_V = 2 \tan^{-1} \left( \frac{M_V}{2f} \right) \quad 6)$$

and  $M_V$  is the height of the image capture medium (15 mm high sensor in this instance). The vertical distance across the seafloor to any point  $n$  in the image ( $V_i$ ) was then able to be estimated by:

$$V_i = H_C \tan \left[ \beta + \left( \frac{\alpha_V P_{V_i}}{P_V} \right) \right] \quad 7)$$

where  $P_{V_i}$  is the vertical height of point  $i$  in the image in pixels taken from BVA and  $P_V$  is the total height of the image in pixels.



The distance on the seafloor between two horizontally aligned points in an image ( $H_{i,j}$  where  $V_i=V_j$ ) was determined by:

$$H_{i,j} = V_i [\tan(\theta_i) + \tan(\theta_j)] \quad 8)$$

where  $\theta_i$  is the angle between the centre of the axis of perspective and point  $i$  on the seafloor, estimated by:

$$\theta_i = \left| \alpha_H \left( \frac{P_{Hi}}{P_{Htot}} - \frac{\alpha_H}{2} \right) \right| \quad 9)$$

where  $P_{Htot}$  is the width of the image in pixels,  $P_{Hi}$  is the horizontal pixel count to point  $i$ , and  $\alpha_H$  is the horizontal angle of view of the lens, estimated as:

$$\alpha_H = 2 \tan^{-1} \left( \frac{M_H}{2f} \right) \quad 10)$$

Equations 7 and 8 were used to estimate the distance across the seafloor to the foreground and background extent ( $V_{min}$  and  $V_{max}$  respectively) and the left and right extent of the visible region ( $H_{min}$  and  $H_{max}$  respectively).

The area of the readable region ( $A_R$  in  $m^2$ ) was then estimated as:

$$A_R = (V_{max} - V_{min})(H_{max} - H_{min}) \quad 11)$$

Due to the oblique camera angle, random points allocated lower in the foreground of readable region of images were distributed more densely with respect to the seafloor than random points allocated in the background. Thus, the relative density of a taxon beneath a random point varied with the position of the point in the readable region of an image. Consequently, a weighting factor,  $F_i$  for the occurrence of an organism overlapping with any point  $i$ , estimated based on the ratio of  $H_i$ , the width of the readable region on the seafloor at the vertical height at point  $i$ , to  $H_{max}$  the width of the readable region at its widest point, i.e:

$$F_i = \frac{H_i}{H_{max}} \quad 12)$$

The sum of the weighted occurrences of taxa at random points across the readable area  $A_R$ , ignoring shadowing, gave an estimate of  $D_t$ , that is the density of any taxon  $t$  encountered in an image, i.e.:

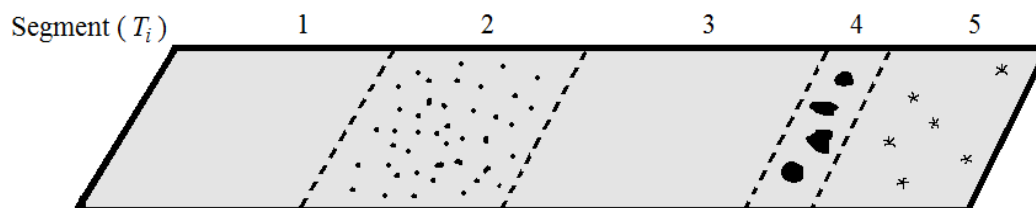
$$D_t = \frac{\sum F_i}{A_R} \quad 13)$$

These density values were summed across images within sites to give total density by taxa, by site. The density values within each image were summed across taxa to give total density values by image. The mean of the total densities per site across images was calculated, and the coefficient of variation was considered an indication of the patchiness of the habitat at each site.

### Rapid analysis of video footage

The Benthic Impacts Camera System (BICS, see Appendix 4) provided video footage of the seafloor encountered by the beam trawl. Footage collected for each site by the BICS was viewed using BVA from the point at which the beam trawl contacted the seafloor to its final departure from the seafloor. Footage was viewed in segments with the segment duration defined by changes in faunal assemblage or substrate (Figure A5.1). Within each segment, the time over which the benthos was observable (i.e. when the beam trawl was in motion) was recorded. The substrate type (primary and secondary types where a mixture was evident, e.g. drop stones on mud) and the bed-form relief were recorded for each segment (Table A5.1). The approximate density of all structure-forming invertebrate taxa (approximately 10, 5, 1, 0.5 and 0.05 taxa/m<sup>2</sup> recorded as high density, dense, low density, sparse and barren respectively), patchiness, and the relative dominance of all observed taxa were also rated in each segment.

**Figure A5.1. Diagram of the rapid method of defining segments during rapid analysis of video footage. For example, footage from one site may consist of 5 segments (1 – 5) differentiated as (1) barren sand, (2) patchy cobble on sand with benthos, (3) barren sand, (4) boulders with benthos and (5) sand with uniform ophiuroids.**



**Table A5.1. Attributes and qualitative categories assessed during rapid assessment of the seafloor in footage captured by the BICS.**

Attributes	Categories					
<b>Substrate</b>	Rock	Boulder	Cobble	Sand	Mud	Drop Stones
<b>Density of benthos</b>	Barren~ 0.05 taxa.m <sup>-2</sup>	Sparse~ 0.5 taxa.m <sup>-2</sup>	Moderate~ 1 taxa.m <sup>-2</sup>	High~ 5 taxa.m <sup>-2</sup>	Very high~ 10 taxa.m <sup>-2</sup>	
<b>Seafloor relief</b>	Rippled	Bioturbated	Flat	Low relief	Moderate relief	High relief
<b>Patchiness of Benthos</b>	Uniform	Moderate	High			
<b>Taxon Dominance</b>	1: Most common	2: Common taxa, up to half as common as category 1	3: Common taxa, up to a quarter as common as category 1	4: Present, but not common taxa in segment		

An estimate of the density of the structure-forming invertebrate taxa by site was generated with consideration of the relative importance of each taxon, the density of the benthos, and the swept area of each sequence, using the following formula:

$$D_{tV} = \frac{\sum I_i D_i T_i}{\sum T_i} \quad 14)$$

Where  $D_{tV}$  is the video density estimate for taxon  $t$  across all video segments at a site,  $I_i$  is the relative importance rating for a taxon  $t$  in video segment  $i$  (a value of 1, 0.5, 0.25 or 0.05 for importance ratings 1, 2, 3 and 4, respectively),  $D_i$  is the density rating of all structure-forming taxa in a segment  $i$  (a value of 10, 5, 1, 0.5 or 0.05 per m<sup>2</sup> corresponding to faunal density category), and  $T_i$  is the duration of video segment  $i$ . Note that  $T_i$  must be summed in both the numerator and the denominator because a taxon may not be encountered in every video segment at a site.

### Comparison of sampling methods

The densities, summed across structure-forming taxa from each sampling method (beam trawl, stills and rapid assessment using video) were compared by site to investigate differences in the relative detection of taxa, distribution and relative abundance of structure-forming invertebrates.

### Results

The video and stills sampling methods were deployed successfully at 19 sites over three broad habitat types in East Antarctic waters: an off-shelf plateau (PL<sub>1</sub> and 2), a typical section of shelf-break (SB<sub>1</sub> to 12), and the head of a shelf-break canyon feature (CA<sub>1</sub> to

5) (Table A5.1). Complications such as a torn codend precluded quantitative analysis of beam trawl samples from 5 sites (PL1, PL2, SB4, SB6 and SB7).

### **Beam trawl samples**

Samples derived from the beam trawl codend provided a range of benthic invertebrate taxa with considerable variation in the quantity of biota landed (Table A5.2). Over 400 different taxa were encountered including numerous small motile invertebrates.

Structure-forming taxa were well-represented in catches, but were generally in fragments due to the mechanical forces exerted by the beam trawl and in the codend after capture. Structure-forming invertebrate taxa collected by the beam trawl included sponges (Porifera), hard corals (Scleractinia), gorgonians and soft corals (Alcyonaria), hydrocorals (Hydrozoa), bryozoans (Bryozoa), tube worms (Polychaeta), sea lilies (Crinoidea), and ascidians (Ascidiacea).

### **Stills camera footage**

The stills camera captured well-illuminated, high resolution images (Figure A5.2) that readily enabled identification and enumeration of benthic invertebrates, in particular larger structure-forming invertebrates. The densities calculated using CPCe provided plausible estimates of the relative abundance of structure-forming taxa in the habitats sampled. For example, in the image in Figure A5.2A, densities for the highest ranked structure-forming invertebrates, in order, were hydrocorals, gorgonians, sponges and tube worm cases.

### **Video camera footage**

The BICS video footage was of sufficient resolution to allow identification of larger structure-forming taxa such as sponges, hydrocorals, gorgonians, sea lilies, tube worm cases, and anemones (Actiniaria) (Figure A5.2). For example, in the approximately three minutes duration sequence containing the frame in Figure A5.2B and overlapping with the still image in Figure A5.2A, the four highest density invertebrates identified were hydrocorals, gorgonians, tube worms and sponges, identical to the still image. Viewing the footage in sequences defined by changes in the faunal assemblage or substrate rapidly yielded estimated densities of structure-forming invertebrates and measures of the patchiness of the habitat more rapidly than the other methods.

Viewing the video footage also revealed that the beam trawl did not always collect a consistent sample of the benthos, as it was observed at times to lift from the seafloor or gouge more deeply into the substrate. Consequently, swept area was based on the observed time on the seafloor from video footage rather than swept area calculated from the ship track.

Table A5.2. Sample sites and summary sample data. PL = offshore plateau, SB= shelf-break, CA=canyon head. Densities are of estimated for structure-forming invertebrates.

Station	Biological Samples			Visual samples				
	Mean depth (m)	Swept area (m <sup>2</sup> )	Density (g/m <sup>2</sup> )	Stills footage			BICS video footage	
				Visual swept area (m <sup>2</sup> )	Density (Number/m <sup>2</sup> )	Number of images	Density (individuals/min)	Duration (mm:ss)
PL1	1260	- <sup>a</sup>	-	124	0.30	5	- <sup>b</sup>	-
PL2	1271	- <sup>a</sup>	-	13	0.00	6	0.09	03:31
SB1	1076	1395	0.42	61	5.88	5	6.67	06:52
SB2	833	847	0.08	142	3.60	5	1.90	02:09
SB3	662	1644	0.17	80	1.69	7	2.29	07:50
SB4	611	- <sup>a</sup>	-	142	0.95	5	2.65	07:39
SB5	561	1793	0.08	126	1.48	11	1.46	09:03
SB6	779	- <sup>a</sup>	-	193	2.43	11	5.87	09:47
SB7	953	- <sup>a</sup>	-	133	0.55	10	1.86	08:09
SB8	758	1096	0.11	92	4.33	5	1.53	02:15
SB9	701	1644	0.55	168	0.25	9	2.85	07:59
SB10	442	1943	1.47	46	35.85	6	19.87	04:54
SB11	1157	2192	0.10	104	0.00	8	2.14	06:12
SB12	699	2142	0.40	144	6.62	7	3.44	06:36
CA1	728	2391	0.48	304	8.34	13	19.51	10:07
CA2	522	2591	0.80	191	13.58	13	21.34	09:58
CA4	404	1943	0.40	212	5.30	11	19.13	03:44
CA5	547	498	2.43	90	20.39	3	23.15	00:03
CA6	527	598	23.13	108	90.70	5 <sup>c</sup>	53.79	06:04

<sup>a</sup>Codend torn, precluding quantitative analysis of biological samples

<sup>b</sup>No useful footage obtained

<sup>c</sup>Most stills obscured by sediment

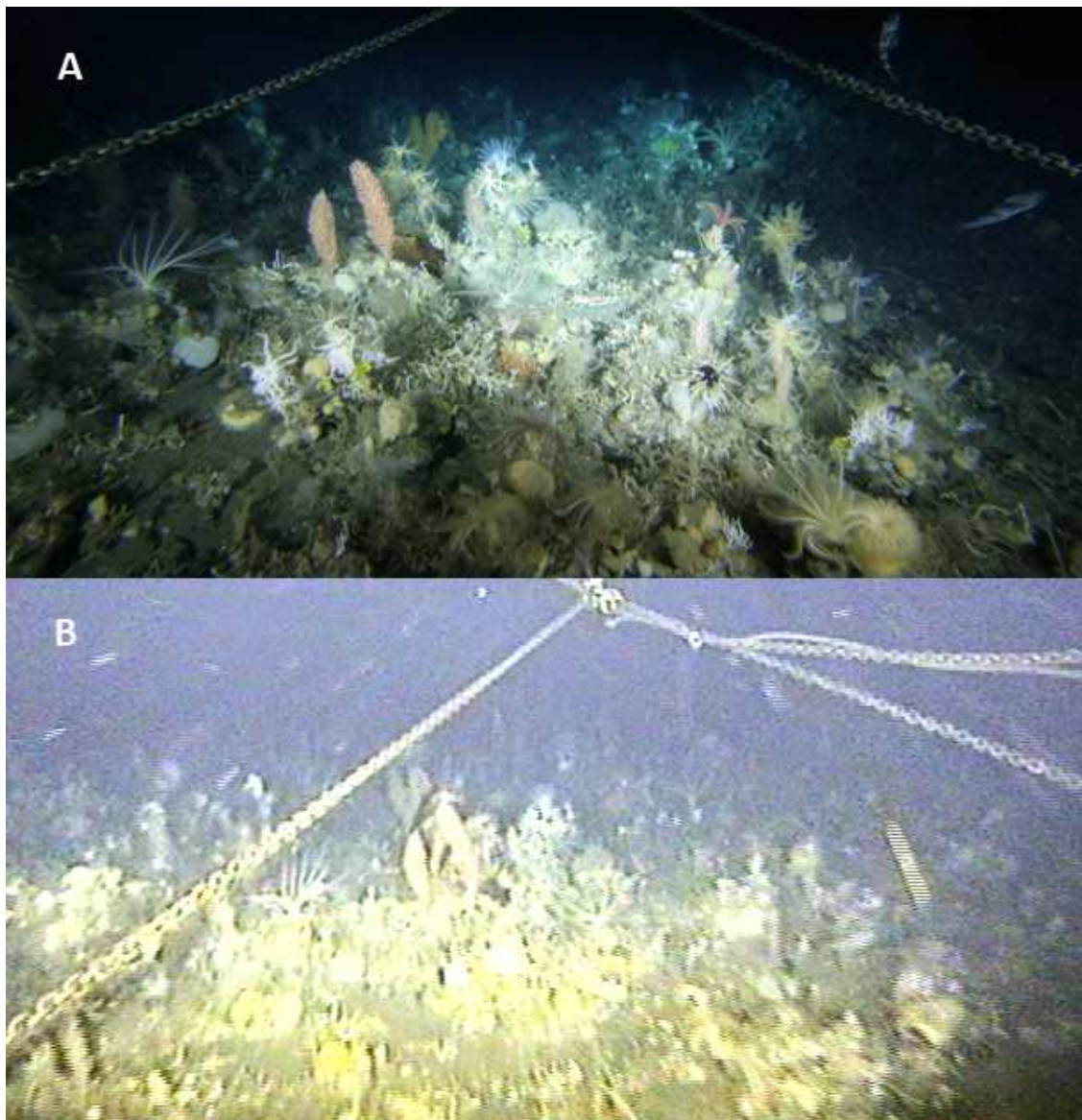


Figure A5.1. Images of the same benthos captured with a beam trawl mounted digital still camera (A) and compact video camera system (B).

### Comparison of camera footage and biological determinations of habitat type and distribution

Trends in proxy estimates for density trends across sites in total densities of structure-forming taxa derived from still images, video and biological sampling were consistent (Figure A5.2). Exceptions to this relationship were SB9, where the biological sample was dominated by a small number of large sponges, and CA6 where sediment resulted in few usable stills and limited video footage, and both indicated generally low density of biomass. However, video footage from CA6 indicated the beam trawl gouged deeply

into a particularly abundant patch of benthos, contributing to the apparent differences in density estimated by each method in this instance.

Rank correlations were highly significant in all pair wise comparisons, and were strongest between the BICS and beam trawl samples (Table A5.3).

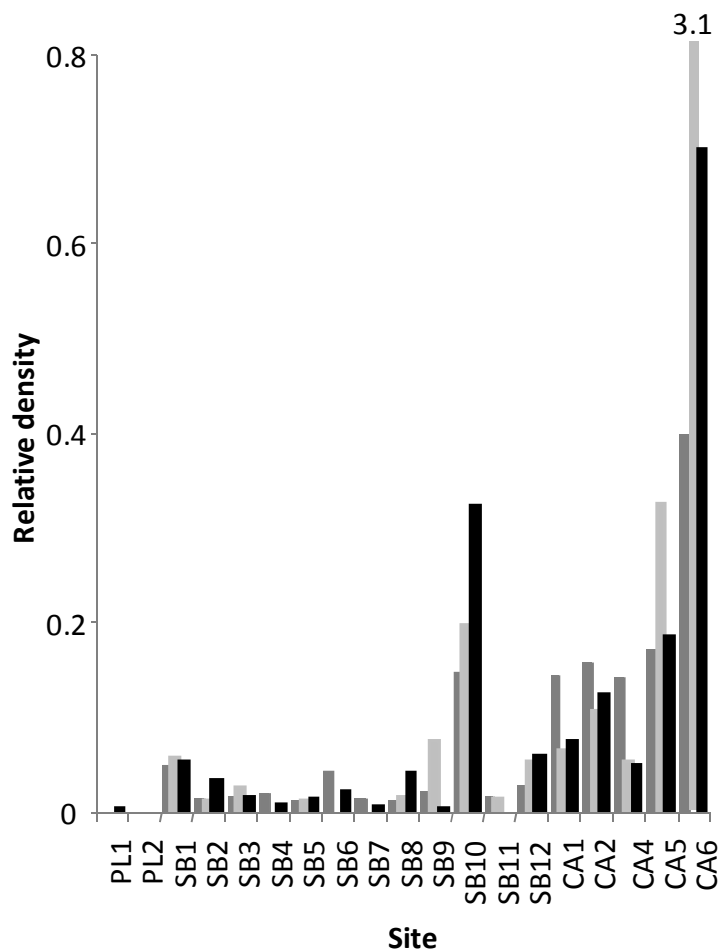


Figure A5.2. Relative densities of structure-forming invertebrates derived from digital still images (black columns), beam trawl codend samples (light grey columns) and BICS video (dark grey columns). Densities were standardised to relative density by dividing the density at each site by the total density across sites for each sample method, with the exception of the biological density value for site CA6 which was excluded to maintain an appropriate scale for the remaining sites (equivalent value of 3.1).

Table A5.3. Rank correlation statistics for pair wise comparisons between sampling methods.  $\tau$  = Kendall's rank correlation,  $\rho$  = Spearman's rank correlation,  $p$  = probability that true correlation between ranks is zero.

Methods compared	$\tau$	$p$	$\rho$	$p$
Stills, BICS	0.67	<0.001	0.86	<0.001
Stills, Beam trawl	0.69	<0.001	0.79	0.001
BICS, Beam trawl	0.76	<0.001	0.91	<0.001

## Discussion

In this study, the three sampling methods displayed different capabilities when applied to deep-sea, high latitude, benthic sampling (Table A5.4). The choice of methods used will critically depend on the types of information sought during research. For example biological samples from the beam trawl codend provide the opportunity to obtain data at the highest taxonomic resolution, as well as providing physical samples which are essential for useful for studies on population connectivity and endemism. However, in our experience this method also required a relatively large field team and infrastructure for the deployment of sample gear and the sorting and preservation of biological samples at sea and further laboratory analysis of samples after the voyage. The length of beam trawl shots was constrained by the size of the codend and by the loss of spatial habitat resolution if more than one habitat type is encountered, as taxa across habitats will be mixed in the codend.

**Table A5.3. Comparison of beam trawl, stills camera and Benthic Impacts Camera System sampling of benthos for information content, at-sea and analysis capability requirements.**

Sampling method	Information content	At-sea capability	Analysis capability
<b>Beam trawl</b>	<ul style="list-style-type: none"> <li>• High taxonomic resolution</li> <li>• Size structure</li> <li>• Genetic relationships</li> <li>• Taxa density</li> <li>• Variability between samples</li> </ul>	<ul style="list-style-type: none"> <li>• Deploy beam trawl</li> <li>• Rough sorting</li> <li>• Short term curation</li> </ul>	<ul style="list-style-type: none"> <li>• High/moderate level taxonomic expertise</li> <li>• Wet/dry storage/lab</li> </ul>
<b>Stills</b>	<ul style="list-style-type: none"> <li>• Taxa density</li> <li>• Bedform, sediment</li> <li>• Moderate taxonomic resolution</li> <li>• <i>In situ</i> patchiness, associations</li> <li>• Variability between samples</li> </ul>	<ul style="list-style-type: none"> <li>• Program camera</li> <li>• Lower camera</li> <li>• Image curation</li> <li>• Recharge batteries</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate taxonomic expertise</li> <li>• Image analysis expertise</li> </ul>
<b>BICS</b>	<ul style="list-style-type: none"> <li>• Taxa density</li> <li>• Bedform, sediment</li> <li>• Moderate taxonomic resolution</li> <li>• <i>In situ</i> patchiness, associations</li> <li>• Variability between samples</li> </ul>	<ul style="list-style-type: none"> <li>• Program camera</li> <li>• Lower camera</li> <li>• Image curation</li> <li>• Recharge batteries</li> </ul>	<ul style="list-style-type: none"> <li>• Moderate level taxonomic expertise</li> <li>• Image analysis expertise</li> </ul>

Despite providing lower taxonomic resolution, stills image sampling required less onsite infrastructure, and image curation transportation and storage. The duration of stills camera shots was limited by battery and/or memory media capacities, however this was generally less limiting than the capacity of the codend for biological samples. For example, in this study the size of the beam trawl codend limited bottom times to less than 10 minutes, whereas the stills and video cameras had sufficient capacity to collect footage in excess of 5 hours. This allowed for a broader range of habitats to be sampled for a given sampling window, habitat boundaries could be recorded, and the spatial relationship between taxa *in situ* could be assessed in a way not possible when specimens are intermingled in a codend.



The densities of structure-forming taxa estimated from still images and the rapid video assessment yielded no significant differences ranking of sample sites by density of structure forming invertebrates. In the instance where density estimates were divergent, it is likely that issues such as the net digging into the substrate were more likely the cause rather than any systematic bias in any sampling method. Hence, at the level of estimating relative density and distribution of structure forming invertebrates, the methods evaluated here are interchangeable.

Ideally, a combination of sampling methods would be available to deploy concurrently to provide the maximum information possible. However, in the Southern Ocean where information on the distribution of structure-forming invertebrates and their relationships to fishing locations or topographic features are sparse, collecting high resolution taxonomic information on the distribution and abundance of structure forming invertebrate taxa may not be the most efficient way to assess and manage the impacts of bottom fishing. This is implicit in the current management measures used by CCAMLR, which use quantities of VME indicator taxa (*sensu* SC-CAMLR 2009), generally identified no lower than the order or suborder level to trigger management responses. Figure A5.1 shows that groups at this level can be readily identified in stills and video. Furthermore, the rapid analysis procedure described above enables rapid synthesis of this data in around 10% of the time to collect the same data from stills or biological samples. Therefore, we contend that the use of a system such as the BICS, which is designed to make it relatively simple to deploy off research and fishing vessels, with relatively little infrastructure or expertise, provides the potential for cost-effective collection of data to ground truthing where fisheries bycatch indicates the presence (or apparent absence) of indicators of vulnerable marine ecosystems.

## Appendix 6. Macro-epibenthic faunal diversity and assemblages in the Heard Island and McDonald Islands region

Ty Hibberd

### ABSTRACT

Biodiversity of macro-epibenthos (organisms living on the surface of the seafloor ~10mm or larger) in the Heard Island and McDonald Islands (HIMI) region, encompassing the southern end of the Kerguelen Plateau, was analysed using biological samples collected from several areas covering a range of depths and topographies. The investigations were undertaken to determine the types and distribution of benthic invertebrates, their conservation value in the context of the subantarctic region and current status of representation within the HIMI Marine Reserve. Benthic fauna in the region was diverse both in regard to species and assemblage composition, and while many taxa were apparently site restricted and including some likely endemic forms, diversity was broadly typical of deep-sea subantarctic faunal assemblages. Included among these taxa were a range of slow-growing forms, with relatively high vulnerability to disturbance by bottom fishing including sponges, arborescent bryozoans and octocorals. Assemblage composition ranged from structurally complex, high diversity/density communities on the shallow western and northern banks (< 300 metres), a low biomass but high diversity community composed of numerous rare taxa on Shell Bank, to low diversity/density communities characteristic of the deeper plateau to the Northeast (> 700 metres). Similarities identified between the central localities of HIMI suggest that this area may serve as a biogeographic contact zone, with mixing of taxa from east to west across the Kerguelen plateau around HIMI, although unique assemblages occur within this area (e.g. notable population of the endemic solitary scleractinian, *Flabellum* spp., at Gunnari Ridge). This study provides the most detailed quantitative description distribution, abundance and species composition of macrobenthic invertebrate assemblages in the HIMI region, providing a rich dataset with which to evaluate biogeographic pattern in the high latitudes of the Southern Ocean, and spatial distribution of vulnerable benthos to enable focussing management on areas of highest risk of impact from bottom fishing.

## Introduction

Heard Island and McDonalds Islands are among a number of geographically isolated islands situated throughout the subantarctic sector of the Southern Ocean, roughly between 46° and 60°S (Figure A6.1). Heard Island and McDonald Islands form Australia's most remote sovereign territory, and one of two Australian Exclusive Economic Zones (EEZ) distant from the continental EEZ in subantarctic waters. The ecology (marine and terrestrial) and oceanographic conditions surrounding these islands is considered to be quite distinct from other subantarctic islands such as Macquarie Island (DEH 2002). They lie directly in the path of the Antarctic Circumpolar Current (ACC) forming a convergence zone where cold-temperate oceans meet polar waters (Park *et al.* 2008, Sokolov & Rintoul 2009, van Wijk *et al.* 2010).

The distribution and structure of benthic assemblages surrounding these Subantarctic islands are among the least well known of the world's oceans, and yet many, like HIMI, are likely to encounter disturbance by bottom fishing. Since April 1997 an Australian bottom fishery targeting Patagonian toothfish (*Dissostichus eleginoides*) has been in operation in the HIMI region, managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Australian Government. To provide protection for representative or vulnerable benthic communities in the region, in October 2002 a marine reserve was declared under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). The protection of benthic biodiversity within the reserve was based largely on data at low taxonomic resolution collected opportunistically from trawl surveys of fish in the early 1990s (Meyer *et al.* 2000). At the time of its establishment, it was recognized that targeted scientific sampling would be required to evaluate representativeness, and to determine whether MPA candidate areas identified outside the reserve (Conservation Zones in Figure A) warrant inclusion under the EPBC Act.

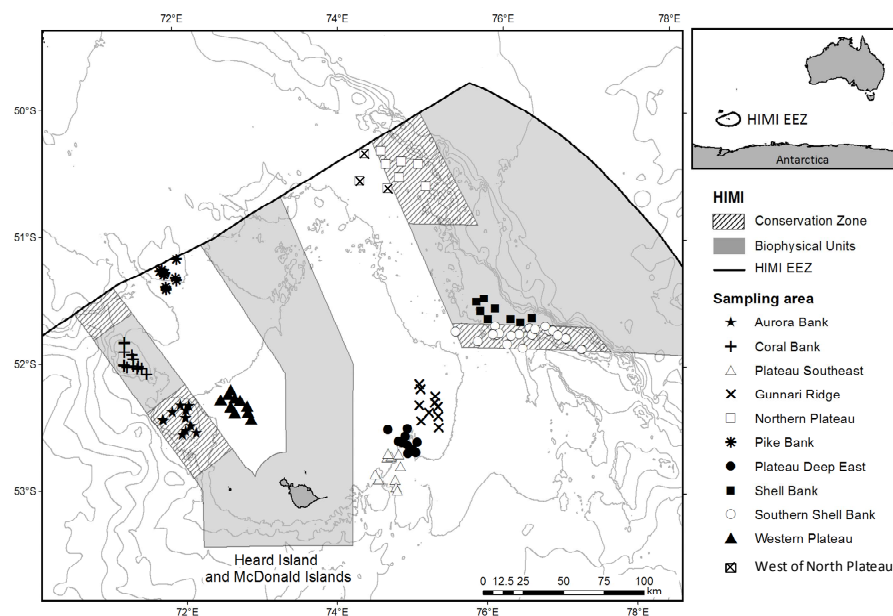
Scientific sampling was therefore undertaken to provide quantitative data on the distribution and diversity of epibenthic fauna in the region, to enable a description of the biogeographic patterns in that fauna, and support the evaluation of current management, such as the Marine Reserve and Conservation Zone in minimising risk of unsustainable impacts to biodiversity at HIMI.

## Methods

### Field sampling

The investigations were carried out aboard the fishing vessel *Southern Champion* during cruises SC26 (April/May 2003), SC46 (June 2007) and SC50 (June 2008). Data were collected from 129 sites using either beam trawl (SC26, SC 46, and SC50) or benthic sled (SC26 only) fitted with a 0.01 m × 0.01 m mesh codend liner. When deployed, the epibenthic sled was towed on a parallel but slightly offset course to a neighbouring beam trawl, in an attempt to provide data to compare mesoscale patterns in biodiversity provided by different sampling gears.

The areas sampled throughout HIMI were selected for the purpose describing patterns in faunal composition across the region, while stratifying sampling locations to provide sufficient power to characterise with mesoscale variability with reference to the 'biophysical units' defined by Meyer *et al.* (2000) and the location of the HIMI Marine Reserve and Conservation Zone. these areas include Aurora Bank (ABA), Coral Bank (CBA), Pike Bank (PBA), Shell Bank (SBA), Southern Shell Bank (SSB - conservation zone at the southern end of the Shell Bank), Western Plateau (WPL), Northeast Plateau (both within (NPL) and to the west (WNP) of the Conservation Zone) and the southeast sector of the Southern Plateau; subdivided into Plateau Southeast (PSE), Plateau Deep East (PDE) and Gunnari Ridge (GRI) (Table A6.1, Figure A6.1). Sampling sites were randomly positioned within each geographic area.



**Figure A6.1. Location of sampling areas and stations within the HIMI AEEZ (Marine Reserve boundaries solid lines, Conservation Zone (CZ) boundaries dashed lines)<sup>8</sup>. Note that CZ Area 1, north of Coral Bank, was not sampled in this study.**

<sup>8</sup> Data provided by the AAD Data Centre. Bathymetry from Beaman and O'Brien (2011). The HIMI Marine Reserve boundaries were created by The Australian Government Department of the Environment, Water, Heritage and the Arts (<http://www.environment.gov.au/coasts/mpa>).

**Table A6.1. Geographic areas sampled throughout the HIMI region and the rationale behind their selection (CZ = Conservation Zone; MR = Marine Reserve). Depth range based on the depth of the midpoint of each haul estimated from Beaman and O'Brien (2011). \*SSB was sampled a second time on cruise SC46 to confirm the earlier findings of cruise SC26.**

Sampling region	Acronym	Description and Sampling Rationale	Depth Range Sampled (m)	Cruise
Aurora Bank (CZ)	ABA	Similar depth and topography to CBA	225-389	SC26
Coral Bank (MR)	CBA	Sampled to compare with nearby ABA and the eastern banks	282-426	SC26
Western Plateau	WPL	Comparable depth range to CBA, ABA, low relief.	276-466	SC26
Southern Shell Bank (CZ)	SSB	Unique topography and geomorphology, inside MR	197-355	SC26/46*
Shell Bank (MR)	SBA	Unique geomorphology, similar depth and topography to other banks, inside CZ	229-778	SC46
Northern Plateau (CZ)	NPL	Includes deepest samples of plateau terrain, inside CZ	578-1010	SC46
West of Northern Plateau	WNP	Includes samples of deep plateau terrain in the northeast	609-774	SC46
Pike Bank	PBA	Similar depth and topography to CBA and ABA, outside MR or CZ.	172-536	SC50
Plateau Southeast	PSE	Slope west of Heard Island, deeper and higher relief than adjacent PDE	291-898	SC50
Plateau Deep East	PDE	Slope west of Heard Island, deeper moderate depth and relief compared to adjacent PSE	172-536	SC50
Gunnari Ridge	GRI	Aggregations of mackerel icefish by commercial fishing	212-325	SC50

### Sample handling and identification

Australian Fisheries Management Authority (AFMA) observers and staff of the AAD onboard the FV *Southern Champion* undertook the processing of samples. Due to the limited laboratory space and storage space available on board, after weighing the entire catch, subsampling was conducted as follows: where the total sample weight is < 10 kg, sort the entire sample as far as possible onboard and retain all material for later laboratory analysis or where the total sample weight is > 10 kg, weight the entire catch then randomly subsample ~10 kg of the catch, handle the subsample as above and discard the remainder. Retained material was frozen and returned to the AAD for more detailed sorting and identification.

In the laboratory the samples were defrosted, sieved through a 1 mm sieve and sorted to a coarse level (typically phylum). During this process, sediment characteristics were opportunistically observed and classified against Wentworth's (1922) grain-size classification scheme.

Most phyla were initially fixed in formalin or Steedman's Solution (10% solution of formaldehyde in sea water) (Steedman 1976) and transferred to 70% ethanol after approximately two months. Bryozoans, poriferans and holothurians were preserved in 98% ethanol only. Groups were then separated, using gross morphological differences, into taxonomic groups likely to represent species in most cases (*sensu* 'operational

taxonomic units' (Butler *et al.* 2000), 'putative taxa' (Ward *et al.* 2006) or 'morphotypes' (Meyer *et al.* 2000)). Unique codes developed by the AAD were used to label the taxa and all data were entered into a project-specific database.

All organisms were patted dry and weighed in the lab. Non-colonial taxa like asteroids or crustaceans were counted and weighed individually, and then lumped to provide mass at each sample location. Colonial taxa like sponges, hydrozoans, bryozoans and octocorals, which could not be counted as individuals, were separated to genus or species where possible and then lumped, and a whole weight recorded per sample. With the assistance of taxonomic specialists (Appendix 7), fine sorting and identification was completed for most broad taxonomic groups, although separation of some colonial groups, like sponges and bryozoans, is currently incomplete. For the purpose of this study, incompletely sorted groups were omitted from diversity analyses.

Biomass and abundance of mega-epibenthic invertebrates by site was standardised to per square metre of the seafloor (m<sup>2</sup>). The area of sampled seabed at each site was determined by multiplying trawl distance by the opening of the beam trawl or sled.

### **Data standardisation**

The principal units used for expressing the quantity of benthic invertebrates per geographic area were: 1) diversity, as the number of species/taxa per geographic area, 2) density, as the number of individual specimens per m<sup>2</sup> of seafloor sampled and 3) biomass, as the wet weight in grams per m<sup>2</sup> of seafloor sampled.

As noted above, fine sorting and identification of specimens was completed for most taxonomic groups. However, for many groups the confirmation of these taxa by taxonomic experts was incomplete, and separation of some groups like bryozoans and amphipods was incomplete. Lastly, some samples were deemed 'unreliable' due to sampling problems (i.e. holes in the beam trawl net) or inconsistent sub-sampling. Therefore for the purposes of analyses the taxa were divided into four groups:

- Group 1 taxa - those sorted to species and reliably sampled
- Group 2 taxa - those not sorted to species completely but reliably sampled
- Group 3 taxa - those sorted to species but not reliably sampled
- Group 4 taxa - those not sorted to species completely and not reliably sampled.

The analyses using presence/absence data and biomass were conducted on Group 1 and 3 taxa only while analyses on abundances or diversity use Group 1 taxa only. Colonial and non-colonial taxa were analysed separately.

### **Assemblage analysis**

Multivariate analyses of diversity, abundance and assemblage differences between sampling areas were conducted using the computer package PRIMER-E (Clarke & Gorley 2006). The Bray-Curtis resemblance measure was used to construct a matrix of faunal similarities across samples which then were represented visually through non-metric Multi Dimensional Scaling (nMDS) or ordination plots. Analysis of similarities (ANOSIM) was used to test for significant differences within and between sampling methods and sampling areas, and the SIMPER routine was used to elucidate those taxa contributing most to the similarities among, or differences between, groupings. The rate of taxa collection was analysed using a species accumulation plots (Clarke & Gorley 2006), which plots the cumulative total number of species observed as samples increase, providing an indication of whether additional samples may have yielded a greater species diversity in any one area

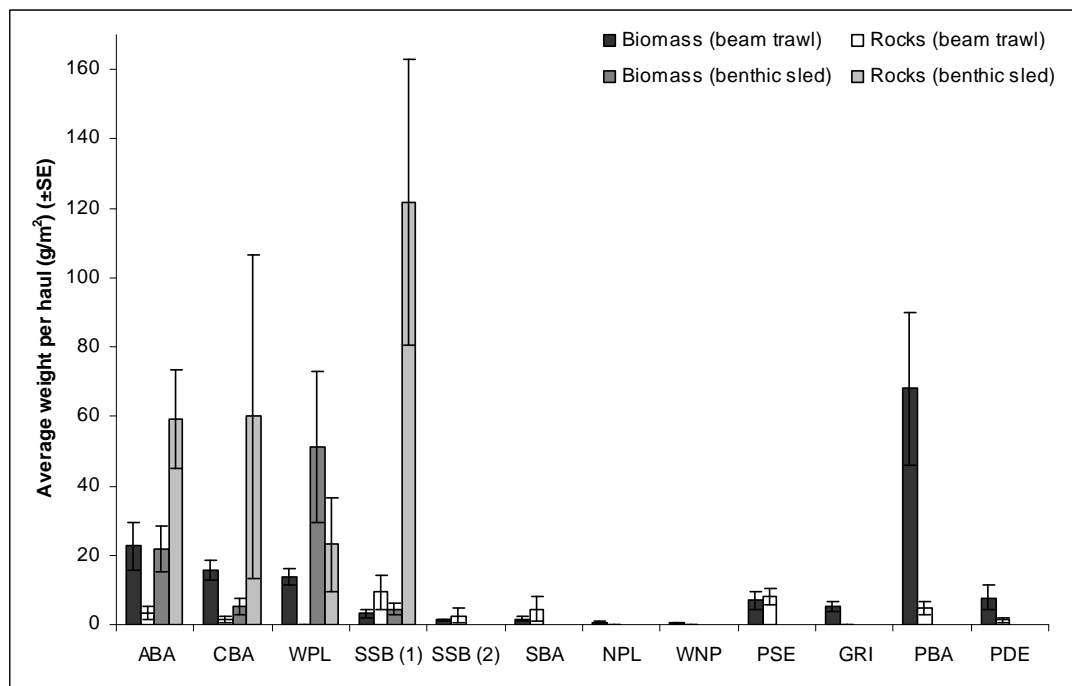
## **Results**

### **Sample Composition**

Samples from beam trawls and benthic sleds comprised mixes of sediment (rocks, gravel, sand and silt) and biota (Figure A6.2). Overall, the Northeast Plateau (WNP & NPL) returned the lowest catch rate of biological material followed by SSB. Samples from PSE, SSB and nearby SBA marine reserve contained more rocks and sediment than biota. When standardised by total swept area (m<sup>2</sup>), both SSB and SBA share a similarly low biomass.

Beam trawls at Pike Bank (PBA) recorded the highest biomass, while WPL had relatively large biological samples from the benthic sled. ABA and CBA returned similar amounts of biomass, although at CBA, six of the benthic sled tows had large holes torn in the net due to large catches of rocks and were excluded from the analyses. Four benthic sled samples from WPL were also excluded from the analysis due to inconsistent sub-sampling.

Comparing the samples collected by the two gear types indicated that the gears have different sampling efficacy, as a result of the configuration of the gear as well as the dominant substrate present in the sampling area. The benthic sled generally returned a larger total landed weight, and a higher proportion of sediment compared with the beam trawl. This is likely to be due to the benthic sled being designed to plough into the substratum and therefore collected a substantial amount of rock and silt at locations such as SSB and ABA, and also collected more sediment-dwelling infauna, like polychaetes and bivalves, in the soft mud or silt at WPL than the samples by the beam trawl in the same area. In contrast, the sled samples from ABA, CBA and SSB returned samples dominated by rocks and gravel, while these locations showed some of the highest catch rates and proportions of biota in the beam trawl.



**Figure A6.2. Weight of total biomass and sediment (rocks) per m<sup>2</sup> by sampling area and method. (Note only beam trawls were conducted in 2007 and 2008. Six benthic sled tows at CBA were excluded due to net tears and four benthic sled tows at WPL were excluded due to unrecorded subsampling).**

However, overall the two methods returned a similar number of taxa and there did not appear to be particular taxa which would not have been collected had only one method been used. Additionally, resulting conclusions about the diversity and assemblage differences of the sampling areas did not differ when analyses were conducted using results from only one method (Hibberd *et al.* in prep.). Thus, for these purposes this analysis, samples from both methods were considered equivalent.

### Rate of species accumulation

Species accumulation curves for the majority of individual sampling areas demonstrate asymptotic curves (Figure A6.3), indicating a rapidly declining rate of additional taxa per additional area sampled, and therefore comparisons between these areas are unlikely to be significantly affected by sampling biases. However, while the samples from locations in the northeast of the plateau (NPL & WNP) showed some of the lowest rates of accumulation of taxa, the relatively low total area sampled at these locations, and the lack of any asymptotic decline in species accumulation at these sites, indicate taxa are likely to be under-sampled in these locations.



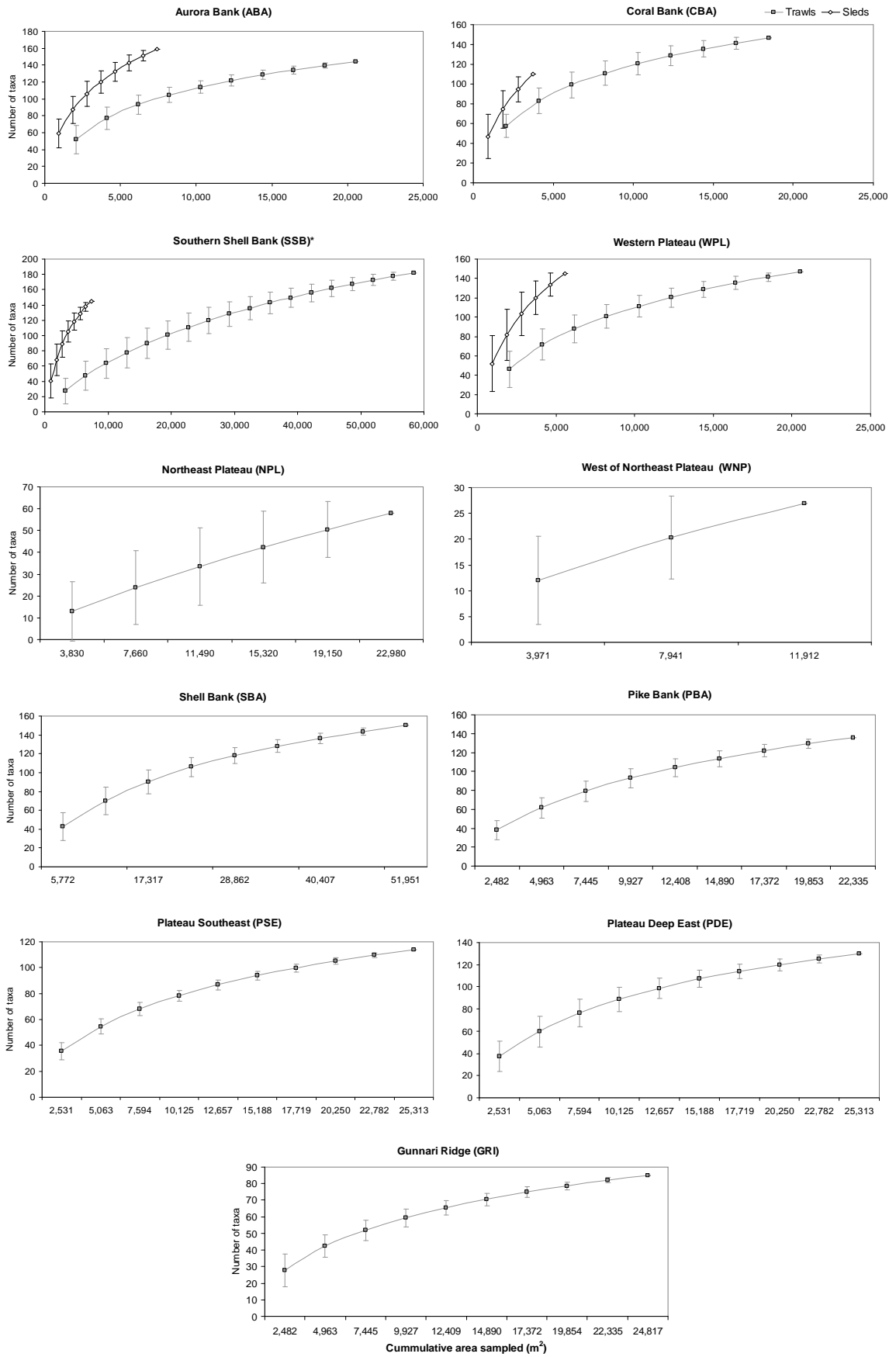


Figure A6.3. Cumulative taxa by area sampled (m<sup>2</sup>) for each geographical area and by method (\*SC26 and SC46 data combined for SSB).

### **Regional faunal diversity**

A total of 503 taxonomic groups were identified in this study, representing 14 phyla and 34 lesser groups such as subphyla, classes, subclasses, and orders (Table A6.2, a full listing is shown in Appendix 8). The dominance of these groups, ranges from relatively minor (components that account for less than 0.1% in number of individuals and biomass) to dominant components that make up 20% or more in number of individuals or biomass. The 39 major taxonomic groups, with percentage of total number of individuals (Group 1 only) and percentage of total biomass for each (Group 1 and 2), and classification into four dominance categories, I to IV, are shown in Table A6.3. Approximately 70% of both the biomass and number of individuals in the macrobenthos is formed by only eight taxonomic groups. These were classified in category I in Table A6.3. Sponges (Demospongia and Hexactinellida) were the dominant contributor (46.8%) to the biomass. Echinodermata (Ophuroidea, Holothuroidea, Echinoidea and Asteroidea) were numerically dominant (60.6%) and was also a major component in terms of the biomass; asteroids in particular (10.8%). Bivalvia, on the other hand, were important numerically (13.9%) but contributed only 1.1% of the biomass. Polychaeta were a major contributor to the biomass (10.6%), but sampling inconsistencies prevented accurate counts for this group. Category II in Table A6.3 consisted of nine taxonomic groups that contributed moderate biomass (1.0 to 5.2% of the total fauna) and eight groups contributed a moderate number of individuals (1.0 to 4.3% of the total fauna). Categories III and IV contain those taxa that contributed small to very small quantities to the total biomass and density.

### **Localised diversity**

The highest diversity (based on combined data for both gear types) of reliably sorted taxa was recorded from WPL ( $n = 252$  taxa) followed closely by ABA ( $n = 236$  taxa) (Table A6.2). Diversity was marginally higher within SBA ( $n = 146$  taxa) as opposed to adjacent SSB ( $n = 137$ ), which shared a similar diversity to PBA ( $n = 132$  taxa), however the diversity represented at SSB was made up of a relatively high number of low dominance species, indicated by the low biomass collected from this sampling area relative to other locations. The lowest diversity was recorded from WNP ( $n = 30$  taxa) with marginally higher numbers within the NPL conservation zone ( $n = 60$  taxa).

The combined total diversity for SSB ( $n = 198$ ) was considerably higher than the total for each individual survey ( $n = 137$  taxa for both SC26 and SC46), and nearer to that of CBA ( $n = 185$  taxa).

**Table A6.2. Number of morphospecies in general taxonomic groups at each of the sampling locations (based on Group 1 & 3 taxa only). SSB data is displayed by cruise (SSB 1 is SC26 and SSB2 is SC46) and as a combined total to display species accumulation between surveys. \*, \*\* indicates groups not sorted to lowest taxonomic level.**

Phylum/Subphylum	Class/Order	Common name	GEOGRAPHIC AREAS													Total SSB
			ABA	CBA	WPL	SBA	NPL	WNP	PBA	PSE	PDE	GRI	SSB1	SSB2		
Cnidaria	Actiniaria	anemones	10	8	19	5	7	3	5	5	10	9	6	3	9	
	Alcyonacea	soft corals	6	10	6	4	1	1	5	5	5	2	8	6	10	
Brachiopoda	Ceriantharia	tube-anemones	7	5	21	4	2		5	7	5	7	6	6	10	
	Gorgonacea	gorgonians														
	Pennatulacea	sea pens	1	1	2	1	2	2	1	2	2	1	1	2	2	
	Scleractinia	stony corals	2	2	2	2	2	2	1	2	2	1	1	0	4	
Cheliceriformes	Articulata	lamp shells	4	5	2	2	2		3	1	1	2	3	4		
	Pycnogonida*	sea spiders	10	11	14	3	1	1	2	5	6	3	11	*		
Crustacea	Amphipoda**	sand hoppers	2	1	4	4	5	1	3	1	3	2	0	8		
	Cirripedia	barnacles	2	5	4	1	1	1	2	2	2	2	2	3		
Mollusca	Cumacea	hooded shrimp	1		2	1			1				0	1		
	Decapoda	prawns/shrimp			1				1		1	2	0	3		
	Euphausiacea	krill										0	2	2		
	Isopoda	sea slaters	27	18	26	10	7	3	8	7	9	4	7	13		
	Ostracoda	seed shrimps	4	2	4	3			1	1	1	1	1	1		
	Tanaidacea	tanaids	1	1	2	1	1		1			2	2	3		
	Bivalvia	clams	23	20	18	13			15	4	5	3	11	8		
	Cephalopoda	octopus & squid	2	2	3	1	1		1	2	2	1	1	0		
	Gastropoda	sea snails	33	11	37	25	2	0	14	7	13	12	13	14		
	Echinodermata	Opisthobranchia	sea slugs	6		9	3	2		1	1	2	1	3	2	
Polyplacophora		chitons	3	4	1	1			1	1	1	2	1	4		
Scaphopoda		tusk shells	1			2	1	2	1	1	1	1	1	1		
Asteroida		sea stars	37	34	26	19	3	3	28	28	22	10	22	24		
Crinoidea		feather stars	21	19	26	18	10	8	18	16	17	13	2	2		
Echinoidea		sea urchins	4	4	2	2	1	2	2	2	2	1	3	3		
Holothuroidea		sea cucumbers	6	6	8	3	2	1	3	3	4	2	14	10		
Ophiuroidea		brittle stars	20	13	12	14	5	2	8	5	9	5	15	18		
Pterobranchia		pterobranchs	4	2	1	2			2	2	2	2	2	2		
Turbellaria		flat worms	1			1			1	1	1		0	1		
Priapulida	penis worm	1						1				0	0			
Sipuncula	peanut worm	1	1	1	1	3	1	1	1	1	1	1	0			
<b>TOTAL TAXA</b>			<b>236</b>	<b>185</b>	<b>252</b>	<b>146</b>	<b>60</b>	<b>30</b>	<b>132</b>	<b>113</b>	<b>127</b>	<b>82</b>	<b>137</b>	<b>137</b>	<b>198</b>	

**Table A6.3. Rank order of major taxonomic groups according to percentage composition of the total macro-epibenthic fauna (including motile and sessile fauna) in terms of biomass (group 1 and 2, reliably sampled) and number of specimens (group 1 only). Percentage of total number of specimens based on enumerated individuals (non-colonial taxa) in group 1 (reliably sampled and identified to lowest taxonomic level).**

Dominance category	All taxa	Mean % Biomass	Enumerated taxa	Mean % Abundance
I	Demospongiae	26.4	Ophiuroidea	21.5
	Hexactinellida	20.4	Holothuroidea	16.8
	Asteroidea	10.8	Bivalvia	13.9
	Polychaeta	10.6	Echinoidea	12.5
			Asteroidea	9.8
	<i>Total</i>	<i>68.4</i>	<i>Total</i>	<i>74.6</i>
II	Bryozoa	5.2	Cirripedia	4.3
	Echinoidea	5.2	Isopoda	4.0
	Ophiuroidea	4.1	Crinoidea	3.9
	Ascidiacea	4.0	Brachiopoda	3.9
	Holothuroidea	3.9	Gastropoda	2.4
	Actiniaria	1.9	Tanaidacea	2.0
	Bivalvia	1.1	Actiniaria	1.8
	Hydrozoa	1.1	Amphipoda	1.0
	Cirripedia	1.0		
	<i>Total</i>	<i>27.6</i>	<i>Total</i>	<i>23.2</i>
III	Cephalopoda	0.9	Scaphopoda	0.8
	Crinoidea	0.8	Polyplacophora	0.4
	Brachiopoda	0.7	Pycnogonida	0.4
	Alcyonaria	0.5	Cephalopoda	0.2
	Pterobranchia	0.4	Sipuncula	0.1
	Gastropoda	0.3	Ostracoda	0.1
	Isopoda	0.1	Scleractinia	0.1
	Scaphopoda	0.1	Cumacea	0.1
	Hydrocorallia	0.1	Ceriantharia	0.1
	Scleractinia	0.1		
	<i>Total</i>	<i>3.9</i>	<i>Total</i>	<i>2.2</i>
IV	Ceriantharia	all <0.1	Euphausiacea	all <0.1
	Tanaidacea		Platyhelminthes	
	Pycnogonida		Decapoda	
	Sipuncula		Pennatulacea	
	Polyplacophora		Priapula	
	Amphipoda			
	Platyhelminthes			
	Priapula			
	Pennatulacea			
	Decapoda			
	Crustacea			
	Euphausiacea			
	Ostracoda			
	Cumacea			
	Thaliacea			
	<i>Total</i>	<i>&lt;0.1</i>	<i>Total</i>	<i>&lt;0.1</i>

## Faunal density

Benthic sleds returned the highest number of taxa per m<sup>2</sup> where used, while beam trawls collected a similar number of taxa per m<sup>2</sup> across all SC26 sampling areas (Figure A6.4). Taxa density per m<sup>2</sup> at SSB was not significantly different between sampling years, and was also not significantly different between SSB and SBA. Samples from Northeast Plateau (NPL & WNP) recorded the lowest taxa per m<sup>2</sup>, reflecting a low density distribution of taxa over a large swept area (m<sup>2</sup>). Beam trawls in 2008 returned a marginally higher density of taxa from PBA, and similar taxa densities across the remaining areas.

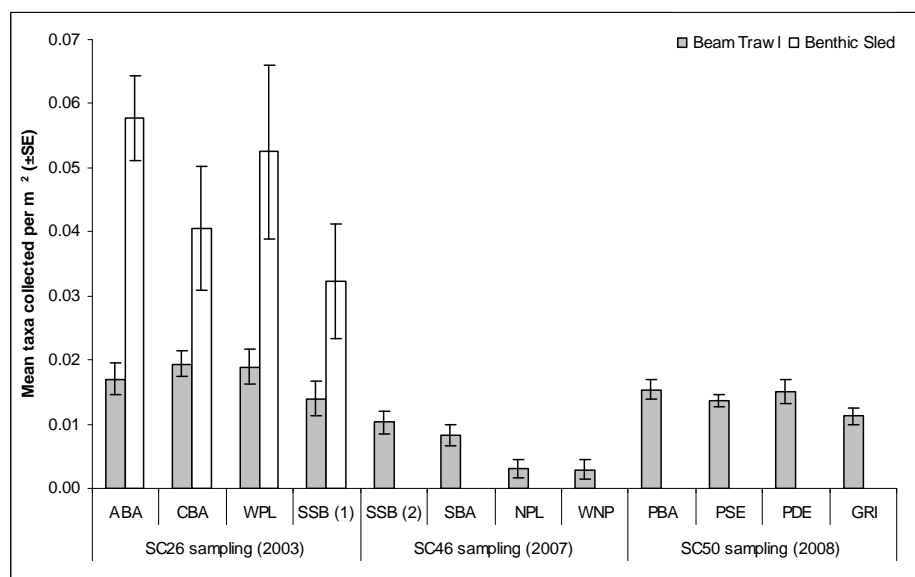


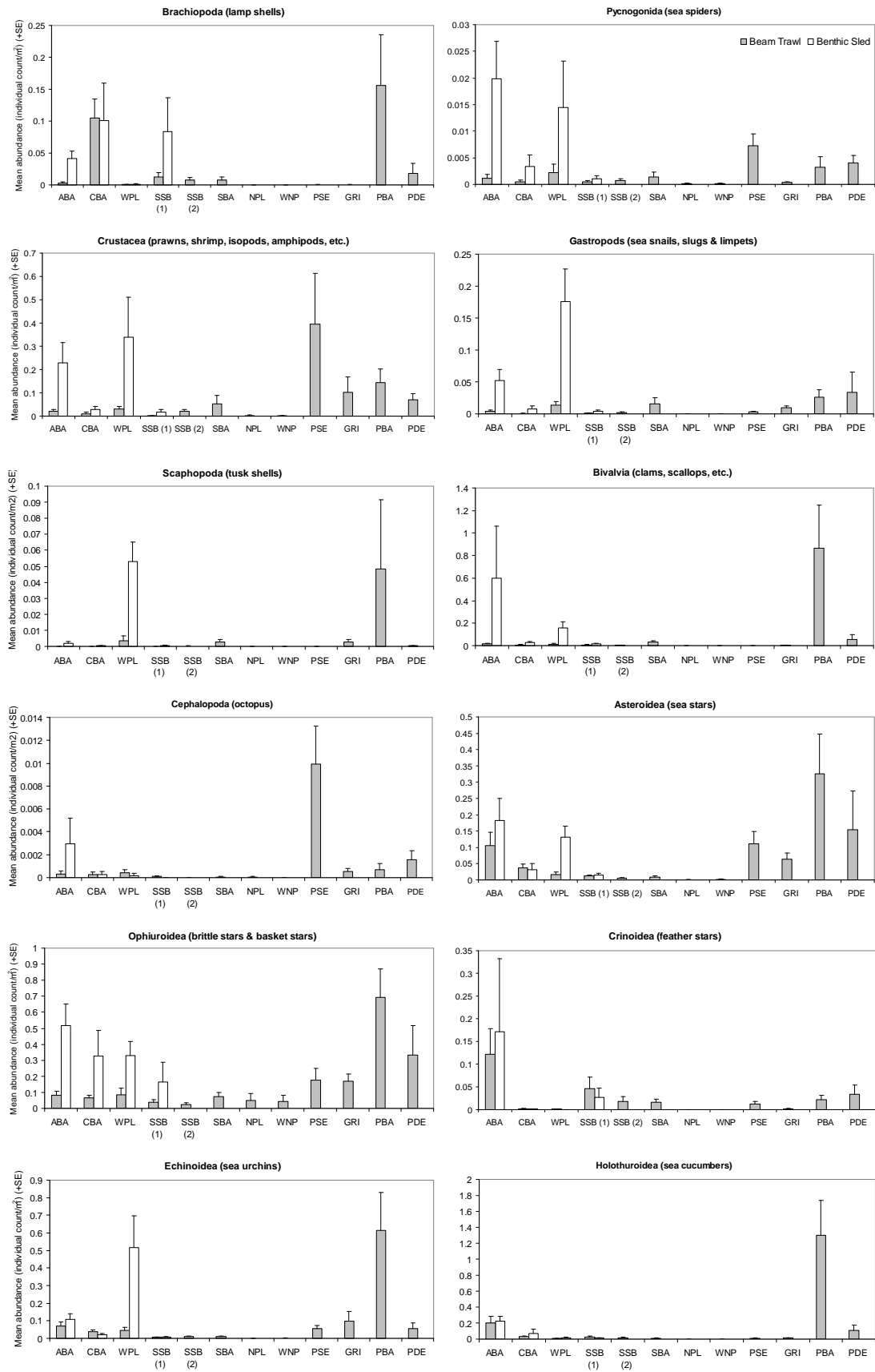
Figure A6.4: Numerical abundance of non-colonial, reliably sorted taxa per m<sup>2</sup> by the two gear types standardised for swept area of the sampling gear.

## Distribution and abundance

The distribution of each taxonomic group was analysed by separating taxa into either motile (i.e. taxa not fixed to the substrata) or structure-forming (emergent, sessile attached organisms) groups.

### Motile taxa

For this analysis motile, non-colonial taxa were grouped into major taxonomic rankings to facilitate comparisons of abundance across the sampling areas. There were clear differences between regions. For example, comparatively large numbers of brachiopods were found at CBA, echinoids (chiefly heart urchins), scaphopods (tusk shells) and gastropods at WPL, crinoids and pycnogonids at ABA, crustaceans at PSE, asteroids, ophiuroids and holothurians at PBA and comparatively low numbers for all groups throughout Northeast Plateau (NPL & WNP) (Table A6.4 and Figure A6.5).



**Figure A6.5. Numerical abundance of non-colonial, motile taxa per m<sup>2</sup> by major taxonomic groupings at each geographic area and for the two sampling methods (Note differences in scale on the y-axis in each panel).**

**Table A6.4. Numerical abundance of non-colonial, motile taxa per m<sup>2</sup> by major taxonomic groupings at each geographic area and for the two sampling methods. Highest densities by taxon are italicised, and by location are bold.**

Taxon	Benthic sled				Beam trawl											
	Cruise SC26 - only				Cruise SC26				Cruise SC46*			Cruise SC50*				
	ABA	CBA	WPL	SSB (1)	ABA	CBA	WPL	SSB(1)	SSB(2)	SBA	NPL	WNP	PSE	GRI	PBA	PDE
ARTICULATA																
Brachiopoda	0.042	0.101	0.001	0.084	0.003	<b>0.105</b>	0.001	0.013	0.008	0.008	-	-	<0.001	<0.001	<i>0.156</i>	0.018
ARTHROPODA																
Pycnogonida	<i>0.020</i>	0.003	0.014	0.001	0.001	0.001	0.002	<0.001	0.001	0.001	<0.001	<0.001	0.007	<0.001	0.003	0.004
Crustacea	0.229	0.030	0.340	0.019	0.020	0.011	0.032	0.002	0.022	0.054	0.002	0.002	<b>0.394</b>	0.102	0.145	0.071
MOLLUSCA																
Bivalvia	<b>0.600</b>	0.027	0.160	0.015	0.018	0.008	0.012	0.005	0.003	0.032	-	-	0.001	0.004	<i>0.865</i>	0.053
Cephalopoda	0.003	<0.001	<0.001	-	<0.001	<0.001	<0.001	<0.001	-	<0.001	<0.001	-	<i>0.010</i>	0.001	0.001	0.002
Gastropoda	0.052	0.008	<i>0.176</i>	0.004	0.004	<0.001	0.014	0.001	0.002	0.015	<0.001	-	0.003	0.010	0.026	0.034
Scaphopoda	0.002	<0.001	<i>0.053</i>	<0.001	-	-	0.004	-	<0.001	0.003	-	<0.001	-	0.003	0.048	<0.001
PLATYHELMINTHES																
Turbellaria	0.001	-	-	-	-	-	<0.001	-	<0.001	<0.001	-	-	-	<0.001	-	-
PRIAPULA	-	-	-	-	-	<0.001	<0.001	-	-	-	-	-	-	-	-	<0.001
SIPUNCULIDA	-	<0.001	-	-	-	-	<0.001	<0.001	-	-	<0.001	-	<0.001	-	<i>0.013</i>	-
ECHINODERMATA																
Asterozoa	0.182	0.032	0.131	0.015	0.106	0.038	0.018	0.012	0.006	0.010	0.001	0.002	0.110	0.064	<i>0.326</i>	0.155
Ophiurozoa	<i>0.518</i>	<b>0.324</b>	0.331	<b>0.165</b>	0.080	0.066	<b>0.083</b>	0.040	<b>0.023</b>	<b>0.071</b>	<b>0.051</b>	<b>0.042</b>	0.177	<b>0.167</b>	<i>0.694</i>	<b>0.333</b>
Crinozoa	<i>0.171</i>	0.001	<0.001	0.027	0.122	0.002	0.001	<b>0.046</b>	0.018	0.016	<0.001	-	0.012	0.002	0.021	0.034
Echinozoa	0.107	0.021	<b>0.518</b>	0.008	0.071	0.039	0.046	0.007	0.011	0.009	<0.001	0.001	0.057	0.097	<i>0.616</i>	0.055
Holothurozoa	0.226	0.070	0.016	0.013	<b>0.198</b>	0.030	0.005	0.025	0.015	0.009	0.001	<0.001	0.011	0.013	<b>1.297</b>	0.111
TOTAL	13	10	10	10	10	9	11	9	10	11	4	4	10	10	13	11

\* Beam trawls only

The benthic sled recovered more specimens per m<sup>2</sup> of many of the taxa groups than the beam trawl including crustaceans, echinoids, ophiuroids, bivalves, gastropods and pycnogonids. The bulk of these specimens were collected at ABA and WPL. Error bars on the figures allow some indication of unevenness or patchiness in the distribution of the taxa. For example, crinoids at ABA were collected in large numbers in three beam trawls and then rarely in the other trawls, indicated by a large error bar and suggesting a clumped distribution.

Differences in the composition of taxa between sites was likely to be related to contrast in substrata between areas, with a number of taxa appearing to be restricted to specific sampling locations and quite possibly, specific substrata. Substratum type showed large variation between sites, ranging from fine silt or sand (WPL and NPL) to coarse sand and gravel (SSB, ABA and CBA), and even small cobble or rocks (PSE). SSB is also distinguished by a covering of shell grit which is unique in the HIMI region.

### Structure-forming taxa

Specific structure-forming benthic taxa (equivalent to VME indicator taxa *sensu* SC-CAMLR 2009) were compared across sampling areas in an attempt to summarise the assemblage types encountered in the HIMI region (Table A6.5). These taxa are all sessile, attached organisms which are usually upright and thus add structural complexity to the seafloor, providing habitat for other organisms.

The habitat-forming assemblages of PBA and WPL are clearly different when compared with the other sampling areas (Figure A6.6). The assemblage at PBA is dominated by a large biomass of sponges (glass and siliceous sponges), gorgonians (order Gorgonacea), bryozoa and ascidians (class Ascidiacea); markedly higher than from any other locality throughout the HIMI region. For WPL, hydroids (class Hydrozoa), actinarians (class Actiniaria), alcyonarians (order Alyconacea) and solitary scleractinians all comprised more of the biomass of this shallow plateau assemblage than on the banks; with only a few taxa comprising the majority of this biomass. Relatively high levels of biomass of ascidians and pterobranchs were collected at ABA and CBA. Of the 'habitat-forming' taxa, bryozoa and gorgonians show a contrast between ABA and CBA. Bryozoa are clearly more plentiful at ABA while gorgonians were recorded at higher levels at CBA.

Only small amounts of biomass were recorded at SSB, with larger patchy amounts of bryozoa, ascidiacea and gorgonacea occurring in single tows. SSB was similar to the surrounding SBA marine reserve, although average biomass for most habitat-forming taxa was slightly higher in SBA. Hydrozoa and gorgonacea show a contrast between SSB and SBA, with gorgonians more plentiful within SSB and hydrozoans at SBA.

Table A6.5. Structure-forming taxa compared across sampling areas.

Phylum/Subphylum	Class/Order	Common name
Porifera	Demospongia	bath or siliceous sponges
	Hexactinellida	glass sponges
Cnidaria	Actiniaria	anemones
	<i>Alyconacea</i>	soft corals
	<i>Gorgonacea</i>	horny corals
	Scleractinia	hard corals
	Hydrozoa	hydroids or sea ferns
	<i>Hydrocorallida</i>	hydrocorals
Bryozoa		lace coral
Crustacea	Cirripedia	barnacles
Hemichordata	Pterobranchia	pterobranchs
Urochordata	Ascidiacea	sea squirts



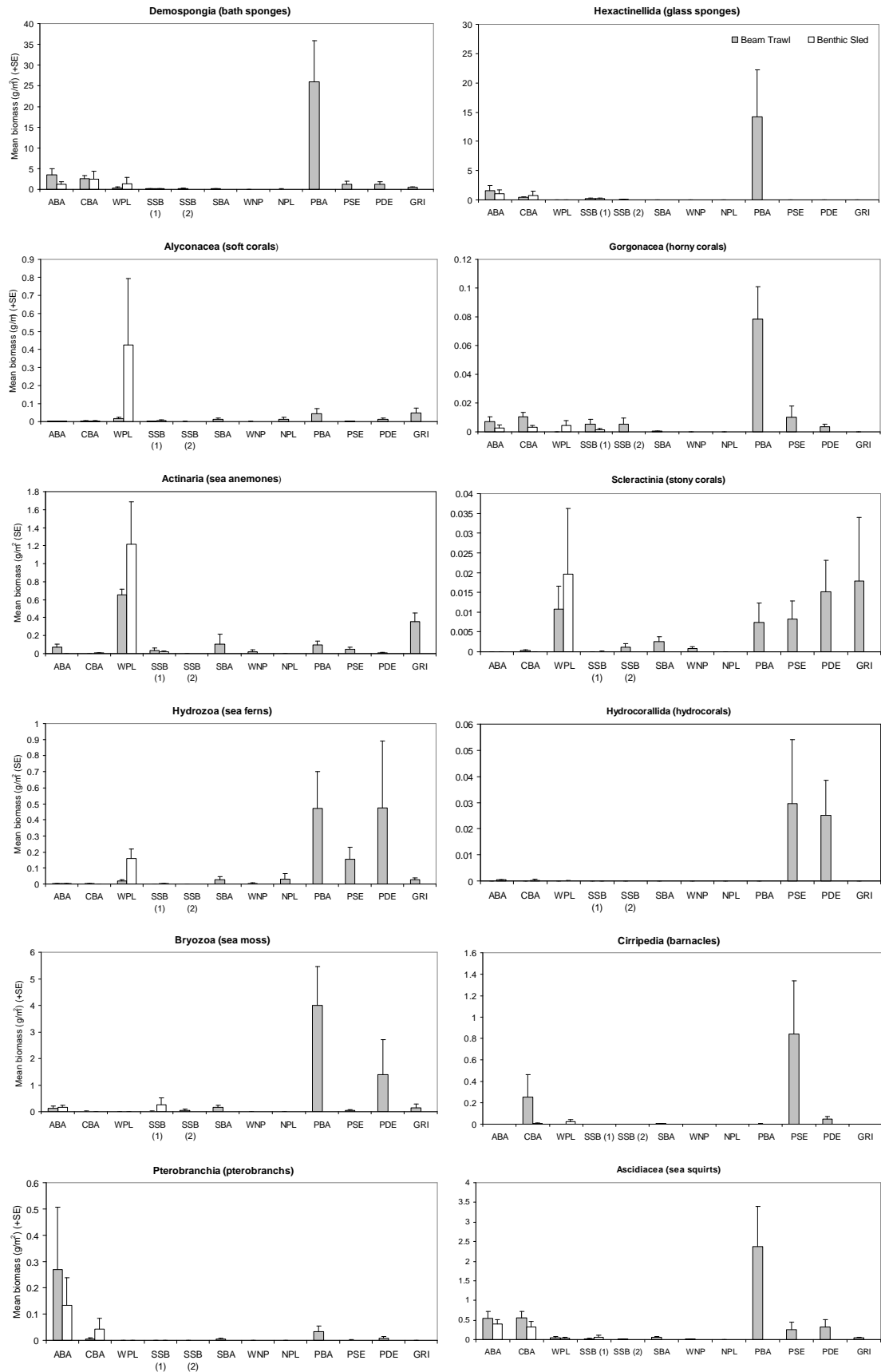


Figure A6.6. Biomass ( $\text{g}/\text{m}^2$ ) of structure-forming taxa by major taxonomic groupings at each geographic area and for the two sampling methods (Note differences in scale on the y-axis).

PSE was notable for a relatively high biomass of stalked barnacles (Cirripedia) and hydrocorals, with large error bars suggesting a patchy distribution of both throughout this locality at the sampled scale. This biomass of cirripedes is unique to PSE, and the hydrocoral biomass is shared only with neighbouring PDE. PDE shared other similarities with PSE to the south and GRI to the north, including a large biomass of solitary scleractinians at GRI, and to a lesser extent, ascidians and gorgonians at PSE. However, distinguishing features included notable densities of hydrozoans and bryozoans at PDE, and actinarians at GRI.

NPL and WNP shared the lowest biomass of all habitat-forming groups suggesting relatively low densities of such taxa in these deep plateau communities.

### Site-restricted taxa

Combined values for SSB (i.e. SC26 & SC46) revealed the highest number of 'site-restricted' taxa (taxa that only occurred at one sampling area) in this region (Table A6.6). WPL ranked second highest, which may reflect the relatively limited sampling of shallow plateau habitat compared to topographically complex areas such as the Shell, Pike, Aurora and Coral Banks. The western banks (ABA, CBA and PBA) had relatively high numbers of restricted taxa, indicating important variability within and between the western banks and Shell Bank. NPL recorded similar numbers of site-restricted taxa to PDE and PSE despite a significantly lower diversity and biomass in the region. Like WPL, this too is likely to be a function of substrate or depth as the Northeast Plateau region is considerably deeper than the majority of geographic areas sampled. The number of taxa restricted to the central localities of GRI, PDE, and to a lesser extent PSE, was comparably lower than the eastern and western banks, suggesting a mixing of species across these geographic areas.

**Table A6.6. Abundance of site-restricted Group 1 taxa (occurring at only one of the geographic areas) and total seafloor area sampled using all gear types.**

Rank	Geographic areas (Acronym)	Number of 'Site-restricted' taxa	Total area sampled (m <sup>2</sup> )
1	Southern Shell Bank (SSB)*	21	57 803
2	Western Plateau (WPL)	15	27 321
3	Aurora Bank (ABA)	10	28 255
4	Coral Bank (CBA)	9	20 861
5	Shell Bank (SSB)	9	50 130
6	Pike Bank (PBA)	8	22 335
7	Plateau Southeast (PSE)	7	25 313
8	Northeast Plateau (NPL)	6	22 980
9	Plateau Deep East	6	25 313
10	Gunnari Ridge	2	24 817
11	West of Northeast Plateau (WNP)	0	11 912

\*SC26 and SC46 SSB surveys combined

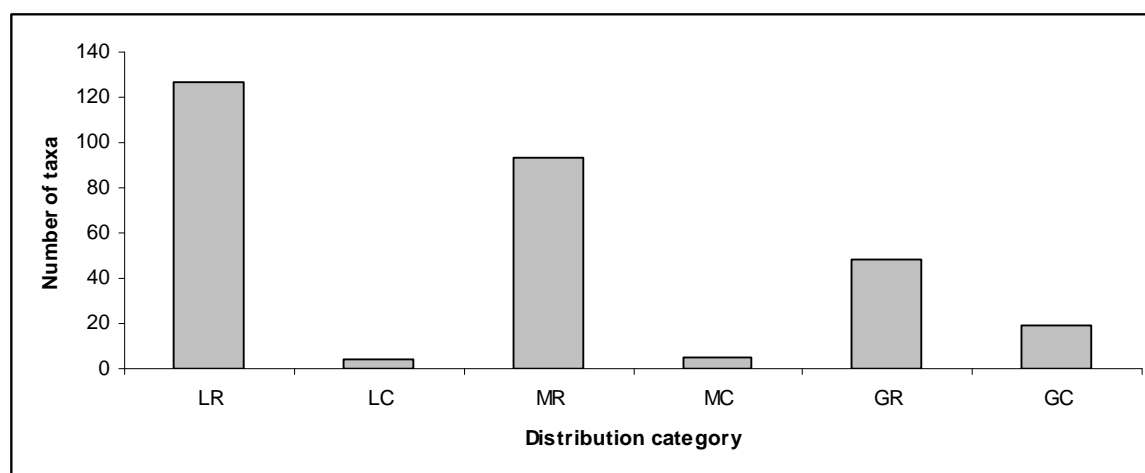
The site-restricted taxa were made up largely of cnidarians, crustaceans, echinoderms and molluscs. Most of them were only found in one or two tows which suggest very limited distributions and abundances. Some taxa were found in substantial amounts but only within one sampling area, for example, *Bivalvia* spE and *Actiniaria* spL (anemone) exclusively occurred within PBA, and *Holothuroidea* spH (sea cucumber) at PDE.

### Distribution categories

The distribution and abundance characteristics of group 1 and 3 taxa (individuals/m<sup>2</sup>) across the HIMI region were assessed by characterising these taxa according to six distribution categories described in Table A6.7. Results from this analysis indicate that the majority of taxa in the present study are considered either 'locally' or 'moderately' rare (Figure A6.7).

**Table A6.7. Categories used to describe the distribution and abundance of Group 1 & 3 non-colonial taxa.**

Category	Definition
<i>Locally rare (LR)</i>	Localised distribution (occurring at 1-2 geographic areas) in lower abundance (<0.01 individuals/m <sup>2</sup> )
<i>Locally common (LC)</i>	Localised distribution (occurring at 1-2 geographic areas) in higher abundance (>0.01 individuals/m <sup>2</sup> )
<i>Moderately rare (MR)</i>	Moderate distribution (occurring at 3-6 geographic areas) in lower abundance (<0.01 individuals/m <sup>2</sup> )
<i>Moderately common (MC)</i>	Moderate distribution (occurring at 3-6 geographic areas) in higher abundance (>0.01 individuals/m <sup>2</sup> )
<i>Globally rare (GR)</i>	Global distribution (occurring at 7-11 geographic areas) in lower abundance (<0.01 individuals/m <sup>2</sup> )
<i>Globally common (GC)</i>	Global distribution (occurring at 7-11 geographic areas) in higher abundance (>0.01 individuals/m <sup>2</sup> )



**Figure A6.7. Number of taxa with restricted, moderate or global distributions (see Table A6.7 above for classification scheme); non-colonial taxa only.**

### Endemicity

Nineteen taxa were identified as likely to be endemic to the HIMI region as undescribed or new species (Table A6.8). SSB had the highest number of these species despite the overall low biomass collected from this area. Most of the undescribed

species were categorised as locally rare. Eight undescribed species were categorised as moderately rare and two species, *Flabellum* sp1 and *Eumorphometra*, was categorised as globally rare. Given that several diverse groups are still largely unsorted (e.g. amphipods, bryozoans, molluscs, pycnogonids), there is a high likelihood that undescribed and/or endemic forms still remain to be discovered in these samples. For instance, the molluscan fauna of the HIMI region is not well known, and hence the majority of molluscs (bivalves, gastropods, opisthobranchs, etc.) are likely to be undescribed (L. Turner, pers. comm., Nov 21, 2008<sup>9</sup> S. Slack-Smith, pers. comm., Nov 19, 2008<sup>10</sup>; R. Willan, pers. comm., Nov 18, 2008<sup>11</sup>).

Two taxa groups studied to a high taxonomic resolution in the present study were the holothurians (sea cucumbers - Class Holothuroidea) and pycnogonids (sea spiders - Class Pycnogonida) (SC26 data only) and they both indicate considerable diversity, low abundances and degrees of endemism or isolation within the HIMI region. Four of the five holothurians (a relatively well-studied group world-wide) listed as occurring at only one site are likely to be undescribed species (M.O'Loughlin, pers.comm.<sup>12</sup>). Many of the pycnogonids species were only found once and of the 29 recorded in this study 12 of them may be undescribed species (D. Staples, pers. comm.<sup>13</sup>).

**Table A6.8. List of undescribed and likely to be endemic taxa identified by the sampling areas at HIMI.**

Group/species	Geographic areas											Occurrence
	ABA	WPL	CBA	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI	
Cnidaria												
<i>Flabellum</i> sp 1		●	●	●	●	●		●	●	●	●	9
Crustacea												
<i>Eisothistos</i> sp. nov.	●											1
Pycnogonida*												
<i>Ammothea</i> sp1			●							●		2
<i>Austrodecus</i> sp 1			●									1
<i>Austropallene</i> sp 1			●									1
<i>Colossendeis</i> sp 1				●					●	●	●	4
<i>Colossendeis</i> sp 2				●	●							3
<i>Nymphon</i> sp 1	●	●	●	●								4
<i>Nymphon</i> sp 3	●		●	●								3
<i>Nymphon</i> sp 4		●										1
<i>Pycnogonum</i> sp 1		●	●						●	●		4
<i>Pycnogonum</i> sp 2		●										1
<i>Tanystylum</i> sp 1		●										1
Holothuridae												
<i>Cucumaria</i> sp 1	●											1
<i>Dactylochirotida</i> sp1				●	●							2
<i>Molpadiidae</i> sp1		●		●	●	●	●					1
<i>Pseudostichopus</i> sp 1				●	●							2
<i>Synallactes</i> sp 1				●		●						2
Crinoidae												
<i>Eumorphometra</i> sp 1	●	●	●	●	●	●		●	●	●	●	10
<b>TOTAL</b>	<b>5</b>	<b>8</b>	<b>9</b>	<b>10</b>	<b>6</b>	<b>4</b>	<b>1</b>	<b>2</b>	<b>4</b>	<b>5</b>	<b>3</b>	

\*Note only specimens from SC26 have been scrutinised by an expert.

<sup>9</sup> Liz Turner. Curator of Invertebrate Zoology, Tasmanian Museum and Art Gallery.

<sup>10</sup> Shirley Slack-Smith. Curator of Molluscs, Western Australian Museum.

<sup>11</sup> Richard Willan. Curatorship in Molluscs, Museum and Art Gallery of the Northern Territory.

<sup>12</sup> Mark O'Loughlin. Honorary Associate – Marine Biology, Museum Victoria.

<sup>13</sup> David Staples. Pycnogonida specialist, Museum Victoria.

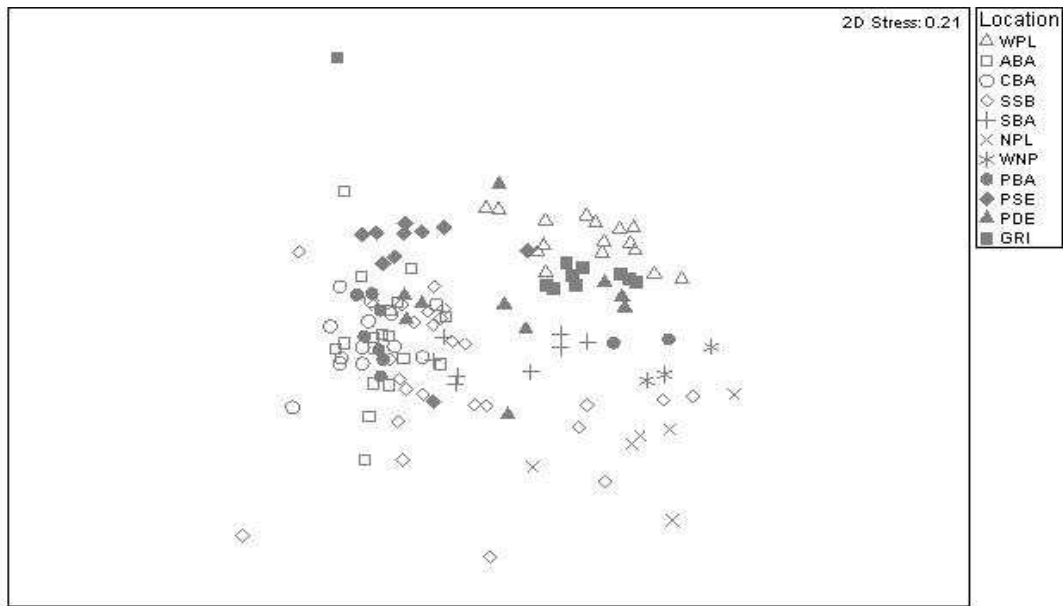
## Vulnerability

Locally rare, or site-restricted taxa in particular, are likely to have increased vulnerability to disturbance or other processes which might lower the viable reproductive population or further isolate the taxa. In this study, the majority of site-restricted taxa are also locally rare, and therefore have limited distributions and abundances within one area. These rare, spatially isolated taxa may be restricted in terms of population exchange, range expansion and re-colonisation, making recovery following local extinctions less likely. Taxa which are locally common, although present in greater numbers or biomass, are also vulnerable to disturbance at the area scale due to their limited distributions.

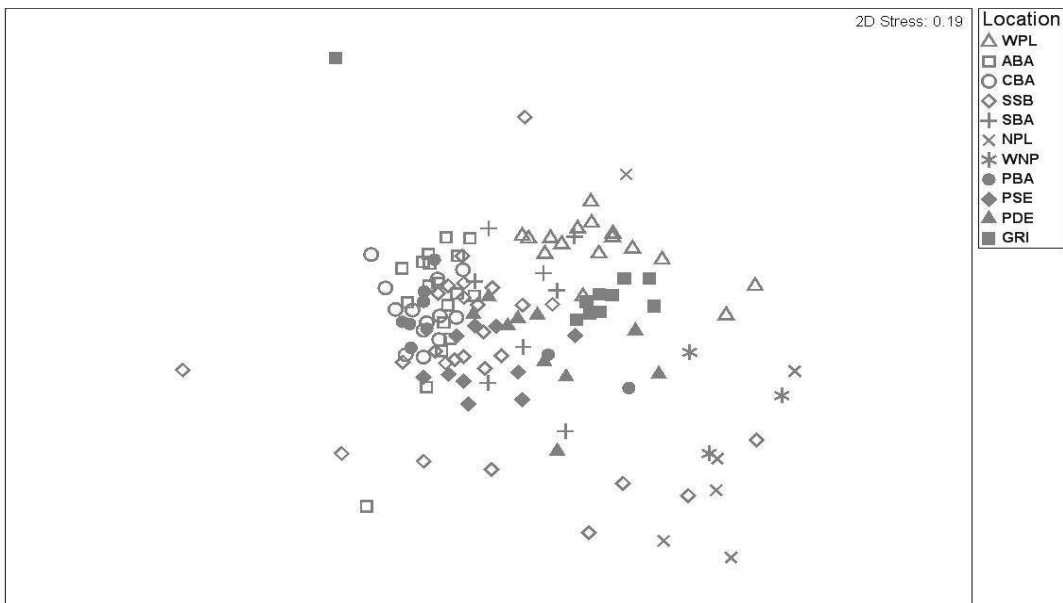
## Faunistic similarity among sampling areas

A comparison of faunistic relationships between sampling areas based on biomass and diversity per m<sup>2</sup> was completed using square-root transformed data and Bray-Curtis similarities (Figure A6.8 & Figure A6.9). The MDS ordination plot indicates assemblages share similarities across areas, particularly between the western banks (ABA, CBA and PBA). The samples from WPL, and to a lesser extent GRI and Northeast Plateau (NPL & WNP) formed largely discrete clusters, indicating within location similarity and dissimilarity to the other areas sampled. Samples from PDE showed similarities with GRI as well as SSB, CBA and ABA, as evidenced by their spread across the same area of the plots as the samples from those locations. SSB showed some samples with similarities with the majority of areas sampled, although the wide scattering of the SSB samples reflect the large variation and low biomass of taxa observed at SSB, including forms located elsewhere, as well as the fact that a large number of taxa were restricted to SSB.

Assemblage differences between sampling areas were significant both in terms of biomass ( $R = 0.503$ ;  $p < 0.1\%$ ; ANOSIM) and diversity of taxa (using Group 1 presence/absence only;  $R = 0.458$ ;  $p < 0.1\%$ ; ANOSIM) per square metre. The values of average dissimilarity (Table A6.9) reflect the patterns observed in the ordination plots. Low dissimilarity was evident between the western banks (PBA, ABA and CBA); PDE shared similarities with GRI and PSE, and SSB reflected similarities with all geographic areas; in particular PBA, ABA, and CBA.



**Figure A6.8.** Assemblage structure based on biomass of Group 1 & 3 taxa. MDS ordination of the seven sites based on square-root transformed biomass per m<sup>2</sup> data and Bray-Curtis similarities (stress = 0.21). Widely separated points are more dissimilar than points close together.



**Figure A6.9.** Benthic invertebrate diversity of Group 1 taxa. MDS ordination of the seven sites based on square-root transformed presence/absence data and Bray-Curtis similarities (stress = 0.19). Widely separated points are more dissimilar than points close together.

**Table A6.9. Dissimilarity percentage among sampling areas based on biomass (g/m<sup>2</sup>) and diversity (m<sup>2</sup>). The higher the value the greater the dissimilarity between groups.**

Biomass (g/m <sup>2</sup> )	WPL	ABA	CBA	SSB	SBA	NPL	WNP	PBA	PSE	PDE
ABA	91									
CBA	98	44								
SSB	58	16	12							
SBA	83	59	80	-3						
NPL	91	94	96	53	80					
WNP	88	98	100	43	77	-24				
PBA	80	19	53	5	36	63	61			
PSE	95	71	82	25	90	89	99	53		
PDE	75	58	69	18	44	70	67	30		
GRI	40	84	87	45	59	62	61	47	77	33

Diversity (individuals/m <sup>2</sup> )	WPL	ABA	CBA	SSB	SBA	NPL	WNP	PBA	PSE	PDE
ABA	77									
CBA	91	31								
SSB	46	13	3							
SBA	77	60	81	5						
NPL	93	96	96	60	82					
WNP	92	97	100	53	81	-22				
PBA	86	34	47	4	48	89	95			
PSE	88	64	77	11	85	88	98	41		
PDE	74	59	69	10	51	80	83	34	19	
GRI	45	80	86	35	64	67	65	65	73	42

## Discussion

### Assemblage structure in a regional context

The current study provides the first detailed analysis of the patterns of diversity and in the benthic assemblages across the banks and Plateau of the HIMI region in waters down to 1000 m. From the localities sampled, the 503 mega-epibenthic taxa found came from 14 phyla, of which 255 taxa identified to family level or better came from 137 families, representing a dramatic increase in the diversity catalogued for this region, and indicating that there are important conservation values to maintain in the region. This is further reinforced by evidence that shallow water areas inside the 12 nm zone around Heard Island appears to have a different suite of taxa (Edgar & Burton 2000, Meyer *et al.* 2000). Furthermore, infauna and taxa smaller than the mesh size used in this study would have been poorly selected, and further expert analysis identification and separation the taxa collected is likely to add further species to the list, many of which may be endemic to the region. As noted above, holothurians and pycnogonids, when scrutinised by relevant experts showed high levels of undescribed and apparently endemic species. Similarly the majority of bivalve, gastropod and opisthobranch molluscs identified thus far are thought to be undescribed. Also, some groups like the Bryozoa and Amphipoda are largely unsorted at this stage and they

may yield some of the highest species numbers of all groups, as they have shown to be highly diverse in other high latitude studies (Arntz *et al.* 2006, Clarke & Johnstone 2003, Gray 2001).

Subantarctic islands are potential sites for relatively low diversity and high degrees of endemism due to their isolation, unique oceanographic influences and small size (Branch *et al.* 1993, Gutt *et al.* 2006). The ACC facilitates some east-west dispersal, in part explaining circumpolar distribution for some benthic taxa. For example recent studies on Bouvet Island (Arntz *et al.* 2006) found faunal affinities with the Antarctic Peninsula, near the Antarctic continent and the Magellanic region of South America. However, these assemblages are effectively isolated from the other continents, as well as having long distances between potential habitat in the Scotia Arc, Kerguelen Plateau and Macquarie Ridge, leading to a high potential for speciation and endemism within locations. Consequently, a high level of endemism within the Southern Ocean is generally observed, particularly for those taxa without a pelagic larval phase that are unable to exploit broad scale dispersal via currents (Arntz *et al.* 1994, Clarke & Johnstone 2003). However axes such as the Scotia Arc, Kerguelen Plateau and Macquarie Ridge provide a potential for contact between the temperate and Antarctic faunas. Butler *et al.* (2000) found few species with restricted distributions around Macquarie Island, and instead suggested the island is a biogeographic contact zone with mixing of many species from north to south. O'Hara (1998) also found few endemic echinoderms at Macquarie Island.

The results from the current study indicate that the benthic assemblages at HIMI share affinities with those identified in other studies around the Subantarctic islands and Antarctic continent (Arntz *et al.* 1997, Arntz *et al.* 2006, Clarke & Johnstone 2003, Dell 1972, Gutt *et al.* 2004, Poore & Wilson 1993, Ward *et al.* 2006). Within the region itself, there are indications that some groups are relatively widespread (i.e. 'globally rare/common' taxa), however most others have relatively restricted distributions (i.e. 'locally rare/common' or 'site-restricted' taxa), including degrees of endemism in some groups. There were also clear disparities between geographic areas and geological regions, with some taxa restricted to only one region possibly due to topography and substrate (i.e. plateau or bank substratum) or oceanographic conditions (i.e. productivity on the western versus the eastern plateau). Hence this suggests that the pattern observed at HIMI are a product of the overall biogeographic history of the Southern Ocean, as well as factors operating at meso- and smaller scales. Therefore there is considerable potential for further testing hypotheses regarding the role of the subantarctic as a circumpolar stepping stones, as well as a contact zone or corridor between temperate and Antarctic fauna by comparing the dataset collated in this study with others from the Southern Ocean, such as those noted above and from the northern Kerguelen Plateau (Améziane *et al.* 2011, Feral & Poulin 2011).



### **Benthic invertebrate & habitat diversity across HIMI**

Prior to this research, information on the distribution of benthic invertebrates in the HIMI region was largely qualitative. As opposed to the presence-only data available to Meyer *et al.* (2000), the current study has enabled a more detailed insight into the composition of benthic fauna and habitats across the study area. This quantitative analysis has allowed us to examine the conservation values of selected geographic areas in terms of the distribution of benthic invertebrate communities, species composition and taxa abundance.

The assemblage at Aurora Bank overlaps to some extent with Coral Bank in the marine reserve. Together, these communities have the potential to act as replicate ecosystems, capable of assisting in re-colonisation and maintenance of genetic diversity for a diverse range of habitat-forming, rare endemic and vulnerable species. Minor similarities were observed between these areas and Pike Bank, although the assemblage at Pike Bank is characterised by a relatively high biomass but only a relatively modest diversity of taxa, dominated by patchy distributions of sponges, bryozoans, gorgonians and echinoderms.

The diverse assemblage of Western Plateau was clearly a different habitat when compared with the other sampling areas; dominated by large numbers or biomass of particular species or taxa which could be considered indicative of plateau benthic communities at corresponding depths. Whether the high diversity found at the Western Plateau is replicated within the existing marine reserve is difficult to discern. However, the Southern Plateau area (encompassing Western Plateau) was considered as a bioregional unit in Meyer *et al.* (2000), mainly because of the uniformity of substratum and depth, hence it is reasonable to assume similar assemblages and assemblage structure between Western Plateau and the southern part of the central MPA.

Southern Shell Bank supports a unique assemblage, distinguished by low biomass, high diversity and high levels of rare and endemic species. Southern Shell Bank shared affinities with the nearby Shell Bank Marine Reserve and the western banks, although it had the highest number of 'site-restricted' taxa of any areas sampled. Of these, most are 'locally rare' and therefore particularly vulnerable to disturbance, damage or other processes which might lower the viable reproductive population or further isolate the taxa. Similarities were also observed with the remaining geographic areas, indicating that this area may provide habitat with intermediate characteristics between the western banks and the plateau, and therefore support taxa found in both areas.

Northeast Plateau is characterised by a relatively sparse, lightly populated benthic habitat with a paucity of structure forming taxa. However, despite the low diversity and biomass collected from the region, Northeast Plateau recorded similar numbers of 'site-restricted' taxa to Plateau Southeast and Plateau Deep East. This highlights the

conservation value of Northeast Plateau, as it would appear to host a suite of taxa potentially restricted to deep plateau communities.

The central localities of Plateau Southeast, Plateau Deep East and Gunnari Ridge shared similarities in regard to both biomass per square metre, numerical abundance of taxa and diversity. This indicates that these areas serve as a biogeographic contact zone, with mixing of taxa from east to west, supporting claims by Meyer et al. (2000) for an east-west divide of species throughout the HIMI region. Nevertheless, each area was had distinctive characteristics features such as significant population of barnacles and hydrocorals at Plateau Southeast, high density patches of hydrozoans and bryozoans at Plateau Deep East, and a low diversity/moderate density assemblage dominated by solitary scleractinians and actinarians at Gunnari Ridge.

### **Conclusions**

Analysis of these areas has revealed a range of distinctive benthic epifauna assemblages, composed of high diversity and biomasses of structure forming invertebrates on Aurora, Coral and Pike Banks, to diverse but less dense assemblages like Southern Shell Bank, to relatively depauperate assemblages in deeper waters of Northeast Plateau. This dataset forms an important basis for further analyses to evaluate the importance of subantarctic regions in the development of patterns of biodiversity and biogeography observed in the Southern Ocean.

A high proportion of these taxa would be relatively vulnerable to disturbance from bottom fishing gears, such as sessile, brittle, slow-growing suspension feeders like sponges and corals. Furthermore, some of the motile taxa showing high apparent endemism, such as pycnogonids are likely to be predators of sessile forms such as bryozoans, and so may also be vulnerable to disturbance by bottom fishing. Hence the data and analyses described in this study form a critical step in attempting to estimate the extent to which bottom fishing in the region has disturbed these assemblages, and evaluating the effects of mitigating this disturbance through management measures such as the introduction of the Marine Reserve at HIMI.

## Appendix 7 Taxonomic experts consulted during the project

We would like to acknowledge the following people and organizations for their assistance with indentifying the benthic taxa collected during this project.

<b>Taxonomist</b>	<b>Organisation</b>	<b>Taxon</b>
Daphne Fautin	University of Kansas, US	Actiniaria
Andrea Crowther	University of Kansas, US	Actiniaria
Cardin Wallace	Queensland Museum	Actiniaria
Elizabeth Turner	Tasmanian Museum & Art Gallery	Bivalvia & Gastropoda
Phillip Bock	Museum Victoria	Bryozoa
Mark Norman	Museum Victoria	Cephalopoda
Andrew Hosie	Western Australian Museum	Cirripedia
Gary Poore	Museum Victoria	Crustacea
Joanne Taylor	Museum Victoria	Decapoda
Mark O'Loughlin	Museum Victoria	Holothuroidea
Jan Watson	Museum Victoria	Hydrozoa
Genefor Walker-Smith	Tasmanian Museum & Art Gallery	Invertebrates
Kirrily Moore	University of Tasmania	Invertebrates
Liz Turner	Tasmanian Museum & Art Gallery	Mollusca
Tim O'Hara	Museum Victoria	Ophiuroidea & Asteroidea
Igor Smirnov	University of Russia	Ophuroidea
Dick Williams	Australian Antarctic Division	Osteichthyes & Chondrichthyes
Robin Wilson	Museum Victoria	Polychaeta
David Staples	Museum Victoria	Pycnogonida
Karen Miller	University of Tasmania	Scleractinia

## Appendix 8 Benthic Invertebrate Faunal Diversity at Heard Island and the McDonald Islands

Benthic invertebrate taxa collected on three cruises aboard the fishing vessel 'Southern Champion' in the HIMI region from 2003 to 2008 (presence-only data). Geographic areas sampled: ABA – Aurora Bank, CBA – Coral Bank, WPL – Western Plateau, SSB – Southern Shell Bank conservation zone, SBA – Shell Bank marine reserve, NPL – Northeast Plateau, WNP – West of Northeast Plateau, PBA – Pike Bank, PSE – Plateau Southeast, PDE – Plateau Deep East, GRI – Gunnari Ridge. Table sorted to conventional phylogenetic order by phylum ('Taxon' headings in all capitals). \* Denotes taxonomic groups incompletely sorted from one, or all, sampling locations. Endemic taxa thought to be undescribed species are shaded.

Taxon	Geographic areas											
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI	
PORIFERA*												
Demospongia												
Porifera spA	•	•	•	•								
Porifera spB	•	•	•	•								
Porifera spC	•	•	•	•				•				
Porifera spD	•			•								
Porifera spE	•	•		•								
Porifera spF	•	•		•								
Porifera spG	•	•		•				•				
Porifera spH	•	•	•	•								
Porifera spI	•	•										
Porifera spJ	•	•		•								
Porifera spK	•	•		•								
Porifera spL	•	•	•	•				•	•			
Porifera spM	•											
Porifera spN	•	•										
Porifera spO	•											
Porifera spP		•										
Porifera spQ	•	•	•	•								
Porifera spR	•	•	•	•								
Porifera spS	•	•										
Porifera spT	•	•		•								
Porifera spU		•		•								
Porifera spV	•	•		•								
Porifera spW		•		•								
Porifera spX			•	•								
Porifera spY		•	•									
Porifera spZ	•	•	•	•								
Porifera spAA	•		•									
Porifera spAB				•								
Porifera spAC	•			•								
Porifera spAD				•								
Porifera spAE		•		•								
Porifera spAF	•	•		•								
Porifera spAG				•								
Porifera spAH	•			•								
Porifera spAI		•										
Porifera spAJ	•	•										
Porifera spAK	•											
Porifera spAL			•									
Porifera spAM			•									
Porifera spAN	•	•										
Porifera spAO				•	•			•	•	•		
Porifera spAR				•								
Porifera spAS								•				
Dendroceratida												
Darwinellidae												
<i>Dendrilla</i> spA	•	•										
<i>Dendrilla</i> spB	•	•		•								

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Poecilosclerida											
Latrunculiidae											
<i>Latrunculia</i> spA	•	•		•	•			•	•	•	
<i>Latrunculia</i> spB	•	•	•		•			•	•		
Hadromerida											
Stylocordylidae											
<i>Stylocordyla borealis</i>	•	•	•	•				•		•	
Suberitidae											
<i>Suberites caminatus</i>	•	•		•	•			•	•	•	
Spirophorida											
Tetillidae											
<i>Cinachyra antarctica</i>		•		•							
<i>Tetilla leptoderma</i>	•	•	•	•			•	•			
Calcarea											
Clathrinida											
Leucettidae											
<i>Leucetta leptoraphis</i>	•		•								
Hexactinellida											
Hexactinellida spA	•	•		•	•						
Hexactinellida spB	•	•	•	•							
Hexactinellida spC								•			•
CNIDARIA											
Anthozoa											
Alyconacea (soft corals)											
Cnidaria sp6	•	•	•	•	•	•	•	•	•	•	•
Cnidaria sp16	•		•	•	•	•	•	•	•	•	•
Cnidaria sp17	•	•	•	•					•		
Cnidaria sp18	•		•	•				•			•
Cnidaria sp20		•	•								
Cnidaria sp25				•	•	•					
Cnidaria sp30	•	•	•	•		•		•	•	•	•
Cnidaria sp35			•							•	•
Cnidaria sp36	•		•								
Cnidaria sp42		•		•				•			
Cnidaria sp43		•	•	•						•	•
Cnidaria sp52						•					
Cnidaria sp55						•					
Cnidaria sp58				•	•		•			•	•
Cnidaria sp62				•							
Cnidaria sp64					•					•	
Cnidaria sp68										•	
Cnidaria sp70											•
Cnidaria sp72										•	•
Alyconacea (gorgonians)											
Cnidaria sp1	•	•		•				•			
Cnidaria sp2	•	•	•	•	•			•	•	•	
Cnidaria sp3	•	•	•	•					•	•	
Cnidaria sp4	•	•	•	•	•			•	•	•	
Cnidaria sp24		•		•	•			•	•	•	•
Cnidaria sp29	•	•	•	•	•	•				•	•
Cnidaria sp34		•									
Cnidaria sp45				•							
Cnidaria sp59				•				•			
Cnidaria sp65									•		
Pennatulacea											
Cnidaria sp14				•							
Cnidaria sp66									•		
Pennatulacea spC										•	
Actiniaria											
Actiniaria spA	•	•	•	•				•	•	•	
Actiniaria spB	•		•								
Actiniaria spC	•	•	•								•
Actiniaria spD			•	•	•			•			•
Actiniaria spE			•						•		
Actiniaria spF			•	•							
Actiniaria spH						•		•	•		
Actiniaria spI				•					•		
Actiniaria spJ				•							
Actiniaria spK					•						•
Actiniaria spL								•			
Actiniaria spM									•	•	

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Capnea											
<i>Capnea georgiana</i>		•	•		•				•	•	•
Actiniidae											
<i>Bolocera</i> spp.	•		•								
<i>Glyphoperidium bursa</i>			•		•	•				•	•
Actinostolidae											
<i>Actinostolidae</i> spp.			•								
Hormathiidae											
<i>Hormathiidae</i> spp.	•	•	•	•					•		•
Liponematidae											
<i>Liponema</i> spp.	•		•	•				•	•	•	•
Ceriantharia											
Ceriantharia spA			•	•		•			•	•	
Ceriantharia spB		•			•	•		•	•	•	
Scleractinia											
Cnidaria sp40		•		•	•	•			•	•	
Flabellidae											
<i>Flabellum</i> sp.		•	•	•	•	•		•	•	•	•
Zoanthidae											
Cnidaria sp19	•		•			•			•	•	
Cnidaria sp23				•			•				
Hydrozoa*											
Hydrozoa spA	•	•	•	•	•	•	•	•	•	•	•
Hydrozoa spB	•	•	•	•				•	•	•	•
Hydrozoa spC		•	•	•	•						
Hydrozoa spD	•	•	•	•							
Hydrozoa spE	•	•	•	•				•	•	•	
Hydrozoa spF		•	•	•							
Hydrozoa spG	•	•	•	•							•
Hydrozoa spH		•	•	•							
Hydrozoa spI	•		•	•							
Hydrozoa spJ	•	•	•	•							
Hydrozoa spK			•	•							
Hydrozoa spL			•	•							
Hydrozoa spM	•										
Hydrozoa spN	•										
Hydrozoa spO	•	•		•							
Hydrozoa spP	•	•		•	•	•	•	•	•	•	•
Hydrozoa spQ				•							
Hydrozoa spR				•							
Hydrozoa spT							•				
Hydrozoa spU									•		
Hydroidolina											
Hydrocorallinidae spA									•	•	
Stylasteridae											
<i>Errina</i> spp.	•	•							•	•	
Scyphozoa			•			•					
Scyphozoa spA											
PLATYHELMINTHES											
Polycladida spA	•										
Polycladida spB			•	•	•						
Polycladida spC											•
PRIAPULIDA											
Priapulidae											
Priapulidae spA		•	•							•	
SIPUNCULIDA											
Sipuncula spA		•	•	•							
Sipuncula spB						•					
Sipuncula spC								•			
Sipuncula spD									•		
Sipuncula spE								•			
Sipuncula spF								•			
MOLLUSCA											
Bivalvia											
Bivalvia spA	•	•		•	•			•	•	•	
Bivalvia spC					•						
Bivalvia spD				•				•			
Bivalvia spE								•			

Taxon	Geographic areas											
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI	
Pholadomyoidea												
Cuspidariidae												
Cuspidaria spA	•		•	•	•			•				
Euciroidae												
Euciroa spA		•						•				
Laternulidae												
Laternula spA			•						•	•	•	
Myoidea												
Hiatellidae												
Hiatella spA	•	•	•					•	•	•		
Veneroidea												
Veneroidea spA		•										
Cardiidae												
Cardiidae spA	•				•							
Cardiidae spB			•	•	•							
Crassatellidae												
Crassatellidae spA	•		•		•							
Crassatellidae spB	•	•		•	•			•				
Cyamiidae												
Cyamiidae spA	•	•		•	•			•				
Cyamiidae spB	•		•	•								
Kidderia spA		•										
Psammobiidae												
Psammobiidae spA			•									•
Veneridae												
<i>Gouldia (Gouldiopa) spA</i>	•	•		•	•			•				
Nuculoidea												
Nuculanidae												
Nuculana spA			•									
Nuculana spB	•	•	•									
Arcidae												
Arcidae spA				•				•				
Limopsidae												
Limopsidae spA	•	•	•	•	•			•		•	•	
Limopsidae spB	•	•		•	•			•	•	•		
Limopsidae spC	•			•								
Limopsidae spD				•				•				
Philobryidae												
<i>Hochstetteria meridionalis</i>	•	•										
Ostreoidea												
Ostreidae												
Ostreidae spA	•	•		•	•							
Pectinidae												
<i>Cyclopecten spA</i>	•	•	•		•			•				
Cephalopoda												
Octopoda												
Octopodidae												
<i>Benthoctopus levis</i>	•	•	•	•	•			•	•	•	•	
<i>Graneledone antarctica</i>	•	•	•	•		•			•	•		
Gastropoda												
Gastropoda spA	•		•		•							
Gastropoda spB			•	•	•			•	•	•	•	
Gastropoda spC	•		•		•							
Gastropoda spE					•							
Gastropoda spF					•							
Gastropoda spH					•							
Gastropoda spI					•							
Gastropoda spJ				•	•							
Gastropoda spK				•	•							
Gastropoda spL				•								
Gastropoda spM					•							
Gastropoda spN										•		
Gastropoda spO										•		
Opisthobranchia												
Opisthobranchia spA			•									
Opisthobranchia spB	•				•							
Opisthobranchia spC			•									
Opisthobranchia spD			•									
Opisthobranchia spE	•		•							•		
Opisthobranchia spF			•									•
Opisthobranchia spG	•		•	•	•							•

Appendix 8

Taxon	Geographic areas											
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI	
Opisthobranchia spH	•											
Opisthobranchia spJ						•						
Opisthobranchia spK					•	•						
Nudibranchia												
Bathydorididae												
<i>Bathydoris</i> sp.									•			
Dorididae												
<i>Austrodoris kerguelensis</i>	•		•	•								
Prosobranchia												
Archaeogastropoda												
Fissurellidae												
Fissurellidae spA	•	•		•				•	•	•	•	
Trochidae												
Trochidae spA	•		•	•	•				•		•	
Docoglossa												
Nacellidae												
<i>Nacella</i> spA	•	•	•	•	•	•		•		•		
Neogastropoda												
Buccinidae												
Buccinidae spA	•		•	•						•	•	
Buccinidae spB	•	•	•	•				•		•	•	
Buccinidae spC	•		•	•	•			•			•	
Buccinidae spD			•									
Cancellariidae												
Cancellariidae spA	•		•	•		•		•				
Cancellariidae spB	•		•		•						•	
Fascioliariidae												
Fascioliariidae spA	•											
Muricidae												
Enixotrophon spA	•		•	•								
Enixotrophon spB	•										•	
Enixotrophon spC	•		•	•	•						•	
Enixotrophon spD				•				•				
Nassariidae												
Nassariidae spA	•				•							
Terebridae												
Terebridae spA	•	•			•			•				
Turridae												
Turridae spA	•		•	•	•			•	•	•	•	
Turridae spB	•		•	•				•				
Turridae spC	•	•	•		•							
Turridae spD					•							
Volutidae												
<i>Provocator pulcher</i>	•	•		•	•			•	•	•	•	
Neotaenioglossa												
Capulidae												
<i>Icuncula</i> spA	•	•	•	•	•			•		•		
<i>Trichotropis</i> spA	•		•	•				•	•	•		
Cerithiopsidae												
Cerithiopsidae spA	•	•		•								
Epitoniidae												
Epitoniidae spA	•		•		•			•				
Lamellariidae												
Lamellariidae spA	•	•	•	•	•							
Naticidae												
Naticidae spA	•	•	•	•	•					•	•	
Ranellidae												
<i>Fusitriton aurora</i>	•		•									
Polyplacophora												
Polyplacophora spA	•	•	•	•								
Neoloricata												
Lepidopleuridae												
<i>Leptochiton kerguelensis</i>	•	•		•	•			•	•	•		
Scaphopoda												
Dentaliida												
Dentaliidae												
<i>Dentalium aegeum</i>	•	•	•	•	•		•	•		•	•	



Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
ANNELIDA*											
Polychaeta											
Polychaete spA						•					
Polychaeta spB					•						
Polychaete spC					•						
Polychaete spD								•		•	•
Capitellida											
Maldanidae											
Maldanidae sp.			•	•	•	•	•	•		•	
Eunicida											
Lumbrineridae											
Lumbrineridae sp.		•									
Phyllodocida											
Aphroditidae											
Aphroditidae spA	•	•	•	•	•	•		•	•	•	•
Aphroditidae spB						•					
Aphroditidae spC											•
Glyceridae											
Glyceridae sp.			•								
Nephtyidae											
Nephtyidae sp.			•								
Nereididae											
<i>Neanthes kerguelensis</i>	•	•		•							
Phyllodocidae											
Phyllodocidae sp.			•								
Polynoidae											
Polynoidae sp.			•								
Sigalionidae											
Sigalionidae sp.			•								
Syllidae											
Syllidae sp.	•										
Sabellida											
Sabellidae											
Sabellidae sp.			•			•					
Serpulidae											
Serpula spA	•	•	•	•	•	•	•	•	•	•	•
Terebellida											
Ampharetidae											
Ampharetidae sp.			•								
Flabelligeridae											
Flabelligeridae sp.			•								
Terebellidae											
Terebellidae sp.			•								
BRYOZOA*											
Bryozoa spA								•			
Bryozoa spB										•	
Bryozoa spC								•		•	•
Gymnolaemata											
Cheilostomata											
<i>Klugeflustra</i> spA	•										
Arachnopusiidae											
<i>Arachnopusia inchoata</i>	•										
<i>Arachnopusia</i> spA	•										
<i>Arachnopusia</i> spB			•								
Bitectiporidae											
<i>Schizomavella</i> spA	•										
Buffonellodidae											
<i>Buffonellodes</i> spA	•										
Bugulidae											
<i>Cornucopina</i> spA				•	•						
Calwelliidae											
<i>Malakosaria sinclarii</i>	•			•							
Candidae											
<i>Bugulopsis</i> spA			•								
<i>Caberea darwinii</i>	•										
<i>Notoplites</i> spA			•								
Cellariidae											
<i>Cellaria</i> spA	•										
<i>Cellaria</i> spB			•								

Appendix 8

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Celleporidae											
<i>Galeopsis bullatus</i>	•										
<i>Osthimosia</i> spA	•										
Chaperiidae											
<i>Chaperiopsis</i> spA			•								
Cribrilinidae											
<i>Filaguria</i> spA	•										
Flustridae											
<i>Carbasea ovoidea</i>	•										
<i>Isosecuriflustra angusta</i>		•	•								
Lekythoporidae											
<i>Turritigera</i> spA	•										
<i>Turritigera</i> spB	•									•	
Phidoloporidae											
<i>Reteporella</i> spA	•										
Romancheinidae											
<i>Lageneschara lyrulata</i>	•										
Sclerodomidae											
<i>Cellarinella</i> spA	•	•		•							
Smittinidae											
<i>Pemmatoporella marginata</i>			•								
<i>Smittina anecdota</i>	•		•								
<i>Smittoidea ornatipectoralis</i>	•										
<i>Thrypticocirrus</i> spA	•										
Ctenostomata											
Ctenostomata spA			•								
Stenolaemata											
Cyclostomata											
Entalophoridae											
<i>Entalophoridae</i> spA	•										
Filisparsidae											
<i>Nevianipora</i> spA	•										
Oncousoeciidae											
<i>Oncousoecia</i> spA	•										
BRACHIOPODA											
Articulata											
Articulata spA	•	•	•	•	•			•	•	•	•
Articulata spB		•						•			
Articulata spC				•							
Rhynchonellida											
Hemithyrididae											
<i>Notosaria nigricans pyxidata</i>	•	•		•	•			•			
ARTHROPODA											
Pycnogonida*											
Pantopoda											
Ammotheidae											
<i>Ammothea adunca</i>	•		•						•	•	
<i>Ammothea</i> sp1			•							•	
<i>Ammothea</i> sp3			•								
<i>Ammotheidae</i> sp1			•								
<i>Tanystylum</i> sp1			•								
<i>Tanystylum</i> sp2		•									
Austrodecidae											
<i>Austrodecus simulans</i>	•										
<i>Austrodecus</i> sp1		•									
Callipallenidae											
<i>Austropallene brachyara</i>	•										
<i>Austropallene</i> sp1		•									
<i>Oropallene dimorpha</i>	•										
<i>Pseudopallene glutus</i>		•									
Colossendeidae											
<i>Colossendeis enigmatica</i>				•							
<i>Colossendeis lilliei</i>	•							•	•		•
<i>Colossendeis</i> sp1				•					•	•	•
<i>Colossendeis</i> sp2		•		•	•						
<i>Colossendeis</i> spp.				•							
<i>Decolopoda australis</i>			•	•	•					•	

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Nymphonidae											
<i>Nymphon brachyrhynchum</i>	•		•								
<i>Nymphon</i> sp1	•	•	•	•							
<i>Nymphon</i> sp2		•									
<i>Nymphon</i> sp3	•	•		•							
<i>Nymphon</i> sp4			•								
Pallenopsidae											
<i>Pallenopsis vanhoffeni</i>				•							
Pycnogonidae											
<i>Pycnogonum</i> sp1		•	•						•	•	
<i>Pycnogonum</i> sp2			•								
Cirripedia											
<i>Litoscalpellum</i> c.f. <i>fissicarinatum</i>	•	•	•	•	•		•	•	•	•	•
<i>Bathylasma</i> c.f. <i>corolliforme</i>		•	•	•		•		•	•	•	•
Malacostraca											
Amphipoda											
Amphipoda spA				•						•	
Amphipoda spB				•	•	•		•		•	
Amphipoda spD				•							
Amphipoda spE				•							
Amphipoda spF				•							
Amphipoda spG					•						
Amphipoda spH						•					
Amphipoda spI				•				•			
Amphipoda spJ				•							
Caprellidae											
<i>Caprellidea</i> spA	•	•	•								
Gammaridae											
<i>Gammaridea</i> spC						•					
Epimeriidae											
<i>Epimeria</i> spA			•	•	•	•					•
Hyperiididae											
<i>Themisto gaudichaudii</i>				•	•	•	•				
Cumacea											
Cumacea spA	•		•	•	•			•			
Decapoda											
Caridea spA			•								
Nephropidae											
<i>Thymopides grobovi</i>				•		•	•				•
Pasiphaeidae											
<i>Pasiphaea</i> spA				•							
Euphausiacea											
Euphausiidae											
<i>Euphausia triacantha</i>				•					•		
<i>Euphausia vallentini</i>				•							
Isopoda											
Isopoda spA	•	•		•		•					
Isopoda spB	•	•	•		•	•		•	•		•
Isopoda spC	•		•								
Isopoda spD	•		•	•	•						
Isopoda spE			•	•							
Isopoda spF	•	•									
Isopoda spG	•										
Isopoda spH		•	•	•	•						
Isopoda spI			•			•					
Isopoda spJ	•			•				•			
Isopoda spK	•	•	•	•							
Isopoda spL	•	•	•	•							
Isopoda spM	•		•								
Isopoda spN	•			•							
Isopoda spO	•	•	•								
Isopoda spP	•		•								
Isopoda spR				•	•						
Isopoda spS										•	

Appendix 8

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Antarcturidae											
<i>Antarcturus oryx</i>	•	•	•	•	•	•	•	•	•	•	•
Arcturididae											
<i>Arcturides cornutus</i>	•	•	•	•	•			•	•	•	•
Cirolanidae											
<i>Natanolana</i> spA	•		•					•	•	•	
Expanathuridae											
<i>Eisothistos</i> sp.nov.	•										
<i>Panathura</i> spA	•	•	•	•	•			•		•	
Gnathiidae											
<i>Euneognathia gigas</i>	•	•	•	•	•			•		•	
Serolidae											
<i>Ceratoserolis cornuta</i>	•	•	•	•	•	•	•		•	•	•
<i>Serolis gracilis</i>			•	•		•	•	•	•	•	
Sphaeromatidae											
<i>Cymodopsis</i> spA	•	•	•	•	•	•			•	•	
Tanaidacea											
<i>Apseudomorpha</i> spA	•			•	•						
Tanaidacea spA	•		•	•	•						
Nototanaididae											
<i>Nototanais</i> spA	•	•	•	•	•			•	•	•	
Ostracoda											
Ostracoda sp.	•	•	•	•	•	•		•			
ECHINODERMATA											
Asterozoa											
Asterozoa spA	•	•	•	•	•	•	•	•	•	•	
Asterozoa spB	•	•		•	•			•	•	•	
Asterozoa spC	•	•		•	•			•	•	•	
Asterozoa spD				•				•			
Asterozoa spE			•								
Asterozoa spF	•		•	•	•			•	•	•	•
Asterozoa spG			•	•							
Asterozoa spI				•				•		•	
Asterozoa spJ				•							
Asterozoa spK				•							
Asterozoa spL				•					•		
Asterozoa spM					•				•		
Asterozoa spN				•							
Asterozoa spS									•		
Asterozoa spT									•		
Asterozoa spU									•		
Forcipulatida											
Asteriidae											
<i>Anteliaster</i> spA		•									
<i>Asteriidae</i> spA	•		•	•	•			•	•	•	•
<i>Smilasterias</i> spA	•	•	•	•	•			•	•	•	•
Labidiasteridae											
<i>Labidiaster annulatus</i>	•	•	•	•	•			•	•	•	•
Paxillozoa											
Astropectinidae											
<i>Bathybiaster loripes</i>	•	•	•	•	•	•	•	•	•	•	•
<i>Leptychaster kerguelensis</i>	•	•	•	•	•			•	•	•	•
Benthopectinidae											
<i>Cheiraster (Luidiaster) hirsutus</i>			•	•	•		•	•	•	•	•
Spinulopsida											
Asterinidae											
<i>Tremaster mirabilis</i>	•	•		•	•			•	•	•	
Echinasteridae											
<i>Henricia obesa</i>								•			
<i>Henricia</i> spA	•	•		•	•			•		•	
<i>Rhopiella hirsuta</i>	•	•	•		•			•	•		
Ganeriidae											
<i>Cycethra verrucosa</i>	•	•						•		•	
Poraniidae											
<i>Porania antarctica</i>	•	•	•	•	•			•	•		
Pterasteridae											
<i>Hymenaster</i> spA	•	•	•	•	•			•	•	•	
<i>Pteraster rugatus</i>	•	•		•	•			•	•	•	
<i>Pteraster</i> spB	•	•	•	•	•	•		•	•	•	

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Solasteridae											
<i>Cuenotaster involutus</i>	•	•		•				•	•	•	
<i>Solaster regularis subarcuatus</i>	•	•		•				•	•		
Valvatida											
Goniasteridae											
<i>Hippasteria falklandica</i>	•	•		•	•			•	•	•	
Odontasteridae											
<i>Acodontaster elongatus</i>	•	•	•	•	•			•	•	•	•
<i>Odontaster meridionalis</i>	•	•	•	•	•			•	•	•	•
Ophiuroidea											
Ophiuroidea spA	•		•	•	•	•		•			
Ophiuroidea spB			•		•						
Ophiuroidea spC	•	•		•	•			•	•		
Ophiuroidea spD				•	•			•	•		
Ophiuroidea spE					•			•		•	
Ophiuroidea spF				•							
Ophiuroidea spG									•	•	•
Ophiuroidea spH								•			
Ophiurida											
Amphiuridae											
<i>Amphiura (Amphiura) spA</i>	•	•	•	•	•			•	•	•	
<i>Amphiura (Amphiura) spB</i>			•	•	•	•	•	•		•	
<i>Amphiura (Amphiura) spC</i>				•	•		•				
Ophiacanthidae											
<i>Ophiacantha imago</i>	•	•	•	•	•			•	•	•	•
<i>Ophiacantha pentactis</i>	•	•	•	•		•	•	•	•	•	•
<i>Ophiacantha spp.</i>		•		•							
<i>Ophiacantha vivipara</i>	•	•	•	•	•			•	•	•	•
Ophiodermatidae											
<i>Ophioderma brevispinum</i>	•		•	•	•	•	•	•	•	•	•
Ophiuridae											
<i>Ophiocten amitinum</i>	•	•	•	•	•	•				•	•
<i>Ophiomisdium speciosum</i>	•	•		•	•			•			
<i>Ophionotus hexactis</i>			•			•			•	•	•
<i>Ophiura ambigua</i>	•	•	•	•	•		•	•	•	•	•
<i>Ophiura sp1</i>	•		•	•	•	•	•	•	•	•	•
<i>Ophiurolepis carinata</i>	•	•	•	•	•			•	•	•	•
Phrynophiurida											
Asteronychidae											
<i>Asteronyx loveni</i>				•	•	•	•	•	•	•	•
Gorgonocephalidae											
<i>Astrotoma agassizii</i>				•		•			•	•	
<i>Gorgonocephalus chilensis</i>		•	•	•	•	•	•	•	•	•	•
Crinoidea											
Comatulida											
Antedonidae											
<i>Promachocrinus kerguelensis</i>	•	•		•	•			•	•	•	
<i>Eumorphometra spp.</i>	•	•	•	•	•	•		•	•	•	•
Echinoidea											
Echinoida											
Echinidae											
<i>Dermechinus horridus</i>		•									
<i>Sterechinus diadema</i>	•	•	•	•	•	•		•	•	•	•
Spatangoida											
Schizasteridae											
<i>Abatus cordatus</i>			•							•	
<i>Brisaster antarcticus</i>	•	•	•	•	•	•	•	•	•	•	•
Cidaroida											
Cidaridae											
<i>Ctenocidaris nutrix</i>	•	•	•	•	•			•	•	•	
Holothuroidea											
Holothuridae spA					•						
Holothuridae spB				•	•	•		•	•	•	•
Holothuridae spC					•						
Holothuridae spD				•							
Holothuridae spE				•	•					•	
Holothuridae spF				•							
Holothuridae spH										•	

Appendix 8

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Apodida											
Chiridotidae											
<i>Paradota marionensis</i>	•										
Molpadiida											
Molpadiidae											
<i>Molpadia musculus</i>	•			•	•			•			
<i>Molpadiidae</i> sp.nov.			•	•	•	•	•				
Aspidochirotida											
Synallactidae											
<i>Pseudostichopus peripatus</i>	•	•		•	•						
<i>Pseudostichopus</i> sp.nov.				•	•						
<i>Synallactes</i> sp.nov.				•		•					
Dactylochirotida											
<i>Dactylochirotida</i> sp.nov.				•		•	•	•			
Dendrochirotida											
Cucumariidae											
<i>Cucumaria kerguelensis</i>	•		•	•	•					•	
<i>Cucumaria</i> sp.nov.	•										
<i>Heterocucumis godeffroyi</i>	•	•	•	•							
<i>Pseudocnus laevigatus</i>	•	•	•	•	•			•	•	•	•
<i>Staurocucumis liouvillei</i>	•	•	•	•	•			•	•	•	•
<i>Trachythyone muricata</i>			•	•	•	•					•
Psolidae											
<i>Psolidium poriferum</i>	•	•	•	•	•			•	•	•	•
<i>Psolus ephippifer</i>	•	•		•				•		•	
<i>Psolus paradubiosus</i>	•	•		•	•			•	•	•	
HEMICHORDATA											
Pterobranchia											
Pterobranchia spA	•	•	•	•	•			•	•	•	
Pterobranchia spB	•			•	•			•	•	•	
CHORDATA											
Ascidiacea*											
Ascidiacea spB			•								
Ascidiacea spF								•		•	•
Ascidiacea spG								•			
Ascidiacea spH					•				•		
Ascidiacea spA	•	•									
Ascidiacea spC	•			•						•	
Ascidiacea spD	•			•							
Ascidiidae											
<i>Ascidia challengerii</i>	•	•		•							
<i>Ascidia</i> spA	•	•							•		
Diazonidae											
<i>Tylobranchion speciosum</i>			•		•					•	
Didemnidae											
<i>Didemnidae</i> spA	•	•									
<i>Didemnidae</i> spp	•	•	•	•							
Holozoidae											
<i>Sycozoa sigillinoides</i>	•			•	•	•			•	•	
Polyclinidae											
<i>Aplidiopsis discoveryi</i>			•			•					
<i>Polyclinidae</i> spA	•	•	•	•							
<i>Polyclinidae</i> spB	•	•	•	•							
<i>Polyclinidae</i> spC	•	•						•			
<i>Polyclinidae</i> spD	•	•	•	•				•			
Pleurogona											
Molgulidae											
<i>Eugyra kerguelensis</i>	•										
<i>Molgula kerguelensis</i>	•	•		•							
<i>Molgula malvinensis</i>	•	•	•	•							
<i>Molgula pedunculata</i>	•	•	•	•	•			•	•	•	•
<i>Molgula sluiteri</i>	•										
<i>Molgulidae</i> spA	•	•									
<i>Molguloides</i> spA	•	•									
Pyuridae											
<i>Pyura</i> spB		•									
<i>Pyura vittata</i>	•	•		•				•	•	•	

Taxon	Geographic areas										
	ABA	CBA	WPL	SSB	SBA	NPL	WNP	PBA	PSE	PDE	GRI
Styelidae											
<i>Cnemidocarpa verrucosa</i>	•	•	•		•		•	•	•	•	
<i>Oligocarpa megalorchis</i>	•		•								
<i>Polyzoinae</i> spA	•	•									
<i>Polyzoinae</i> spB	•	•	•	•							
<i>Styela nordenskjoldi</i>	•	•		•							
<i>Styela</i> spA	•	•									
<i>Styela</i> spB	•	•	•	•							
<i>Styelinae</i> spA	•	•		•							
<i>Styelopsis</i> spA	•	•		•							
Thaliacea											
Salpida											
<i>Salpida</i> spA							•				

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## Appendix 9      Prediction of vulnerable marine benthos across the Heard Island and McDonald Islands region

Ty Hibberd, Steve Candy and Graeme Ewing

### **ABSTRACT**

An estimate of the impact on benthic habitats by demersal fishing in the region of Heard Island and McDonald Islands depends on the distribution of biodiversity across the seascape in areas where fisheries have occurred. Surrogacy models were developed where synoptic data of environmental variables were used as surrogates for the distribution of vulnerable taxa. Quantitative sampling of benthos and the co-located attributes of the environment were used to parameterise these models for 12 key vulnerable benthic taxa. These parameters were subsequently used to predict the distribution of biomass across HIMI within a Generalised Linear Modelling (GLM) framework. Estimates revealed that sessile, suspension-feeding vulnerable taxa were most prevalent above 300 m, and where physical parameters are likely to provide favourable attachment and feeding conditions (i.e. western banks, south facing slopes and around Heard Island). In the depth range from 500–1000 m, biomass of vulnerable taxa was lower and patchier, and below 1000 m the seabed was relatively devoid of vulnerable mega-epifaunal taxa. This framework provides a valuable tool for estimating plausible upper and lower bounds of the biomass of vulnerable organisms where biological specimens have not been collected.



## Introduction

Bottom fishing has the potential to cause significant adverse impacts to benthic communities, specifically vulnerable marine ecosystems (VMEs), and there is an international imperative to conserve and mitigate impacts to benthic marine ecosystems with the United Nations General Assembly adopting a resolution calling on all States and Regional Fisheries Management Organisations/Arrangements to implement measures to protect biodiversity from destructive fishing practices (UNGA 2007). However, in high latitude, deep-sea regions, assessing these impacts is hampered by the paucity of information on the spatial distribution of vulnerable benthos. This situation is unlikely to undergo wholesale change given the difficulties and expense associated with working in these remote and extreme environments. Evaluating methods for using the available data to develop a better understanding of the distribution of benthic biodiversity is therefore vital to assess the likely impacts caused by deep-sea fisheries, and to develop robust management strategies to avoid unsustainable fishing practices.

One approach to deriving the distribution of benthic habitats in data-poor circumstances, such as the Southern Ocean, bases habitat predictions on relationships between biota and environmental or spatial parameters, referred to as 'physical surrogates' (McArthur *et al.* 2010, Meynard & Quinn 2007). The goal of surrogacy research is to determine which easily measurable physical parameter(s) (e.g. depth, substrate etc.) best describe the variations in distribution of biota (i.e. species, assemblages), and then based on those surrogates, predict the distribution of biota across the seascape using synoptic physical data (Dunstan & Johnson 2005, McArthur *et al.* 2009). The study of benthic habitats and their distributions has often focused on the association between biodiversity and components of the physical habitat (Auster 2005, Grant *et al.* 2006, Hixon *et al.* 1991, Nasby-Lucas *et al.* 2002, Stein 1992, Yoklavich *et al.* 2000); with depth, temperature, productivity and sediment composition all prominent drivers of benthic biodiversity (Snelgrove 2001). With the advent of powerful mathematical and statistical tools like GAMs (Generalised Additive Models) and GLMs (Generalised Linear Models), and the increasing availability and spatial resolution of physical data worldwide, scientists have been able to better characterise these surrogacy relationships to create robust predictive models of single species, taxonomic groups or communities that define presence, abundance or biomass as a function of environmental gradients (Elith *et al.* 2006, Guisan & Thuiller 2005, Guisan *et al.* 2006, Oppel & Huettmann 2007).

Regionalisation techniques using physical parameters have been used to classify and determine the distribution of different benthic environment types in the Southern Ocean (Hibberd *et al.* 2010, Lockhart & Jones 2008, Meyer *et al.* 2000). However, the relationship between these physical parameters and individual benthic taxa (whether species or taxonomic or functional groups) and their subsequent potential to infer biodiversity patterns, has had less attention. Given the impetus for the protection of

representative areas and/or vulnerable marine ecosystems in the Southern Ocean, and the practical difficulties associated with obtaining synoptic empirical data on the distribution of benthic taxa or assemblages, it is timely to explore tools to support the development and evaluation of management strategies seeking to protect biodiversity in the Southern Ocean.

The Heard Island and McDonald Islands region (HIMI) has been shown to contain a wide diversity of benthic invertebrates and assemblages, including a range of low productivity taxa, often with low abundance and limited distributions (Hibberd & Moore 2009, Hibberd *et al.* 2010, Meyer *et al.* 2000). Whilst HIMI is data-poor compared to some less remote and shallower regions, by Southern Ocean standards it is relatively well researched, with quantitative samples of the benthos collected from numerous locations across the region (Appendix 6), providing an opportunity to trial surrogacy methods that may be applied there and to other regions in the Southern Ocean.

Since April 1997 an Australian demersal fishery targeting Patagonian toothfish (*Dissostichus eleginoides*) has been in operation in the HIMI region, therefore estimates of biodiversity in this study will focus on those organisms considered most vulnerable to disturbance from demersal gears. Organisms were considered vulnerable if their morphological or life-history characteristics meant they were susceptible to damage or mortality on exposure to a particular agent of disturbance i.e. the interaction between disturbing force (e.g. contact with the footrope of a bottom trawl) and taxa (e.g. coral) (Martin-Smith 2009b). This can be most easily understood by considering the example of low productivity deep-sea corals which are damaged or destroyed by bottom fishing (Roberts & Hirshfield 2004). These organisms have been identified as key components of biodiversity in marine ecosystems (Auster 2005, Hiefertz 2002, Puniwai 2002, Tissot *et al.* 2004), possessing the ability to influence ecosystem function by providing biogenic habitat for fish and other invertebrates. Hence, understanding their distribution with respect to the distribution of fishing activity is important to developing an assessment of bottom fishing disturbance. Therefore sessile suspension feeders, such as sponges and soft corals, comprised the majority of vulnerable taxa assessed, based on the invertebrate taxa recorded in the region (Appendices 6 and 8), that also have characteristics that make them vulnerable to bottom fishing (e.g. SC-CCAMLR 2009).

In this study we present an analysis of the distribution and extent of the vulnerable taxa in relation to physical data-sets available in the HIMI region to identify the key physical parameters which explain variability in benthic biota. Based on those parameters we develop a modelling framework that utilizes these relationships to predict the distribution and biomass of vulnerable taxa across the seascape at HIMI, at a resolution similar to the scale of disturbance caused by individual fishing events.

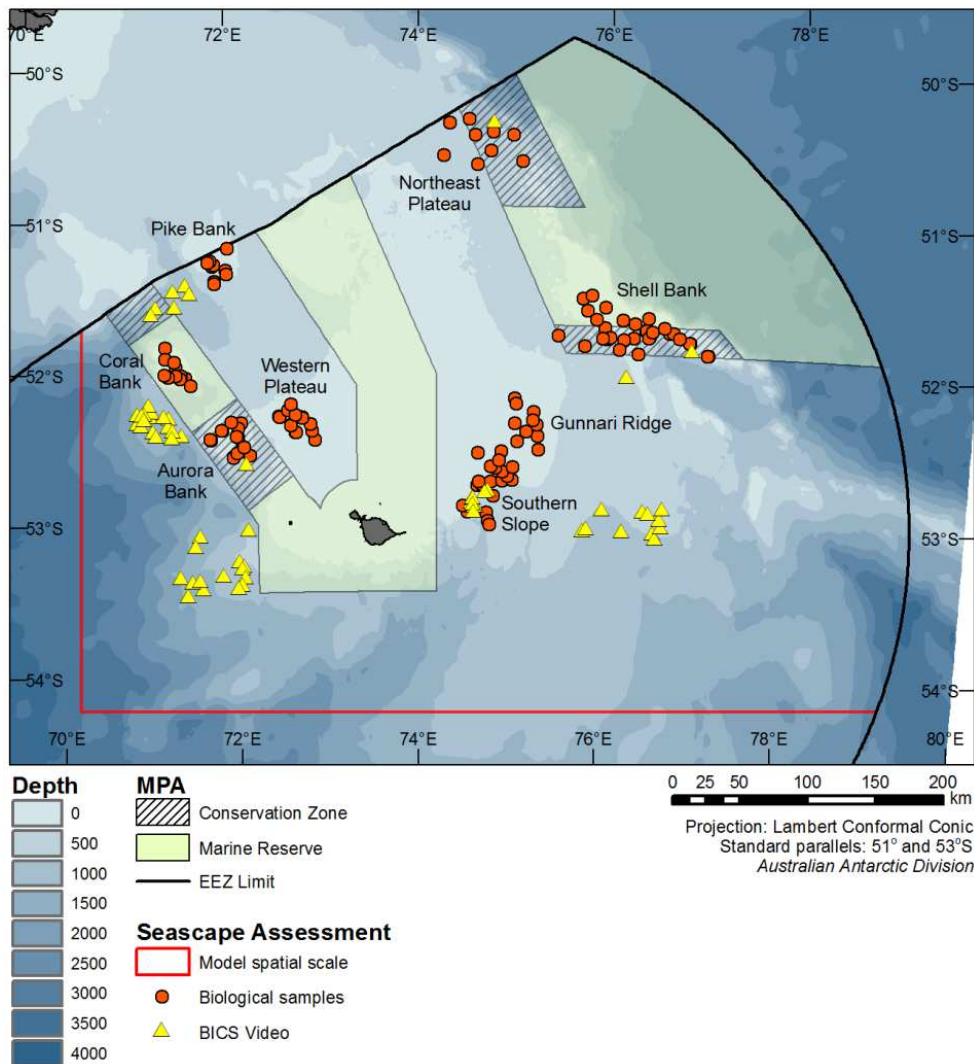
## Methods

### Biological data

The biomass ( $\text{kg}\cdot\text{m}^{-2}$ ) of vulnerable taxa from the HIMI region was derived from 129 quantitative biological samples collected from the HIMI region by beam trawl and benthic sled to assess the representativeness of the HIMI marine reserve (Figure A9.1(Hibberd & Moore 2009); Hibberd & Moore 2009; Appendix 6). Taxa considered vulnerable to disturbance by bottom fishing (*sensu* SC-CCAMLR 2009) and identified at HIMI are listed in Table 9.1. A spatial analysis was conducted to assess the extent of commercial fishing activity that had occurred within the footprint of each research sample (Appendix 11) and 5 samples considered likely to be substantially affected by prior fishing activity were excluded. Video camera footage from commercial fishing deployments (Appendix 3) was used in conjunction with biological samples to assess the distribution of biota and physical attributes of the seafloor.

**Table A9.1: List of invertebrate taxa vulnerable to bottom fishing assessed in the HIMI region, including their motility (S= sessile or M= motile) and total number of biological samples in which they were captured out of 129 samples available for analysis. \* Denotes groups whose distributions were predicted across the seascape.**

Taxon	Common name	Motility	Records (n)	Records (%)
PORIFERA				
Demospongiae*	bath or siliceous sponges	S	91	70.5
Hexactinellida	glass sponges	S	69	53.5
CNIDARIA				
Actinaria*	anemones	S	83	64.3
Scleractinia*	hard corals	S	45	34.9
Alcyonacea*	soft corals or alcyonarians	S	84	65.1
Gorgonacea *	horny corals or gorgonians	S	80	62.0
Pennatulacea	sea pens	S		
Zoanthidae	zoanthids	S	11	8.5
Hydrozoa				
<i>Stylasteridae</i>	hydrocorals	S	17	13.2
<i>Hydroidolina*</i>	hydroids or sea ferns	S	102	79.1
ANNELIDA				
Serpulidae*	serpulid tube worms	S	82	63.6
BRYOZOA*	lace coral	S	76	58.9
BRACHIOPODA	lamp shells	S	68	52.7
ARTHROPODA				
Cirripedia	stalked barnacles	S	67	51.9
ECHINODERMATA				
Crinoidea	stalked crinoids	S		
Echinoidea*	pencil urchins	M	80	62.0
Euryalida*	snake or basket stars	M	46	35.7
HEMICHORDATA				
Pterobranchia*	pterobranchs	S	48	37.2
CHORDATA				
Ascidiacea*	sea squirts	S	105	81.4



**Figure A9.1.** The model study area (red line) across which predictions were made, encompassing biological samples, video footage, and the majority of Australian fishing effort in the region.

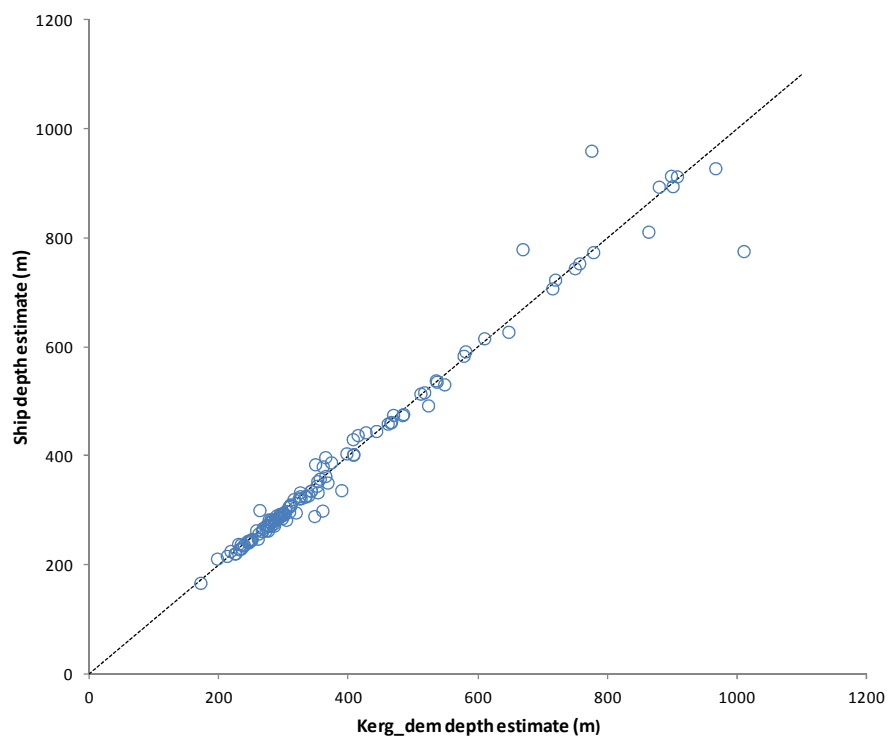
### Physical surrogate data

Depth, slope, seafloor geomorphology, and water column temperature and chemistry have shown to be useful explanatory variables for describing mesoscale patterns in invertebrate distribution (Brandt *et al.* 2007a, Carney 2005, Kaiser *et al.* 2011), and hence were in the first instance sought as the best potential as surrogates for predicting biodiversity beyond the locations where biological samples were available.

The values assigned to each biological sample to establish taxa/physical relationships, was determined as the midpoint of the beam trawl deployment from which the sample was collected. Mean trawl sites were generally across relatively flat topography, however there was uncertainty in the depth for which the sample is representative due

to variation in depth within each beam trawl shot. The mean tow length of beam trawls was 1545 m, with a maximum length of 2900 m. Consequently, the grid cell size chosen to interpolate the values of physical variables at each biological sampling location was a  $3 \times 3$  km square ( $9 \text{ km}^2$ ).

Depth and slope for the region were compiled from the Kerguelen digital elevation model (DEM) (Beaman & O'Brien 2011) using bilinear interpolation of cell values within each  $9 \text{ km}^2$  square. This bathymetric grid, called *kerg\_dem*, was created by Geoscience Australia in 2010 in order to better define the seabed geomorphology and depth contours across the Kerguelen Plateau inside the Australian EEZ, using comprehensive data holdings from commercial and research vessel. Predicted depths showed close correspondence with the midpoint of depths recorded from sample tows (Figure A9.2). The *kerg\_dem* was reclassified to a grid pixel size of 0.01-arc degree (ca. 1000 m) with a horizontal datum of WGS84 and a vertical datum of MSL (Beaman & O'Brien 2011). Slope was calculated from the *kerg\_dem* for a cell size of 1000 m using spatial analyst procedures in ArcGIS. Slope values describe the maximum change in elevation over the extent of a cell in respect to its eight neighbouring cells (i.e. encompassing a  $3 \times 3$  km square). The lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain (Burrough & McDonell 1998, ESRI 2008).



**Figure A9.2** Comparison between depths estimated at the midpoint of sampling tows from vessel depth soundings, and estimated depth corresponding to the midpoint on the *kerg\_dem* bathymetric grid. Dotted line shows a 1:1 correspondence.

Geomorphic units were established through interpretation of *kerf\_dem* data (depth and slope) by the Australian Antarctic Data Centre mapping section, coupled with substrate information obtained on three research cruises of the Ocean Drilling Program (ODP) (1987/1988, 1988 and 1998/1999) (ODP 1998), observations made during the three AAD research cruises to the area in 1990, 1992 and 1993, and video observations from the *in situ* video footage of fishing deployments (Appendix 3).

Water column temperature and chemistry data were also obtained for each cell from World Oceans Atlas database<sup>14</sup>. However the spatial scale and data resolution (grid pixel size of 1-arc degree) were considered too coarse for the purposes of this study, and consequently these data were not used further in this analysis.

### **Predictive framework**

GAMs with a quasi-Poisson error model and log-link function, implemented in *R* (R Development Core Team 2010) using the *mgcv* package (Wood 2006) and GLMs were used to investigate relationships of abundance for each taxon with the environmental variables. To account for sampling intensity the response variable used was the total weight (g) of the particular taxonomic group, with the log of the swept area included as an offset in the linear predictor of the GAM. Although the response variable is not strictly a count, the quasi-Poisson error distribution was considered a reasonable approach given that standard errors of parameters accounted for the estimated dispersion parameter which could be greater than or less than 1. The estimated dispersion parameter was obtained as the residual deviance divided by its degrees of freedom. The ability to investigate interactions and other high level terms was limited by the relative small sample size of 124 beam trawl sample sites used in the analyses.

## **Results**

### **Distribution of key physical parameters**

Water depth across the extent of the model ranges from the shoreline surrounding HIMI to more than 4000 m to the east and west of the region (Figure A9.4). Data on vulnerable taxa extends from approximately 150 – 1100 m for biological samples, and video data on community structure and substratum extends from approximately 500 – 2500 m. Predictions of vulnerable taxa were conducted over a depth range of 150 – 1200 m.

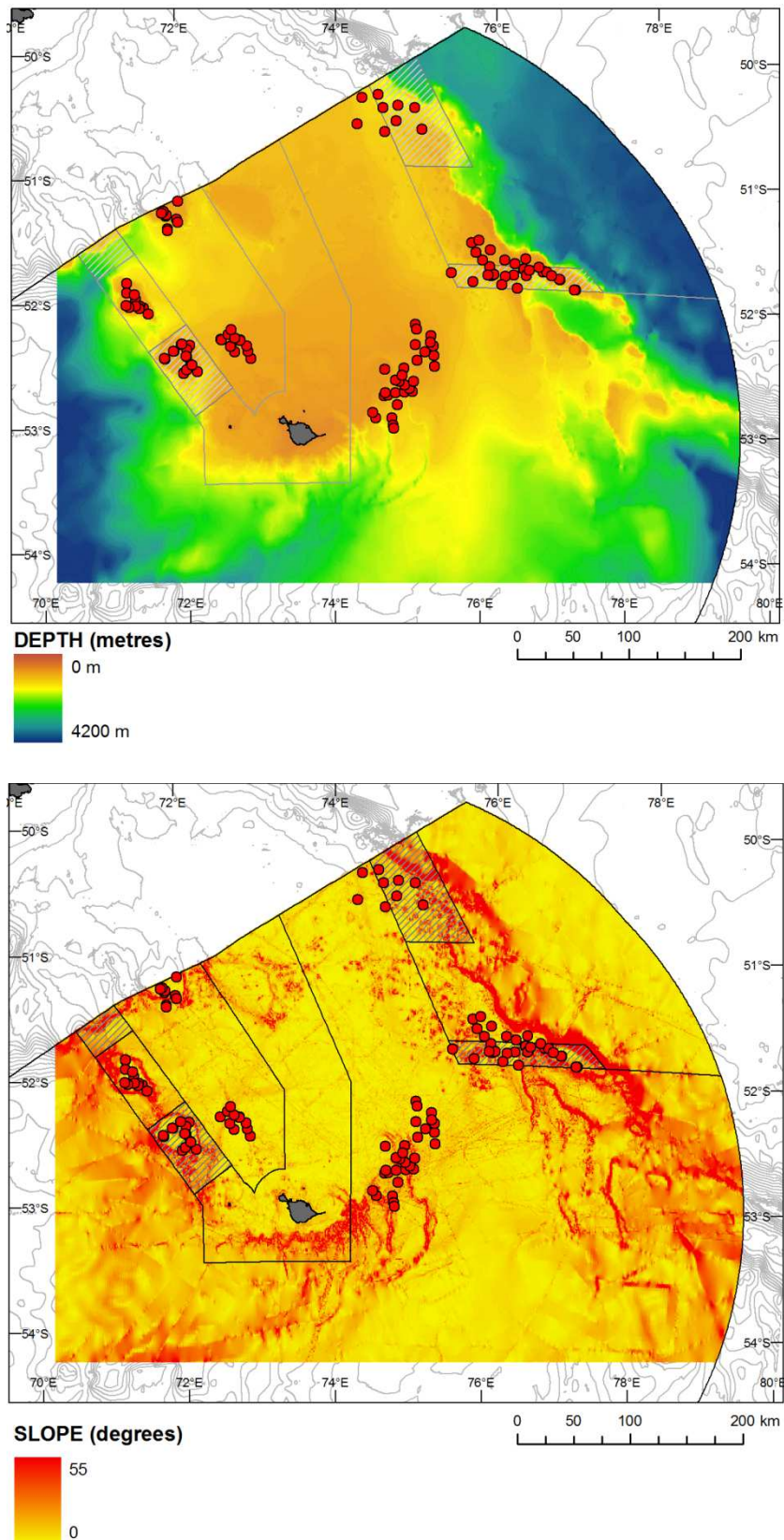
Bedform elevation across the region was typically flat (Slope = 0; yellow in Figure A9.4). Slope was highest near Shell Bank, on the periphery of the western banks and throughout the complex terrain south of Heard Island.

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<sup>14</sup> [http://www.nodc.noaa.gov/OC5/WOD/pr\\_wod.html](http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html)

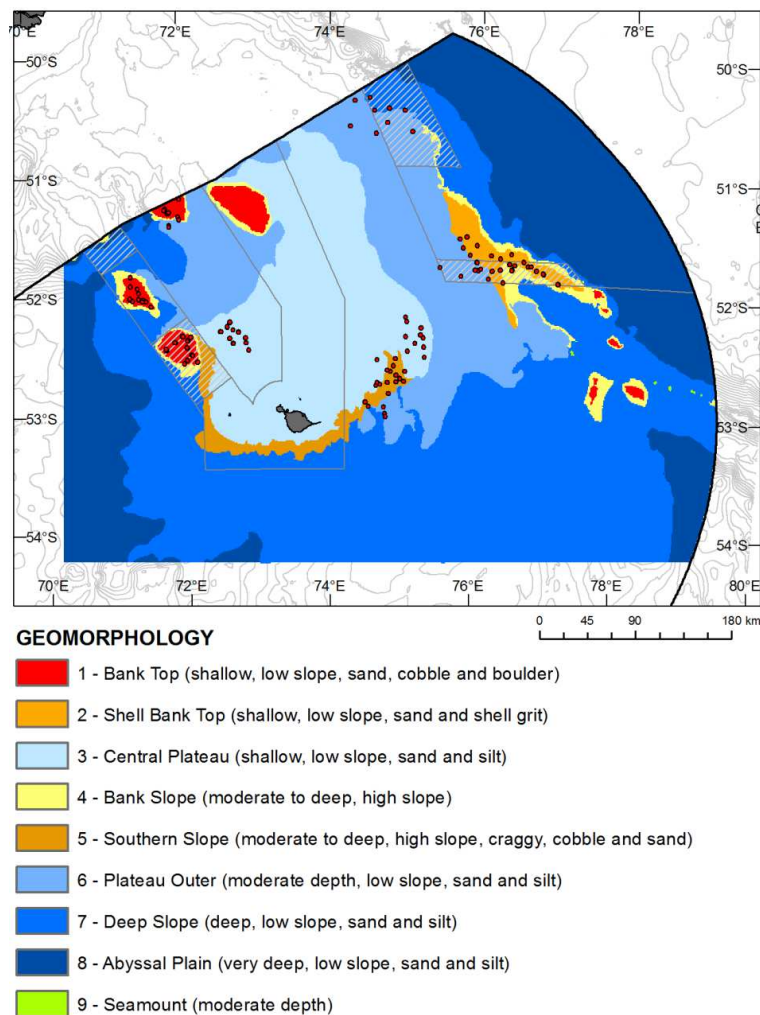
Observations of the seafloor using the BICS camera, coupled with substrate information collected in biological samples (Hibberd *et al.* 2009) and other studies including data on HIMI geology (Meyer *et al.* 2000, ODP 1998), suggests that the substrata across HIMI consists primarily of sand and mud. Rocks (gravel > 4 mm Ø; cobble > 64 mm Ø, and boulder > 256 mm Ø, (Wentworth 1922)) were an important feature of the substratum on the bank tops to the west, Shell Bank, the slopes south of HIMI and nearer to the island. Large quantities of shell grit were common to biological samples collected from Shell Bank, supporting previous statements that the top of the bank is uniquely characterised by shell grit (Meyer *et al.* 2000).

The combination of depth, slope and broad-scale substrate characteristics was used to define 9 geomorphic categories across the region (Figure A9.5). The geomorphic category 'Bank Top' was characterised by rugged seabed with pinnacles, cobble, boulders and a covering of sand, at least in regard to Aurora, Coral, Discovery and Pike Banks (Meyer *et al.* 2000). 'Shell Bank Top' was separated from the remaining bank tops as the substrate here was different, as was its topography. 'Bank Slope' encompasses the steep, craggy sides of the banks from their flat tops to the base of the slope, encompassing a depth range from 500 – 1300 m. 'Southern Slope' was characterised by a complex, craggy terrain covered in cobble and sand. The remaining geomorphs from the 'Central Plateau' to the 'Abyssal plain' were delineated by depth, divided into < 500 m, 500 – 900 m and > 900 m. These zones were defined with reference to *kerf\_dem* data, and commonly ascribed faunal depth zonations reported on other studies (Haedrich *et al.* 1980, Howell 2010, Menzies *et al.* 1973). BICS video from these geomorphic types revealed a substratum of sand and silt.



**Figure A9.3** Depth (m) (upper panel) and slope (°) (bottom panel) across the model study area and the location of biological samples (red circles). The lower the value of slope, the flatter the terrain; the higher the slope value, the steeper the terrain. Apparently straight lines are artefacts from ship tracks.





**Figure A9.5. Geomorphic units across the model study area characterised depth, slope and broad-scale substratum types. Biological sample or video data was available for all geomorphs except the Abyssal Plain (Geomorph 8) and the small Seamounts southeast of Shell Bank (Geomorph 9).**

### Observations of biota

The distribution of biomass of vulnerable taxa was highly variable throughout the region. Dominant groups in order of abundance (i.e. number of records) were ascidians, hydroids, demosponges, alcyonarians, actinarians, serpulids, gorgonians and bryozoans (Figures A9.3 and A9.4).

Echinoderms classified as vulnerable taxa in the region were the pencil urchin, *Ctenocidaris nutrix*, and the ophiuroids in the order Euryalida, which includes the snake stars and basket stars. *C. nutrix* was common on the banks and Western Plateau, whereas euryalids were more common at Western Plateau, deeper Southern Slope sites and Northeast Plateau.

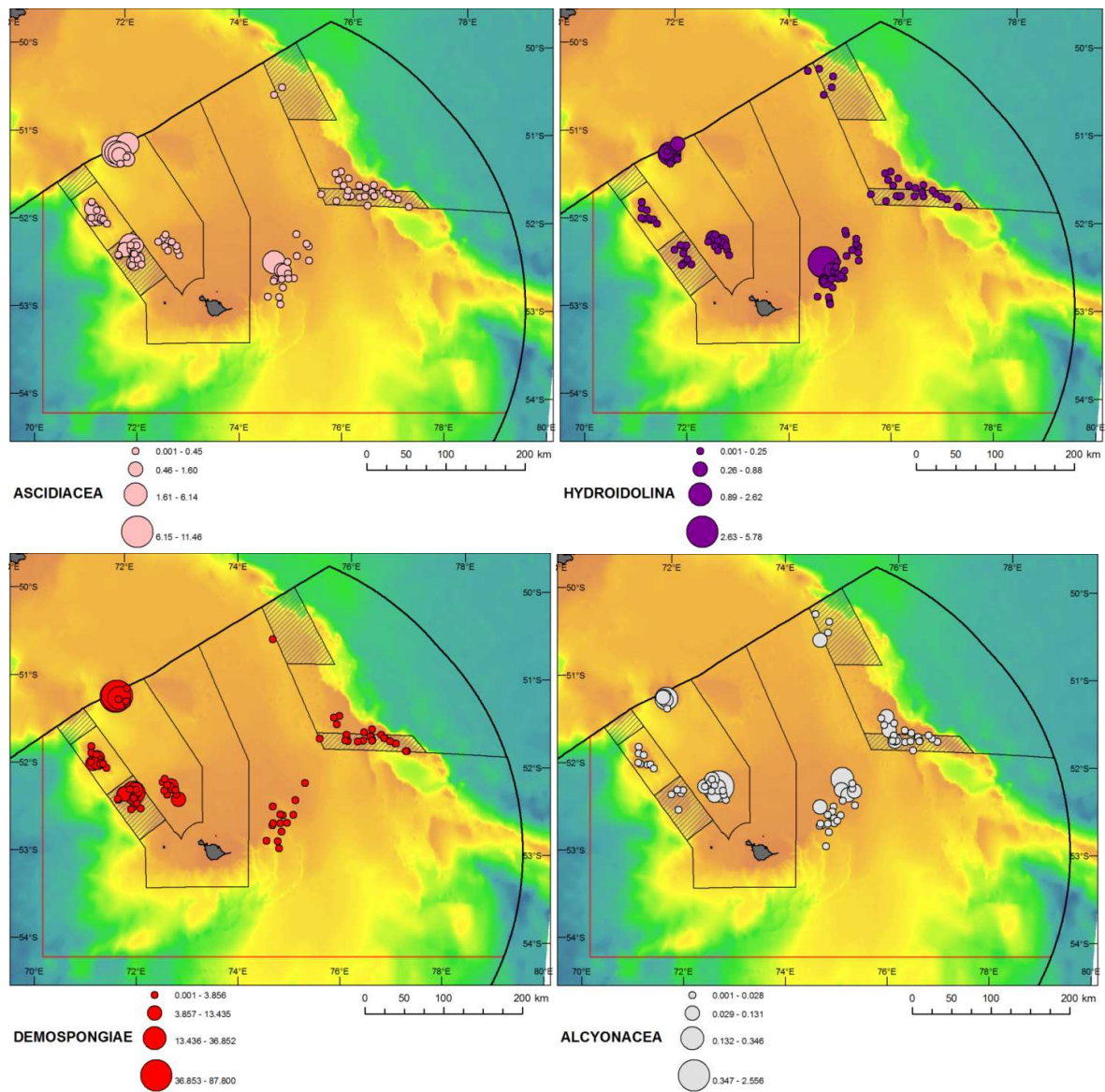
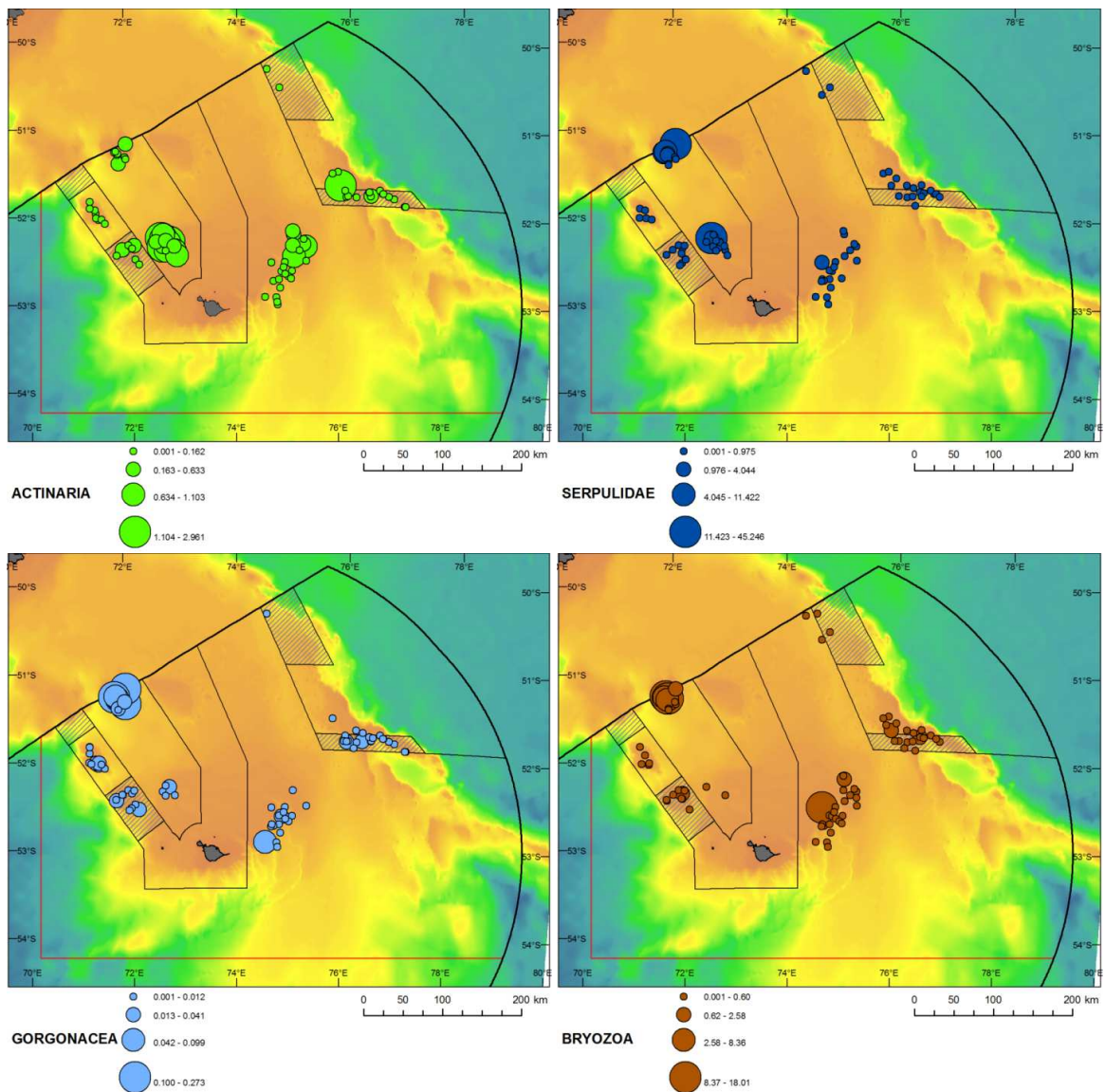


Figure A9.3. Observed distribution and biomass ( $\text{g.m}^{-2}$ ) of common benthic taxa (i.e. present in > 60 % of biological samples) across the HIMI region. Top left: Ascidiacea (sea squirts), top right: Hydroidolina (hydroids), bottom left: Demospongiae (bath sponges), bottom right: Alcyonacea (soft corals). Also shown are the Marine Reserve (light black boundary with no fill), Conservation Zone (light black boundary with grey stripe fill), Australian EEZ (heavy black line) and the extent of the region modelled (heavy red line), superimposed on the kerg\_dem bathymetry.



**Figure A9.4.** Observed distribution and biomass ( $\text{g.m}^{-2}$ ) of common benthic taxa (i.e. present in > 60 % of biological samples) across the HIMI region. Top left: Actinaria (anemones), top right: Serpulidae (tube worms), bottom left: Gorgonacea (gorgonian corals), bottom right: Bryozoa (lace coral). Also shown are the Marine Reserve (light black boundary with no fill), Conservation Zone (light black boundary with grey stripe fill), Australian EEZ (heavy black line) and the extent of the region modelled (heavy red line), superimposed on the kerg\_dem bathymetry.

Biomass was greatest on the western and northern banks shallower than 300 - 400 m for most taxa, especially Pike Bank, and especially for demosponges. High biomasses of ascidians, hydroids, gorgonians and bryozoans were also found at shallow Southern Slope sites on the south-eastern quadrant of the central plateau geomorphic unit. Bryozoans were also typical of shallow Shell Bank sites. Serpulids were notably common on Pike Bank, but were also present throughout Western Plateau. Alcyonarians, scleractinians, and in particular actinarians were the only groups that were less common on the banks, and were observed in greater biomass throughout

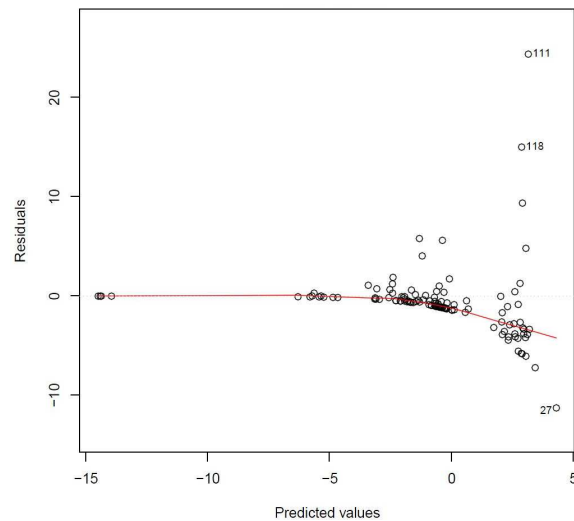
Western Plateau, Gunnari Ridge and the westward facing slope of Shell Bank. Those less dominant, attached taxa like the cirripedes and pterobranchs exhibited a similar trend, with biomass typically greater on the shallow banks and slopes then decreasing in biomass, and increasing in patchiness, with depth.

Very little benthic biota was observed in BICs footage. Out of the 48 samples taken at HIMI, a number of stalked crinoids were seen on a haul in 1310 m depth growing in a silty substratum to the north of Coral Bank, and a single pennatulacean (sea pen) in a haul at 1850 m depth growing in a silty substratum to the east of the McDonald Islands.

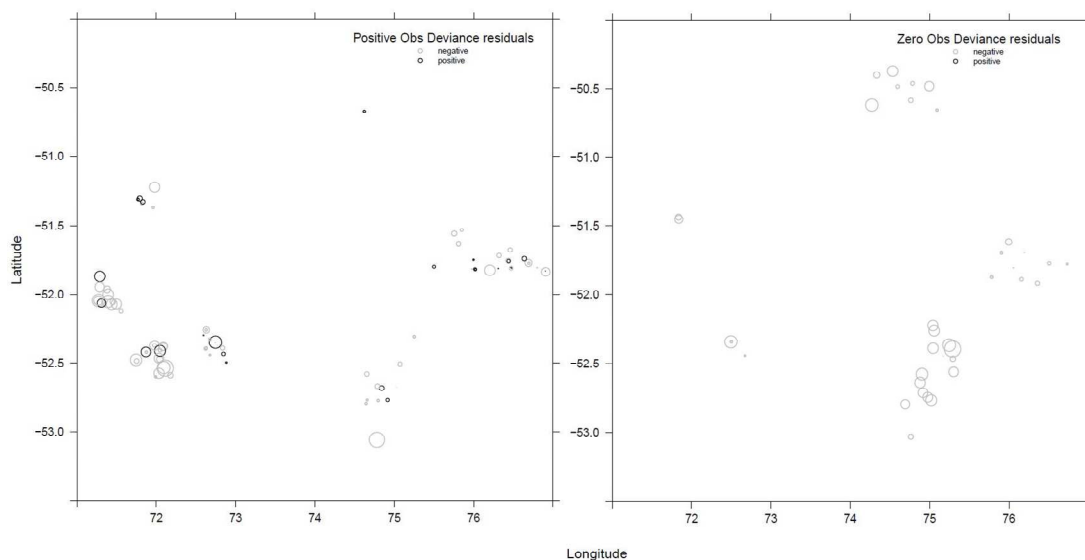
### **Model properties**

By comparing nonlinear smooth terms in continuous variables in the GAM with linear versions, it was determined that a GLM (McCullagh & Nelder 1989) performed as well as a GAM, and hence a GLM was used for all models. The model was consistently informative across most species groups, and involved a simple linear term in  $\log(\text{Depth})$  combined with 7 categories of geomorphology. Models including slope and curvature did not significantly improve model fit across all species and so was omitted from predictive models.

Due to the apparently patchy distribution of many taxa across the seascape, density data included many zeros, and it was evident that the GLM tended to overestimate density in locations where observed abundance was zero (e.g. Figure A9.5). Modelling errors using the Tweedie distribution, which is recommended in instances of zero inflated data (Candy 2004) did not substantially improve the properties of the model over a quasi-Poisson error model. However as there was no apparent spatial pattern in these negative residuals (e.g. Figure A9.6), it was concluded that the model was not introducing significant spatial bias at the scale of sampling locations into predictions based on this model. Consequently the GLM was used to predict the distribution of biomass of vulnerable taxa across the seascape at HIMI shown in Figure A9.1.



**Figure A9.3.** Plot of residuals against predicted values of biomass for the GLM of Demosponge density  $\sim \log(\text{Depth}) + \text{geomorph}$ , with an offset term of  $\log(\text{swept area})$  and quasi-Poisson error distribution. The red line is a LOESS regression, indicating a tendency for the GLM to predict higher values on average than observed.



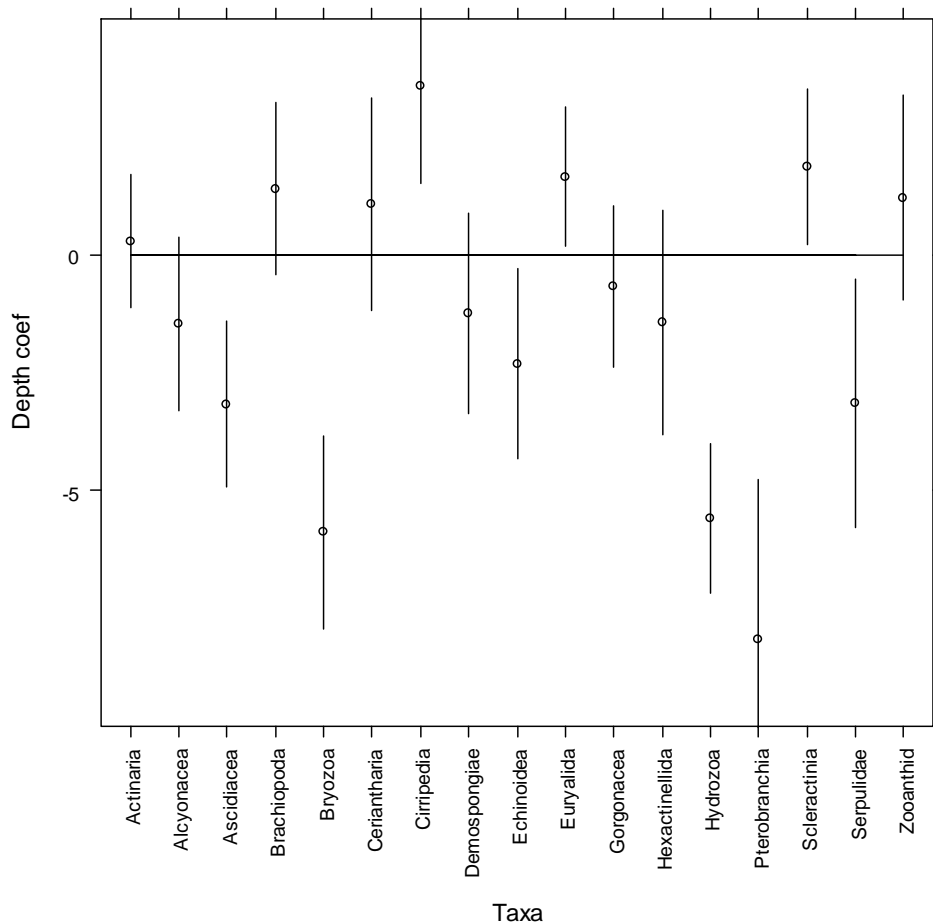
**Figure A9.3.** Plots of the spatial distribution of residuals against non-zero observation (left panel) and zero observations of biomass for the GLM of Demosponge density  $\sim \log(\text{Depth}) + \text{geomorph}$ , with an offset term of  $\log(\text{swept area})$  and quasi-Poisson error distribution. Higher proportions of negative (grey) values indicate a tendency for the GLM to predict higher values than observed.

### Relationship between vulnerable taxa and physical parameters

The GAMs developed indicated the variation in biomass of vulnerable taxa was best explained by a combination of water depth and geomorphology. GAMs that included fitted smoothing splines on slope variables did not show any significant improvement in fit. The relationship with depth was taxon specific (Figure A9.6). Negative coefficients were observed for ascidians, bryozoans, hydroids (Order Hydroidolina),

serpulids, pterobranchs and the pencil urchin, *Ctenocidaris nutrix*; indicating the declining biomasses of these taxa with increasing depth. Positive coefficients were observed for scleractinians, cirripedes and euryalids (basket stars and snakes stars), indicating higher biomasses of these taxa with increasing depth.

The relationship between the biota and geomorphic features was tested for geomorph types 1 – 7; no beam trawl or video data was available below 2500 m (Abyssal Plain) or for those small seamounts southeast of Shell Bank. There was a strong correlation between biota and geomorphs 1 (Bank Top) and 3 (Central Plateau), both supporting greater biomasses of vulnerable taxa than the remaining geomorphs sampled (Figure A9.7). The biomass of cirripedes was positively correlated with Bank Slope and hydroids with Southern Slope. Apart from these two groups, a weak correlation was observed between biota and geomorphs below 500 ( $\pm 50$ ) m (types 4 – 7) suggesting patchy distributions of these biota below such depths throughout HIMI.



**Figure A9.6. Relationship between the coefficients of depth by taxa group estimated by the GLM ( $\pm 2 \times$  SE). A positive coefficient denotes an increase in biomass with depth and the converse for the negative. Where error bars intersect the zero line no statistically significant relationship with depth was detected.**

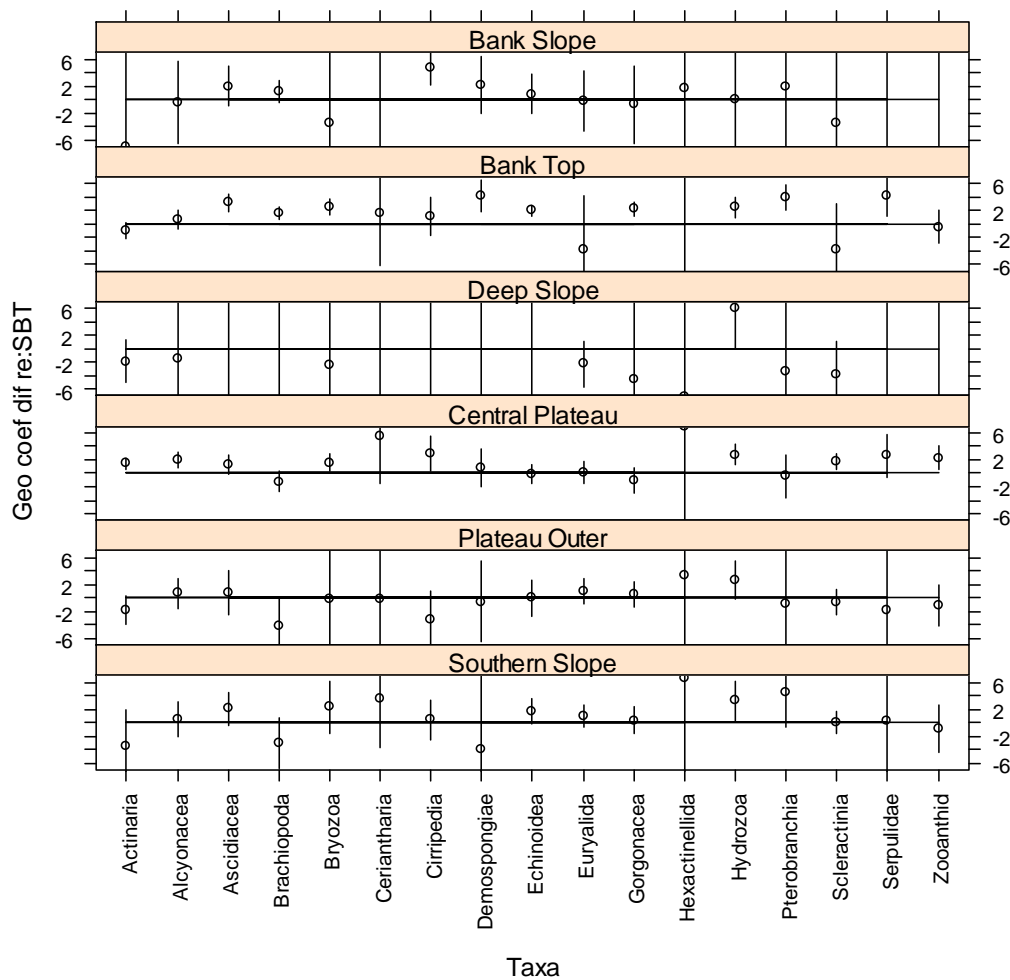


Figure A9.7. Relationship between the coefficient of geomorphology by taxa group estimated by the GLM ( $\pm 2 \times SE$ ) using Shell Bank top (SBT; geomorphic group 2) as a reference class. A positive (negative) coefficient denotes a higher (lower) biomass by geomorphic group relative to the reference class. Where error bars intersect the zero line no statistically significant difference between geomorph and the reference class was detected.

### Predicted biomass of VME forming organisms across HIMI

Predictions of biomass across the model study area were estimated by the GLM on the joint coefficient of depth and geomorphology for each 9 km<sup>2</sup> cell for those well predicted vulnerable taxa (Table A9.2). Groups that were poorly predicted, i.e. their relationship with geomorphology and depth coefficients were not significantly different from zero, namely brachiopods, ceriantherians, hexactinellids and zooanthids, were excluded from the predictive GLM framework.

**Table A9.2: Mean and lower bound of the 95% confidence interval of predicted biomass ( $\text{g.m}^{-2}$ ) for reliably predicted vulnerable taxa across HIMI, between 150m-1200m depth. Values were derived from the GLM on the joint coefficients of depth and geomorphology for those 13 groups significantly correlated with these correlates. SD= standard deviation; 95%ile range = range of values between the 2.5 and 97.5 percentiles for the predicted values.**

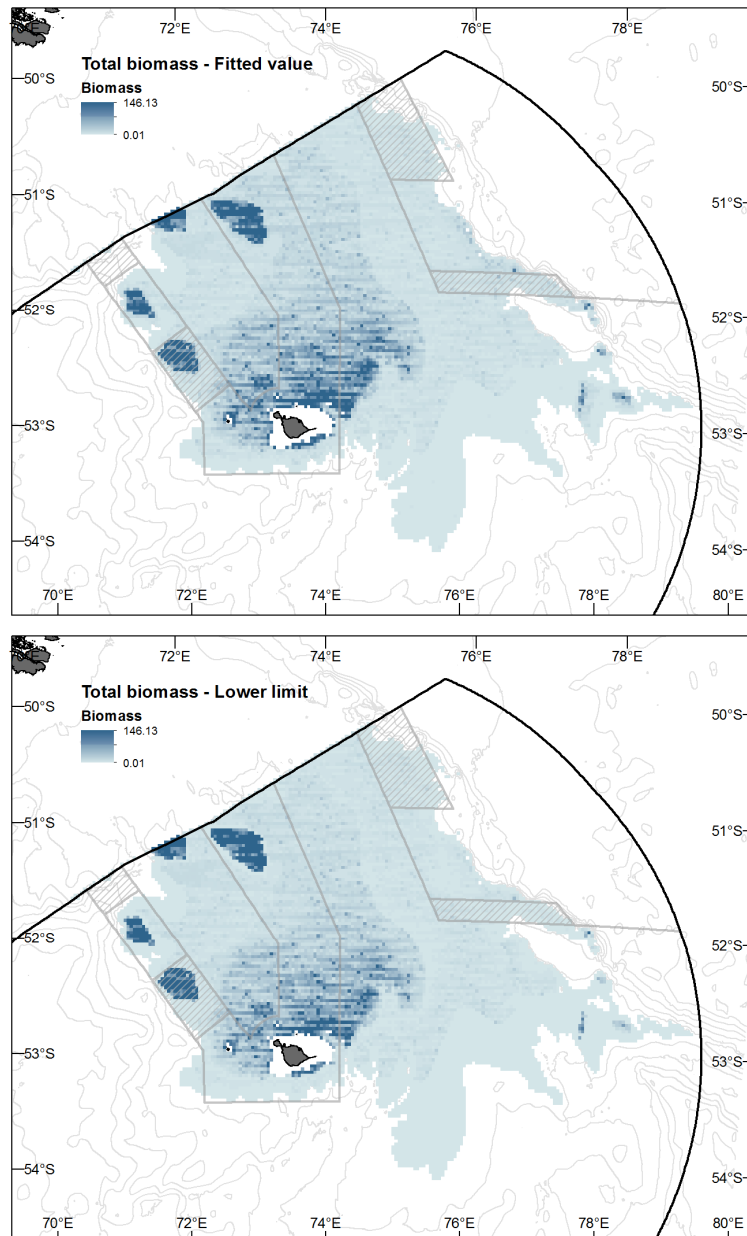
PHYLUM	GROUP	Mean		Lower Bound	
		Prediction (SD)	95%ile range	Prediction (SD)	95%ile range
PORIFERA	Demospongiae	1.08 (4.08)	0-11.81	0.54 (3.28)	0-6.79
CNIDARIA	Actiniaria	0.40 (0.63)	0-1.98	0.22 (0.39)	0-1.23
	Alcyonacea	0.06 (0.10)	0-0.35	0.03 (0.05)	0-0.18
	Gorgonacea	0.01 (0.01)	0-0.04	0.00 (0.01)	0-0.02
	Scleractinia	0.02 (0.03)	0-0.11	0.01 (0.02)	0-0.06
	Hydrozoa (Hydroidolina)	0.32 (1.19)	0-3.06	0.18 (0.65)	0-1.87
ANNELIDA	Serpulidae	0.78 (2.06)	0-6.63	0.30 (0.99)	0-2.51
BRYOZOA	Bryozoans	0.89 (3.28)	0-8.37	0.43 (1.47)	0-4.21
ARTHROPODA	Cirripedia	1.61 (11.77)	0-10.92	0.28 (1.28)	0-3.01
ECHINODERMATA	<i>Ctenocidaris nutrix</i>	0.05 (0.11)	0-0.32	0.02 (0.07)	0-0.14
	Euryalida	0.36 (0.49)	0-1.71	0.19 (0.32)	0-1.09
HEMICHORDATA	Pterobranchia	0.02 (0.29)	0-0.12	0.01 (0.04)	0-0.12
CHORDATA	Ascidiacea	0.26 (0.72)	0-2.17	0.13 (0.47)	0-1.06

The predicted distribution of biomass of vulnerable taxa across the HIMI seascape was highly variable on a cell-by-cell basis (Figure A9.8). The greatest biomass and concentration of biota were predicted above 300 m on bank tops and on the shallow central plateau, increasing in extent towards Heard Island. The biomass of most groups thereafter decreased from the periphery of the central plateau geomorph to the abyssal plain, reducing in biomass and increasing in patchiness below 500 m. The lower bound of the 95% confidence interval (i.e. where the model estimated a greater than 95% probability that biomass of a taxon in any pixel was above the value shown), shows consistent distribution patterns. For example, overall biomass was still predicted to be highest on bank tops and the shallow central plateau (Figure A9.8).

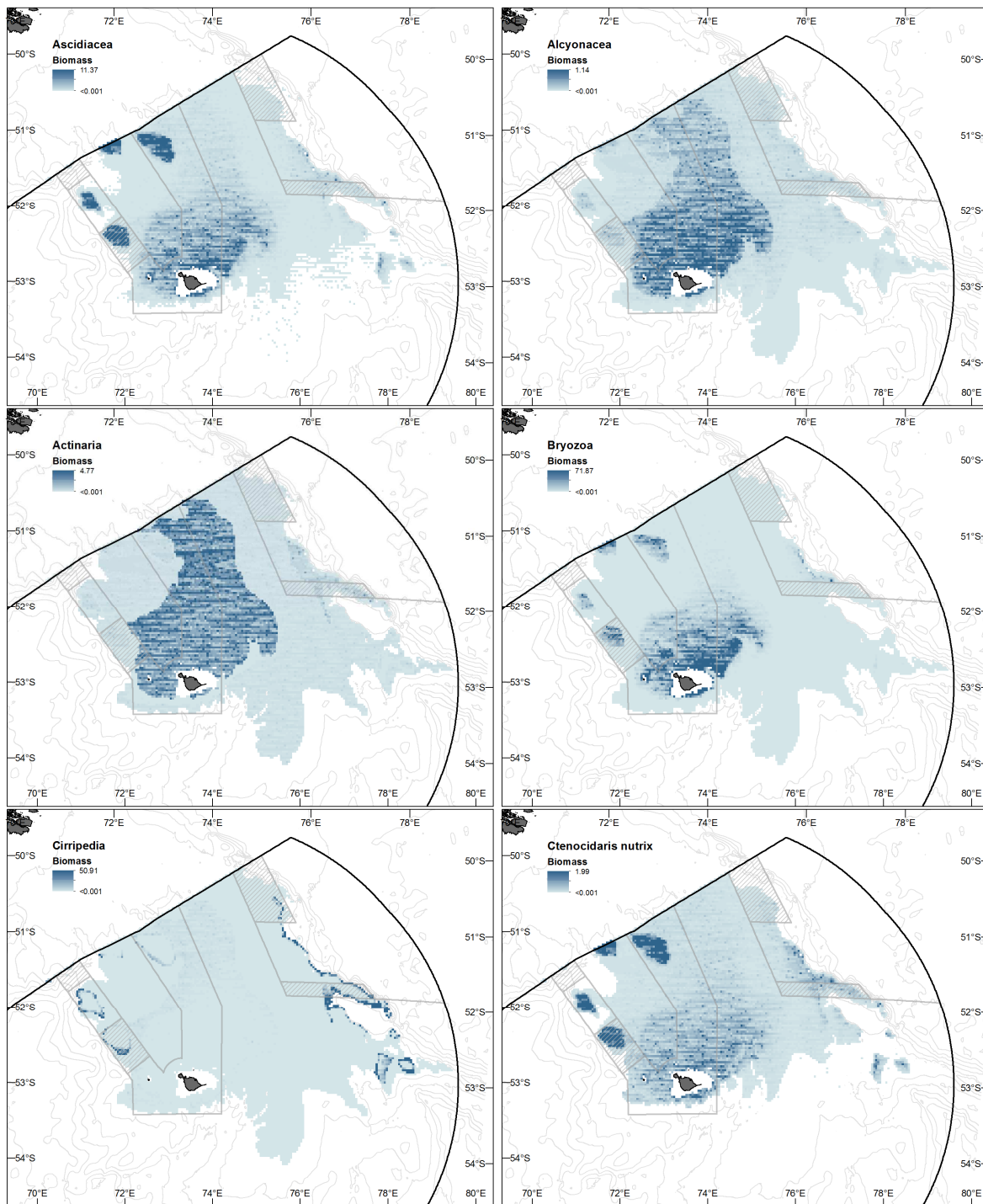
The ascidians were predicted to be concentrated on the bank tops and on the bank slopes and shallows of the central plateau, particularly toward the top of the Southern Slope (Figure A9.9). The predicted biomass of alcyonarians and actinarians was greatest throughout the central plateau geomorphic unit, with low to very low biomasses across the banks and from the central plateau to greater depths. The distribution of bryozoans and serpulids was also predicted to be highest on the bank tops and shallow central plateau nearest Heard Island, possibly due to deposits of cobble and boulder throughout these geomorphs. Uniquely, cirripedes were predicted to be relatively narrowly distributed along the bank slopes, particularly on the deeper margins of the western Banks and Shell Bank. The predicted distribution of demosponge biomass was markedly higher on the bank tops (i.e. Coral, Aurora, Pike and Discovery Banks) and the shallow slopes above 300 m, with lower biomasses widespread throughout the central plateau and on the top of Shell Bank. Gorgonian biomass was predicted to be concentrated on the bank tops, but was also predicted at lower biomass across the central plateau and plateau outer geomorphic units. Highest hydroid biomass was predicted for the shallow central plateau, increasing closer to



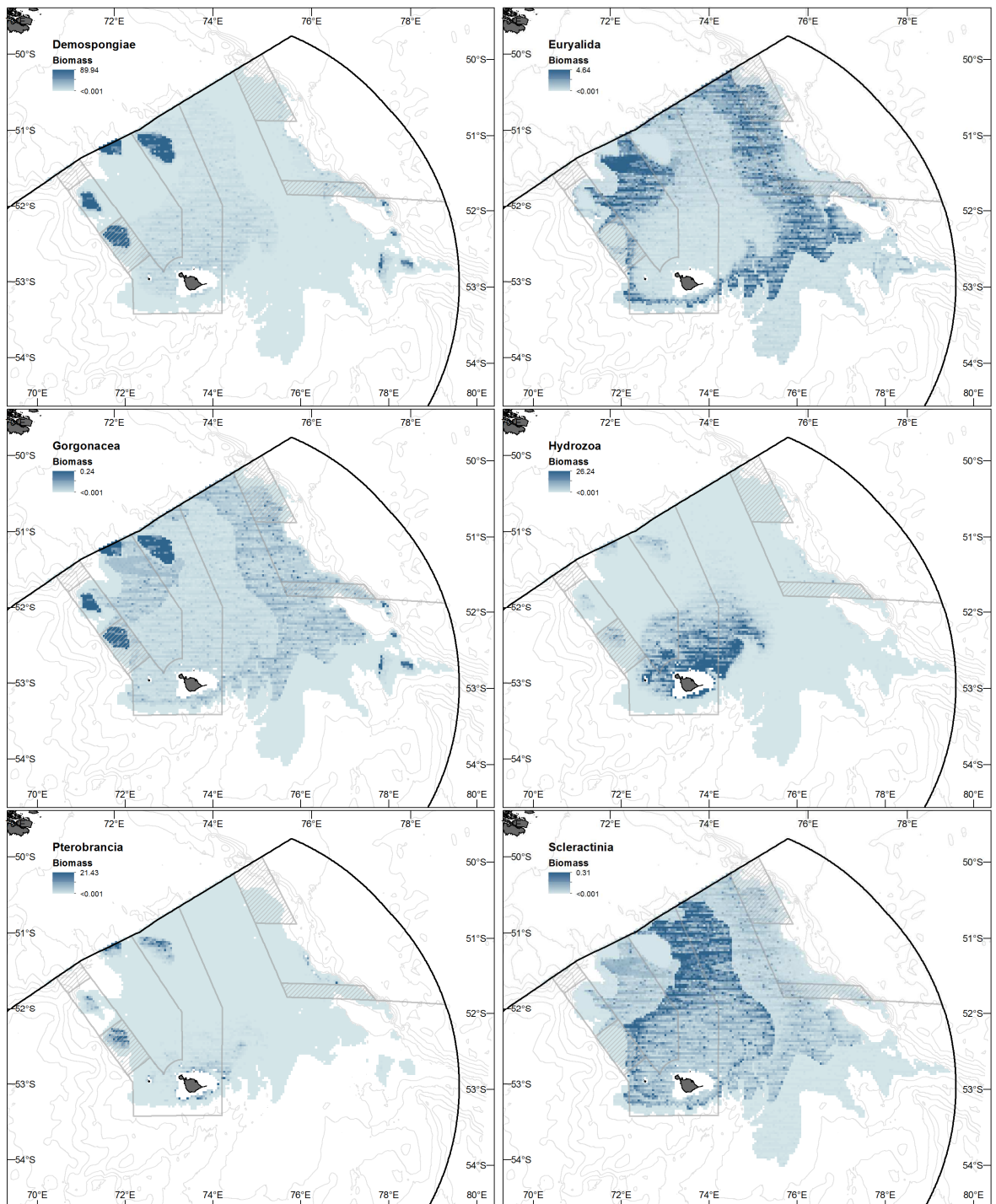
Heard Island, but was also predicted to be present on the bank tops. The predicted biomass of *Ctenocidaris nutrix* was greatest on the western banks, the shallows of central plateau and Shell Bank, and euryalids (snake stars and basket stars) were predicted to be more common at depths > 500 m. Of those groups predicted, the pterobranchs and scleractinians were the least common. The predicted biomass of pterobranchs was highest on the banks and above 200 m surrounding Heard Island and the highest biomass of scleractinians was predicted across the central plateau geomorph.



**Figure A9.8. Predicted distribution of biomass ( $\text{g}\cdot\text{m}^{-3}$ ) of vulnerable taxa across the HIMI seascape. Biomass is displayed as the mean fitted value (upper panel) and lower bound (i.e. 95% of cells are predicted to have biomass above these values). These values were predicted on the joint coefficients of depth and geomorphology.**



**Figure A9.9. Predicted distribution of biomass (g.m<sup>-2</sup>) of abundant vulnerable taxonomic groups that were well predicted across the HIMI seascape. Biomass is displayed as the predicted value (mean) calculated from the GLM for each 3 × 3 km pixel.**



**Figure A9.9 (continued).** Predicted distribution of biomass (g.m<sup>-2</sup>) of abundant vulnerable taxonomic groups that were well predicted across the HIMI seascape. Biomass is displayed as the predicted value (mean) calculated from the GLM for each 3 × 3 km pixel.

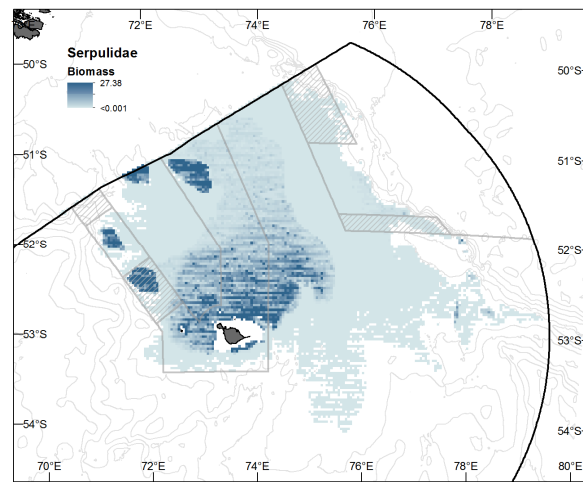


Figure A9.9 (continued). Predicted distribution of biomass ( $\text{g.m}^{-2}$ ) of the most abundant vulnerable taxonomic groups that were well predicted across the HIMI seascape. Biomass is displayed as the predicted value (mean) calculated from the GLM for each  $3 \times 3$  km pixel.

## Discussion

### Biological and physical associations

This study has demonstrated that there are sufficiently consistent relationships between the distribution of biomass and physical parameters across a range of vulnerable taxa that may be used to predict where biota are likely to occur across the HIMI seascape. Depth was the most important environmental gradient for determining the distribution of benthic fauna and the structure of the seabed. Community changes with depth concerned not only the distribution of vulnerable taxa, but also the composition and biomass of these fauna. Typically biomass was greatest above 300 m on the bank tops (where predicted sponge, gorgonian, ascidian, serpulid and pencil urchin biomass was highest) and the shallow central plateau (where predicted hydrozoan, bryozoan, alcyonacean and actiniarian biomass was highest), decreasing as depth increases. The influence of depth, and other environmental parameters associated with depth, on the distribution and composition of vulnerable taxa are likely to be complex. Depth-related changes in parameters like temperature, pressure, salinity and oxygen concentration have all been ascribed a direct influence over the distribution and composition of benthic communities (Branch *et al.* 1993, Gutt 2000, Jones *et al.* 2007a, Linse *et al.* 2007). Evaluating the influence of these parameters was not possible for the HIMI region in this study and depth served as a surrogate for the combined influence of these parameters on the distribution of key vulnerable biota.

There was a strong correlation between the distribution of biota and geomorphology. High biomasses of sessile, suspension feeding vulnerable taxa, like demosponges and gorgonians, were associated with the tops of Aurora, Coral and Pike Banks, and the shallow slopes south of HIMI. Seabed features which offer greater topographic

complexity, like banks and craggy slopes, have been shown to harbour populate and diverse communities of sessile organisms and are important habitats for fish and other biota (De Leo *et al.* 2010, Koslow *et al.* 2001, O'Hara 2007, Ramirez-Llodra *et al.* 2010, Rowden *et al.* 2004). These associations are frequently explained by the influence of topography on currents. Seabed features like seamounts and the upstream sides of banks and plateaus often act as barriers to major currents, resulting in localised upwelling (Koslow & Gowlett-Holmes 1998) and favourable feeding conditions for suspension feeding organisms (Starmans *et al.* 1999). The Kerguelen Plateau is a major barrier to the eastward flow of the Antarctic Circumpolar Current (ACC) and is in close proximity to, and south of, the Polar Front. In the Heard Island region, most water is thought to move in an easterly direction across the plateau to the north and south of the island, with a passage of water moving in a north-westerly direction up through the trough between the central plateau and west of Shell Bank (van Wijk *et al.* 2010). South of Heard Island, surface water currents move in a north easterly direction, whereas water currents at about 800 m move in a north westerly direction up the slope to Heard Island. Water is also thought to eddy around the east of Shell Bank in an anticlockwise direction forming productive waters in the region (van Wijk *et al.* 2010). The passage of the ACC throughout the western banks and across the slopes south of HIMI is likely to form productive conditions, which may at least partially explain the distribution of suspension feeding vulnerable taxa in these regions. Data layers incorporating current information are currently being developed to refine predictive models for the region (Hibberd, unpublished)

Although data on the seafloor characteristics at HIMI are sparse, it is likely that the variety of substrates and physical habitats provided across the variety of features in the region contribute to the high biomass observed and predicted around the banks and slopes of the region. The roughness and complexity of the seafloor has been recognised as an important influence on habitat type and biodiversity (Greene *et al.* 2007). Rugose benthic habitats (i.e. high relief) offer refuge and settlement surfaces not available on flat bottoms (McArthur *et al.* 2009). Thus, one would expect higher biodiversity where the elevation of the seabed changes at fine spatial scales, like on the upstream sides of banks or plateaus, or on sedimentary bedforms littered with cobble or rock. Seafloor topographic complexity at fine spatial scales is also ecologically important as it alters boundary-layer flow over the seabed which in turn affects larval settlement, controls delivery of food to sessile suspension feeders (Lenihan *et al.* 1995), and influences erosion, transport and deposition of sediments (Widdows *et al.* 1998). The substrate from the central plateau to the abyssal plains appears to consist primarily of sand and silt (Meyer *et al.* 2000, ODP 1998), providing favourable conditions for sediment-dwelling infauna, but less so for sessile benthic megafauna who require hard substrata for attachment. Cobble and boulder was an important feature of the substratum on the bank tops to the west, and on the slopes south of HIMI and nearer to the island, offering favourable conditions for attached fauna, which include the majority of

vulnerable taxa assessed. Habitats may therefore be differentiated at a broad level based on our knowledge of these substrates and the life history modes of these vulnerable biota which are discussed further in Appendix 12.

In this study, geomorphology provided a useful predictor for the combined influence of depth, seafloor topography and substrate where data at fine spatial resolutions were unavailable. A source of uncertainty in the predictions in this study arises when using a categorical descriptor like geomorphology, as these categories force boundaries in subsequent predictions; when in reality, changes in the physical gradients and faunal distributions may be gradual in many instances (such as for geomorphic types 6, 7 and 8 which were primarily distinguished by depth bands). Hence, the apparent abrupt discontinuities in predicted biomass are an artefact of the variables available. However, for boundaries such as those between the flat tops of banks and their steeper sides, we consider that large changes in taxa abundance and distribution at relatively small spatial scales are not unrealistic.

### **Predictions across the HIMI seascape**

Based on the assumption that the biomass of vulnerable taxa will be similar in areas where physical properties are also similar, we have extrapolated the distribution of vulnerable taxa across the seascape at HIMI. Given the relatively high intensity of sampling in the geomorphic types including the banks and shallow plateau, we have higher confidence in the predictions of benthic invertebrate biomass in these areas, and it is these areas that apparently support the highest biomass and diversity of taxa. Relatively high biomasses of demosponges, gorgonians, bryozoans and hydroids were revealed across the tops of the western and northern banks and shallower than 300 m around Heard Island. Such benthic megafaunal invertebrates add 3-dimensional structure and complexity to their surroundings and have recently been considered as proxies for biodiversity, offering biogenic habitat for fish and other invertebrates (Callaway 2006, Nakamura & Sano 2005). For example, Antarctic sponge assemblages have been shown to support rich communities of colonizing epibionts and other motile invertebrates, providing biogenic structure and a source of nutrients to prospective predators, like spongivorous sea stars (McClintock *et al.* 2005). This high biomass of vulnerable habitat-forming organisms is likely to be important in supporting the abundance of motile benthic invertebrates observed in Appendix 6.

The deeper areas of the plateau are less well sampled, however they seem to support lower biomasses overall, and with the exception of euryalids and cirripedes no taxa are predicted to be encountered in their higher abundance on the deeper slopes and plateau. Video observations below 1000 m also indicate that longlining occurs on expanses of relatively bare, homogenous substrata of mud and sand, with few instances of epifauna with the exception of single individual stalked crinoids and pennatulaceans. However, these observations do not preclude the existence of locations where important aggregations of deep-sea taxa are present but were not

observed and, therefore, were unable to be predicted using the modelling framework developed here. However, as the framework developed can readily assimilate new observations, targeted sampling of deeper geomorphs, such as the seamounts to the southeast of Shell Bank, would improve the robustness of the conclusions of this study. Bycatch data is also likely to become more useful as observers now have access to field guides which have been shown to dramatically improve the identification of invertebrates (Hibberd 2009, Hibberd & Moore 2009, SC-CAMLR 2009).

### **Conclusions**

This framework provides a valuable tool for estimating plausible biomass values of vulnerable taxa over broad areas where fisheries occurred, but limited quantitative samples are available. This information is timely given the immediacy of the issue of managing bottom fishing to prevent significant adverse interactions with VMEs and the practical difficulties associated with obtaining empirical data from the Southern Ocean. There is a degree of uncertainty associated with estimating biomass in regions where biological and physical data are not available, like on the bank tops southeast of Shell Bank, Discovery Bank (east of Pike Bank) and below 1000 m. The high patchiness of biota also results in zero-inflated datasets, which tend to under-estimate zeroes as in this study (Gray 2005). Further studies incorporating other environmental datasets are likely to improve the predictive specificity of the model. Further ground truthing of model predictions through additional targeting sampling of the seabed (i.e. sediments) and biota, as well as in locations not well sampled, and through the analysis of fishery bycatch data is also likely to improve the power of the model to identify the most important locations for vulnerable benthos in the region.

## Appendix 10      Estimating the gear footprint of demersal trawl and longline fishing gears used in the Heard Island and McDonald Islands fisheries

Graeme Ewing and Robbie Kilpatrick

### ABSTRACT

Any fishing gear that has contact with the seafloor will interact with the benthic habitat where it is deployed. Benthic habitats may be exposed to a number of types of interactions, each with particular swept areas, due to differences in the components in contact with the seafloor within a single gear, or among gears in multi-gear fisheries. To allow comparison of these interactions and estimates of the total disturbance to the benthos from their effects, the demersal gears used in the Heard Island and McDonald Islands fishery have been disaggregated to estimate the swept area of each of their components separately. *In situ* video footage and theoretical analyses have been used to estimate swept area, and the 'gear footprint' where the footprint of a fishing gear is considered to be the sum of the swept areas of its components, with consideration of overlapping swept areas within gears. Demersal trawl gear is considered to exert two types of interactions with the benthos, with non-overlapping swept areas: 1) blunt interactions with a swept area equal to the sum of the effective width of the foot line and the trawl doors (20 m), over the length of the tow, and 2) shearing interactions for the effective width of the lower bridles and warps (100 m), over the parts of the tow when they are in contact with the benthos. Demersal longline gear is considered to exert two types of interactions with the benthos, with overlapping swept areas: 1) line shearing interactions and 2) hooking interactions. The swept area of both of these interactions is strongly dependant on the manner in which lines move on the seafloor during a fishing event and analyses suggested that longlines are very likely to move across the seafloor in both longitudinal and lateral directions during their retrieval (an average of 6.2 m lateral movement).



## Introduction

Any fishing gear that has contact with the seafloor will have an effect on the benthic habitat where it is deployed. Effects on benthic habitats include physical damage to invertebrate fauna, scouring and structural damage to sediments, removal and rearranging of structural elements through grooming, and smothering of invertebrates from re-suspended sediments. Impacts will be dependent on the type of benthic habitat, the type of fishing gear, and other factors affecting the physical contact of the gear with the seafloor such as operator proficiency, sea-state, current and wind.

Mobile fishing gears that are designed to capture target species by moving across the seafloor, such as benthic dredges and demersal trawls, can cause serious impacts to the benthos, particularly in areas where natural disturbance regimes happen over longer time scales or at smaller scales than that of fishing, such as in the deep ocean (Cryer *et al.* 2002, Kaiser *et al.* 2006, Koslow *et al.* 2001, Thrush & Dayton 2002). Disturbance from such fishing is related to changes in biodiversity, productivity and biomass of the benthos, including changes in dominant species from large sessile suspension feeders to smaller opportunists and scavengers, reductions in the age and size structures of resident fauna, and increases in habitat heterogeneity (Clark & Rowden 2009, Sainsbury *et al.* 1997, Thrush & Dayton 2002). Conventional wisdom suggests that static gears (such as demersal longline, gillnet, traps) have a lower impact than mobile fishing gears (Chuenpagdee *et al.* 2003). However, the extent of this impact, particularly under conditions that promote movement of static gears across the seafloor when retrieved, has received relatively little attention from researchers (however see Auster & Langton 1999, Kilpatrick *et al.* 2011, Lokkeborg 2007, Sharp *et al.* 2009).

Assessments of the impacts of demersal gears have often been gear specific in such a way as to make comparison between gears difficult (Thrush & Dayton 2002). This is especially the case with comparing mobile and static gears. Under circumstances where static gears move across the seafloor (for example as they drift or are retrieved), they have the potential to impart greater impacts as more of the benthos is encountered and due to their large size (i.e. longlines can be 10s of km long). Therefore, such a comparison becomes particularly relevant for impact evaluation when mobile and static gears are used to target the same stocks and there is a potential for an overlap across methods.

The Heard Island and McDonald Islands (HIMI) fishery is comprised of demersal fishing (trawl, longline and experimental trapping) targeting Patagonian toothfish (*Dissostichus eleginoides*) and demersal and pelagic trawling for mackerel icefish (*Champscephalus gunnari*). The fishery has been in operation since 1997 when exploratory trawl fishing commenced. Demersal longlining was introduced in 2003, and there are a number of proposals by Australian fishers to further develop their

distant water fishing capability with longlines in the Australian EEZ near the Antarctic Continent.

Assessment of the impact of demersal fishing operations in the HIMI region requires an estimate of the area of the seafloor that encounters fishing activity (i.e. the “footprint” of the fishery). The area affected by any single fishing event (i.e. the gear footprint) of mobile fishing gear such as demersal trawling is the swept area of the gear itself (that is, the area of seafloor with which the gear is in direct contact), and an additional area indirectly impacted by the gear; such as adjacent bottom impacted by smothering from re-suspended sediments. An estimate of the gear footprint of static fishing gear is more problematic because much less empirical data is available, and as they long and flexible have the potential to be more variable. Ideally, such gear is stationary on the seafloor throughout a fishing event, so the footprint is limited to the area of the gear itself. However, there is evidence that demersal longlines set in the HIMI region and on the Antarctic continental shelf move across the seafloor under certain conditions, particularly during retrieval (United Kingdom 2010, Welsford & Kilpatrick 2008).

The aims of this analysis are to develop a system for estimating the fishing footprint of each component of the static and mobile gears used in the HIMI region. It will also examine the likelihood and implications of cumulative impacts from overlapping fishing events.

## **Methods, Results & Discussion**

### **A framework for estimating the swept areas of the components of demersal fishing gears**

Each component of a demersal fishing gear that has contact with the seafloor has the potential for impact, but impacts are likely to vary between these components on the basis of their relative swept areas, structures and behaviours. A system of three dominant interaction types is proposed to allow the swept area from each component of these gears to be assessed separately. This system has the advantage that different gear types, and their components, can be compared more directly and the outcomes for key invertebrates that result from an interaction be assessed separately against each component of each gear type.

The three types of interactions by fishing gear on the benthos considered in this analysis are;

- Blunt interactions as applied by a broad object in motion across, through, or onto the benthos and may include a scouring component
- Line shear interactions as applied by a narrow object in motion across, through, or onto the benthos

- Hooking interactions as applied by fish hooks in contact with the benthos

Smothering of invertebrates from re-settlement of fine sediments disturbed by deployment of demersal fishing gears is discussed by other authors (Jones *et al.* 2007b). However, given the prevalence of relatively strong currents on the seafloor in the HIMI region and the generally coarse sediments observed in footage from demersal trawl deployments, any additional disturbance caused by re-suspended sediments has not been estimated as part of the footprint.

### Estimating the fishing footprint of demersal trawl gear

The footprint of demersal trawling can be considered as the sum of the effective widths of the constituent parts of the gear in contact with the seafloor (doors, wires and sweeps, ground chains, foot line and trailing net mesh) multiplied by the distance over which it is towed (Figure A10.1).

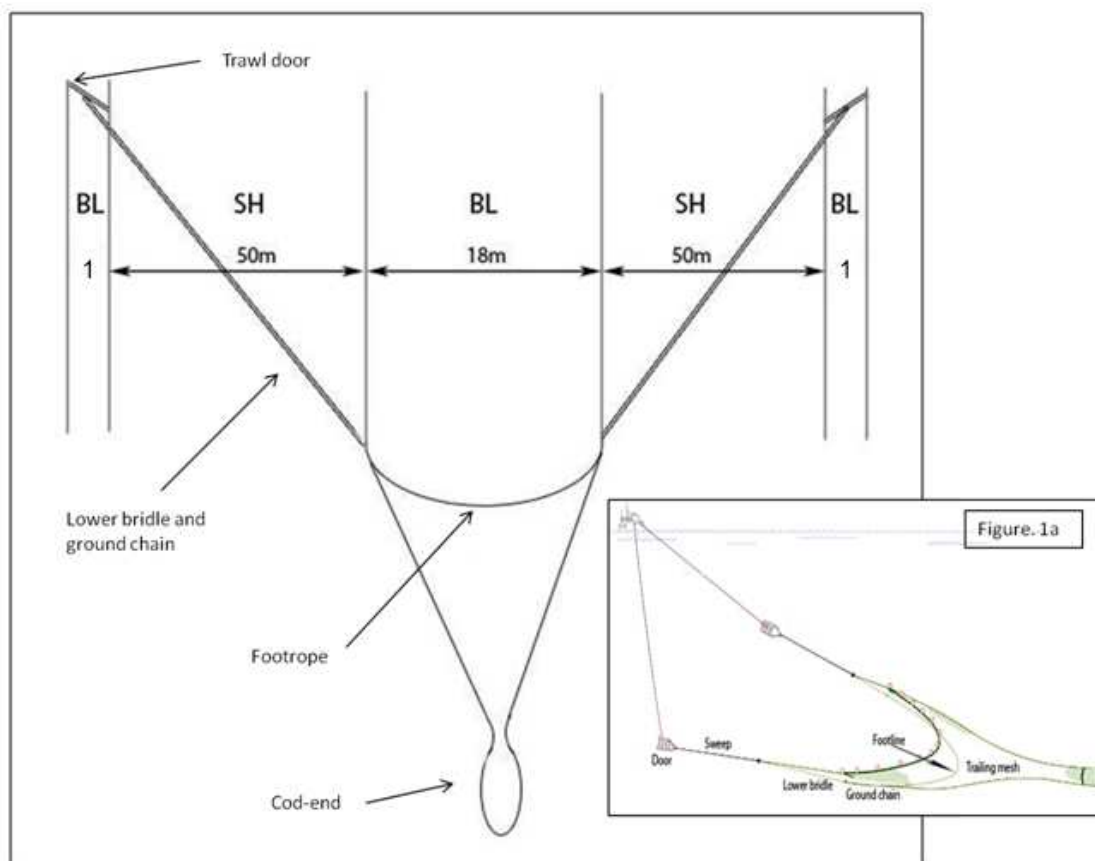


Figure A10.1. Schematic of the *Champion* demersal trawl net showing the indicative widths of the blunt (BL) and shear (SH) interaction areas exerted on the seafloor during a fishing event. Note that the dimensions of the net are not drawn to scale. Inset Figure A10.1a: Components of a demersal trawl for which benthic impact is considered.

### **Blunt interactions delivered by trawl gear to the benthos**

Blunt interactions are exerted by broad and effectively immovable components of the demersal trawl which are in direct contact with the benthos. These components are the foot line, trawl doors and mesh from the net, codend or chafe mat.

#### **Foot line**

The foot line is the component of the ground gear of a demersal trawl at the mouth of the net and is composed of bobbins, rubber discs and spacers, and ground chain. Whilst a demersal trawl does 'fly' occasionally, the intention is generally to stay in contact with the seafloor throughout a fishing event to maximise catch. Consequently, the foot line is considered to be in constant contact with the seafloor over the reported length of a tow. Figure A10.2 shows the foot line of a demersal trawl distorting under tension and ultimately lifting over a large rock. While this is the purpose of so named 'rock-hopper' ground gear, there is also evidence from footage of scouring, re-distribution of substrates and observer records reporting capture of rocks in excess of 1000 kg which indicates that the downwards pressure of the gear is commonly well beyond that required to damage invertebrate taxa, scour and overturn rocks, and redistribute sediment.

Figure A10.3 shows evidence of trawl scars which suggest that under normal conditions the blunt interaction from demersal trawling will penetrate into softer sediments. This is particularly the case with the doors which regularly penetrate into the substrate. Camera footage also shows clear evidence of a large cloud of sediment entrained into the water column which provides further evidence that the foot line exerts a significant downwards force onto the benthos and can re-distribute loose sediments (Figure A10.4).



Figure A10.2. Sequence of stills taken from footage of rock-hopper ground gear of a demersal trawl distorting under tension and ultimately lifting over a large (c. 2.5 ton) rock. The rock is completely turned over during this process.



Figure A10.3. Scour marks running parallel from top to bottom (left) and diagonally (right) most likely caused by bobbins, trawl doors or large boulders being dragged across the surface by a demersal trawl.

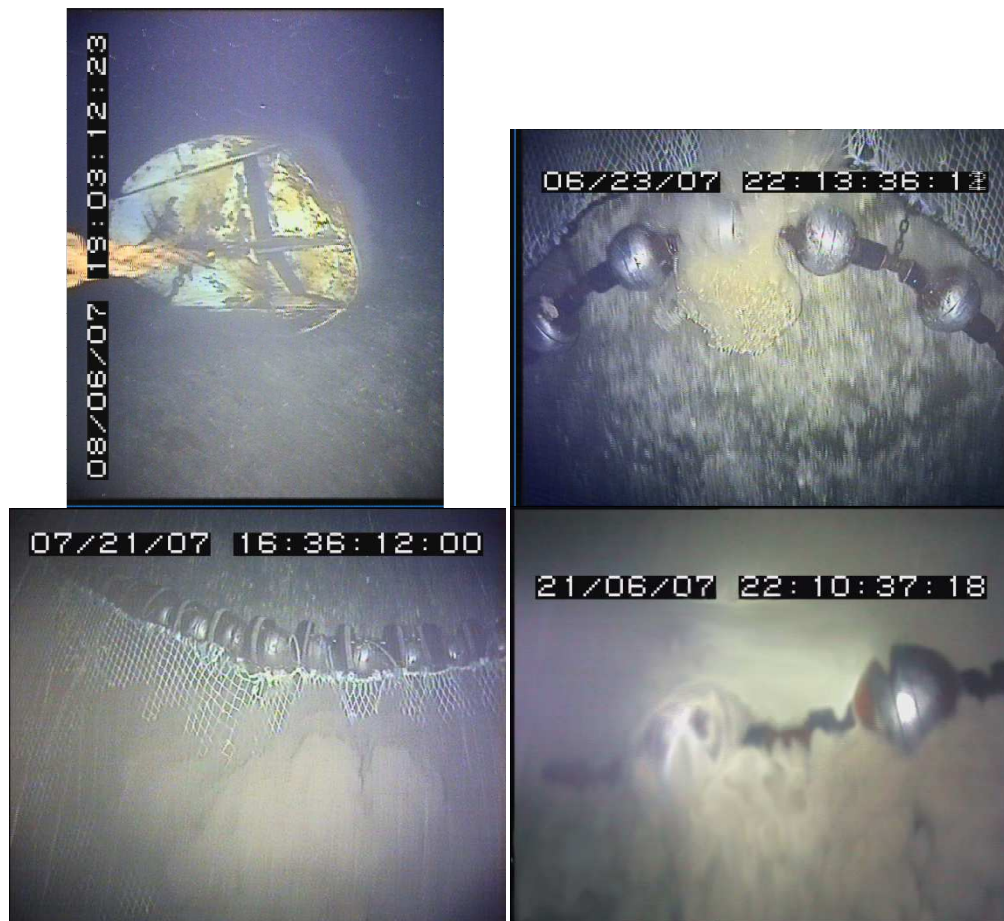


Figure A10.4. Video stills of trawl door and sweep (top left) and foot line (top right) in contact with seafloor on FV *Southern Champion* at c. 570 m (HIMI). Foot line embeds approx. 200 mm into soft sediments (bottom right). Abrasive interactions of net mesh contributing potential smothering of taxa and the redistribution of sediments and rocks (bottom left).

Individual components of the ground gear such as steel bobbins and rubber discs are mandated by AFMA to be a minimum diameter of 520 mm (for bobbins). These components are aligned side by side across the lower mouth of the net (Table A10.1). When these components move across the seafloor, under the outwards and downwards tension mentioned above, they deliver blunt forces across the seafloor. These forces are likely to crush rather than sever taxa unable to evade the net. The blunt interaction footprint was calculated on the effective width of the foot line, taking into account its arc.

### **Trawl doors**

Trawl doors are constructed of plate steel and are in routinely in contact with the seafloor as their role is to keep the mouth of the net open and near the seafloor. Consequently, they will exert blunt interactions on the benthos. The narrow width of the edge of the doors (in comparison with bobbins) enables their penetration into unconsolidated substrata (Figures A10.3 and A10.4). Scours encountered in footage of trawling in the main trawl grounds of HIMI are most likely to be trawl door marks and indicate the depth of their penetration into the substrate may be in excess of 200 mm.

### **Trailing mesh**

Evidence from footage of trawl fishing events and the use and abrasion of chafe mats suggest that it is normal for trailing mesh of the demersal trawl to be in contact with the seafloor. The forces imparted by mesh under tension will contribute to the redistribution of sediments and rocks (Figure A10.4). This was considered as contributing to the blunt interaction component of the trawl gear.

### **Line shear interactions delivered by trawl gear to the benthos**

There is the potential for line shear interactions to be exerted on the benthos by the sweeps and lower bridles of the trawl net that connect the net to the doors. These wires are 26 mm diameter (Table A10.2) and their effective rigidity is due to the tension induced by the combination of the angle of the trawl doors, the speed of tow and the net design, and will vary between shots. Whilst this tension does not render these lines completely unable to be deflected by massive objects, like the net foot line, sweeps and lower bridles are effectively rigid with respect to the benthic invertebrates resident in the HIMI region. When towed, the sweeps and bridles of a demersal trawl travel obliquely near or on the seafloor. Their angle to the direction of tow will be influenced by their length, the angle of the trawl doors, the tow speed and the net design, and will vary between shots. The line shear interaction footprint was therefore calculated on the effective width of their track on the seafloor, taking into account their angle to the direction of the tow.

The fishing footprint of a demersal trawl was therefore considered to be the sum of the effective widths of the blunt and shear components of the gear, multiplied by the

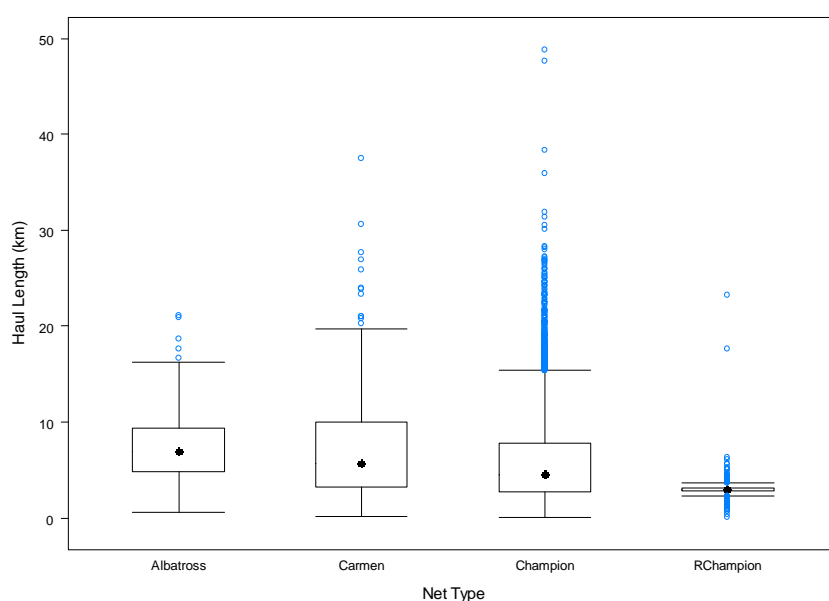
length of the trawl. Following is an example using a net commonly deployed in the HIMI fishery.

### Fishing footprint of demersal trawl nets

Three nets have been used for demersal trawling in the HIMI fishery. The characteristics of the demersal nets used is summarised in Table A10.1, and the distribution of distances between logbook haul start and finish locations in Figure A10.5.

**Table A10.1: Characteristic dimensions of the demersal trawl nets used in the HIMI region demersal fishery.**

Parameter	Net			
	Albatross	Carmen	Champion	Champion
Number of fishing events (% of total)	90 (0.5)	674 (3.9)	13 952 (81.3)	2 493 (14.5)
Fishing Mode	Commercial	Commercial	Commercial	Survey
<b>Foot line</b>				
Wing spread (m)	38	32-35	26-28	20-26
Foot line length (m)	71.4	25.7	18.1	18.1
Bobbin height (m)	0.56	0.56	0.56	0.56
Bobbin material	Steel	Steel	Steel	Steel
Foot line footprint (m)	38	28	19	19
<b>Trawl doors</b>				
Door wt (air, kg)	1900-2400	1900-2400	1900-2400	1900-2400
Door width (m)	2.8	2.8	2.8	2.8
Door footprint (m)	1	1	1	1
<b>Bridle and sweeps</b>				
Sweep length (m)	120	125-150	100	100
Bridle length (m)	25	25	25	25
Door spread (m)	120	160-165	150-155	135-160
<b>Bridle and sweeps footprint (m)</b>	<b>72</b>	<b>127</b>	<b>138</b>	<b>92</b>
	<b>122</b>	<b>157</b>	<b>157</b>	<b>101</b>



**Figure A10.5 Distribution of demersal trawl net haul distances based on logbook start and finish locations. RChampion=Champion net when used for research surveys.**



Footage has not been captured of the sweeps and lower bridles of the Champion demersal trawl net in action however as shown in the top left panel of Figure 10.1, the sweeps connect to the trawl doors above the sweeps are under pressure and are unlikely to be in contact with the seafloor along their entire length. A lack of regular polishing or wear of these components also suggest that the sweeps of Champion net they are rarely in complete contact with the seafloor. This is particularly the case during research hauls, when the *Southern Champion* lays out less warp than during shots in commercial grounds to avoid pin ups, and the doors may be up to 20 metres off the bottom. However, for the purposes of further analysis, the footprint of each trawl event in the HIMI region was estimated to be an area which is the product of the bridle and sweeps, door and footline footprints and the tow distance.

### Estimating the fishing footprint of demersal longlines

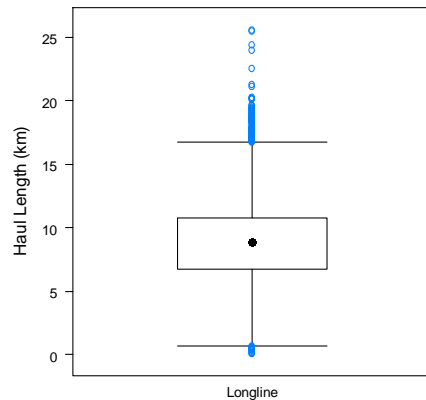
To capture toothfish, integrated weight longlines deliver baited hooks to the seafloor. Due to negative buoyancy the line is in constant contact with the seafloor between deployment and retrieval, usually around 24 to 36 hours. Due to a narrow gauge, it has the potential to deliver shearing or severing interactions to emergent taxa and hook interactions to all taxa. The extent of these interactions will vary with the length of the line, the tension on the line, and the extent that the line moves across the seafloor during the fishing event.

#### Longline length

The characteristic of integrated weight longlines (IWL) used in the toothfish fishery in the HIMI region are shown in Table A10.2. Lines are generally deployed in a series of magazines joined end to end with each magazine around 1200 m in length, with an average total distance between the start and end of lines of 9 km (Figure A10.6).

**Table A10.2. Characteristics of the integrated weight longline used in the HIMI region.**

Parameter	Dimensions
<b>Number of fishing events</b>	4424
<b>Mainline</b>	
gauge (mm)	11
wt (kg.m <sup>-1</sup> )	0.05
magazine length (m)	1200
<b>Hooks</b>	
Snood length (mm)	450
Hook frequency (m <sup>-1</sup> )	0.71
Hook gape (mm)	22



**Figure A10.6** Distribution of demersal longline set lengths based on logbook start and finish locations.

### Longline tension

Given that the breaking strain of IWL is approximately 2 tonnes, and that the snood/hook combination can support large toothfish, the fragility of the HIMI benthic invertebrate taxa is such that if an invertebrate becomes snagged by the line or hooked, the invertebrate will typically give way long before the line parts. Further, a longline under tension has a higher rigidity relative to benthic invertebrates and consequently has a higher destructive potential than an untensioned longline. Generally, the intention when deploying longlines is to keep the line under tension to minimise the likelihood of tangles and to maximise the spread of hooks available to toothfish. However footage captured by the BICS has shown that in 48% of observed longline deployments, the line was not under tension during setting and settled loosely in coils and loops on the seafloor (Figure A10.7). While this lack of tension may have been contributed to by the camera, this affect is unlikely to be substantial due to the neutral buoyancy and relatively low profile of the camera. Furthermore, the vessels often report substantial tangles in the first magazine of longlines, and therefore observing sections of untensioned line is most likely to be a product of the difficulty in maintaining tension along the entire length of several kilometres of longline as they sink to depth.



Figure A10.7. Video stills of longline settling on seafloor during 4 separate deployment events. The images at the top and the bottom left depict deployments where the line is settling onto the seafloor under low tension, and the bottom right image shows a line under tension as it reaches the seafloor.

### Longline movement across the seafloor

A stationary demersal longline will exert a minimal area of interaction with the benthos. However, movement of the line when it comes under tension has the potential to significantly increase the area over which line shear interactions may occur. Movement across the seafloor can be longitudinal (i.e. in the direction of the line), or lateral (i.e. the line moving sideways across the substrate).

### Estimating lateral line movement

Estimates of the extent of lateral line movement observed in *in situ* footage of longline deployments were derived using *Benthic Video Annotator* (AAD developed software described in Appendix 5). Measurements of the relative pixel dimensions of longline components of known length, presented on the horizontal plane, but at various apparent vertical locations within the image (Figure A10.8), were used to derive a relationship between distance and pixels for a given vertical position in a frame (Figure A10.9). This relationship assumes that the angle of the camera to the longline is approximately constant. Cameras were set at a nominal angle to the longline of  $25^\circ$  to the perpendicular prior to deployment (Figure A4.2). However, on occasion the camera angle was affected by impact on deployment or flotation problems, and footage from these shots was not used in this analysis.

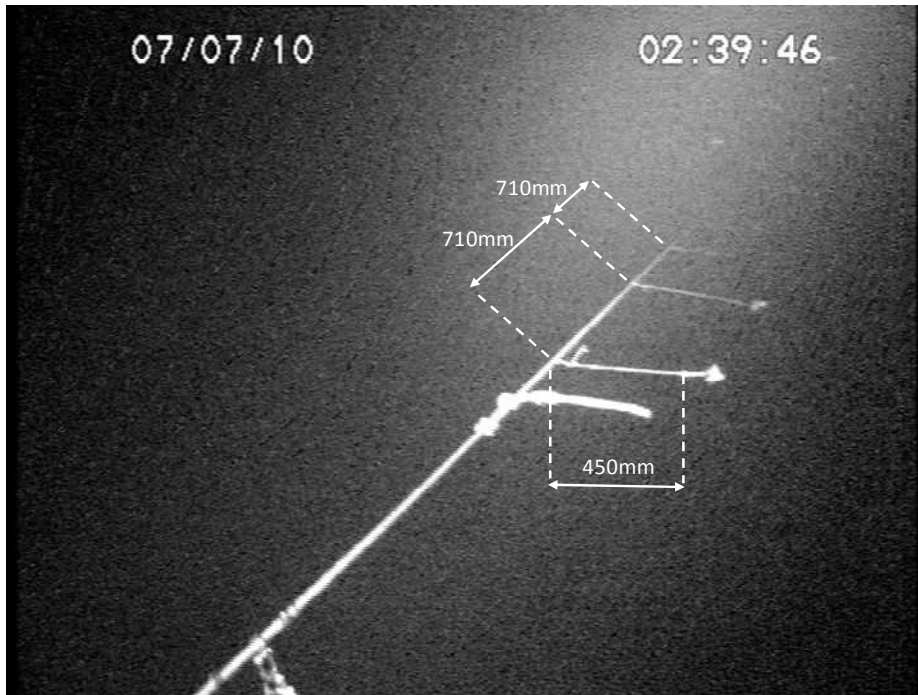


Figure A10.8. Video still image showing multiple snoods attached to the mainline. Longline components of known length (i.e. 450 mm snoods and 710 mm spacing between snoods) were used to derive a relationship for measuring horizontal distance for a given vertical position in frame.

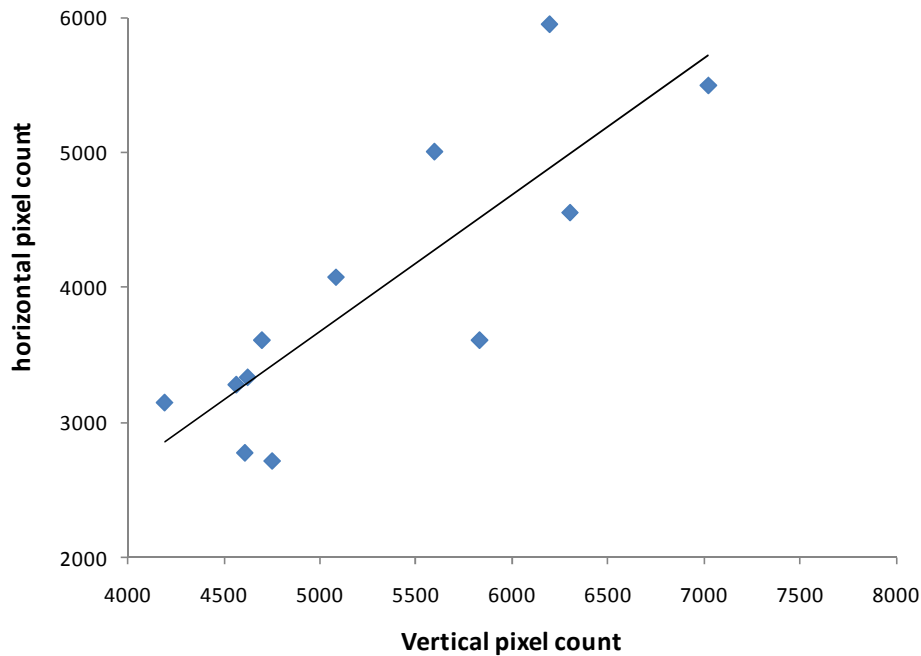


Figure A10.9. Relationship between the number of pixels in frame that correspond with a distance of 450 mm for a given vertical position in pixels.

Using this relationship, still frames from footage of lateral line movement were taken at intervals (Figure A10.10) such that where line movement occurred in the frame with landmarks of known dimensions, a series of horizontal line movement measurements taken in frame could be summed to give total horizontal line movement.

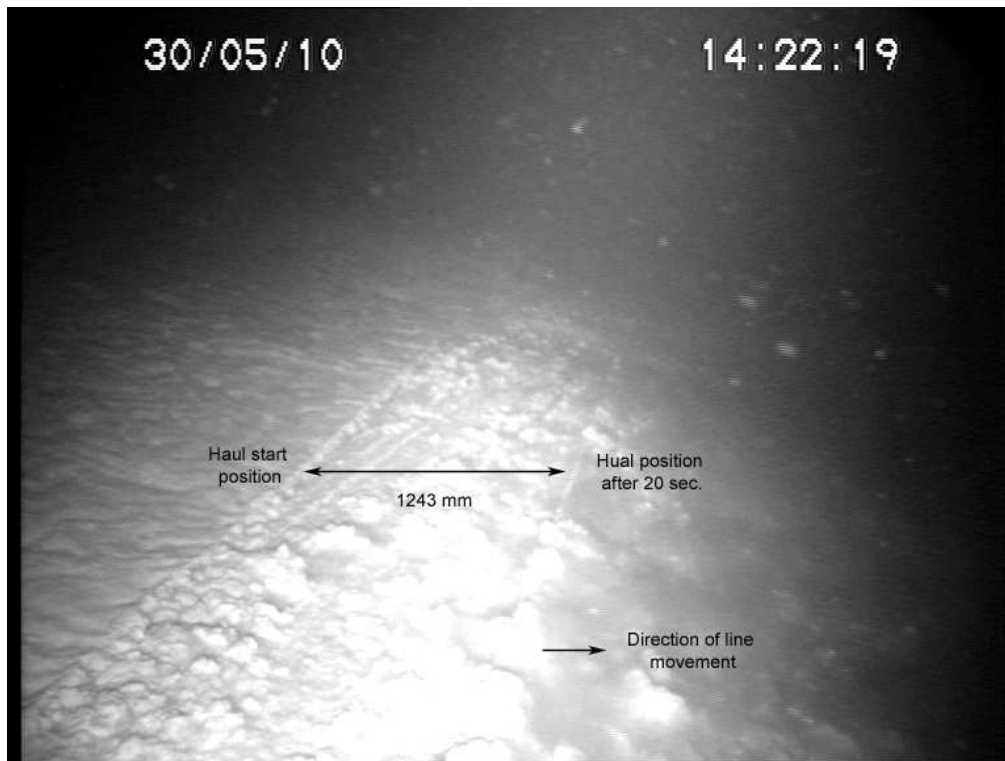
### Frequency and patterns of occurrence of line movement

The BICS camera was successfully deployed 48 times on longlines in the HIMI region. Of those 48 deployments, 27 included footage of the longline settling onto the seafloor (deployment events), and 27 included footage of the longline as it was leaving the seafloor (retrieval events). No line movement was detected in any of the 48 shots where the line was observed on the seafloor between deployment and retrieval. Line movement was also not detected in any of the 26 deployment events observed. Of the 27 retrieval events observed, 26 showed line movement on the seafloor (Table A10.3). The extent of lateral line movement was estimated for 19 movement events that satisfied the pre-conditions of the video line movement method described above, i.e. the line was visible for the entire duration of hauling until the seafloor was no longer visible. Lateral movement exceeding 1m was detected in nearly every retrieval event, with a mean movement of 6.2 m, a maximum of over 30 m, and a standard deviation of 8.2 m.

Variation in lateral movement was not related to depth ( $r^2=0.07$ ,  $F_{2,26}= 1.95$ ,  $p= 0.11$ ) (Figure A10.11). The highest longitudinal movement was recorded for a line that was not under tension at the location of the camera when set, however, only two such events were recorded, precluding meaningful statistical analysis of the effect of line tension on lateral line movement. There was also a trend for lateral line movement to increase as longitudinal movement increased, but was not statistically significant ( $F_{2,18}= 1.18$ ,  $p= 0.33$ ). These relationships are further discussed in a theoretical framework below. The line movements measured are likely to be a conservative estimate of lateral movement at the location of the camera, because it was generally due to apparently rapid line movement and consequent sediment clouding or camera angles that precluded in-frame measurement.

**Table A10.3. The number and percentage (in brackets) of longline deployments with footage captured at each stage of a longline set, and those with line movement.**

	Deployment	Line on seafloor	Retrieval
<b>Total events</b>	27	48	27
<b>Line movement events (%)</b>	0 (0)	0 (0)	26 (96)



**Figure A10.10.** Video still image showing approximately 1243 mm of lateral line movement in the first 20 seconds of a retrieval event. In retrieval events where lateral movement exceeded the width of one or more video frames, the amount of movement in each frame was individually calculated.

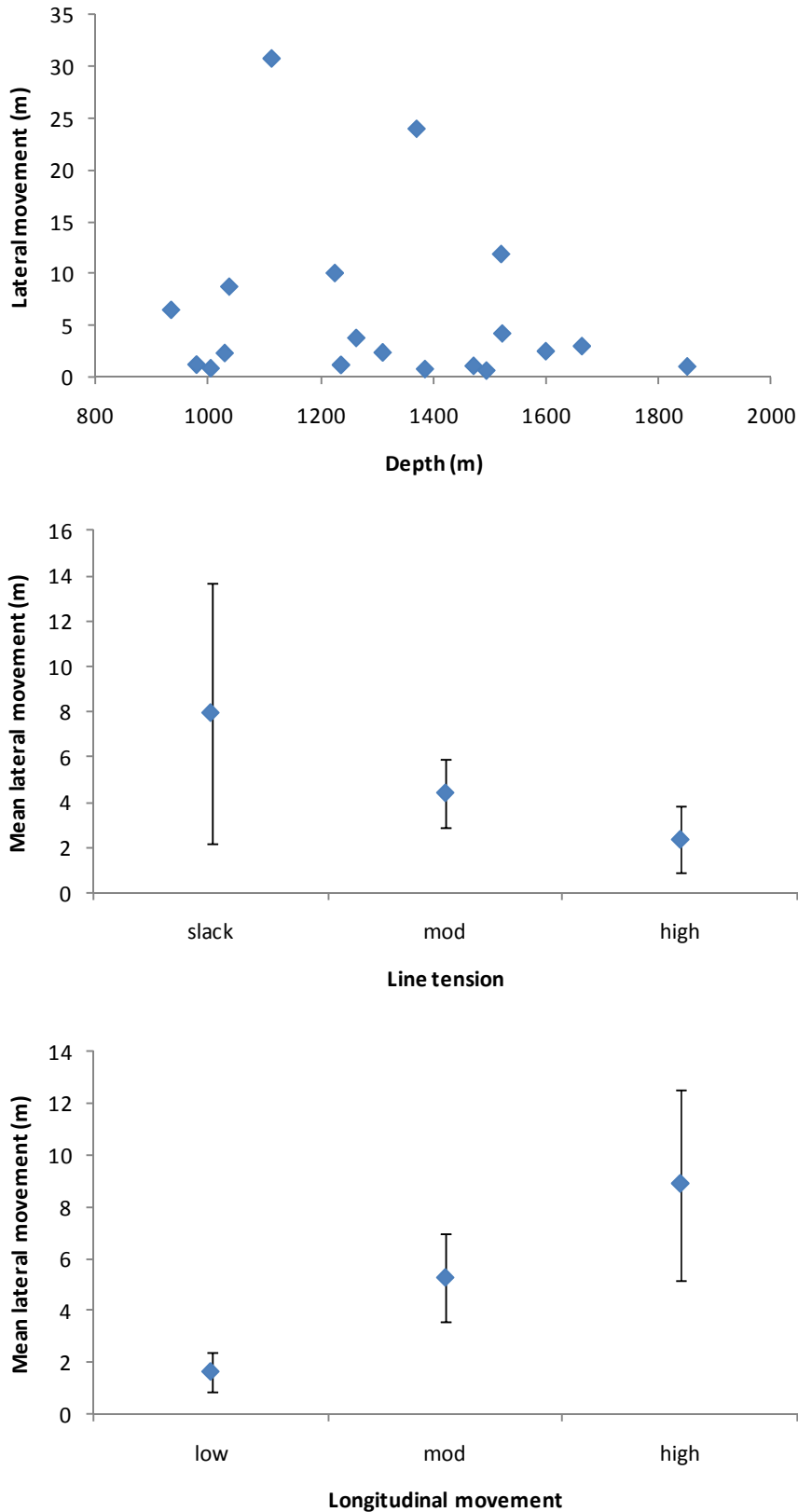


Figure A10.11. The relationships between lateral longline movements on the seafloor (measured from frames of *in situ* video of lateral longline retrieval events), and depth (top), categories of tension in the line on the seafloor (middle), and categories of the extent of longline movement (bottom). Error bars are standard error.

Tensioning of the line during retrieval is the most likely time that line movements occur. Factors affecting the extent and direction of longline movement during retrieval are likely to include line tension, position of the vessel relative to the longline segment being hauled, depth, sea-state, current, seafloor topography and the part of the line being hauled. Due to the significant technical challenges in deploying cameras on longlines, and the difficulty in predicting soak times accurately enough to allow the camera to be programmed to capture retrievals (Appendix 4), the number of retrieval events captured is insufficient to allow formal comparisons of the influence of most of these factors. However, the range of sea conditions, depths and camera positions on the line, from which retrieval events were captured, would suggest that some movement on retrieval is likely under most conditions experienced at HIMI.

### **Direction of line movement**

In the camera footage of longline retrievals, lines were observed to move longitudinally, i.e. in the direction of the haul, laterally (perpendicular to the direction of the haul) and diagonally (a combination of both).

### **Longitudinal line movement**

Longitudinal line movement is likely to occur when there is a mismatch between the lifting section of the line tension and the ship's position, and will involve either movement of the line as slack portions are straightened and/or dragging of line anchors, the former during the start of the haul and the latter towards the end of the haul. The factors that influence longitudinal line movement can be split into two types; those influencing the line on the seafloor and those influencing the line in the water column.

### **Factors affecting the line on the seafloor**

The primary factor affecting longitudinal line movement on the seafloor is its coefficient of drag (i.e. its resistance to moving). The amount of drag on a line will be a result of a number of factors; the most important are likely to be the weight and length of the line on the seafloor, its tension, and the presence and/or proximity of anchors. The coefficient of drag will be lower if a line is slack or looped and will be higher if the line is taut on the seafloor. Camera footage of longline sets also show that loose or looped lines will be pulled taught prior to the line lifting from the seafloor. Other factors that are likely to influence the coefficient of drag are the substrate and topography, the presence of snags and obstacles, and hooked animals. At any position on a longline on the seafloor, the line will only move over the substrate if the drag coefficient exerted on the line is exceeded by horizontal tension on the line from the portion of the line being hauled up to the vessel, but less than breaking tension.

### **Factors affecting the line in the water column**

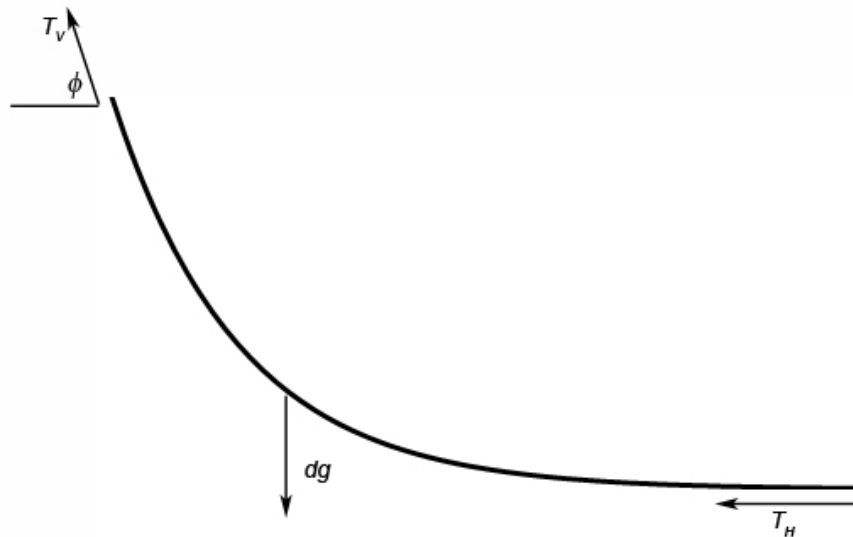
If the line is stationary, on the basis of its own weight, it will hang in a catenary across the space between the vessel position and the point at which the line leaves the



seafloor (Figure A10.9). In these circumstances there will be no vertical component to the tension on the cable on the seafloor and the horizontal tension  $T_H$  is proportional to the line tension delivered at the vessel  $T_V$  by the formula:

$$T_H = T_V \cos \phi \quad 1)$$

Where  $\phi$  is the angle of the tangent to the catenary at the vessel with the horizontal. The horizontal tension  $T_H$  is inversely proportional to the angle of the tangent to the longline with the horizontal at the vessel (Figure A10.12). Therefore, with increasing distance from the vessel to the lifting point, and shallowing of the angle  $\phi$ , more of the tension on the line at the vessel ( $T_V$ ) is realised as horizontal force on the seafloor ( $T_H$ ), resulting in a higher likelihood that the drag coefficient of the line on the seafloor will be exceeded.



**Figure A10.12.** Diagram showing the forces at equilibrium in a static catenary and representing a longline being retrieved. Longitudinal line movement is a function of the horizontal tension  $T_h$ , which is proportional to the line tension  $T_v$  and increases with the cosine of  $\phi$ . The downward force exerted by the mass of the line above the seafloor ( $d$ ) and gravity ( $g$ ), forms the vertical tension component when the line is static.

The horizontal tension in a catenary is proportional to the length of line suspended between the hauling point and the lifting point on the seafloor ( $L$ ), the mass of the line suspended in the water ( $d$ ) the gravitational constant ( $g$ ) and the water depth as shown in equation 2 (adapted from equation 15 of Garza-Rios et al.(1997)):

$$T_H \propto dg \left( \frac{L^2 - h^2}{2h} \right) \quad 2)$$

Where  $d$  is the mass of the longline in water,  $L$  is the length of the suspended line, and  $h$  is the depth. Clearly, the longer the line suspended in the water for a given depth,

the greater the horizontal tension on the line on the seafloor. Hence, in a static system, reducing the distance from the vessel to the lifting point, and the amount of line suspended in the water column, will reduce the likelihood of line movement.

With the additional tension added with line hauling, the system is no longer static. The additional hauling tension will result in the presence of both horizontal and vertical components in the forces acting on the line at the lifting point. Hauling tension will add to the horizontal component of the tension at the lifting point due to the angle of delivery induced by the catenary. Further, the extent to which haul tension contributes a vertical (lifting) force at the seafloor is likely to depend on the nature of the catenary (i.e. the distance between the vessel and the lifting point, the depth, and the weight of line in the water column). And finally, the extent to which the components of vertical force (from hauling tension) and horizontal force (from catenary and hauling tension) delivered to the line, cause it to either lift from the seafloor, induce line movement across the seafloor, or both, will depend on the drag coefficient of the line.

In summary, a mismatch in the position of the vessel with respect to the lifting point will promote longitudinal movement of the line on the seafloor due to a greater amount of line in the water column and/or due to a lower angle as it leaves the vessel. Deeper water will also promote longitudinal movement due to a greater quantity of line in the water column.

Managing the mismatch in position between the vessel and the lifting point is complicated by a lack of knowledge of the precise location of the line on the seafloor due to currents and vessel layback. A second complicating factor is that the lifting point is very dynamic in response to the position of the vessel, the coefficient of drag of the line on the seafloor, and the tension on the line in the water column.

Consequently, minimising this mismatch will likely depend on the skill and experience of the skipper in handling the vessel over the most likely lay of the line and assessing line tension at the surface.

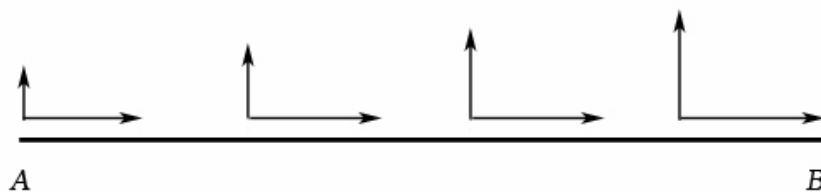
### **Lateral line movement**

Lateral line movement is likely to occur in response to a lateral mismatch in position between the vessel and the lift point during hauling and will be likely to involve a component of longitudinal movement. Lateral movement will occur when a sideways horizontal force applied by the line in the water column, to the line on the seafloor, exceeds the line's lateral coefficient of drag. The magnitude of lateral forces will be governed by the lateral mismatch in position between the vessel and the lifting point and the consequent lateral component to the catenary of the line in the water column. Like longitudinal movement, a lack of knowledge about the exact location of the line is a complicating factor for minimising the mismatch between the line and the vessel. However, unlike longitudinal movement, the relative position of the vessel to the constantly moving lifting point is likely to have less of an influence on the magnitude

of lateral movement. This means that a skipper can have more influence over lateral than longitudinal movement because lateral positioning over the line, which is stationary, is more achievable than longitudinal positioning over the lift point (which is constantly moving).

Lateral and longitudinal movement are also dissimilar due to the coefficient of drag for longitudinal movement being essentially constant along the line (excepting loops and slack sections), whereas the lateral coefficient of drag will vary with the proximity to the lifting point. Whilst the lateral coefficient of drag will be affected by factors such as substrate topography and line tension, it will be lower at the lifting point, and will increase along the line (Figure A10.11). This means that radial movement of a long section of line under high tension is unlikely in comparison to lateral movement of a short section of line, under lower tension, in the vicinity of the lifting point, where the coefficient of lateral drag is lowest (Figure A10.13).

Footage of retrieval events show that lateral movement under high tension is not uncommon and suggest that the lateral horizontal force applied to the line from the sideways component of the catenary can induce tension sufficient to damage or remove sessile taxa unable to deform to allow the line to pass.



**Figure A10.13.** Representation of the coefficients of drag for a section of longline on the seafloor (aerial view). The lifting point where the line leaves the seafloor is indicated by A and the line continues beyond B. The resistance to lateral movement across the seafloor is lowest at the lifting point and increases along the line, whereas the resistance to longitudinal movement is essentially constant along the line.

### Other evidence of line movement

Indirect evidence of line movement is provided by the regular occurrence of line breakages during retrieval. Movement across the seafloor increases the likelihood that the line will encounter a snag. Snagging leading to line breakages has been reported in a small percentage of hauls at HIMI, requiring conditions where static tension exceeds the 2000 kg breaking strain of IWL longline. While some snagging may occur as the line is set, it also is likely that line movement during retrieval has caused the line or anchors to encounter a snag.

In summary, video footage indicates that some longitudinal line movement occurs regularly. Based on the geometry of hauling longlines in deep water some amount of movement will be hard to avoid, and is more likely where there is a mismatch in the

relative position of the vessel and the lift point, when the line has kinks and loops on the seafloor, and when more line is in the water column (including in deeper water). Similarly, video evidence and geometric analysis indicates that lateral movement also occurs regularly, but neither as often nor as far as longitudinal movement. It most likely occurs near the lift point.

Environmental factors will also have an influence on the likelihood and extent of line movement. Strong currents at or below the surface will influence the accuracy of the predicted position of the line and could directly increase horizontal forces at the lifting point due to drag on the line in the water column and are likely to be exacerbated in deep water. Adverse sea states will make accurate positioning during retrieval more difficult (Table A10.5).

### Estimating the footprint of longline hooks

The hooks on demersal longlines present a potential source of mortality and damage different to that of the mainline. On a typical longline set in the HIMI fishery, 15/0 hooks with a gape of 0.015 m are used on 0.45 m snoods spaced every 1.4 m. For the purposes of this analysis we ignore any interactions with the snoods themselves, however they may also cause damage or mortality if they are under tension when on or near the seafloor.

For a line moving longitudinally only as it is hauled, assuming that snoods are perpendicular to the line as hauling commences, the hooks swept by the hooks can be approximated as a polygon the length of the quarter of a circle with a radius of the snood length and the width of the hook gape. This process will occur as the line is hauled longitudinally by approximately a snood length. Then, as they lie parallel to the mainline, the hooks combined will sweep an area that is approximately the length of the line and the width of the gape of the hook. So the area can be estimated as:

$$A_{hk} = mw + s \left( \frac{\pi lnw}{2} - 2 \right) \quad 3)$$

Where  $A_{hk}$  is the total area exposed to hooks,  $m$  is the total distance of longitudinal movement of the line on the seafloor,  $w$  is the gape of a hook,  $s$  is the snood length,  $l$  is the total length of the longline with hooks attached and  $n$  is the number of bare hooks per unit length of line. By example, the hooks on an 8 km longline, with 1000 hooks per km, and 22 mm gape width hauled longitudinally 30 m would interact with an estimated 124 m<sup>2</sup> of seafloor; 123 m<sup>2</sup> due to the hooks moving from the perpendicular, and the remainder prior to the line lifting off the seafloor as the hooks are dragged parallel to the mainline.

Where some component of lateral movement is involved, the area of hook interaction can be estimated as:

$$A_{hk} = lnw \left( \sqrt{m^2 + p^2} - s \right) \quad 4)$$

where  $p$  is the lateral component of movement. By example, for an 8 km longline hauled 20 m laterally and 30 m longitudinally prior to leaving the seafloor, hooks would interact with an estimated 6266 m<sup>2</sup> of the seafloor. Clearly lateral movement substantially increases the amount of seafloor area subject to interactions by hooks. However, it is worth noting that in the same circumstances the footprint of the mainline, estimated as the product of total distance moved across the seafloor and the length of the longline, would be estimated as 160 000 m<sup>2</sup>, more than 25 times greater than the hook footprint.

### **Conclusions**

This analysis develops a novel approach to estimating gear footprint by disaggregating the components of the gear to address the footprint of each component separately. This approach allows the interactions between the benthos and each component of a gear to be assessed separately and facilitates comparison of interaction across gears. Comparison across gears becomes important in multi-gear fisheries with overlap between gears and fisheries. Disaggregation is particularly useful where components of the gear deliver types of interactions in a different footprint. A moving longline delivers both line interactions and hooking interactions. Not only is the footprint of the hooks narrower than the line, but different taxa may have differing vulnerability to these components.

Longlines are not intended to move across the seafloor during a fishing event. Despite this, the empirical and theoretical analyses presented here indicate that some line movement is very likely on retrieval. The theoretical analysis suggests that reducing lateral line movement is more achievable than reducing longitudinal line movement. An understanding of the factors affecting the direction and extent of line movement requires the collection of considerably more empirical data from more camera deployments and/or other means of detecting line movement and over a range of conditions. Gear footprints derived here will be used to develop a fishery footprint for each gear in the HIMI region in Appendix 11.

**Table A10.5. Factors likely to increase the movement of longlines across the seafloor**

<b>Factor</b>	<b>Axis</b>	<b>Reason</b>
Longitudinal mismatch in position of vessel and lifting point of the line	Longitudinal	More line in water and/or more acute angle on line from surface
Sideways mismatch in position of vessel and longline on seafloor	Lateral	Lateral component in horizontal forces applied at the lifting point
Deep water	Longitudinal or lateral	More line in the water
Low tension in line on the seafloor	Longitudinal or lateral	Lower coefficient of drag on line
Strong current at surface or below	Longitudinal or lateral	Greater chance of position mismatch and greater horizontal forces at the lifting point due the drag in the water column
Adverse sea states (e.g. swell, ice)	Longitudinal or lateral	More difficult to align vessel with the line

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## Appendix 11      Estimates of the multi-gear footprint of the toothfish fishery at HIMI

Dirk Welsford, Michael Sumner and Graeme Ewing

### **ABSTRACT**

An understanding of spatial patterns of effort is essential to estimate and manage the impact of demersal fishing on benthic habitats. In this study, every recorded demersal trawl and longline fishing event in the Heard Island and the McDonald Islands (HIMI) fishery was characterised as a polygon consistent with its estimated swept area. A profile of effort for each grid cell was calculated to describe the area unfished, fished once, fished twice, and so on. Demersal trawling is heterogeneously distributed across the HIMI region with most fishing occurring in five patches of concentrated effort that feature extensive overlapping events. Demersal longlining is also heterogeneously distributed, but patches of fishing effort are generally less concentrated than trawling, with less overlapping fishing events. There is minimal overlap between the two fisheries with trawling generally conducted in waters shallower than, and longlining deeper than, 800 m. An analysis of detection of the overlap of fishing and benthic habitat at varying spatial scales showed that fine spatial scales are required to minimise bias when both fishing effort and habitats are patchy. As modern positioning systems and software facilitate spatial analysis, we recommend that all effort data should be assessed at fine spatial scales to identify areas of concentrated effort that indicate a higher risk of impact to the benthic habitats present in these areas.

## Introduction

As target species, bycatch and habitats are rarely distributed at random in the seascape, an understanding of spatial and temporal patterns of fishing effort is essential for managing a fishery (Bellman *et al.* 2005, Parnell *et al.* 2010, Ragnarsson & Steingrímsson 2003). Historically, the absence of accurate positioning systems in fishing fleets has led to the collection of spatial fishing effort data at low spatial resolution (McCluskey & Lewison 2008). The appropriateness of a spatial scale of fisheries management will depend on the fleet dynamics and on the heterogeneity of patterns of effort (Bellman *et al.* 2005). However, a finer spatial scale may be required to manage the impact of a fishery on the benthic environment, due to factors such as the heterogeneity of both effort and habitat distributions and the potential for a relationship between the two (Parker & Smith 2011, Pitcher *et al.* 2000, Pitcher *et al.* 2009). Furthermore, the effects of overlapping fishing events may need to be considered as disturbance may vary over successive fishing events due to factors such as sub-lethal damage increasing vulnerability of taxa (Rose & Jørgensen 2005).

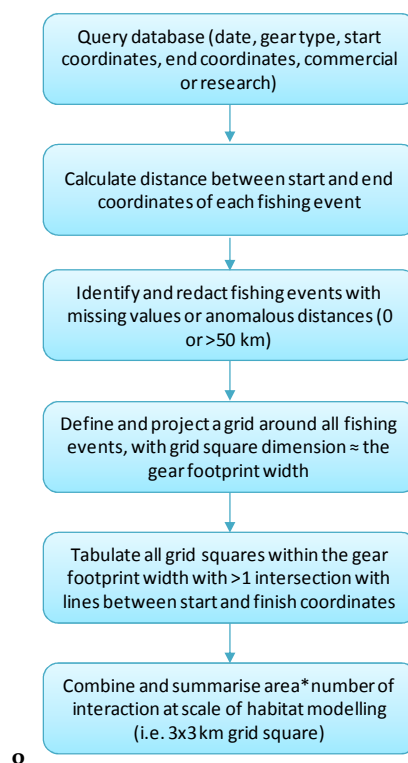
Modern fishing fleets equipped with GPS (global positioning system) and VMS (vessel monitoring system) and GIS (Geographic Information System) applications provide the means for analysing fishing effort data at fine spatial scales. These tools enable the analysis of effort data at a range of spatial scales, down to that of individual events, to allow assessment of the efficacy of current management strategies for limiting impacts to vulnerable marine ecosystems (VME), as well as assessing the potential for the scale of analysis to influence the results of assessments of disturbance and/or impact (Rijnsdorp *et al.* 1998).

The Patagonian toothfish and mackerel icefish fishery in the HIMI region developed contemporaneously with the availability of accurate civilian GPS, and accurate logging by vessels of the timing and location of fishing effort at the level of individual fishing events was a requirement for participating in this fishery since it began in 1997. The aims of this analysis were to compile the location and characteristics of individual fishing events in the HIMI region between 1997 and 2010, to provide an estimate of the cumulative fishery footprint. These data are also used to investigate the degree of bias that may arise in estimating the footprint as a consequence of the choice of scale that the footprint is summarised.



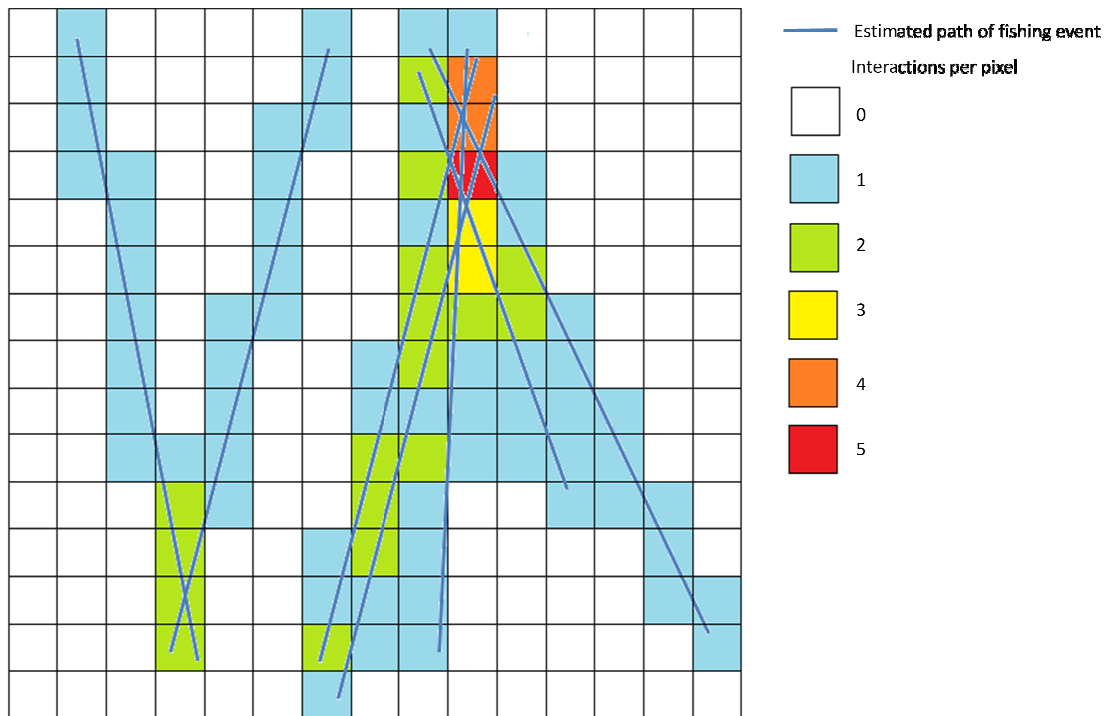
## Methods

The approach for developing the combined footprint, summarised in Figure A11.1, was implemented in R (R Core Team 2013), and is included with the Supplementary Materials. All individual fishing events in the AAD database were characterised by date, haul start and end coordinates, gear type (longline, or one of three types of trawl net) and purpose (commercial fishing or Random Stratified Trawl Survey). While in some instances fishing events may not be in a straight line, for the purposes of this analysis it was assumed that a line drawn between the reported start and finish coordinates was the best approximation for the location of the gear on the seafloor.



**Figure A11.1** Key steps in the method to calculate the location and area affected by the multi-gear fishing footprint at HIMI.

Start and end coordinates were projected on a Lambert Conformal Conic with a central meridian of  $74^\circ$  and a standard parallel of  $-52^\circ$ , and straight line distances between start and end calculated. Hauls with missing values, of zero length, or with length of greater than 50km were considered erroneous and excluded from further analysis (totalling 54 hauls out of a total of 21 710 fishing events recorded, or 0.25%). A virtual grid was then projected to encompass these fishing events, with the grid size chosen with reference to the gear specific footprints widths estimated in Appendix 10, and the number of intersections by lines of infinitesimal width, formed by each pair of start and end coordinates, and the each square of the virtual grid squares where determined (Figure A11.2).



**Figure A11.2** Illustration of the method of calculating number of interactions per pixel based on intersections with the estimated path of fishing events, for a hypothetical location with seven fishing events. Note the pixel size approximates that of the gear specific footprint, i.e. ~10m for longline, or ~100-160m for the different trawl gear configurations used at HIMI (see Appendix 10).

The total area with 0, 1, 2, etc. intersections was then summed for each gear type, and then tabulated across 3 x 3 km grid squares, as used for predicting the distribution of benthic taxa as show in Appendix 9. Consequently, every grid square across the entire HIMI seascape could be characterised by the amount of area with no interactions with fishing, 1 interaction or multiple interactions, and which gears had caused the interactions.

## Results

### Patterns of trawl and longline effort

Due to the commercial-in-confidence nature of the effort data analysed, a map of the fishing effort region-wide is not presented, however a numeric summary of fishing effort by gear is presented in Table A11.1. A comparison between the sum the length of all fishing events by the nominal width of the gear (polygon method), and the equivalent sum estimated by the pixellation of the seascape as shown in Figure A11.2 indicated that the pixel method over estimates the footprint area by 27-32%. Hence the total areas calculated by this method were adjusted accordingly (Table 11.2).

Trawl effort has been heterogeneously distributed, with a small number of areas where the majority of trawling effort is concentrated, and fishing events frequently overlap, with the remainder of effort distributed sparsely across the rest of the region (Table A11.3). For example, trawls conducted during the Random Stratified Trawl Survey, conducted each year by the *Southern Champion* are spread out across the shallow plateau, however in the main trawling ground (an area of ~155 km<sup>2</sup>) has received heavily concentrated trawling effort with one area in the main trawling ground is estimated to have been trawled over 400 times. This concentration of trawl fishing is also shown by the estimate that within the trawl footprint, locations have been trawled more than 6 times (Table A11.2).

**Table A11.1. Summary values for fishing effort and estimated effort footprints in the HIMI region, 1997-2013. Total area fished with no overlaps is the sum of the area of every fishing event, as estimated by the sum of length of all fishing events by the nominal width (polygon), or the numbers of pixels intercepted (as shown in Figure A11.2).**

Parameter	Gear type				
	Champion (C)	Champion (R)	Albatross	Carmen	Longline
Number of fishing events	13 952	2 439	90	674	4 424
Nominal footprint width (m)	160	100	120	160	10
Mean length of fishing events (km)	5.67	2.95	7.56	7.09	8.92
Median length of fishing events (km)	4.53	2.95	6.86	5.63	8.81
CV of length of fishing events (km)	0.72	0.23	0.56	0.72	0.40
Mean depth fished (m)	552	468	461	430	1 303
Median depth fished (m)	548	432	494	441	1269
CV of depth fished (m)	0.23	0.47	0.31	0.43	0.31

**Table A11.2. Summary values of estimated effort footprints in the HIMI region, 1997-2013. Total area fished with no overlaps is the sum of the area of every fishing event, as estimated by the sum of length of all fishing events by the nominal width (polygon), or the numbers of pixels intercepted (as shown in Figure A11.2). Total area fished - overlap is the area of the seafloor affected by fishing taking account of overlapping events, estimated by the number of pixels intercepted along the track of each fishing event, and adjusted for the relationship between the pixel and polygon method.**

Parameter	Gear type					
	Champion (C)	Champion (R)	Albatross	Carmen	All Trawl	Longline
Total area fished – no overlap (km <sup>2</sup> ) (polygon)	12 656.3	720.6	81.7	764.2	14 222.8	394.8
Total area fished – no overlap (km <sup>2</sup> ) (pixel)	16 662.4	943.8	108.1	1 012.0	18 726.3	502.3
Ratio pixel: polygon area	1.31	1.31	1.32	1.32	1.32	1.27
Total area fished – overlap (km <sup>2</sup> ) (pixels)	2 156.4	881.3	87.5	397.9	2 922.1	493.6
Total area fished – overlap (km <sup>2</sup> ) (adjusted)	1 646.1	672.7	66.3	301.4	2 213.6	388.7
Mean number of interactions within footprint	7.7	1.1	1.2	2.5	6.4	1.0

**Table A11.3. Estimated fishing intensity within the longline and trawl footprint in the HIMI region, 1997-2013, estimated using the pixel method shown in figure A11.2.**

Number of interactions	Area within footprint (km <sup>2</sup> )		
	Trawl	Longline	All gears
1	2009.5	492.8	2502.3
2	223.7	0.6	224.3
3	90.7	0.2	90.9
4	58.2	0.1	58.3
5	45.6	0.0	45.6
6	37.5	0.0	37.5
7	32.7	0.0	32.7
8	28.4	0.0	28.4
9	26.6	0.0	26.6
≥10	369.2	0.0	369.2
Total	2922.1	493.6	3415.8

The total area of seafloor, estimated from the bathymetry in *kerf\_dem* (Beaman & O'Brien 2011) is shown in Table A11.4. Commercial trawl fishing in the HIMI region is conducted primarily on the upper slopes of the banks and the plateau, with a maximum of 4.2% of the 201-400 m depth band falling within the trawl footprint. Only a small proportion of trawling is undertaken in deeper slope waters, and records of hauls apparently conducted at depths greater than 1600 m are unlikely to have maintained contact with the seafloor (Table A11.5).

**Table A11.4. Total seafloor area in 200 m depth bands within the Australian EEZ at HIMI between 0 and 3000 m.**

Depth band (m)	Seafloor area (km <sup>2</sup> )	Percentage of total seafloor area <3000 m deep	Percentage of total seafloor in EEZ, all depths
0-200	4 517.5	1.6	1.1
201-400	28 844.4	10.4	7.0
401-600	26 746.0	9.7	6.5
601-800	23 665.9	8.6	5.8
801-1000	12 266.7	4.4	3.0
1001-1200	16 377.2	5.9	4.0
1201-1400	17 052.4	6.2	4.2
1401-1600	22 428.7	8.1	5.5
1601-1800	20 351.6	7.4	5.0
1801-2000	20 988.9	7.6	5.1
2001-2200	18 216.4	6.6	4.4
2201-2400	15 668.1	5.7	3.8
2401-2600	13 632.4	4.9	3.3
2601-2800	14 914.9	5.4	3.6
2801-3000	20 550.8	7.4	5.0
Total <3001	276 221.9	100	67.3
Total in EEZ all depths	410 722		100

**Table A11.5. Total seafloor area within the trawl-only footprint by 200 m depth bands within the Australian EEZ at HIMI, 1997-2013, estimated using the pixel method shown in figure A11.2. 0.0 = footprint area less than 0.1 but non-zero, - = no footprint area.**

Depth band (m)	Area of Footprint (km <sup>2</sup> )											Total	% of EEZ
	Number of interactions												
	1	2	3	4	5	6	7	8	9	≥10			
0-200	64.4	3.0	0.6	0.1	0.0	-	-	-	-	-	68.1	1.5	
201-400	855.2	121.5	47.6	29.6	21.7	17.2	14.7	12.5	11.4	80.6	1211.8	4.2	
401-600	372.7	38.1	18.3	13.0	10.9	9.7	9.7	8.8	9.3	230.1	720.6	2.7	
601-800	432.2	47.3	23.3	15.6	12.9	10.7	8.3	7.1	5.9	56.6	619.9	2.6	
801-1000	236.5	15.9	3.6	1.7	1.0	0.8	0.5	0.4	0.3	4.3	265.1	2.2	
1001-1200	77.5	1.9	0.2	0.1	0.1	0.0	0.0	-	0.0	0.2	79.9	0.5	
1201-1400	26.0	0.2	0.1	0.0	0.0	-	0.0	-	-	0.0	26.3	0.2	
1401-1600	5.8	0.2	0.1	0.1	-	-	-	-	-	-	6.2	0.0	
1601-1800	0.3	0.0	0.0	-	-	-	-	-	-	-	0.3	0.0	
1801-2000	1.2	-	-	-	-	-	-	-	-	-	1.2	0.0	
2001-2200	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
2201-2400	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
2401-2600	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
2601-2800	0.1	-	-	-	-	-	-	-	-	-	0.1	0.0	
Total	2072.3	228.1	93.6	60.2	46.6	38.4	33.2	28.8	26.9	371.8	2999.9	0.7	

Longline effort is also heterogeneously distributed, focussing mainly on deeper slopes, with a few areas of concentrated effort, with a maximum of 0.6% of the seafloor between 1601-1800m within the fishing footprint (Table A11.6). Most locations within the footprint have had 1 interaction, and a maximum of 17 interactions was estimated at a single 100 m<sup>2</sup> location. Taking into account overlaps reduced the estimated fished area by 6.5 km<sup>2</sup>, indicating that although longline effort tends to be focussed in some areas, as lines are generally deployed parallel or perpendicular to one another, the area of overlap is relatively small (e.g. Figure A11.6).

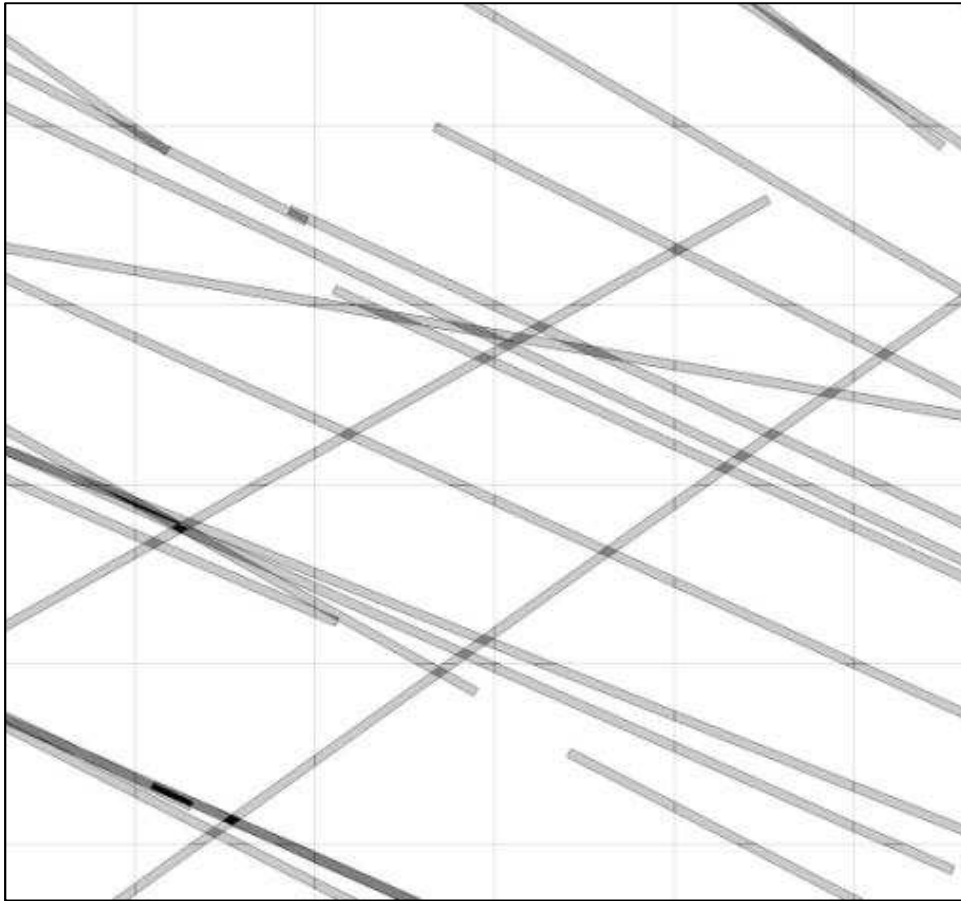
**Table A11.6. Total seafloor area within the longline-only footprint by 200 m depth bands within the Australian EEZ at HIMI, 1997-2013, estimated using the pixel method shown in figure A11.2. 0.0 = footprint area less than 0.1 but non-zero, - = no footprint area.**

Depth band (m)	Area of Footprint (km <sup>2</sup> )											Total	% of EEZ
	Number of interactions												
	1	2	3	4	5	6	7	8	9	≥10			
0-200	-	-	-	-	-	-	-	-	-	-	-	-	-
201-400	0.0	-	-	-	-	-	-	-	-	-	-	0.0	0.0
401-600	1.0	0.0	-	-	-	-	-	-	-	-	-	1.0	0.0
601-800	18.1	0.1	-	-	-	-	-	-	-	-	-	18.1	0.1
801-1000	64.6	0.5	0.0	-	-	-	-	-	-	-	-	65.1	0.4
1001-1200	74.6	0.6	0.0	-	-	-	-	-	-	-	-	75.2	0.4
1201-1400	72.5	0.5	0.0	-	-	-	-	-	-	-	-	73.0	0.3
1401-1600	58.2	0.3	0.0	-	-	-	-	-	-	-	-	58.5	0.3
1601-1800	124.6	1.7	0.0	0.0	-	-	-	-	-	-	-	126.3	0.6
1801-2000	55.8	0.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-	-	57.0	0.3
2001-2200	5.2	0.7	0.2	0.1	0.0	0.0	0.0	0.0	0.0	-	-	6.3	0.0
2201-2400	3.1	0.5	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0
2401-2600	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	-	0.3	0.0
Total	477.9	6.0	0.5	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	484.7	0.1

The trawl and longline fisheries are largely conducted at different depths in the HIMI region. Whilst there are areas of HIMI (e.g. the main trawl ground) where the two gears have been deployed adjacent to one another, longlining has been primarily conducted at greater than, and trawling less than, 800 m depth. However, an estimated 9 km<sup>2</sup> the seafloor has experienced overlapping longline and trawl, the majority of it between 400 and 1000 m deep (Table A11.7).

**Table A11.7. Total seafloor area where longline and trawl footprints overlap by 200 m depth bands within the Australian EEZ at HIMI, 1997-2013, estimated using the pixel method shown in figure A11.2. 0.0 = footprint area less than 0.1 but non-zero, - = no footprint area.**

Depth band (m)	Area of Footprint (km <sup>2</sup> )											Total	% of EEZ
	Number of interactions												
	2	3	4	5	6	7	8	9	≥10				
0-200	-	-	-	-	-	-	-	-	-	-	0.0	-	
201-400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.00	
401-600	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	3.2	4.0	0.01	
601-800	0.5	0.2	0.2	0.1	0.1	0.1	0.0	0.1	0.1	0.4	1.6	0.01	
801-1000	2.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.02	
1001-1200	0.6	0.0	0.0	-	-	-	-	-	-	-	0.6	0.00	
1201-1400	0.2	0.0	-	-	-	-	-	-	-	-	0.2	0.00	
1401-1600	0.0	-	-	-	-	-	-	-	-	-	0.0	0.00	
1601-1800	-	-	-	-	-	-	-	-	-	-	0.0	-	
Total	3.8	0.6	0.3	0.2	0.1	0.1	0.1	0.1	0.1	3.7	9.0	0.04	



**Figure A11.6.** Example of representative moderate density longline fishing effort. Grid cells are 1 km<sup>2</sup> and longline swept area depicted is 50 m wide to allow visualisation. Longline events are thematically shaded with darker tones representing more overlapping events.

### **Impact of summarizing effort data at different spatial scales**

Given the relatively concentrated nature of trawl effort, the scale at which effort data is summarised becomes important. This is especially case in a circumstance where the footprint of individual fishing events may vary across an order of magnitude, as is the case in this analysis where the footprint of a trawl is 10 or more times wider than our best estimate of lateral movement by longlines at HIMI. If effort is summarised at too coarse a resolution, there is the potential to lead to inaccurate conclusions about the extent of intensity of trawl effort, leading to an underestimate of disturbance in the locations where the fishery has focussed (analogous to a type II error), as well as the potential to overestimate disturbance outside of these locations by ‘smearing’ effort across the seascape and the predicted locations of vulnerable biota (analogous to a type I error).

The example in Figure A11.7, using actual trawl and longline data from HIMI and simulated habitat data with coarser spatial scales, shows that both errors are possible when estimating a relationship between habitat and fishing effort where effort is summarised at a scale substantially larger than that at which fishing effort or habitat varies.

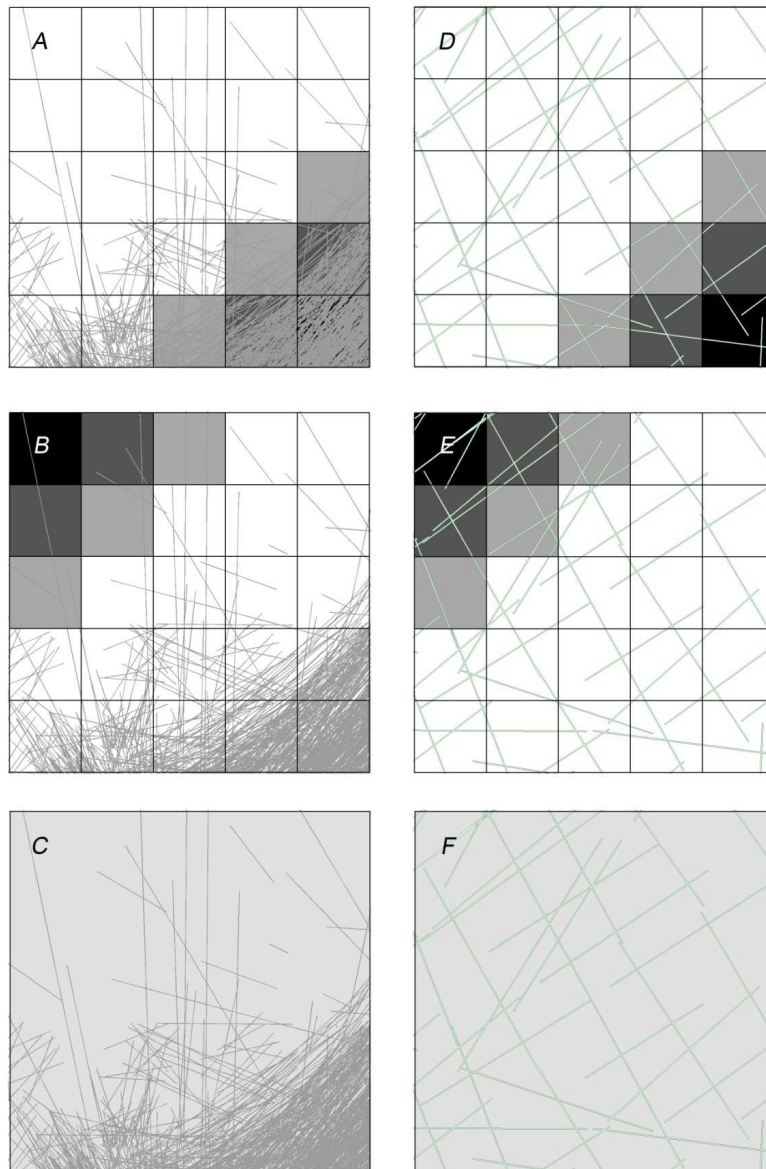


Figure A11.7. Examples of concentrated fishing events (in this case trawl, *A*, *B* and *C*) and less concentrated fishing (in this case, longline fishing *D*, *E* and *F*) and hypothetical gridded habitat graded from high biomass in black through to low biomass in white. The top row shows concentrated fishing effort coinciding with high biomass habitat (*A*) and more homogeneous fishing (*D*). The middle row depicts concentrated fishing which doesn't coincide with high biomass habitat (*B*) and more homogeneous fishing (*E*) and the bottom row which depicts a plausible rendering of either habitat at a coarser spatial scale. The relationship estimated between habitat and effort for concentrated fishing at the coarser spatial scale will be biased for both habitat distributions (top and middle rows) whereas relationship estimated the more evenly spread effort will be less influenced by the choice of spatial scale.



## Discussion

This methodology has provided estimates of the areas of the benthos that have encountered fishing at HIMI and has characterised areas of concentrated effort. Furthermore, an assessment of biases that may be introduced by aggregating effort data where it is heterogeneously distributed across the seascape is provided, allowing a key input into the assessment and management strategy for conserving benthic habitats proposed above.

This study shows that an analysis of spatial patterns of fishing is required to determine the degree to which patchiness in effort, and consequent overlapping of fishing events, affect the area of the seafloor that encounters fishing and the consequent mortality of vulnerable organisms that may have occurred. The issue of overlapping effort is particularly relevant when successive fishing events are likely to yield differing levels of mortality. For example, if sub-lethal effects from a prior fishing event render a benthic community more vulnerable to disturbance, or where heavy concentrations of effort leave benthic communities damaged to the point that successive fishing events only encounter dead organisms.

The distribution of trawl fishing in the HIMI region is highly heterogeneous with relatively small areas encountering the majority of trawl effort. The distribution of longline fishing, when viewed at the same spatial scale as trawling, whilst still heterogeneous, occurs in much less concentrated patches than trawl fishing, with far fewer overlapping fishing events. Due to the smaller scale of disturbance by individual longlines as estimated above, the seafloor area that has encountered trawls is more than 5 times as large as that for longlines. There is little overlap between the two fishing methods, with delineation at around 800 m, below which few trawls have been deployed and above which few longlines have been deployed. Consequently interactions between gears are unlikely to make a large contribution to estimates of the mortality likely to arise from current fishing at HIMI.

The choice of grid cell size is particularly important for patchy fishing, whereby homogenisation of patterns of effort increases with increased grid cell size (Stelzenmuller *et al.* 2005). While consideration of the degree of overlap of effort with respect to the total number of fishing events will provide a measure of the concentration of effort, it does not provide detail of where that effort is concentrated. If fishing is known to be occurring in uniform habitats, low spatial resolution may be acceptable to estimate the impact of fishing effort (provided overlapping effort is considered). However, if habitat distribution is likely to be patchy, higher spatial resolution is required to reduce bias in estimating which high value habitats co-occur with high concentrations of fishing effort (Parnell *et al.* 2010, Stelzenmuller *et al.* 2008).

The results of these analyses also confirm that ignoring overlapping fishing events could lead to spurious conclusions on the impact of fishing activities (Rijnsdorp *et al.* 1998), for example through overestimation of the area of the seafloor that encounters

fishing, as well as areas where overlapping fishing may amplify the consequences of disturbance by fishing gear. Considering the relative ease of collection and availability of fine-scale spatial effort data, and the impressive spatial processing power of contemporary GIS software, estimation of spatial patterns of effort at a fine scale is recommended (Stelzenmuller *et al.* 2008).

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## Appendix 12      Epibenthic megafaunal assemblages off East Antarctica and their relationship to gross geomorphological features

Ty Hibberd and Graeme Ewing

### ABSTRACT

Mega-epibenthic biodiversity off East Antarctica was analysed using seabed digital imagery and biological samples collected simultaneously using a beam trawl from three areas covering a range of depths and topographies (plateau, shelf, and canyon) and substrate types. The investigations, which focused primarily on the sessile, structure-forming invertebrates like sponges and corals, revealed a range of distinct assemblages of varying density and taxonomic richness. Assemblages observed above 800 metres depth were typically characterised by a higher density and abundance of erect, structural invertebrates. These habitats, which were in particularly high density in the vicinity of the canyon feature, were typically associated with hard substrates; more complex geomorphological bed-forms of rock and boulder which were most prevalent on steeper and shallower investigation sites. Lower density assemblages of lower profile sessile invertebrates were observed at shelf sites characterised by soft substrates; fine sediments with infrequent rocks and boulders, typically around 700 m depth. These habitats are likely to be less vulnerable to disturbance than the high density sites, at least in regard to their sessile megafauna. In deeper shelf waters and on the plateau (>1000 m), density diminished, resulting in depauperate communities characterised by very low densities of sponges dwelling on soft substrates and uniform, fine-sediment bed-forms.

## Introduction

To assist with managing the impacts of fisheries on benthic communities in high latitudes consistent with the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) several key questions need to be addressed:

1. What is the nature and extent of benthic habitat types on the Antarctic deep-water continental margin at the scale of disturbance caused by demersal fishing gears (100s-1000s of metres)?
2. What are the key parameters (e.g. topographical, oceanographical, and geophysical) to include in predictive models for the Southern Ocean, so that areas likely to contain vulnerable communities can be identified and protected?

In this study, we examine the distribution and structure of benthic epibenthic megafauna assemblages (primarily organisms living on or attached to the benthos, above ~10 mm in size) of East Antarctica. The study region falls within the CCAMLR Statistical Division 58.4.1, and CCAMLR manages an exploratory longline fishery for toothfish (*Dissostichus* spp.) in this area. This area provides a unique opportunity to address the above questions by collecting data on benthic communities and habitats over a broad range of depths (400-1300 m), topographies (shelf, canyon, plateau) and substrate types that are representative of such geophysical features across the entire area.

At comparable depths elsewhere, benthic assemblages are generally dominated by sessile fauna such as sponges, corals or ascidians (Branch *et al.* 1993, Gutt *et al.* 2006, Starman *et al.* 1999). Recently such taxa have been considered as proxies for biodiversity, as they add 3-dimensional structure and complexity to their surroundings, and habitat for fish and other invertebrates. Numerous studies have noted structure-forming invertebrates as key components of biodiversity in marine ecosystems (Auster 2005, Hiefetz 2002, Puniwai 2002, Tissot *et al.* 2004). However, general morphological traits (attached, emergent, brittle) and life-history characteristics (slow-growing) common to many of these taxa leaves them particularly susceptible to, and slow to recover from, disturbance. Consequently, understanding the distribution of structure-forming invertebrates is fundamental to assessing the relative vulnerability of benthic habitats to impact from disturbance, and the sustainability of activities such as demersal fishing in these habitats.

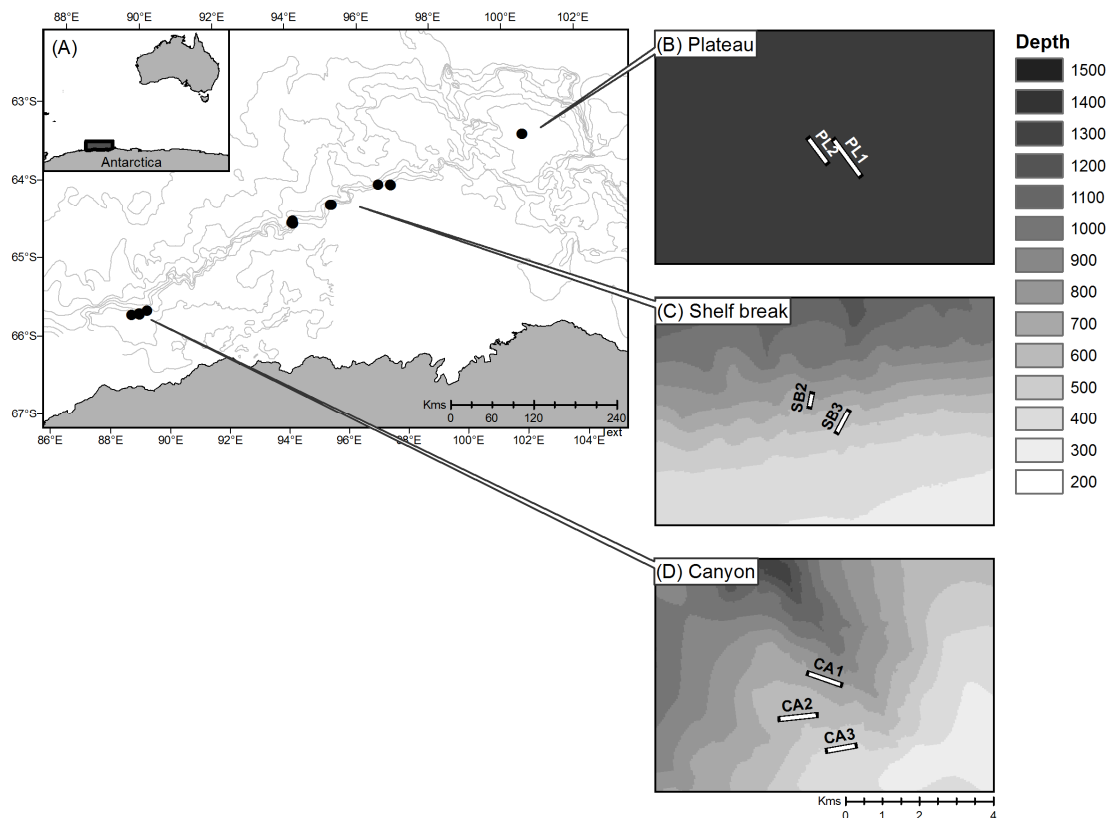
The main objectives of this study were to: (1) document assemblages of structure-forming, epibenthic megafauna off East Antarctica; and (2) describe how they relate to readily measurable physical features that might be used to predict where else such assemblages occur outside of the sampling area.

## Methods

### Epibenthic megafauna sampling

The investigations off East Antarctica were carried out aboard the Australian research vessel *Aurora Australis* during December-January 2009/10. Data were collected from nineteen stations belonging to three geomorphic features chosen for their contrasting physical characteristics (Figure A12.1). These areas, described based on the nomenclature of the International Hydrographic Organisation manual on undersea features (IHO 2005) and descriptions by Heap & Harris (2008), included:

- 1) Plateau; A flat or nearly flat area of considerable extent, dropping off abruptly on one or more sides.
- 2) Shelf break; An area where the seafloor gradient increases abruptly, denoted by closely spaced contours at the seaward edge of the outer shelf
- 3) Canyon; A relatively narrow, deep depression with steep sides, and a continuously sloping bottom.



**Figure A12.1.** Map of benthic sample sites off East Antarctica (A) and fine-scale bathymetric maps of the seafloor of typical sample sites for the three sampled geomorphic features. They include bathymetry typical of (B) the Plateau sites, which in this study, traverses the 1200–1300 m contour only; (C) the Shelf sites (sites SB<sub>1</sub> and SB<sub>4</sub>–SB<sub>12</sub> were adjacent to SB<sub>2</sub> and SB<sub>3</sub> on the shelf break out of frame); and (D) the Canyon feature (sites CA<sub>5</sub> and CA<sub>6</sub> were on the shelf adjacent to the canyon out of frame). Depths are in metres and transect lengths are 600 – 800 m long. Contours in figure A were sourced from GEBCO 2008 and are in 500 m intervals, and depths for figures B to D were interpolated from ships depth soundings during sampling and transit between locations. Site codes refer to Plateau (PL), Shelf break (SB) and Canyon (CA).

Within each of these areas, quantitative sampling of the megabenthos (i.e. those animals >10 mm in linear dimensions living on the seafloor) was undertaken using a research beam trawl equipped with a 10 mm codend liner and a high resolution digital imaging system. To determine the type and extent of megafaunal epibenthic habitats, digital (stills) images were used to determine community distributions and patchiness, and biological samples were used to assess taxa richness and endemism at finer taxonomic resolution. A list of haul parameters summarised by site are given in Table A12.1. The total area of seafloor sampled, expressed in square metres (m<sup>2</sup>), is given for each site, calculated using gear width and tow distance. Taxonomic groups referred to hereafter, both motile and sessile, are listed in Table A12.2. All sessile

**Table A12.1. Research trawl effort data for each site analysed. Site codes refer to Plateau (PL), Shelf (SB) and Canyon (CA). Note no useful video or still footage was obtained from site CA6**

Location	Sample	Bottom time (mins)	Start position	End position	Depth (m)	Swept area (m <sup>2</sup> )
Bruce Rise Plateau	PL1	16	-63.52 S 100.87 E	-63.51 S 100.86 E	1260	2690.2
	PL2	11	-63.52 S 100.86 E	-63.51 S 100.85 E	1271.1	1793.5
Shelf	SB1	15	-64.28 S 96.74 E	-64.28 S 96.73 E	1076	1394.9
	SB2	14	-64.28 S 97.1 E	-64.28 S 97.1 E	833	846.9
	SB3	11	-64.29 S 97.11 E	-64.28 S 97.12 E	662	1644
	SB4	8	-64.56 S 95.35 E	-64.56 S 95.36 E	611	1096
	SB5	11	-64.56 S 95.36 E	-64.56 S 95.35 E	562	1793.5
	SB6	11	-64.56 S 95.32 E	-64.56 S 95.31 E	778.9	1893.1
	SB7	12	-64.55 S 95.31 E	-64.56 S 95.3 E	953.2	2192
	SB8	5	-64.56 S 95.32 E	-64.56 S 95.32 E	758.2	1096
	SB9	9	-64.56 S 95.32 E	-64.57 S 95.31 E	701	1644
	SB10	12	-64.8 S 94.18 E	-64.8 S 94.19 E	442.4	1942.9
	SB11	14	-64.76 S 94.18 E	-64.77 S 94.16 E	1157	2192
	SB12	13	-64.79 S 94.16 E	-64.79 S 94.14 E	698.9	2142.2
Canyon	CA1	13	-65.86 S 89.3 E	-65.86 S 89.28 E	727.6	2391.3
	CA2	14	-65.87 S 89.28 E	-65.87 S 89.26 E	522.4	2590.6
	CA4	12	-65.87 S 89.3 E	-65.87 S 89.29 E	403.6	1942.9
	CA5	13	-65.87 S 89.03 E	-65.87 S 89.04 E	547.1	498.2
	CA6	5	-65.84 S 89.54 E	-65.83 S 89.54 E	526.8	597.8

### Digital images

The stills camera system comprised a digital SLR housed in a pressure casing, including a time lapse controller (shots were taken every 10 seconds), mounted on the beam of the beam trawl facing forward and down at an angle of approximately 20 degrees below horizontal. Stills images were analysed using a Java program Benthic Video Annotator (BVA) (Appendix 4) and Coral Point Count with Excel extensions (CPCe) (Kohler & Gill 2006). This software was used to identify the taxa encountered for diversity estimates, to count individuals by taxonomic group (Table A12.2) for abundance estimates, to calculate a proxy for density of sessile taxa based on their relative dominance in the visual field in images (individuals or colonies per square meter, n/m<sup>2</sup>), and to estimate visual swept area to allow these parameters to be expressed in units of square metres of seafloor. Methods for calculating density and swept area are described in Appendix 5. The digital images also provided an indication of the substrate types and their associations with sessile, structure-forming taxa.

**Table A12.2. Sessile and motile taxonomic groups identified in this study. Digital footage allowed discrimination of groups in the leftmost column; higher resolution group identified from biological sampling. Hereafter reference will be given to the taxonomic group names only. \* The taxonomic group Encrusting is an amalgamation of hydrocorals and lace corals; both are low profile, calcareous, encrusting sessile taxa that were indistinguishable from one another in the digital images, and hence data for these groups were pooled.**

Taxonomic group	Phyla	Taxa (finest resolution)
<b>Sessile</b>		
Sponges	Porifera	Demospongiae (Class) <sup>a</sup> Hexactinellida (Class) <sup>a</sup>
Alcyonarians	Cnidaria	Gorgonacea (Order) <sup>a</sup> Alcyonacea (Order) <sup>a</sup>
Anemones	Cnidaria	Actinaria (Order) <sup>a</sup>
Hydroids	Cnidaria	Hydroidolina (Order) <sup>a</sup>
Sea pens	Cnidaria	Pennatulacea (Order) <sup>a</sup>
Encrusting *	Cnidaria	Stylasterid hydrocorals (Family) <sup>a</sup>
	Bryozoan	Lace corals (Phylum) <sup>a</sup>
Serpulid tube worms	Annelida	Serpulidae (Family) <sup>a</sup>
Sea lilies	Echinodermata	Stalked Crinoidea (Orders) <sup>a</sup>
Sea squirts	Chordata	Ascidiacea (Class) <sup>a</sup>
<b>Motile</b>		
Sea slugs	Mollusca	Heterobranchia (Clades) Amphipoda (Order)
Crustaceans	Arthropoda	Decapoda (Order) Euphausiacea (Order) Isopoda (Order)
Sea spiders	Arthropoda	Pycnogonida (Class)
Brittle stars	Echinodermata	Ophiuroidea (Class) <sup>a</sup>
Feather stars	Echinodermata	Crinoidea (Orders) <sup>a</sup>
Sea cucumbers	Echinodermata	Holothuroidea (Class)
Sea stars	Echinodermata	Asteroidea (Class)
Sea urchins	Echinodermata	Echinoidea (Class) <sup>a</sup>

<sup>a</sup>Groups identified by SC-CAMLR (2009) as containing VME indicator taxa.

### Biological samples

Biological samples were collected from each site using the research beam trawl and were sieved to 10 mm, sorted and preserved in media appropriate for that taxonomic group (crustaceans – formalin, other taxa – 70% ethanol) at the time of sampling. Additional material was preserved in high grade ethanol to enable genetic analyses, and large animals were frozen. Organisms were separated, using gross morphological differences, into species (if known) or in most cases, taxonomic groups likely to represent species (*sensu* ‘operational taxonomic unit’ (OTU) (Butler *et al.* 2000) or ‘putative taxon’ (Ward *et al.* 2006)). Live colour images were taken of each OTU when time permitted. In the laboratory, fine sorting and identification was completed for most broad taxonomic groups, although separation of some colonial groups, i.e. sponges and bryozoans, is currently incomplete. For the purpose of this study, incompletely sorted groups were omitted from analyses relating to taxonomic richness.

### **Community analysis**

Variations in the composition of sessile megafauna between the 19 stations were examined using density ( $n/m^2$ ), as determined from digital images, in the software package PRIMER (Clarke & Gorley 2006). Still image density data was chosen over biological data due to issues of irregular gear behaviour in complex habitats (Appendix 5). Similarities between stations were calculated on square root transformed density data using the Bray-Curtis resemblance measure in PRIMER, and multi-dimensional scaling (MDS) plots were used to visualise these similarities (Clarke & Gorley 2006). Hierarchical clustering of the resulting resemblance matrix was used to group stations according to similarities in their community composition, and the SIMPER (similarity percentages) routine was used to elucidate those key sessile taxa contributing most to the average similarity-within or dissimilarity-between the resulting station groups (Clarke & Warwick 2001).

### **Taxonomic richness**

Indices of total and average taxonomic richness were determined for presence-absence beam trawl data and were compared by area, and then by assemblage type, as determined from the community analysis. Regression analysis was used to test the significance of differences ( $p < 0.05$ ) among assemblages and depth and substrate-type. The PRIMER routine, Species-Accumulation Plot, which plots the increasing total number of different species observed as data from additional sites are successively pooled, provides an indication of whether additional samples may have yielded a greater species diversity in any one area (Clarke & Gorley 2006). Endemicity in the context of the Southern Ocean was inferred for those groups which have received thorough taxonomic scrutiny and identification to genus or species, which thus far includes the soft corals, hydrozoans, nudibranchs, sea cucumbers, crinoids (feather stars and sea lilies) and isopod, amphipod and decapod crustaceans.

### **Patchiness**

Density indices within each image were summed across structure-forming taxonomic groups to give total density values by image. The site mean of the total densities across images was calculated, and the coefficient of variation in density was used as an indication of the patchiness of the habitat at each site (see Appendix 5).

### **Physical covariates with epibenthic assemblages**

Epibenthic distribution patterns were compared with local environmental variables, namely depth, topography and substrate type. Substrate types, calculated as the relative proportions of rock or sediment, were determined from digital images. Relationships between community distributions and environmental variables were analysed using regression analysis.



## Results

### Faunal Diversity

A total of 402 taxa from 13 phyla and 26 subtaxa (subphyla, classes, subclasses, and orders) were identified across all three areas from the biological samples (19 total sample/sites). Of these taxa, 241 were restricted to a single area, with 145 co-occurring at two areas and only 16 distributed across all three.

Diversity of megabenthos for the plateau was low ( $n_{\text{taxa}} = 51$ ), consisting mostly of sessile filter feeders and echinoderms, although more species are likely given the low sampling effort here ( $n = 2$  samples). Diversity on the Shelf and the Canyon was almost identical ( $n_{\text{taxa}} = 265$  and  $263$  respectively), with rich assemblages of sponges, cnidarians, molluscs, bryozoans, echinoderms, pycnogonids and crustaceans. The highest number of site-restricted taxa was recorded from the Canyon ( $n_{\text{taxa}} = 117$ ), followed by the Shelf ( $n_{\text{taxa}} = 107$ ) then the Plateau ( $n_{\text{taxa}} = 17$ ).

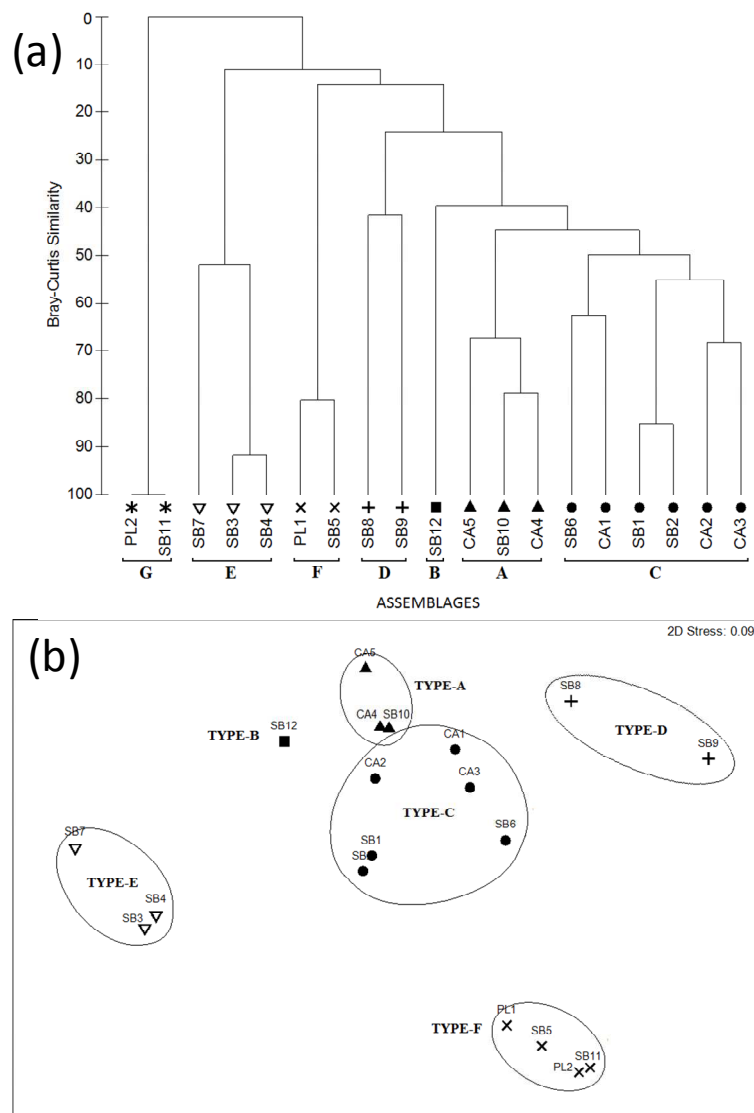
The quantitative faunal composition at a high taxonomic level differed markedly between the three areas. The average density of sessile and motile taxa per unit area was significantly greater at the Canyon area, dominated by hydroids, lace corals, hydrocorals and a significant density of motile taxa. Epifaunal composition on the Shelf was comparable to the Canyon, but at lower densities, whereas the deep Plateau community was depauperate in regard to both density and taxonomic richness.

### Community analysis and discriminator taxonomic groups

Based on densities estimated from the digital images of sessile, structure-forming invertebrates, the 19 sites off East Antarctica were clustered into seven distinct assemblage types. A reduced data set, comprised of the nine sessile taxonomic groups shown in the left hand column of Table A12.2, provided the basis for the dendrogram in Figure A12.2. A gradient in assemblage diversity and epibenthic density was evident from sites SB11 and PL2 to sites SB10, CA5 and CA6, corresponding to a gradient in increasing assemblage complexity. Assemblages were categorised as Type A (high density) to Type F (low density), and those with nil sessile taxa, Type G (Table A12.3).

A general trend towards decreasing density (per unit area) and number of sessile taxonomic groups with depth was evident across assemblages (Table A12.3). The Type A assemblage was found at two sites from the head of the Canyon sites (500 – 700 m) and at one in Shelf waters, all characterised by high density assemblages ( $0.99 \text{ units.m}^{-2}$ ) of hydroids, alcyonarians and sponges (Figure A12.3). The second assemblage, Type B, unique to site SB12 at 699 m, was characterised by a moderate density of sessile invertebrates, discriminated by significant populations of sea anemones and serpulid tube worms. The third assemblage, Type C occupied three sites each on the Shelf and at the Canyon and was characterised by a moderate density of sponges and encrusting invertebrates (lace corals and/or hydrocorals). Sites displaying these assemblage

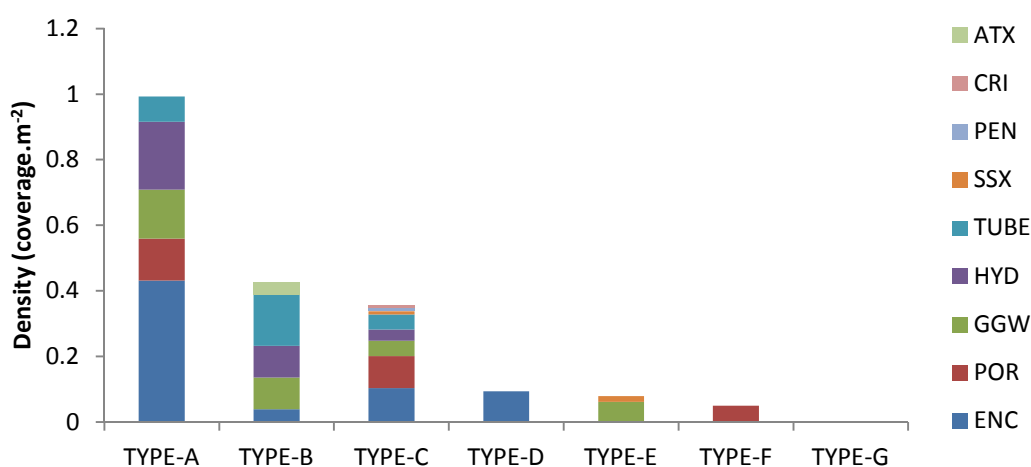
characteristics were typically observed around 700 m with the exception of CA<sub>4</sub> (403.6 m) and SB<sub>1</sub> (1076 m). Assemblage Types D to F were characterised by a small number of sessile taxonomic groups at low density. Type D and E were observed at Shelf depths between 700 – 900 m and were discriminated by alcyonarian corals and encrusting taxa respectively. Type F sites were characterised by a low density of sponges across a wide range of depths (SB<sub>5</sub> = 562 m, PL<sub>1</sub> = 1260.1 m), suggesting a patchy distribution of this taxonomic group across the range of depths sampled. Sessile invertebrates were absent in assemblage Type G, which was encountered at the deepest sites at the Shelf and Plateau.



**Figure A12.2.** Assemblages based on groupings of sessile, structure-forming invertebrates. Clusters representing assemblages, labelled according to decreasing density (Type A – G), are presented visually in the (a) dendrogram and (b) MDS ordination plot clustered at 40-45% Bray-Curtis similarity (notable between-cluster differences in density were observed at this similarity level). Site codes refer to Plateau (PL), Shelf (SB) and Canyon (CA).

**Table A12.3. Characteristics of sessile, structure-forming invertebrate assemblages as estimated from digital image data. Site codes refer to Plateau (PL), Shelf (SB) and Canyon (CA). Assemblage discriminating taxonomic groups, as identified by SIMPER, are also indicated, arranged according to their contribution to assemblage density (average density,  $n.m^{-2}$ ). Discriminating taxa codes refer to sponges (POR), alcyonarian corals (GGW), hydroids (HYD), sea anemones (ATX), encrusting taxa (lace corals and/or hydrocorals) (ENC) and serpulid tube worms (TUBE).**

Assemblage Type	Density class	Sites	Depth range (m)	Density of sessile taxa (coverage.m <sup>-2</sup> ±SD)	Number of sessile taxa ( $n.site^{-1}±SD$ )	Discriminating taxa and average density (coverage.m <sup>-2</sup> )
A	High	CA5, CA6, SB10	442-547	0.99±0.33	4.67±0.58	ENC (0.43) GGW (0.015)
B	Moderate	SB12	699	0.43	5	ATX (0.04) TUBE (0.16)
C	Moderate	CA1-3, SB1,SB2, SB6	404-1076	0.36±0.12	4.17±1.17	POR (0.1) ENC (0.1)
D	Low	SB8, SB9	701-758	0.09±0.08	1	ENC (0.09)
E	Low	SB3, SB4, SB7	611-953	0.08±0.02	1.33±0.58	GGW (0.06)
F	Low	SB5, PL1	561-1260	0.05±0.01	1	POR (0.05)
G	Nil	SB11, PL2	1156-1271	0	0	-



**Figure A12.3. Average contribution of sessile, structure-forming invertebrates to assemblage composition as estimated from digital image data. Taxa codes refer to anemones (ATX), sea lilies (CRI), sea pens (PEN), sea squirts (SSX), serpulid tube worms (TUBE), hydroids (HYD), alcyonarian corals (GGW), sponges (POR), and encrusting taxa (lace corals and/or hydrocorals) (ENC).**

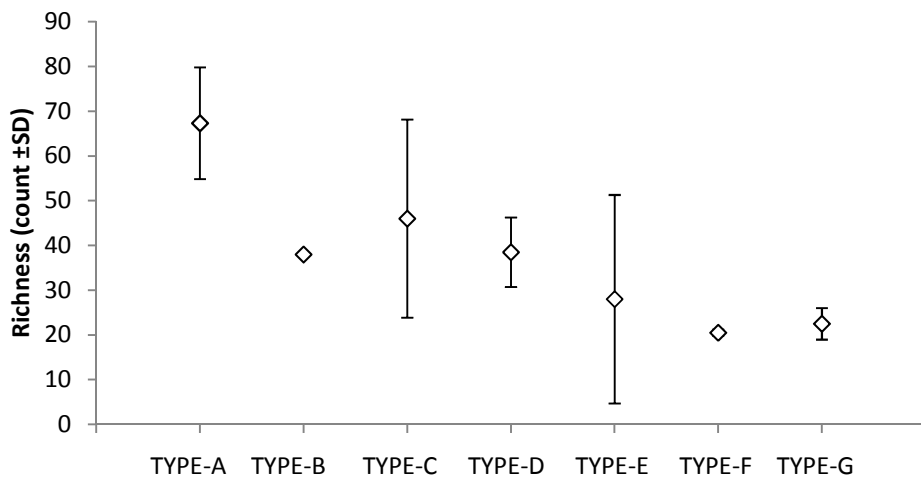
### Taxonomic richness

A discernible positive relationship was evident between assemblage density and taxonomic richness. We estimated taxonomic richness as the total number of sessile and motile taxa recorded by site, calculated on presence-absence biological data excluding bulk groups (i.e. not sorted to taxa level, meaning species or OTU). Average

richness by site was highest for sites classified as Type A assemblages and decreased towards sites of lower density (Figure A12.4). Similarly, the average number of taxa restricted to a site was greatest at Type A and Type C sites (Figure A12.5). These relationships suggest that higher densities of sessile invertebrates, and thus structural complexity, give rise to richer biological communities that in turn, support unique taxa characterised by limited distributions.

Species-accumulation plots for the individual sampling sites demonstrate that we have sampled a considerable proportion of the local megabenthos diversity likely to be present, although increased sampling in all geophysical types is likely to increase the total number of benthic taxa estimated in the current study (Figure A12.6).

Apparent endemic taxa identified so far by taxonomic experts include *Trachythyone* spp. (Holothuroidea), *Psolus* spp. (Holothuroidea) and *Pentametrocrinus* spp. (Crinoidea). Both holothurians occurred around 500 meters on the Canyon and Shelf in limited numbers ( $n_{\text{taxa}} = 3$  per species), and the feather star, *Pentametrocrinus* spp., was restricted to the depths of the Plateau, again in limited numbers ( $n_{\text{taxa}} = 3$ ).



**Figure A12.4.** Average taxonomic richness by assemblage type ( $\diamond$ ) ( $\pm$ SD). Richness by site was calculated on presence-absence biological data for all reliably identified motile and sessile taxa collected in the codend of the beam trawl.

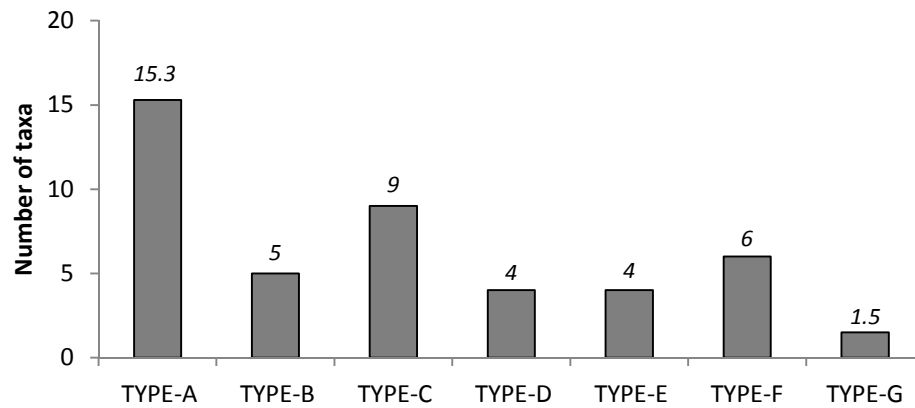


Figure A12.5. Average number of site-restricted motile and sessile taxa (i.e. those taxa restricted to one assemblage type) calculated from biological sample data.

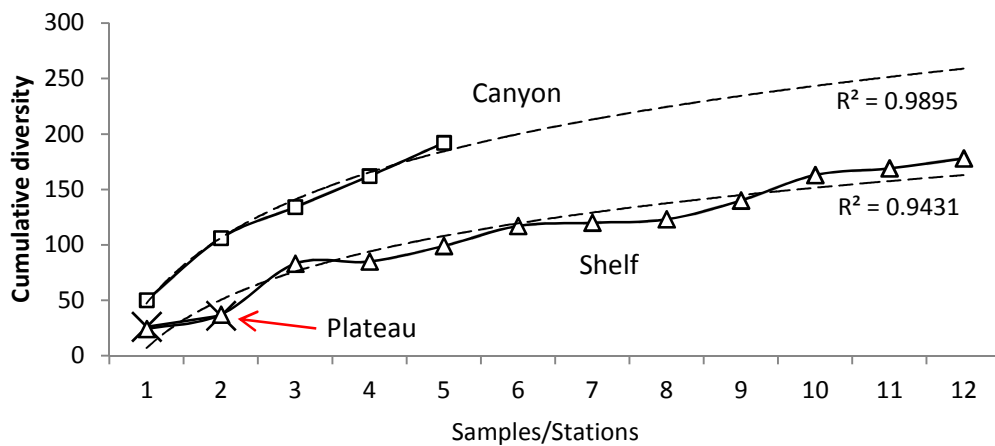


Figure A12.6. Species-Accumulation plots of pooled biological sample data at the three areas of investigation. A logarithmic regression (dashed line) of pooled data indicates the expectation of encountering additional species given further sampling. Symbols denote Canyon ( $\square$ ), Shelf ( $\Delta$ ) and Plateau ( $\times$ ).

### Patchiness

Noting the potential confounding effects of sampling depth (see below), and the relatively low numbers of samples, the coefficient of variation (CV) of total density across images within sites (considered an indication of habitat patchiness), was significantly negatively correlated with log-transformed density values ( $F_{2,16} = 15.03$ ,  $P < 0.05$ ). This result confirms what was seen in the images that generally lower density habitats were made up of patches of biota, whereas high density locations, such as the Canyon sites showed near to complete coverage of the field of view by epifauna at most sites.

## Physical correlates of community patterns

### Depth

A regression analysis comparing density, estimated from digital images, of sessile, structure-forming invertebrates with depth revealed a significant negative relationship ( $p = 0.002$ ) (Figure A12.7). Those assemblages characterised by greater densities of sessile taxa, like Type A to C, were typically found shallower than 800 m, whereas low density assemblages depauperate of benthos, like Type F and G, were generally observed deeper than 1000 m (Figure A12.8). A discernible relationship was also observed between taxonomic richness, as derived from biological samples, and depth. With the exception of SB<sub>4</sub>, which was impacted by gear failure, taxonomic richness declined rapidly from 400 – 800 m depth (Figure A12.9).

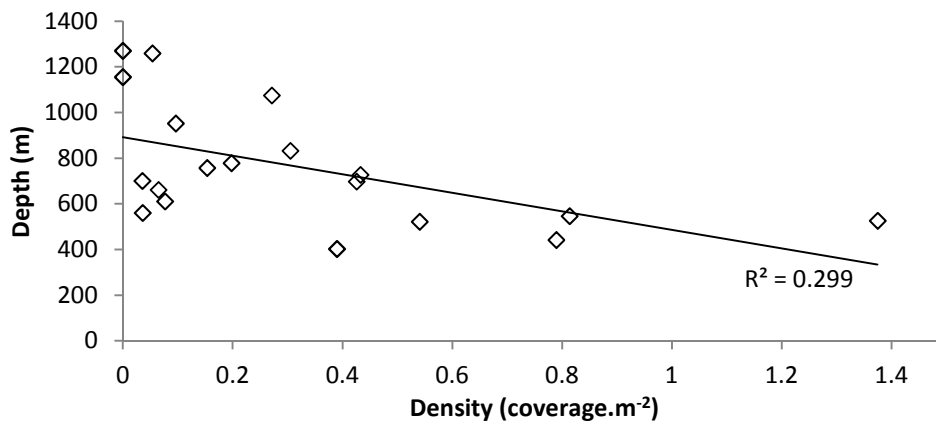


Figure A12.7. Relationship between depth and total density of sessile animals by site (◇). Linear regression is significant at  $p < 0.05$ .

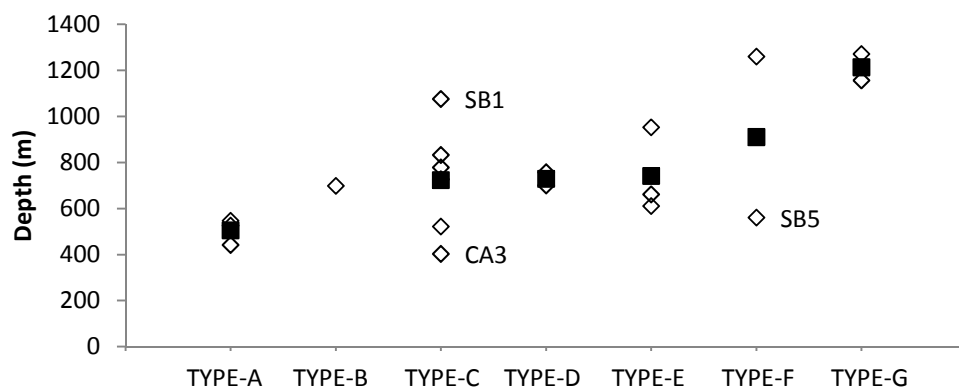


Figure A12.8. Relationship between depth and assemblage type. Depth is displayed by site (◇) and averaged across sites by assemblage (■).

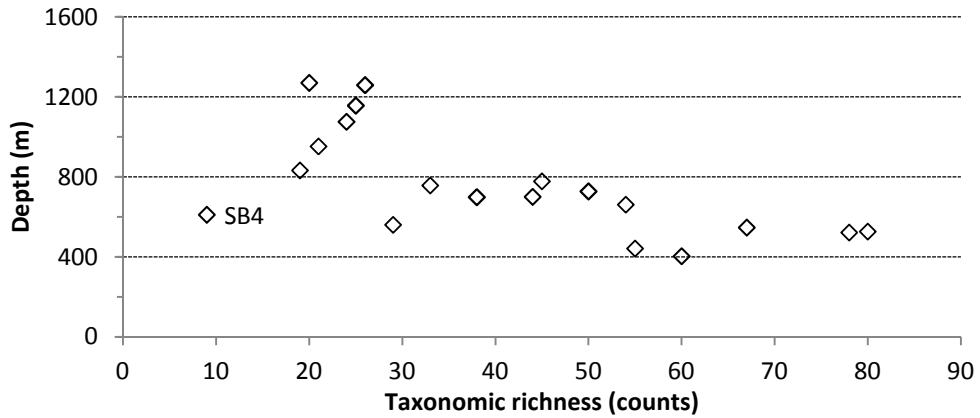


Figure A12.9. Relationship between depth and taxonomic richness by site (◊) calculated on presence-absence biological data. The low taxonomic richness observed at site SB<sub>4</sub> was due to gear failure.

### Substrate

Comparison of the breakdown of camera frames including substrate types against density by site, showed high densities of sessile structure forming taxa were strongly associated with rock or boulder substrates (Figure A12.12), and generally, low density sites were characterised by unconsolidated sand or mud substrates.

The similarity of Type C sites despite large differences in depth may also be related to substrate. Unlike the predominately deep, sandy/muddy sites on the shelf, rocky outcrops were frequently observed at SB<sub>1</sub>, suggesting that at such depths, diverse benthic assemblages can develop if sufficient hard substrate is available.

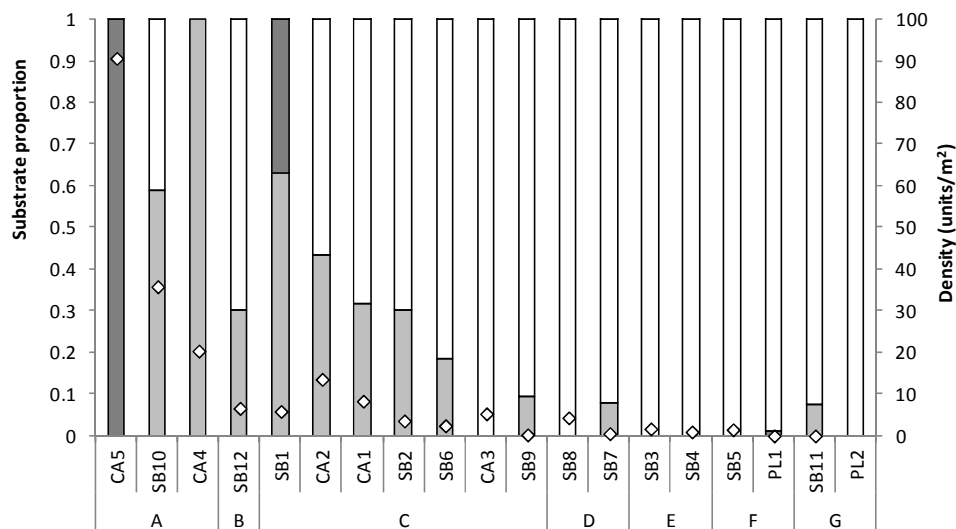


Figure A12.12. Density values of sessile, structure-forming invertebrates by site and assemblage derived from digital images, corrected for visual swept area (m<sup>2</sup>) summed within site (◊) and the proportion of the swept area spent on sand/mud (white bars) rocky substrate (light grey bars) and cobble substrate (dark grey bars). Site codes refer to Plateau (PL), Shelf (SB) and Canyon (CA).

## Discussion

It is apparent from the trawl and video sampled samples collected in this study that the highest densities of sessile, structure-forming epibenthic megafauna such as the sponges, alcyonarians, hydroids and encrusting invertebrates (bryozoans and/or hydrocorals) were generally encountered in shallower waters (400 – 800 m) on hard substrates, typically associated with rock and boulder bed-forms, which were most prevalent on steeper and shallower sites.

The highest densities of epibenthic megafauna in the Type A assemblage, were associated with complex bed forms that were both shallow (~500 m), relatively steep and had significant proportions of hard substrate, like at the head of the Canyon and on shallow Shelf terrain. Moderate density assemblages, Type B and C, were broadly distributed between 400 – 1000 m at both the Canyon and Shelf sites with lower proportions of hard substrate, highlighting the importance of rock and boulder bed-forms to benthic productivity. The low density assemblages (Types C to E), characterised by invertebrates with a lower profile growth form, particularly alcyonarians and encrusting invertebrates, were encountered in Shelf waters generally at depths around 700 m. Below 1000 m, the seabed was primarily characterised by sand and mud with infrequent drop stones dispersed across a uniform, flat bed-form. This lack of topographic complexity and hard substrate, combined with an apparent relationship of decreasing biodiversity with depth, has led to a generally depauperate benthos, with occasional patches of high density observed where hard substrate is available. Consequently, if we can assume that similar taxa have similar resistance and resilience to disturbance across depths and substrates, then fishing demersal gear in depths less than 800 m, or on consolidated substrates is more likely to encounter vulnerable epibenthic assemblages than in deeper water on mud or sand in this region. However we also noted that all types showed site restricted taxa, indicating that all assemblage types encountered have important conservation values to consider in managing the impacts of disturbance to benthos in East Antarctica.

As has been observed by other studies depth and substrate are important covariates of benthic assemblage structure. Results presented here for the canyon sampled support prior observations that suggest that benthic assemblages associated with canyon features may contain greater diversity and biomass than low relief seafloor at equivalent depth (De Leo *et al.* 2010, Ramirez-Llodra *et al.* 2010, Schlacher *et al.* 2007). These complex topographic features are often associated with oceanographic features such as accelerated currents, dense-water cascades and altered patterns of sediment transport and accumulation (Garcia *et al.* 2008, Oliveira *et al.* 2007). Such conditions often lead to concentrations of productivity within canyon habitats (Canals *et al.* 2006, Genin 2004). This may in turn be responsible for enhanced benthic productivity, particularly for those sessile, suspension feeders that rely on the availability of suspended organic matter (Schlacher *et al.* 2007, Vetter *et al.* 2010). Such biodiverse systems are likely to be particularly vulnerable to destructive fishing practices (bottom



trawling and longlining) and ocean acidification caused by anthropogenic climate change, and therefore, should be considered areas likely to support high conservation value assemblages. Noting the relatively limited samples in this study, and the lack of replication across features such as canyons, a priority for future research would be to develop models that can better predict the factors that lead to the patterns of biodiversity in the Southern Ocean, and assist with ensuring current management practise minimise the risk of unsustainable impacts on deep sea benthos.

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## Appendix 13      Assessing the resistance of vulnerable benthic taxa to disturbance from demersal fishing in the HIMI region

Graeme Ewing, Ty Hibberd and Dirk Welsford

### **ABSTRACT**

The vulnerability of taxa is predicated on the nature of the disturbance to which they are exposed. Resistance to a disturbance describes the degree to which taxa will be damaged or killed on the basis of intrinsic morphological and behavioural features. The sequence of events experienced by an individual residing in the footprint of a demersal fishing gear was used to derive a model to estimate the probability of each of the possible outcomes of an interaction (i.e. surviving unharmed, sustaining sub-lethal damage, and removal or lethal damage). The variables governing these outcomes were then estimated on the basis of the resistance of vulnerable benthic taxa to the gears used in the demersal toothfish fishery in the Heard Island and McDonald Islands (HIMI) region. Estimates were based on available data, including known life history and morphological attributes; measurements, observations and manipulation of benthic specimens from research sampling and fishery bycatch; published literature; expert opinion; and *in situ* observations of biological specimens from camera footage collected in the region. Also considered was the likelihood that sub-lethal damage from a fishing event will increase the probability of lethal damage or removal in successive fishing events. Plausible upper and lower limits of resistance were also estimated to allow testing of the sensitivity of predicted mortality to resistance levels.

## Introduction

The vulnerability of, and impact to, benthic ecosystems from interactions with demersal fishing gear will depend on the resistance and resilience of those systems. In the context of this study, resistance is the ability to withstand interactions with bottom fishing gear and will be dependent on the morphological and behavioural attributes of individual taxa (Constable & Holt 2007, Thrush & Dayton 2002) and on the characteristics of the gear imposing an interaction (Kaiser *et al.* 2006). Resilience is the ability of the ecosystem to recover structure and function following changes caused by bottom fishing activities. Many of the most common vulnerable benthic taxa in the Heard Island and McDonald Islands (HIMI) and East Antarctic regions identified in Appendices 5 and 12 display life history traits that may result in recovery from disturbance of the order of tens or hundreds of years.

The HIMI fishery is comprised of demersal fishing (primarily trawl and longline, with some experimental potting) targeting Patagonian toothfish (*Dissostichus eleginoides*) and demersal and pelagic trawling for mackerel icefish (*Champsocephalus gunnari*). The fishery has been in operation since 1997 when exploratory trawl fishing commenced. Demersal longlining was introduced in 2003, and there are a number of proposals by Australian fishers to further develop their distant-water fishing capability with longlines in the Australian EEZ near the Antarctic Continent. As a result there is a need to assess the potential for interaction of demersal fishing gears on benthic habitats in this region.

Mobile fishing gears that capture target species by moving across the seafloor, such as benthic dredges and demersal trawls, may cause serious disturbance to benthic ecosystems, which may result in a reduction in heterogeneity of biological and physical habitats (Clark & Rowden 2009). Static fishing gears such as demersal longlines have been less well studied, however they have been shown to may move across the seafloor on retrieval (United Kingdom 2010, Welsford & Kilpatrick 2008) and may cause line shearing and hooking interactions with benthic invertebrates (Appendix 10).

The resistance of a taxon, that is its ability to resist change as a consequence of being exposed to a disturbance, may be different for each of the components and nature of interaction with bottom fishing gears. Consequently, assessment of the impact of demersal fishing operations in the HIMI region requires estimates of taxa-specific resistance to each component of the gears deployed in the demersal fishery to allow prediction of the mortality of vulnerable benthic taxa from fishing operations in the region.

The aim of this analysis is to estimate taxa-specific resistance for interactions with each of the components of the gears used in the HIMI demersal fishery, and to estimate the probability of no damage, sub-lethal damage, or lethal damage from an interaction with a demersal fishing gear.

## Methods

### Estimating the probability of interaction

An organism (an individual or a colony) has the potential to interact with a component of fishing gear when its position lies within the swept area of that component. The outcomes of an ensuing interaction are governed by:

1. The probability that it will be unable to evade the interaction. This is a function of the motility or attachment of the individual.
2. If unable to evade the interaction, the probability that it will connect with the gear. This is a function of the morphology of the individual (e.g. height above the seafloor, relative to the gear being fished on or near the bottom).
3. If a connection with the gear occurs, the probability that it will be undamaged, or sustain sub-lethal or lethal damage from the connection. This is a function of the structure of the individual (e.g. brittleness).

Consequently, we estimated the probabilities of each outcome, death ( $M$ ), sub-lethal damage ( $D$ ) or unharmed ( $U$ ), for organism of a given taxon that reside in the swept area of a given component of fishing gear as:

$$= a \times h \times m \quad 1)$$

$$D = a \times h \times d \quad 2)$$

$$U = 1 - (M + D) \quad 3)$$

where  $a$  is the probability of being unable to evade the gear,  $h$  is the probability that the morphology of the individual will result in a connection with the gear,  $m$  is the probability that the ensuing connection will result in death, and  $d$  is the probability that it will result in sub-lethal damage.

For individuals exposed to two sequential fishing events with gear components  $c_1$  followed by  $c_2$ , the probabilities of each outcome are:

$$M_{c_1+c_2} = M_{c_1} + (U_{c_1} \times M_{c_2}) + (D_{c_1} \times M_{c_2} \times s) \quad 4)$$

$$D_{c_1+c_2} = D_{c_1} + (U_{c_1} \times D_{c_2}) - (D_{c_1} \times M_{c_2} \times s) \quad 5)$$

$$U_{c_1+c_2} = 1 - (M_{c_1+c_2} + D_{c_1+c_2}) \quad 6)$$

where  $s$  is a factor greater than one to reflect an increased probability of mortality from a second interaction due to sub-lethal damage in the first interaction.

For an individual residing in the swept area of more than one or more successive fishing events ( $n \geq 1$ ) of the same gear component (e.g. overlapping trawl events in an area of concentrated trawl activity), the probabilities of each outcome are estimated as:

$$M_n = \begin{cases} M & \text{for } n = 1 \\ M_{n-1} + (U_{n-1} \times M) + (D_{n-1} \times M \times s) & \text{for } n > 1 \end{cases} \quad 7)$$

$$D_n = \begin{cases} D & \text{for } n = 1 \\ D_{n-1} + (U_{n-1} \times D) - (D_{n-1} \times M \times s) & \text{for } n > 1 \end{cases} \quad 8)$$

$$U_n = 1 - (M_n + D_n) \quad 9)$$

As  $m \times s$  exceeds 1 where  $m > 1/s$  (for example for serpulids and bryozoans in this analysis) for those taxa  $m \times s$  was set at maximum of 1 for calculating  $D$  and  $M$  for  $n > 1$ .

### Identifying key benthic taxa

Bycatch records that include invertebrates have been collected by observers since 1997 on all vessels fishing at HIMI, and so this data was summarised in attempt to identify the key taxa that are vulnerable to removal by demersal trawl and longline gear that may not have been detected in scientific sampling described in Appendix 6.

### Estimating resistance

For each of these taxa vulnerable to interactions with demersal gears, a range of available data on morphology and structure was used to estimate their resistance to an interaction with each component of the demersal trawl and longline gears used in the HIMI toothfish fishery. The interactions considered are blunt interactions from trawls, and line shear and hook interactions from longlines. Estimates of resistance are the probability values  $a$ ,  $h$ ,  $m$  and  $d$ , and were derived by considering the role of the behaviour, morphology and structure of each taxon in the sequence of events that occur during an interaction. Information considered in estimating probability values included the CCAMLR Workshop on Vulnerable Marine Ecosystems report (WS-VME 2009), *in situ* camera footage, measurements and manipulation of specimens of taxa from research and commercial fishing curated at the AAD. A representative resistance value was estimated based on the most common morphology within a taxon at HIMI. Upper and lower limits were also assigned to allow sensitivity testing of resistance values within taxa (e.g. to capture the range of morphologies within a taxon, such as encrusting or arborescent forms).

## Results

### Identifying key benthic taxa

Bycatch quantities recorded by observers for trawls between 1996/97 and 2009/2010 are summarised in Table A13.1. Taxonomic resolution prior to 2009 was generally no lower than the phylum or class level, and in some instances, substantial quantities of 'unidentified invertebrates' were recorded by observers, which are likely to include a mixture of sessile and motile taxa (Figure A13.1). However, after the introduction of a field guide taxonomic resolution and accuracy has improved (Hibberd 2009).

Recent observations indicate the sessile taxa most commonly observed in trawl bycatch are demosponges, actinarians, alcyonarians, scleractinians, gorgonians and ascidians (Hibberd 2009). Despite being relatively common in scientific samples collected in and adjacent to trawled areas, serpulid worm cases and emergent bryozoans are largely absent from trawl catches. However, this is not unexpected as their brittleness makes it likely that they will fragment, and pieces would fall through the net mesh during fishing and net retrieval.

**Table A13.1. Invertebrate bycatch composition in demersal trawls in the Heard Island and McDonald Islands fishery, 1996/97-2009/10. Weights are rounded to the nearest 0.1 tonnes; 0.0 indicates the taxon was recorded, but total catch was less than 0.1 tonnes.**

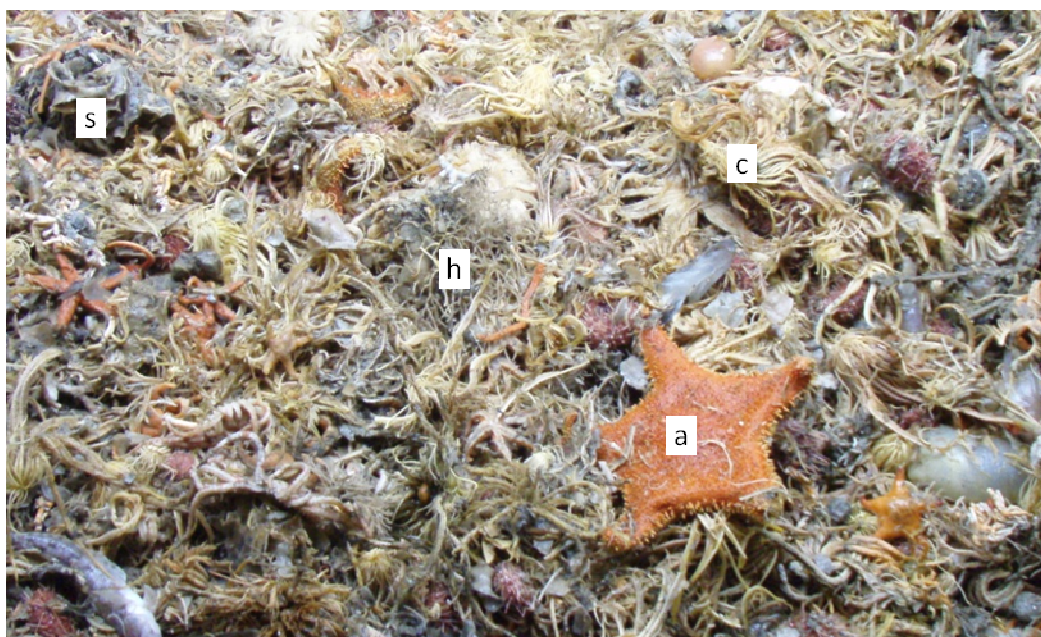
Season	Taxon						Total
	Sponges	Corals <sup>a</sup>	Sea stars and allies <sup>b</sup>	Anemones	Unspecified <sup>c</sup>		
1996/97	1.1	8	1.3	0.0	8.5	18.9	
1997/98	3.3	1.9	1.2	1.4	17.2	25	
1998/99	0.3	0.2	0.1	0.1	2.2	2.9	
1999/00	1.6	0.5	1	0.4	3.2	6.7	
2000/01	4.1	0.4	0.8	0.5	1.7	7.5	
2001/02	1.5	0.6	1.6	0.6	1.1	5.4	
2002/03	1.7	0.3	2.1	3.3	2.5	9.9	
2003/04	1.4	0.1	0.8	0.1	1.7	4.1	
2004/05	1.5	1.6	0.6	0.3	1.4	5.4	
2005/06	1.5	0.5	2.1	0.5	1.6	6.2	
2006/07	1	0.2	1.8	0.1	2.6	5.7	
2007/08	3.1	0.7	2.2	0.3	6.1	12.4	
2008/09	2.5	0.3	2.9	1.6	9.2	16.5	
2009/10 <sup>d</sup>	15.7	1	7.1	10.6	12.4	46.8	
Total	40.3	16.3	25.6	19.8	71.4	173.4	

<sup>a</sup>This group is likely to include gorgonian, alcyonarian and scleractinian corals, based on improved at-sea taxonomic discrimination within this group since 2009

<sup>b</sup>This group includes asteroids, crinoids and ophiuroids

<sup>c</sup>This group includes motile and sessile invertebrate taxa that were generally not identified to lower taxonomic levels prior to 2009/10.

<sup>d</sup>The majority of all invertebrate bycatch in this year derived from two Random Stratified Trawl Surveys conducted in April and September 2010. For example, 13.8 tonnes of sponges were caught in survey hauls.



**Figure A13.1.** Photograph of the typical make up of benthic invertebrate bycatch from the HIMI region, with motile taxa such as non-stalked crinoids (c) and asteroids (a) most abundant, as well as including sessile taxa such as sponges (s) and hydroids (h).

At the phylum level, bycatch recorded from longlines, although much less in quantity, comprised similar groups to those seen in trawls (Table A13.2). Studies of invertebrate bycatch by New Zealand vessels in Ross Sea toothfish longline fishery also indicates that actinarians, hydroids and demosponges (each above 20% of bycatch of vulnerable biota by weight observed retained at the surface) are also vulnerable to being hooked by longlines in that fishery (Tracey et al. 2010). Therefore, all of the common taxa modelled in Appendix 9 were considered likely to be encountered by trawls and longlines, and estimates of resistance were calculated for all of them (Table A13.3).

**Table A13.2.** Invertebrate bycatch composition in longline hauls in the Heard Island and McDonald Islands fishery by season. Catches are calculated for a season from 1 December to 30 November the following year and are rounded to the nearest 0.1 tonnes; 0.0 indicates the taxon was recorded, but total catch was less than 0.1 tonnes.

Season	Taxon		Total
	Seastars and allies <sup>a</sup>	Other <sup>b</sup>	
2002/03	0.0	0.0	0.0
2003/04	0.0	0.0	0.0
2004/05	0.0	0.0	0.0
2005/06	3.0	0.0	3.0
2006/07	0.5	0.0	0.5
2007/08	2.9	0.1	3.0
2008/09	4.2	0.1	4.3
2009/10	2.6	0.0	2.6
Total	13.2	0.2	13.4

<sup>a</sup> This group is likely to include asteroids, crinoids and ophiuroids

<sup>b</sup> This group includes a mix of sessile taxa including corals, anemones and sponges, as well as motile invertebrates such as crabs.

**Table A13.3. Common invertebrate taxa vulnerable to interactions with demersal fishing at HIMI analysed in this study.**

Phylum	Group Name	Taxon
Porifera	Sponges	Demospongiae
Cnidaria	Corals	Gorgonacea
		Alcyonacea
		Scleractinia
	Anemones	Actiniaria
	Hydroids	Hydrozoa
Annelida	Tube worms	Serpulids
Bryozoa	Lace corals	Bryozoa
Arthropoda	Barnacles	Cirripedia
Echinodermata	Sea lilies	Euryalida
	Sea urchins	<i>Ctenocidaris nutrix</i>
Hemichordata	Pterobranchs	Pterobranchia
Chordata	Sea squirts	Ascidiacea

### The probability of evading an interaction

All of the key vulnerable taxa from the HIMI were assigned a value of  $a = 1$  across all gear types, as they generally live permanently attached or embedded in the substrate, and therefore none are sufficiently mobile to evade fishing gear (Table A13.4).

### Influence of morphology on the probability of an interaction

The probability of interacting on the basis of the morphology of taxa is based on the typical distance that organisms protrude from the substratum into the water column, with consideration of the height at which the fishing gears operate. For example, the sweeps of demersal trawl gears may partially fly above the substrate, and rock hopper gear was observed to behave as designed, occasionally bouncing over rocks and boulders. Therefore, while even the most low profile organism will be exposed to interactions with the gear, organisms with tall and/or arborescent morphology were considered to be more likely to interact with the gear inside of the fishing footprint.

Gorgonians were the tallest taxa observed in the HIMI region and were assigned a value of  $h = 0.9$  across all gears (Table A13.4). The morphology of these taxa can be seen in Figure 13.2; similar morphotypes of the family Primnoidea (Figure A13.3) are captured at HIMI and can attain heights greater than 30 cm above the seafloor, and the bubblegum coral (*Paragorgia arborea*) that occurs in the region can exceed several metres in height.

Demosponges and hydroids were assigned a value of  $h = 0.7$  across all gears (Table A13.4) as they can attain heights above the seafloor of the order of 20 - 30 cm. Low profile forms such as Bryozoa, Cirripedia, Scleractinia, Serpulidae, and Pterobranchia were assigned medium values of  $h = 0.3-0.5$  for trawl interactions and values of  $h = 0.2-0.3$  for longline interactions to reflect their relative heights observed in biological samples and observed in camera footage (Table A13.4). Video footage of demersal trawling at HIMI in the main trawl grounds showed cobbles passing under the foot line



and boulders rolled along in front of the foot line showing signs of encrusting bryozoan colonies indicating that they may have a lower exposure to trawling than the other higher profile sessile invertebrates, and hence the bounds for this group includes  $h = 0.2$  up to  $0.8$  to capture this variability in form (Table A13.5).

Actiniaria were assigned  $h = 0.5$  in both trawl and longline interactions (Table A13.4) due to the observed distributions of actinarians in deeper areas with fine sediments where there is evidence of longlines moving through these fine substrata (Figure A13.3).

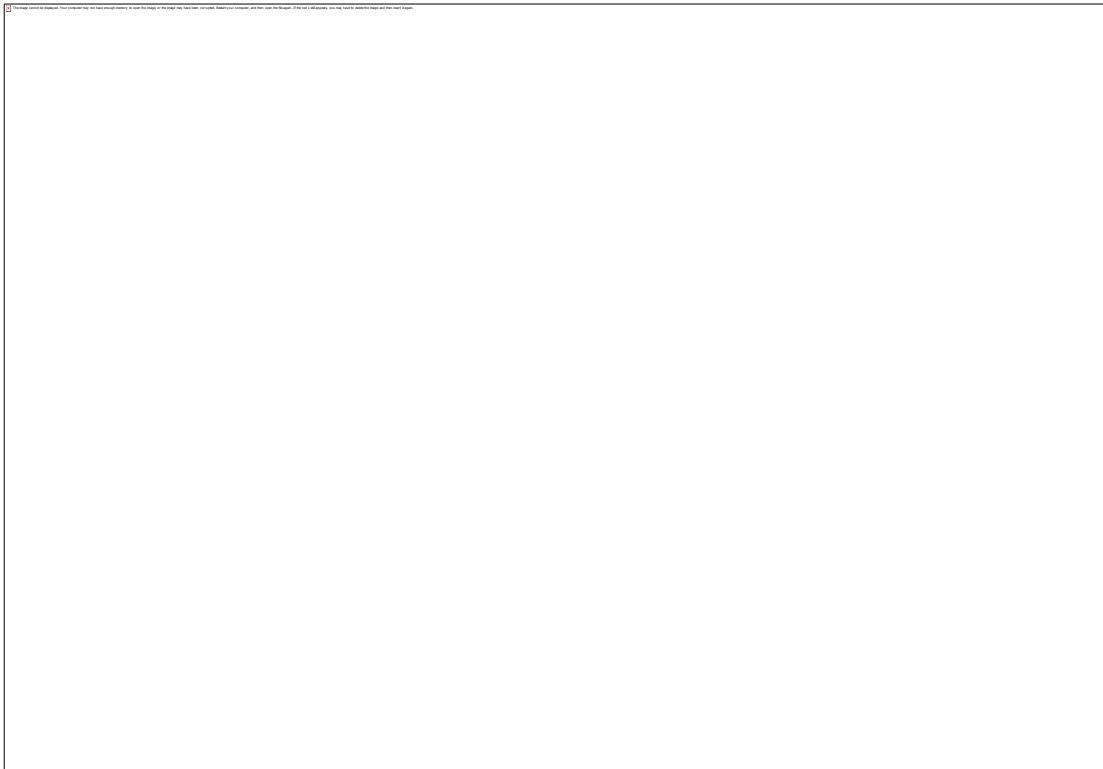


Figure A13.2. An example of an image from east Antarctica that was used to infer  $h$ , the probability that the morphology of an organism will result in an interaction with demersal fishing gear. Morphotypes comparable to those present at HIMI are (A) gorgonians, (B) demosponges, (C) bryozoans, (D) hydroids and (E) *Ctenocidaris nutrix* (pencil urchin)

Table A13.4: Assigned probabilities relating to the resistance of vulnerable taxa that are residing in the footprint of a demersal fishing event. The superscript <sup>1</sup> identifies taxa common in trawl bycatch and <sup>2</sup> common in longline bycatch.  $a$  = the probability of being unable to evade the fishing gear;  $h$  = probability of connecting with the fishing gear due to morphological features such as height above the seafloor;  $m$  = probability of dying from an interaction with the gear;  $d$  = probability of sub-lethal damage from an interaction with the gear;  $s$  = the probability of lethal damage as a result of sub-lethal damage in a prior fishing event;  $DT$  = demersal trawl;  $LN$  = mainline component of a longline interaction;  $HK$  = hook component of longline interaction.

Taxon		Trawl				Longline				$s$				
		$a_{DT}$	$h_{DT}$	$m_{DT}$	$d_{DT}$	$a_{LN}$	$h_{LN}$	$m_{LN}$	$d_{LN}$		$a_{HK}$	$h_{HK}$	$m_{HK}$	$d_{HK}$
Porifera	Demospongiae <sup>1,2</sup>	1	0.7	0.6	0.2	1	0.7	0.2	0.2	1	0.7	0.5	0.2	1.2
Cnidaria	Actinaria <sup>1,2</sup>	1	0.5	0.7	0.2	1	0.5	0.1	0.2	1	0.5	0.5	0.2	1.2
	Scleractinia <sup>1</sup>	1	0.5	0.5	0.2	1	0.3	0.1	0.2	1	0.5	0.3	0.2	1.2
	Alcyonacea <sup>1,2</sup>	1	0.5	0.7	0.2	1	0.3	0.1	0.2	1	0.5	0.5	0.2	1.2
	Gorgonacea <sup>1,2</sup>	1	0.9	0.8	0.2	1	0.9	0.3	0.2	1	0.9	0.5	0.2	1.2
	Hydroidolina	1	0.7	0.7	0.2	1	0.7	0.2	0.2	1	0.7	0.5	0.2	1.2
Annelida	Serpulidae	1	0.3	0.9	0.1	1	0.4	0.3	0.2	1	0.3	0.6	0.2	1.2
Bryozoa		1	0.5	0.9	0.1	1	0.3	0.3	0.2	1	0.3	0.6	0.2	1.2
Arthropoda	Cirripedia	1	0.5	0.9	0.1	1	0.3	0.3	0.2	1	0.3	0.6	0.2	1.2
Echinodermata	<i>Ctenocidaris nutrix</i>	1	0.6	0.5	0.2	1	0.2	0.1	0.2	1	0.2	0.2	0.2	1.2
	Euryalida	1	0.5	0.5	0.2	1	0.2	0.1	0.2	1	0.5	0.9	0.2	1.2
Hemichordata	Pterobranchia	1	0.4	0.6	0.2	1	0.2	0.2	0.2	1	0.3	0.5	0.2	1.2
Chordata	Ascidiacea <sup>1,2</sup>	1	0.5	0.6	0.2	1	0.5	0.2	0.2	1	0.5	0.5	0.2	1.2

Table A13.5: Assigned lower and upper probabilities relating to the resistance of vulnerable taxa that are residing in the footprint of a demersal fishing event.  $a$  = the probability of being unable to evade the fishing gear;  $h$  = probability of connecting with the fishing gear due to morphological features such as height above the seafloor;  $m$  = probability of dying from an interaction with the gear;  $d$  = probability of sub-lethal damage from an interaction with the gear;  $s$  = the probability of lethal damage as a result of sub-lethal damage in a prior fishing event;  $DT$  = demersal trawl;  $LN$  = mainline component of a longline interaction;  $HK$  = hook component of longline interaction.

Taxon		Trawl				Longline				$s$				
		$a_{DT}$	$h_{DT}$	$m_{DT}$	$d_{DT}$	$a_{LN}$	$h_{LN}$	$m_{LN}$	$d_{LN}$		$a_{HK}$	$h_{HK}$	$m_{HK}$	$d_{HK}$
Porifera	Demospongiae	1,1	0.5,1	0.5,0.8	0.1,0.2	1,1	0.7,1	0.1,0.3	0,0.3	1,1	0.7,0.8	0.4,0.6	0,0.3	1,1.5
Cnidaria	Actinaria	1,1	0.3,0.7	0.5,0.9	0.1,0.2	1,1	0.5,0.6	0.1,0.3	0,0.3	1,1	0.5,0.6	0.4,0.6	0,0.3	1,1.5
	Scleractinia	1,1	0.3,0.6	0.3,0.6	0.1,0.4	1,1	0.3,0.4	0.1,0.3	0,0.3	1,1	0.5,0.6	0.2,0.4	0,0.3	1,1.5
	Alcyonacea	1,1	0.3,0.6	0.5,0.8	0.1,0.2	1,1	0.3,0.5	0.1,0.3	0,0.3	1,1	0.5,0.6	0.4,0.6	0,0.3	1,1.5
	Gorgonacea	1,1	0.5,1	0.5,0.9	0.1,0.2	1,1	0.9,1	0.2,0.5	0,0.3	1,1	0.8,1	0.4,0.6	0,0.3	1,1.5
	Hydrozoa	1,1	0.5,0.8	0.6,0.8	0.1,0.2	1,1	0.5,0.8	0.1,0.3	0,0.3	1,1	0.6,0.8	0.5,0.9	0,0.3	1,1.5
Annelida	Serpulidae	1,1	0.2,0.4	0.7,1	0.1,0	1,1	0.4,0.5	0.2,0.4	0,0.3	1,1	0.3,0.5	0.5,0.7	0,0.3	1,1.5
Bryozoa		1,1	0.2,0.8	0.2,1	0.1,0	1,1	0.3,0.5	0.2,0.4	0,0.3	1,1	0.3,0.5	0.5,0.7	0,0.3	1,1.5
Arthropoda	Cirripedia	1,1	0.3,0.6	0.3,0.6	0.1,0.4	1,1	0.3,0.4	0.2,0.4	0,0.3	1,1	0.3,0.5	0.5,0.7	0,0.3	1,1.5
Echinodermata	Pencil urchin	1,1	0.4,0.7	0.4,0.8	0.1,0.2	1,1	0.2,0.3	0.1,0.2	0,0.3	1,1	0.2,0.3	0.1,0.3	0,0.3	1,1.5
	Euryalida	1,1	0.3,0.6	0.4,0.8	0.1,0.2	1,1	0.2,0.3	0.1,0.2	0,0.3	1,1	0.5,0.5	0.7,1	0,0.3	1,1.5
Hemichordata	Pterobranchia	1,1	0.2,0.5	4,0.8	0.1,0.2	1,1	0.2,0.3	0.1,0.3	0,0.3	1,1	0.3,0.4	0.4,0.6	0,0.3	1,1.5
Chordata	Ascidiacea	1,1	0.3,0.9	0.4,0.8	0.1,0.2	1,1	0.5,0.8	0.1,0.3	0,0.3	1,1	0.4,0.7	0.3,0.7	0,0.3	1,1.5

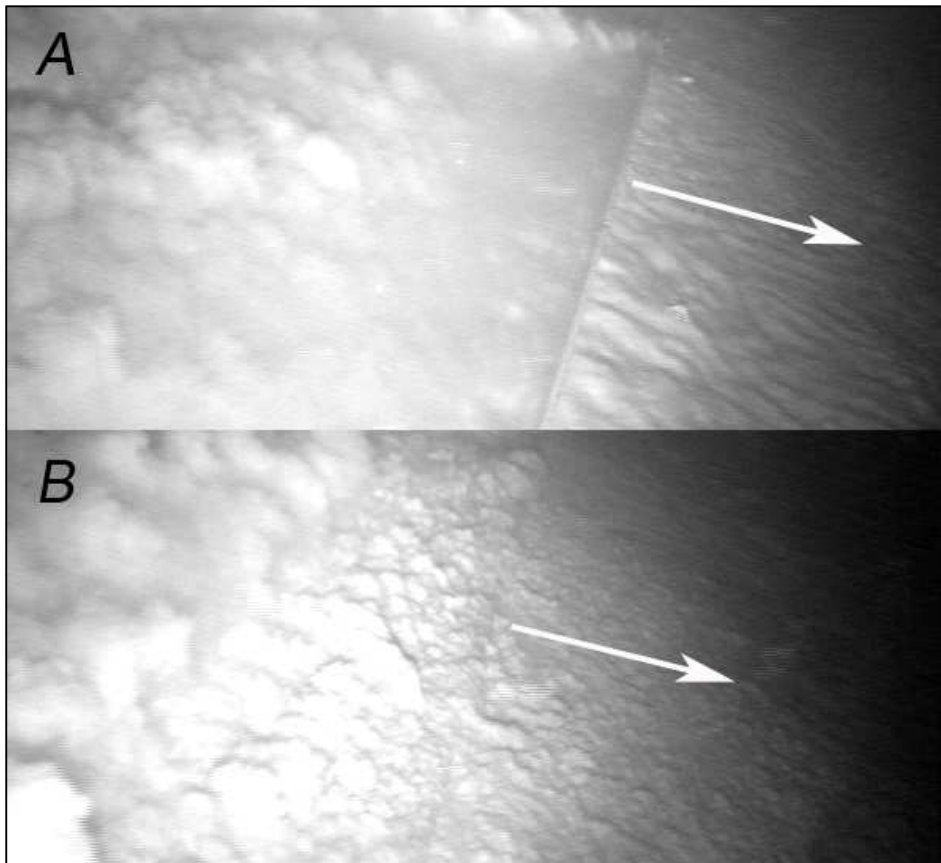


Figure A13.3. Frame from video footage of longline: A) moving across the surface of fine sediments and B) through the substratum. White arrows indicate the direction of movement of the line.

### Interactions with demersal trawl gear

The analysis in Appendix 9 suggests that demersal trawl nets deliver a range of heavy forces to the seafloor during fishing activities from the footline, sweeps and other ground gear. These include heavy blunt forces from the bobbins, doors, ground chains and lines, which are often in contact with seafloor under considerable downwards pressure, and which can smash, dislodge or displace taxa. The scouring force delivered by the trawl and/or chaffing mesh panels can dislodge animals, grind motile species, scour and overturn rocks, suspend and redistribute sediment.

Chitinous or calcareous brittle taxa including gorgonians, serpulids and bryozoans were assigned high probabilities of mortality ( $m_{DT} = 0.8-0.9$ ) from trawl interactions due to their brittleness (Table A13.4, Figure A13.4). Specimens of these taxa in beam trawl and demersal trawl bycatch samples are almost always fragmented (Figure A13.3) and laboratory specimens cracked and broke without deforming when manipulated. In encompassing the range of morphotypes in these taxonomic groups, a lower limit of  $m$  for these taxa ranged from 0.4 for more resistant species (encrusting bryozoans like *Buffonellodes* spp.) to 0.5 (more flexible gorgonian species), and upper limits of 0.9 for all three groups due to highly brittle species encountered in biological samples from

HIMI (e.g. lace coral, *Smittina anecdota* (Bryozoa) and bubblegum coral, *Paragorgia arborea* (Gorgonacea)) (Figure A13.3; Table A13.5).

Taxa of lower brittleness including alcyonarians, ascidians, hydroids, actinarians and scleractinians (noting that the majority of scleractinians at HIMI are unattached solitary forms like *Flabellum* spp.) were also assigned relatively high probabilities of mortality ( $m_{DT}=0.6-0.7$ ) (Figure A13.4). These taxa were occasionally intact in benthic samples and allow moderate deformation prior to cracking or tearing when manipulated. Consequently we estimated lower limits for  $m_{DT}$  for these taxa ranging from 0.4 (accounting for relatively tough, encrusting ascidians like *Styela nordenskjoldi*) to 0.5 (accounting for small actinarians like *Endongaria* spp.), and high upper limits to account for larger, softer non-colonial species (e.g. stalked ascidians, *Sycozoa sillinoides*) (Table A13.5).

Intact colonies of demosponges and pterobranchs are regularly encountered in benthic samples and specimens deform considerably prior to tearing when manipulated due to their spongy or chitinous skeleton. Due to these characteristics these taxa were assigned  $m_{DT}$  values of 0.6 (Table A13.4).

Motile groups including euryalid ophiuroids and the echinoid *Ctenocidaris nutrix* were assigned  $m_{DT}$  values of 0.5 (Table A13.4), with a wide range of upper and lower values to account for size variations (Table A13.5).

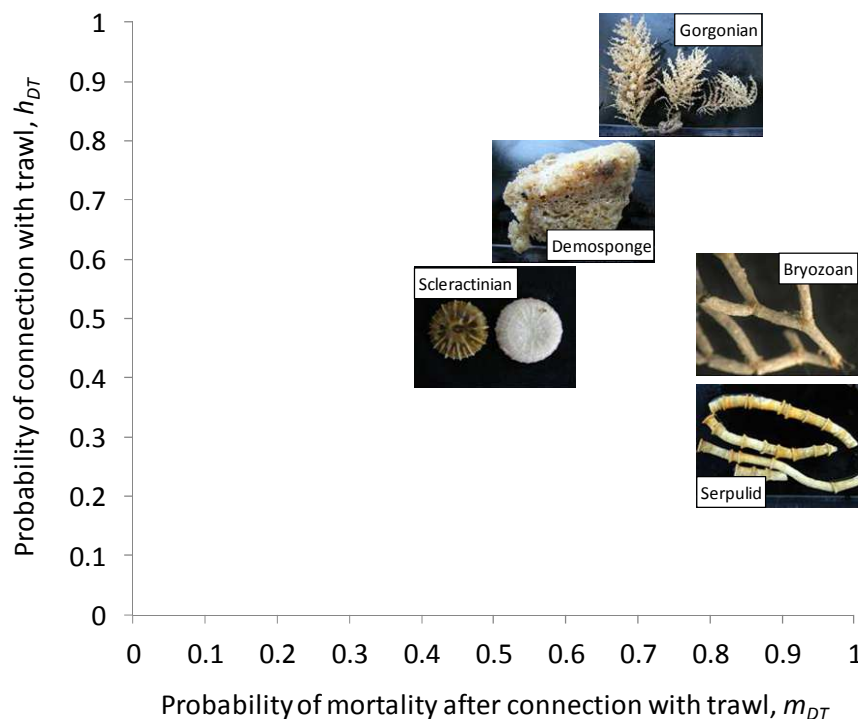


Figure A13.4 Contrast in the values of  $h$  (probability of connection gear within the demersal trawl footprint) and  $m$  (probability of mortality after connection with trawl gear) estimated for different invertebrate taxa encounter at HIMI based on characteristics such as their morphology, height above the seafloor and their brittleness/deformability. Images are approximately centred on the  $m$  and  $h$  values for the respective taxa in Table A13.4.

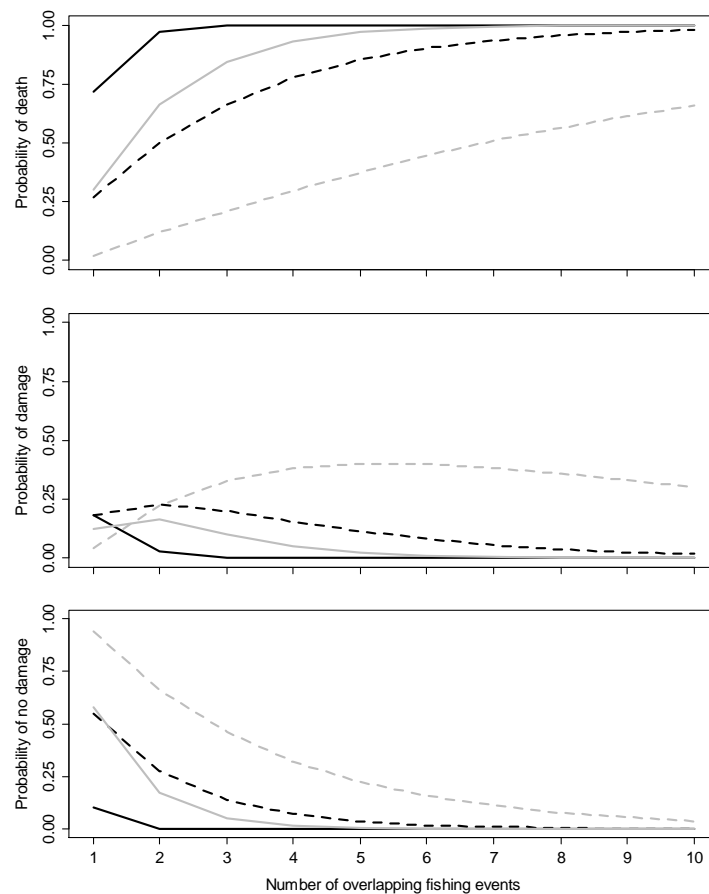
If an individual is in contact with a trawl net and is not removed or lethally damaged, there is a high probability that it will be sub-lethally damaged, estimated as  $d_{DT}$ . Reports of damaged sessile invertebrates in areas exposed to demersal trawling are common in the literature (Grehan *et al.* 2005, Heifetz *et al.* 2009, Kenchington *et al.* 2006). At HIMI, for example, broken spines on *C. nutrix*, and arms of euryalids (e.g. the basket star *Gorgonocephalus chilensis*), are observed in trawl bycatch, and such damage alone is unlikely to result in immediate death. However, the proportion sub-lethally damaged is likely to vary by taxa, and collecting data to estimate this parameter is very difficult. In this study we chose a value of  $d_{DT}$  set at 0.2, with the exception of taxa with an  $m_{DT}$  probability above 0.8, for which a probability was assigned to ensure survival entailed sub-lethal damage (i.e.  $d_{DT} = 1 - m_{DT}$ ). Lower and upper probabilities of  $d_{DT}$  included zero to reflect that nearly all of such organisms interacting with trawl gear would die or sustain some sub-lethal damage (Table A13.5).

A sub-lethally damaged individual may also have lowered resistance if exposed to another fishing interaction. As there are numerous overlapping trawl fishing events in the main trawling grounds of the HIMI region, it is necessary to consider variation in  $m_{DT}$  in successive fishing interactions. The variable  $s$  was set at 1.2 to have the effect of increasing by 20% the probability that a surviving, but sub-lethally damaged, individual will die in a succeeding interaction. Lower and upper probabilities of  $s$  were assigned at zero effect ( $s = 1$ ) and 1.5 respectively.

Applying the probabilities assigned in Table A13.4 and the formulae above, the probability of death from a single interaction with a demersal trawl ranged from 0.24 for pterobranchs to a maximum of 0.72 for gorgonians (Table A13.6). For two and three successive trawl interactions, probabilities of death or sub-lethal damage exceed 0.8 and 0.9 respectively for all taxa, with less than 0.01 probability of a gorgonian surviving a third trawl interaction ( $M_3=0.99$ ), and a probability of 1 of either being damaged or dead after two interactions (Table A13.6, Figure A13.4). More resistant taxa like pencil urchins are predicted to reach greater than 0.95 probability of mortality after 5 interactions, although with a rapid increase in probability of sub-lethal damage for lower numbers of interactions (Figure A13.5).

**Table A13.6. Estimated probabilities of mortality ( $M$ ) and sub-lethal damage ( $D$ ) to benthic invertebrates after 1, 2 and 3 overlapping demersal trawls, and the minimum number of hauls for  $M$  to exceed 0.95.**

Taxon	$M_1$	$D_1$	$M_2$	$D_2$	$M_3$	$D_3$	Minimum trawls for $M_n > 0.95$
Demospongiae	0.42	0.14	0.78	0.13	0.93	0.05	4
Actinaria	0.35	0.10	0.82	0.13	0.96	0.03	3
Scleractinia	0.25	0.10	0.64	0.17	0.83	0.11	5
Alcyonacea	0.35	0.10	0.82	0.13	0.96	0.03	3
Gorgonacea	0.72	0.18	0.97	0.03	1.00	0.00	2
Hydroidolina	0.49	0.14	0.87	0.10	0.97	0.02	3
Serpulidae	0.27	0.03	0.93	0.07	1.00	0.00	2
Bryozoa	0.45	0.05	0.95	0.05	1.00	0.00	2
Cirripedia	0.45	0.05	0.95	0.05	1.00	0.00	2
<i>Ctenocidaris nutrix</i>	0.30	0.12	0.66	0.16	0.85	0.10	5
Euryalida	0.25	0.10	0.64	0.17	0.83	0.11	5
Pterobranchia	0.24	0.08	0.71	0.16	0.90	0.07	4
Asciacea	0.30	0.10	0.73	0.15	0.91	0.07	4



**Figure A13.5. The estimation of probability that an invertebrate with relatively high resistance (pencil urchin, *Ctenocidaris nutrix*, grey lines) or relatively low resistance (gorgonian, black lines) residing in the swept area of successive overlapping demersal trawl events (solid lines) and successive overlapping longline events (dashed lines) will die (top), survive in a damaged state (middle) or survive unharmed (bottom).**

### Interactions with demersal longlines-mainline

The analysis of *in situ* video footage of longline deployments and theoretical analysis of line tension on the seafloor, suggest that line movement is likely and that the extent and direction of line movement will vary between fishing events. As there is limited published literature on the effects of moving longlines on sessile invertebrate species, the ratings assigned for line shear interactions are based on observations captured in video footage during this project (Table A13.7), and on knowledge of the behaviour and morphology of the taxa.

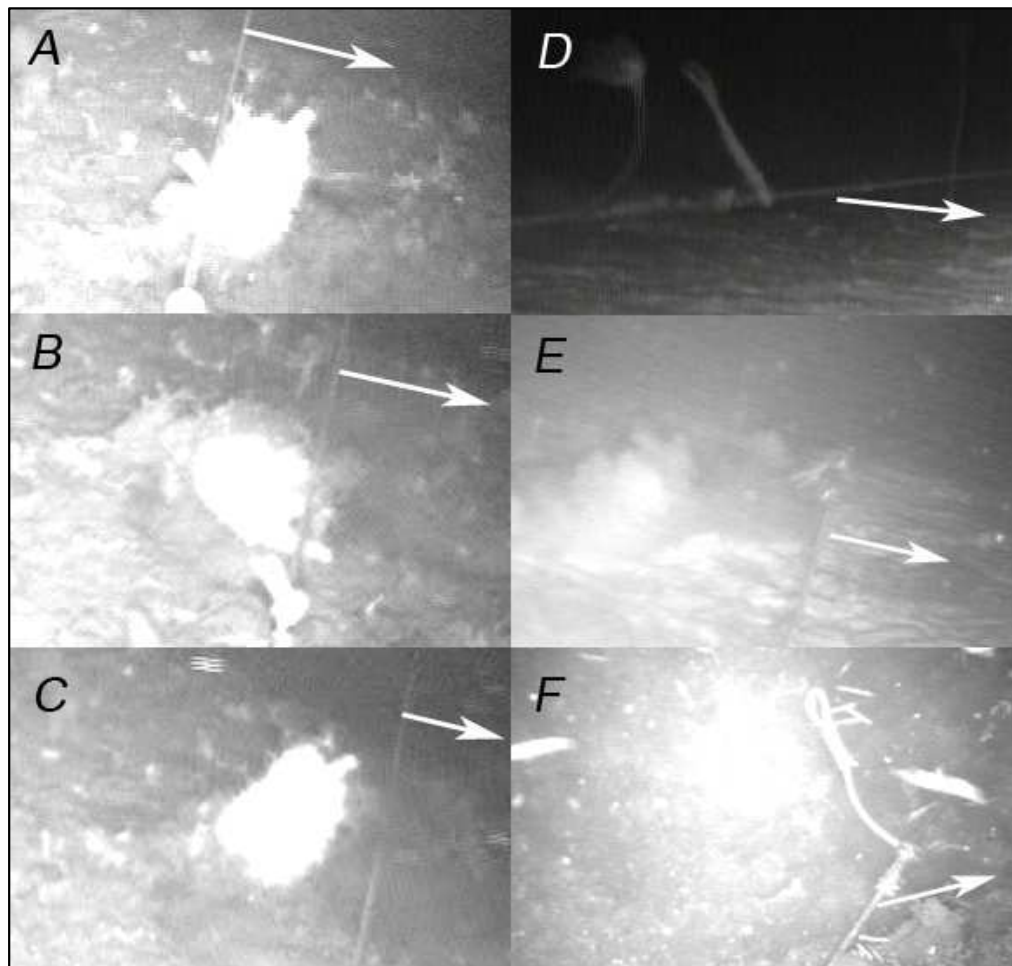
Of the 26 longline fishing retrieval events in which line movement was captured on video, 34 vulnerable invertebrate taxa passed within the visual field of the camera. Of those observations, a moving longline was seen to pass over 8 individuals (all sea pens) (Table A13.7). The scarcity of vulnerable benthic megafauna and interactions observed in commercial fishing deployments is apparently due to the paucity of the deeper habitats where longlining is generally undertaken at HIMI (Appendices 6 and 9). In footage of lateral longline movement in commercial fishing deployments, on 4 occasions the line was seen to move through the substratum for distances greater than 2 m (Figure A13.4). This only occurred when the line appeared to be under high tension and the substrate was fine sediment.

Camera footage of research longlines set in more complex habitats in East Antarctica, from research deployments from the *Aurora Australis* (Appendix 12), yielded observations of line interactions for serpulids, hexactinellids (glass sponges), alcyonarians, and pennatulaceans (sea pens) (Table A13.7). Sponges were observed to deform and pass under simulated longline retrieval. Sponge structure was not obviously damaged, but deflection was seen to cause partial detachment from the substrate causing some deformation (Figure A13.6). Pennatulaceans were also seen to survive interactions with moving longlines (Table A13.7) although in half of the interactions observed they were completely detached from the substrate by the interaction (Figure A13.6). Consequently, soft bodied, spongy or chitinous actinarians were assigned  $m_{LN}$  values of 0.1 (Table A13.4), and upper and lower limits of 0.1 to 0.3 (Table A13.5). Similarly, as echinoderms such as *Ctenodaris* and euryalids are unattached and therefore have the potential to be rolled out of the way by the longline, they were assigned a value of  $m_{LN}$  of 0.1 and lower and upper limits of 0.1 and 0.2.



**Table A13.7. Summary of observed interactions between longline and benthic taxa from video cameras mounted on commercial fishing gear (commercial interactions) and from video cameras mounted on a research longline (research interactions). Interaction consequences are the number of individual organisms of the listed taxa for which observed interactions were killed, showed obvious damage, or appeared undamaged.**

Taxa	Interaction consequences			Comments
	Dead	Damaged	Undamaged	
<b>Commercial interactions</b>				
Pennatulacea	4	-	-	Detached
Pennatulacea	-	2	-	Pushed over and stayed down
Pennatulacea	-	-	2	Pushed over and returned to vertical
<b>Research interactions</b>				
Pennatulacea	1	-	-	Detached
Pennatulacea	-	1	-	Pushed over and stayed down
Alcyonacea	1	-	-	Detached
Hexactinellida	-	1	-	Pushed over and returned to semi-upright position
Serpulidae	10	10	5	Estimates from a cluster of the number smashed, detached and pushed over



**Figure A13.6. Frames from video footage of interactions of vulnerable taxa with a demersal longline moving across the seafloor on retrieval. White arrows indicate the direction of line movement. A, B and C depict a sponge deflecting to allow a line to pass, and then returning to a semi-upright position. D and E depict sea pens being uprooted by the line and F depicts an aggregation of serpulid tube worms being uprooted and broken by a passing line.**

Serpulid tube worms suffered significant damage in footage of interactions with longlines. Around half of a cluster of casings were smashed or detached (Figure A13.6). This suggests that other brittle attached taxa like bryozoans, gorgonians, and cirripedes will also be vulnerable to damage from line movement. Consequently, these taxa were assigned values of  $m_{LN}$  of 0.3 (Table A13.4) and lower and upper limits of 0.2-0.4 (Table A13.5).

If an individual is in contact with a moving line and is not removed or lethally damaged, there is a chance that it will be more susceptible to removal or lethal damage in future fishing events. This was demonstrated by the sponge in Figure A13.6 which deformed to allow the line to pass, but which did not return to a fully upright position. It is likely that the attachment of the sponge to the substrate was compromised reducing its resistance to future fishing events. The probability of sustaining sub-lethal damage from line interactions ( $d_{LN}$ ) has been set arbitrarily at 0.2 (Table A13.4). Plausible lower and upper probabilities of  $d_{LN}$  were assigned at zero and 0.3 (Table A13.5). As for trawl interactions, for all taxa the variable  $s$  was set at 1.2 to increase by 20%, up to a maximum of 1, the probability  $m_{LN}$  that any alive but sub-lethally damaged individuals will die in a subsequent interaction. Lower and upper probabilities of  $S$  were assigned at no sub-lethal effect ( $S = 1$ ) and a 50% increase in subsequent mortality ( $S = 1.5$ ) (Table A13.5).

Applying the probabilities assigned in Table A13.4 and the formulae above, the probability of death from the first interaction with a line component of a demersal longline moving across the seafloor ranged from 0.02 for taxa such as echinoderms and pterobranchs up to a maximum of 0.27 for the most vulnerable group, the gorgonians (Table A13.8). Due to the much lower estimated probability of mortality for this type of interaction, upwards of 10 and sometimes as high as 25 sets were required before the probability of mortality exceeded 0.95.

**Table A13.8 Estimated probabilities of mortality ( $M$ ) and sub-lethal damage ( $D$ ) to benthic invertebrates due to interactions with the mainline of a demersal longline after 1, 5 and 10 overlapping sets, and the minimum number of sets for  $M$  to exceed 0.95.**

Taxon	$M_1$	$D_1$	$M_5$	$D_5$	$M_{10}$	$D_{10}$	Minimum sets for $M_n > 0.95$
Demospongiae	0.14	0.14	0.68	0.23	0.91	0.08	12
Actiniaria	0.05	0.10	0.40	0.40	0.67	0.29	25
Scleractinia	0.03	0.06	0.38	0.40	0.67	0.30	25
Alcyonacea	0.03	0.06	0.38	0.40	0.67	0.30	25
Gorgonacea	0.27	0.18	0.85	0.11	0.98	0.02	8
Hydroidolina	0.14	0.14	0.68	0.23	0.91	0.08	12
Serpulidae	0.12	0.08	0.82	0.13	0.98	0.02	8
Bryozoa	0.09	0.06	0.81	0.14	0.98	0.02	8
Cirripedia	0.09	0.06	0.81	0.14	0.98	0.02	8
<i>Ctenocidaris nutrix</i>	0.02	0.04	0.37	0.40	0.66	0.30	25
Euryalida	0.02	0.04	0.37	0.40	0.66	0.30	25
Pterobranchia	0.04	0.04	0.63	0.25	0.90	0.09	13
Ascidiacea	0.10	0.10	0.66	0.24	0.91	0.08	12

### Interactions with demersal longlines-hooks

As the breaking strain of longline hooks and snoods is far in excess of the structural strength of HIMI vulnerable taxa, if an invertebrate becomes snagged, it will either be detached, fractured or torn, depending on its brittleness. Of the 26 longline fishing retrieval events in which line movement was captured on video footage, one hooking event of vulnerable taxa (sea pen, *Umbellula* spp.) was captured within the visual field of the camera on BANZARE Bank, south of the Australian EEZ at HIMI. The sea pen was pushed over by the line, was directed by the snood onto the hook, and was snagged at the top. It was then dragged more than 10 m along the substrate and then lifted into the water column (Figure 13.7A). Around 10 minutes later, as the line vibrated while ascending, the sea pen was observed to detach from the hook and drift out of view (Figure 13.7B).

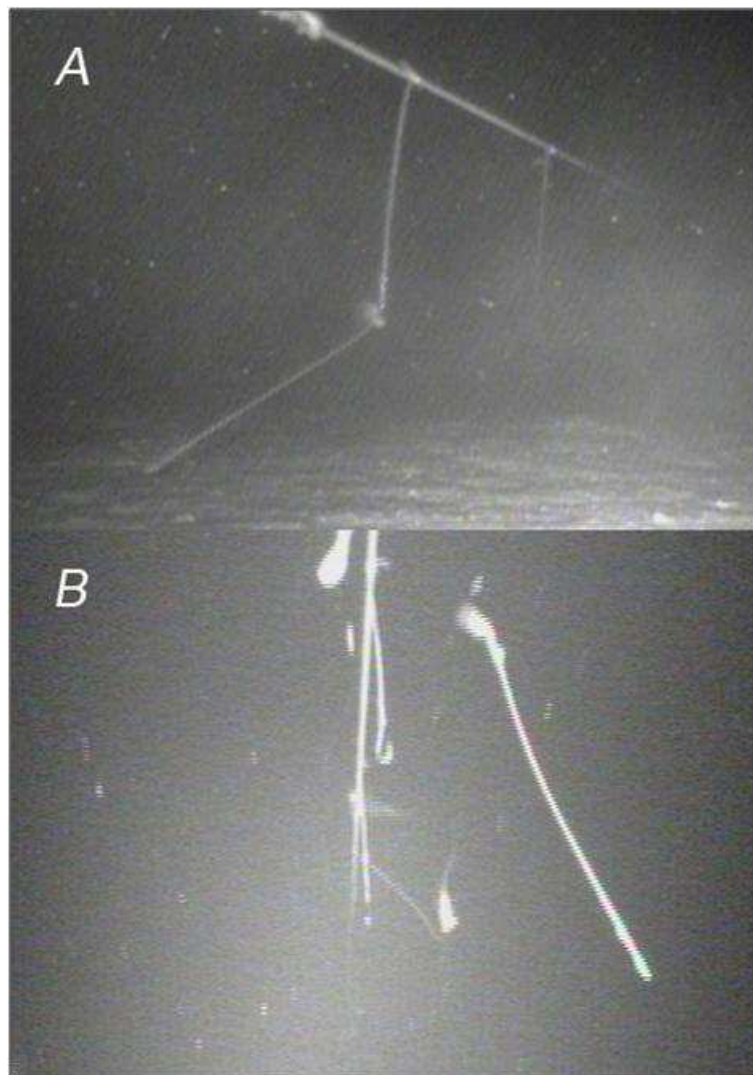


Figure A13.7. Frames from video footage of a longline lifting into the water column after moving laterally across the seafloor for >20m. A) A sea pen (*Umbellula* spp.) is hooked. B) The sea pen falling from the hook around 10 minutes later as the line is being hauled to the surface.

The overwhelming majority of invertebrate bycatch observed at the surface is attached to hooks, hence it likely that all of the taxa are vulnerable to mortality or damage from interactions with hooks. Consequently, demosponges, actinarians, alcyonarians, gorgonians, and ascidians, as the most common taxa seen as bycatch, were assigned  $m_{HK}$  probabilities of 0.5 (Table A13.4) with a range of 0.3-0.7 (Table A13.5). Basket stars (Euryalida), and hydroids whose complex array of arms and/or branches make them highly susceptible to being hooked were assigned relatively high  $m_{HK}$  probabilities (0.7-0.9) accordingly (Table A13.4), and a moderate to very high range (0.6-1.0 for Euryalids and 0.5-0.9 for Hydrozoa, Table A13.5).

We considered that hooks are less likely to snag and retain brittle taxa, however some damage is likely when they pull through serpulids, bryozoans, pterobranchs or cirripedes. Consequently, these taxa were assigned  $m_{HK}$  probabilities of 0.5-0.6 (Table A13.4) and a sensitivity testing that ranges between 0.4 and 0.7 (Table A13.5). Finally, as pencil urchins are most likely taxa to deflect a hook, they were assigned the low  $m_{HK}$  probability of 0.1 (Table A13.4).

The longitudinal and lateral movement, as shown by the empirical and theoretical analysis of longline behaviour in Appendix 9, dramatically increases the likelihood that hooks will interact with benthic taxa. As noted above, for a laterally moving line, the hooks will have a swept area of around 1% of the line (Appendix 9). However, the relative swept area of the hooks will increase with an increasing longitudinal component of line movement until the swept area of the hooks exceeds that of the line as lateral movement nears zero.

The occurrence of non-lethal damage by hooks is indicated by the fragments of vulnerable taxa observed in longline bycatch retained to the surface. The probability of sustaining sub-lethal damage from hook interactions ( $d_{HK}$ ) was set at 0.2 for all taxa (Table A13.4), and the range of  $d_{HK}$  from 0 to 0.3 (Table A13.5). As with the other gear components, the variable  $s$  was set at 1.2 to increase the probability  $m_{HK}$  that a surviving but sub-lethally damaged individual will die in a succeeding interaction, and the same range of 1-1.5 for sensitivity testing.

The estimated probabilities of death from the first interaction with the hook component of a demersal longline moving across the seafloor ranged from 0.04 for *C. nutrix*, up to 0.45 for Gorgonians and Euryalida (Table A13.9). Due to the disparate effects of hooks estimated, some taxa sustained as few as 2 sets before exceeding a probability of mortality of 0.95, while *C. nutrix* was still predicted to persist, albeit with a high probability of sub-lethal damage after more than 10 sets.

**Table A13.9. Estimated probabilities of mortality ( $M$ ) and sub-lethal damage ( $D$ ) to benthic invertebrates due to interactions with the hooks on a demersal longline after 1, 5 and 10 overlapping sets, and the minimum number of sets for  $M$  to exceed 0.95.**

Taxon	$M_1$	$D_1$	$M_2$	$D_2$	$M_5$	$D_5$	Minimum sets for $M_n > 0.95$
Demospongiae	0.35	0.14	0.69	0.16	0.97	0.02	5
Actiniaria	0.25	0.1	0.64	0.17	0.97	0.03	5
Scleractinia	0.15	0.1	0.41	0.21	0.82	0.13	8
Alcyonacea	0.25	0.1	0.64	0.17	0.97	0.03	5
Gorgonacea	0.45	0.18	0.74	0.15	0.98	0.02	4
Hydroidolina	0.35	0.14	0.69	0.16	0.97	0.02	5
Serpulidae	0.18	0.06	0.68	0.17	0.99	0.01	4
Bryozoa	0.18	0.06	0.68	0.17	0.99	0.01	4
Cirripedia	0.18	0.06	0.68	0.17	0.99	0.01	4
<i>Ctenocidaris nutrix</i>	0.04	0.04	0.23	0.21	0.63	0.25	13
Euryalida	0.45	0.1	0.96	0.09	1.00	0.00	2
Pterobranchia	0.15	0.06	0.58	0.18	0.96	0.03	5
Ascidiacea	0.25	0.1	0.64	0.17	0.97	0.03	5

## Discussion

Consideration of the sequence of events involved in a demersal fishing event leading to an interaction with the benthos has provided a model to estimate the probable outcomes for an individual (solitary or colonial) residing in the fishing footprint of a demersal fishing gear. This novel approach has derived plausible probabilities for the likely outcomes of interactions between HIMI vulnerable taxa and the gears deployed in the region, and provides a basis for assessing the disturbance resulting from these interactions. The probabilities assigned have been derived from the diverse range of data available in a transparent manner such that new research findings can be easily incorporated into this framework.

The probability of sub-lethal and lethal damage was estimated to be highest for demersal trawl gears, particularly for taxa like gorgonians, demosponges, and bryozoans that sit relatively high above the seafloor and are brittle or tear readily. Studies in the literature estimate that trawl events may remove or seriously damage at least half of the benthic invertebrate community unable to evade the net (Collie *et al.* 2000, Hiddink *et al.* 2006) with some studies reporting much higher mortality in heavily fished habitats (Althaus *et al.* 2009, Hixon & Tissot 2007). Damage specifically to sponges from trawling has been investigated with damage or removal from a single trawl event estimated to lie in the range of 20% to 70% (Freese *et al.* 1999, Pitcher *et al.* 2000, Sainsbury *et al.* 1997). The probability of lethal damage to an individual predicted by the method developed in this appendix is consistent with these studies, and although no studies are available that directly compare the generally shallow water gear configurations that have been the basis of published studies, and those used deeper water as at HIMI, these values are a reasonable starting point. Furthermore, this method enables new data and calculations to be readily incorporated.

The inclusion of variables to scale resistance for taxa damaged in prior fishing events, supported by observations of this effect in footage of fishing and analysis of bycatch, increases the applicability of this model to situations, such as in the HIMI trawl fishery where there is considerable overlapping fishing in the main trawl grounds. The model predicts that concentrated trawling will quickly increase the probability of mortality of taxa with lower resistance and is likely to dramatically reduce less vulnerable taxa within 6 overlapping trawl events. This highlights the threat of concentrated fishing effort on vulnerable communities if they are exposed to such a pattern of fishing, as well as the possibility for fishing to alter the composition of communities and habitats where co-existing taxa have different resistance.

This model provides a means of estimating the resistance of vulnerable taxa to impacts from demersal gears that may be used to provide an assessment of status of benthic habitats in the HIMI region using model predictions of the biomass of vulnerable taxa in Appendix 9 and gear-specific fishing effort footprint analysed in Appendix 11.

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## **Appendix 14      A simulation model for evaluating management strategies to conserve benthic habitats (vulnerable marine ecosystems) which are potentially vulnerable to impacts from bottom fisheries**

Andrew Constable

*Constable, A. (2009). A simulation model for evaluating management strategies to conserve benthic habitats (vulnerable marine ecosystems) which are potentially vulnerable to impacts from bottom fisheries. CCAMLR Document WG-EMM-09/21, presented to the CCAMLR Working Group on Ecosystem Monitoring and Management*

### **ABSTRACT**

Bottom fisheries are now to ‘avoid significant adverse impacts on vulnerable marine ecosystems’ in order to maintain the ecological structure and function of, particularly, deep-sea benthic habitats. Noting the paucity of data on the ecology of these habitats, this paper provides a practical approach to develop and evaluate fishing strategies aimed at achieving this objective, i.e. what is the most cost-effective way that fishers might be able to collectively enact this resolution? The UNGA requirement can be translated into a simple operational objective: *Maintain the quality of habitats above the level that can naturally restore the original structure and function within 20 years.* It does not require habitats to be categorised as “vulnerable marine ecosystems” or “invulnerable marine ecosystems”, a categorisation fraught with difficulty. Instead, it means that habitats for which this would not easily be met would be more vulnerable than those for which the objective might be met most often. This analysis develops a simulation model for this task, representing key properties of the benthic system such as mosaics of a number of habitats along with their rates of decay, recovery and connectedness between areas. The model has been developed for use by CCAMLR to evaluate, using computer simulations, proposed within-season and post-season assessment and management approaches. Most importantly, the model enables uncertainties to be captured in a straight-forward manner to assist CCAMLR in maintaining its precautionary approach in managing Antarctic fisheries. The functions developed in this paper provide placeholders in the simulation framework and can be replaced when better functions are developed.

## Introduction

Bottom fisheries are now to ‘avoid significant adverse impacts on vulnerable marine ecosystems’ (UNGA, 2006) in order to maintain the ecological structure and function of, particularly, deep-sea<sup>15</sup> benthic habitats. The challenge for fishers and resource managers is to achieve this requirement even though there are (a) few data on which to determine the distribution and abundance of different benthic habitats in the deep-sea or their current status relative to pre-fishing states and (b) almost no knowledge on what is required to maintain the ecology and function of these habitats. This study provides a practical approach to develop and evaluate fishing strategies aimed at achieving this objective i.e. what is the most cost-effective way that fishers might be able to collectively enact this resolution?

The UNGA requirement can be translated into a simple operational objective, following consideration by CCAMLR (2007) and the FAO (2009), hereafter referred to as the VME objective:

*Maintain the quality of habitats above the level that can naturally restore the original structure and function within 20 years.*

This operational objective does not require habitats to be categorised as ‘vulnerable marine ecosystems’ or ‘invulnerable marine ecosystems’; such a categorisation is fraught with difficulty (Constable & Holt 2007). This objective means that habitats for which this would not easily be met would be more vulnerable than those for which the objective might be met most often. It also recognises that vulnerability is dependent on the gear to be used, the intensity with which the gear may be deployed (number of times per annum) and the degree to which effects accumulate over many seasons.

This paper provides a straight-forward simulation model to represent the key parameters to be considered in developing a management strategy to achieve this objective. This model has been developed for use by CCAMLR to evaluate, using computer simulations, proposed within-season and post-season assessment and management approaches. The model is available in the statistical language, R (R Development Core Team 2010). Most importantly, the model enables uncertainties to be captured in a straight-forward manner to assist CCAMLR in maintaining its precautionary approach in managing Antarctic fisheries (Constable *et al.* 2000). The functions developed in this paper provide placeholders in the simulation framework and can be replaced when better functions are developed. The current input data required for the simulations are shown in Appendix 15.

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<sup>15</sup> Here “deep -sea” refers to waters deeper than 300m



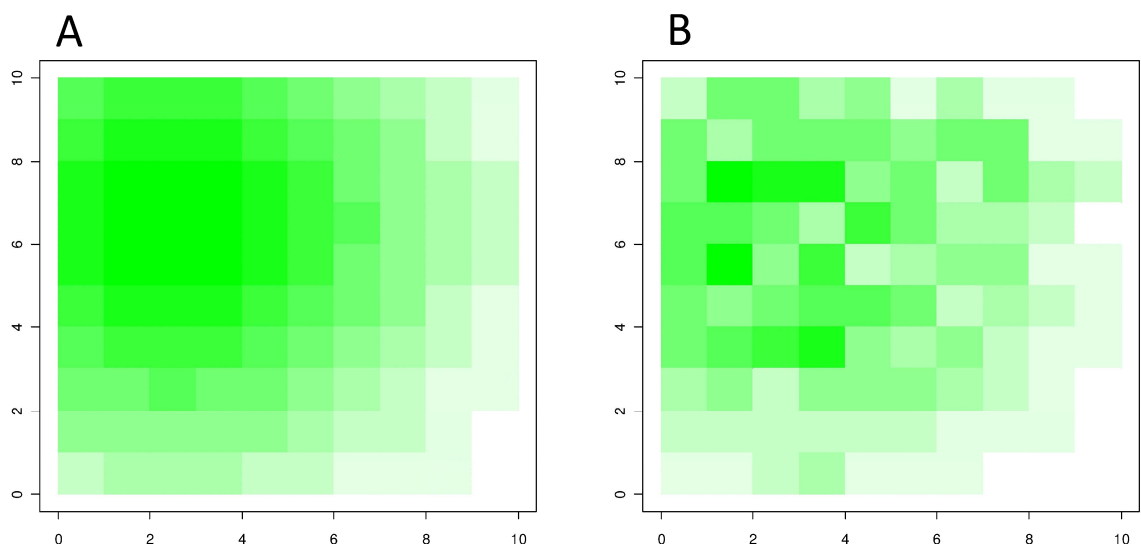
## Methods

### The simulation model

#### Habitats

The biodiversity of habitats can vary greatly. Here, habitats are stylised as a mosaic in the natural arena, or map (Figure A14.1). The unit of a habitat's overall condition in an area is termed its 'quality'. As in the natural environment, areas will vary in the maximum quality of habitat possible. An important feature of a habitat is that, fully mature, it will have a natural cycle of decay and recovery through natural disturbance or inter-specific interactions. These will be considered further in another paper.

A habitat may be tightly constrained or spread widely as a series of patches with differing qualities. It may form a mosaic in an area, with other habitats also present in an intermixed geography of the seascape. The model does not distinguish how many habitats might be represented, nor how biodiversity might be represented, perhaps as different 'habitats' or their spatial extent. This can be determined by the user.



**Figure A14.1. Single habitat determined as a bivariate normal. A) No variation. B) Lognormal variation with  $CV=0.3$**

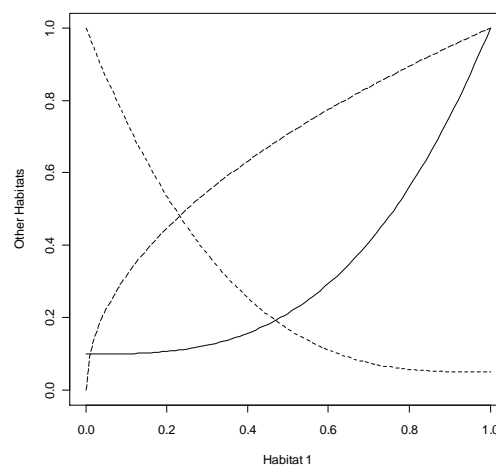
A map is able to be established as a grid of cells (pixels) representing any spatial scale. Many habitats can be present within a cell. While habitats could be established according to a known seascape, which would be ideal, routines have been established to develop seascapes according to scenarios for which the management strategies need to be tested.

Here, a primary habitat is used to distribute other habitats and the target fish species i.e. explore how the degree of association with the target species could impact on the ability for management measures to achieve the VME objective. In the initial trials, a bivariate normal distribution is used to establish one or more 'hot spots' (Figure A14.1).

Log-normal variates can be used to vary the quality of the habitat in a given cell. The other habitats are then described according to the following formula when there is a positive relationship between the primary habitat,  $X$ , and the subject habitat:

$$Q_h = [X^m(1 - b) + b]\hat{Q}_h \quad 1)$$

where  $X$  is the fraction of the maximum possible quality of the primary habitat anywhere in the arena,  $m$  indicates the curvature of the function and  $b$  is the proportion of the limit quality of the subject habitat,  $\hat{Q}_h$ , that is a background level throughout (Figure A14.2). If the relationship is a negative correlation then  $X$  is 1 minus the fraction of the maximum possible quality.



**Figure A14.2. Potential relationships between other habitats and the primary habitat (Habitat 1). Solid line shows a positive relationship with a threshold density greater than zero (exponent = 3). Dashed line is a positive relationship with exponent = 0.5. Dotted line is a negative relationship with exponent = 3 and a threshold greater than zero.**

### Natural disturbance

The decline of habitat quality through natural disturbance is modelled as a mortality function where the loss of habitat is given by:

$$D_h = Q_h[1 - e^{-d_h}] \quad 2)$$

Where  $D_h$  is the annual instantaneous mortality rate for habitat  $h$ .

## Recovery

Recovery of a habitat is modelled as a Beverton-Holt recruitment function:

$$R_h = r\hat{Q}_h \left[ \frac{s}{1 - \left[ \frac{5h-1}{4h} \right] [1-s]} \right] \quad 3)$$

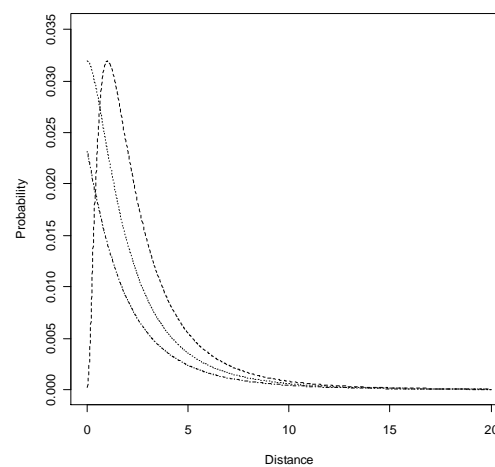
Where  $r$  is the per unit recovery rate,  $s$  is the relative status of the quality of the habitat in the cell and  $h$  is the steepness parameter. Of course, when quality is at its maximum then  $R_h$  and  $D_h$  are equal.

An important aspect of habitat dynamics is the degree to which nearby areas may assist in recovery through the dispersal and migration of individuals. Recovery of a habitat in a cell can be modelled as a weighted contribution from the habitat in other cells. This is provided for here by modelling a dispersal pattern of potential influence of a habitat in one cell contributing to the same type of habitat in another cell. Apart from no external assistance in recovery, two methods could be used. An inverse distance method provides a simple form. However, this does not account for potential types of dispersal of some species, particularly those that may move away from parental areas. A log-normal probability density function is used as the second alternative, based on a mean dispersal distance combined with the variability that might be expected about that mean. A shift parameter is used to enable more concentrated dispersal near to the origin when needed. The log-normal pdf,  $p$ , with a shift parameter is illustrated in Figure A14.3.

Recovery in a given cell can then be formulated as:

$$R'_c = H_c \sum_{c'} R_{c'} p_{c' \rightarrow c} \quad 4)$$

where  $H_c$  is a scaling parameter to ensure that  $R'$  equals  $D$  at equilibrium.



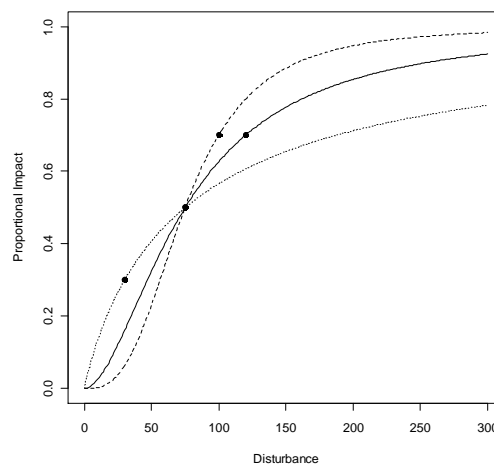
**Figure A14.3.** Example of a dispersal probability density function with shift parameters equal to 0 (dashed), 1 (dotted) and 2 (dot dashed).

## Disturbances

Disturbance of each habitat is modelled in the same way as a Holling function:

$$dQ_{n,s}^D = -\hat{I}_{n,s} \frac{D_{n,s}^{q+1}}{D_{0.5}^{q+1} + D_{n,s}^{q+1}} \quad 5)$$

where  $D$  is the magnitude of the disturbance,  $q$  is the shape function,  $D_{0.5}$  is the magnitude of the disturbance for which 50% of the maximum impact on the habitat is caused and  $I$  is the maximum impact. This is illustrated in Figure A14.4. Although not featured in the annual cycle, natural disturbance could be included for particular habitat types.



**Figure A14.4.** Example curves of impacts of natural disturbance on a habitat. The same approach can be used for the effects of a fishing shot, replacing disturbance with habitat quality. The points represent inputs that can be given to the program in order for the parameters to be determined.

## Fish and fishing

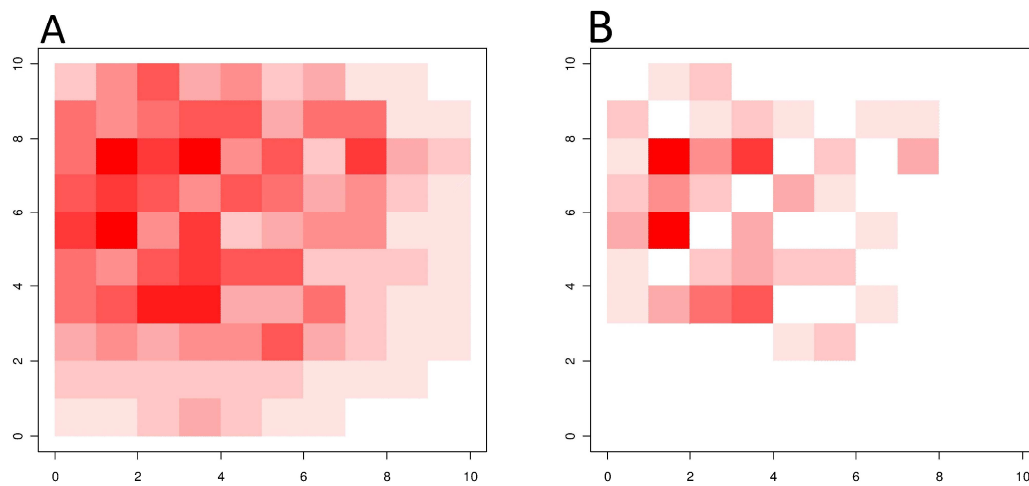
Fish density is calculated the same way as habitat, i.e. its distribution is based on a relationship with the primary habitat; i.e. fish distribution can closely map or be unrelated to the primary habitat (Figure A14.5), or be directly specified as for habitats described above. The simulation has the capacity to redistribute the fish in each year to take account of changes in the distribution of quality locations in the primary habitat.

The disturbance of habitats by a fishing shot is modelled in the same way as natural disturbance except by considering the impact of an individual shot given the habitat qualities that are present, i.e. a shot will be more likely to have a greater individual impact on higher quality habitat. The parameters are then chosen to appropriately reflect that relationship.

At present, the shots are distributed randomly amongst cells according to an ideal-free distribution of fish densities across cells and then the locations within cells drawn randomly, not including the closed locations in the draw.

The catch is governed by the usual catchability parameter and lognormal variation.

Observations of habitat bycatch are governed by probability functions for capture in a shot, retention to be observed and then the amount observed. The amount is governed at present by drawing a value from a log-normal function with mean as the habitat quality in the cell at the time and variability specified by a CV.



**Figure A14.5.** Fish density related to Figure A14.1 B with (A) direct relationship and  $CV=0.1$ , and (B) with exponent = 3 and  $CV=0.2$

### Management strategies

The simulations are set up to simulate the way existing CCAMLR Conservation Measures 22-06 and 22-07 manages the fishery, with observed bycatch of invertebrates leading to closure of areas where high bycatch originated (CCAMLR 2012a). Closures of areas occur at the end of the year rather than during the year, however reporting periods can be modified to help evaluate within-season measures if desired. There is an opportunity to scale the VME units according to notional quality of the different habitats. It is possible to specify how many ‘strikes’ (i.e. observations of invertebrate bycatch above a threshold, as in CCAMLR Conservation ) at a location are needed before it is closed as well as what quantity of bycatch may be needed for a single strike closure. It is also possible to identify how many locations within a cell with single strikes might result in a closure of the cell.

There is also an option to consider all reported data collected over many years in the assessment process or to only consider assessment of closures from data from within a single year rather than accumulating data for more years.

## **Performance**

The following performance measures are available to assess different scenarios and are monitored annually in each trial:

1. Relative quality of the habitats overall
2. Total habitat quality
3. Habitat quality in open and closed areas
4. Catch

## **General attributes of the simulation**

### **Sequence**

The primary sequence of the simulation currently comprises the following steps:

1. Initialise random number sequences required by either creating files or setting pointers to read from existing files
2. Trials
  - a. Initialise habitat and fish distributions
  - b. Initialise fishing log, data reporting and management systems
  - c. Years
    - i. Initialise annual fishing and reporting log
    - ii. If required, redistribute fish relative to the primary habitat
    - iii. Reporting Periods
      1. Choose locations for all shots (Cells, locations within cells), avoiding closed cells and specific closed locations within cells
      2. Observe catch and habitat bycatch on each shot and update fishing log
      3. Add catch and effort summaries for each cell
      4. Submit relevant data for assessment
    - iv. Update actual habitat qualities in open and closed areas taking account of recovery, decay and, in open areas, the disturbance from fishing
    - v. Update management measures

1. Review assessment data to identify locations which are triggered for closures, using the two part rule
    - a. If habitat observation exceeds the maximum number units then closure of the location
    - b. If the requisite number (strikes) of shots for a location with habitat observations exceeding the lower of the critical levels is reached then it is closed
  2. Update register of closed areas and transfer quality of those locations to the overall quality of closed areas
  3. If required, restart Assessment Data for the next year
- vi. Append simulation performance measures to file

### **Random numbers**

Random number seeds are generated prior to the simulations and saved to file. These files can then be retained to ensure that random number sequences are the same for different scenarios. Each use of a random number sequence has its own seed and data series. As a result, choices not to have random variation in some parameters will not impact on the sequences used for the other parameters.

### **Discussion**

The simulation model provides a useful abstraction of a complex and dynamic system to explore how the VME objective may be achieved even with a paucity of data available on the dynamics of benthic ecosystems in the Southern Ocean. It identifies the important combinations of parameters for habitats such as rates of natural disturbance, recovery and connectedness between areas that are essential in considering harvest strategies that ensure fisheries avoid significant adverse impacts on vulnerable marine ecosystems. The simulation model is accessible in R and can be modified in a number of ways because of its general object-oriented nature. A requirement now is to provide plausible bounds to the parameter inputs in a way that can provide meaningful representations of the conditions that management regimes such as CCAMLR needs to consider, particularly the uncertainties in the relationship between the fish, habitats and the fishery.

## Appendix 15 Input data and variables used in the simulation model for evaluating management strategies to conserve benthic habitats (Appendix 14)

The following tables provide the key parameters for input data to run the R simulation described in Appendix 14.

Parameter	List Parameters	Possible values	Description
Nrows		10	Number of rows of pixels (Y coordinates) Map is plotted with the origin in the top left corner
Ncols		10	Number of columns of pixels (X coordinates)
WithinCellLoc		100	Number of fishing locations within a pixel (without needing a specific grid)
<b>Habitats</b>			
Parameter	List Parameters	Possible values	Description
HabitParams	List		Primary habitat – parameters for establishing a bivariate normal with log-normal variability
	UseBVnorm	TRUE	Nominate to use a bivariate normal distribution. If FALSE then uniform distribution across map with log-normal variability
	Xmean	3	X (col) location of the centre of the bivariate normal
	Xsigma	2	Standard deviation of the distribution on X-axis
	Ymean	4	Y (row) location of the centre of the bivariate normal
	Ysigma	2	Standard deviation of the distribution on Y-axis
	XYP	0	Correlation between X and Y
	CellCV	0.3	Coefficient of variation for log-normal deviates for cell variation
RestParams	List		Parameters for a function for log-normal deviates for cell variation
	Corr	c(1,-1)	vector of elements – one for each additional habitat
	Xlim	c(1,1)	Positive or negative unit to indicate correlation with habitat 1
	Exp	c(3,2)	For positive correlations, the value of quality of the primary habitat for which the maximum value of the new habitat is achieved and remains thereafter
	PropYmaxBgrnd	c(0,0.1)	Exponent of the relationship between a new habitat and the primary habitat
	Ylim	c(1,1)	Minimum prop of max quality of the new habitat i.e. background quality across the map
	CV	c(0.3,0.2)	Limit to Y in considering relationship to X
Dispersal	List		CV for within cell variability for each habitat
	Xbar	c(3,3)	Dispersal attributes for cells providing recovery potential to other cells (each parameter has a vector of elements – one for each habitat)
	CV	c(0.1,1.3)	Mean distance of dispersal in log-normal function
	Shift	c(1,3.6)	CV of dispersal distance
	Xmax	c(20,20,20)	Parameter to shift the pdf to enable greater probability density at the origin.
	Type	c("None", "None", "None", "None")	Maximum dispersal distance used when inverse distance weighting used
	Bracket	0.1	"Distance" = use of log normal function if CV > 0, else use inverse distance weighting up to maximum distance after which the weight is zero "None" = no dispersal distance over which the pdf is calculated
Decay	d	c(0.05,0.05,0.05)	Annual natural disturbance rate
Recovery	List		
	H	c(1,0.3,0.7)	Beverton-Holt h
	CV	c(0,0,0)	CV around recovery
Col		c("green", "blue", "orange")	Colour of habitat for use in plotting
RampIntervals		c(10,10,10)	Number of intervals in colour ramp from white to dense colour in plotting densities on maps



Parameter	List Parameters	Possible values	Description
Disturbance	List		Repeat list for different types of disturbance (each parameter has a vector of elements – one for each habitat)
Dq		c(-1,-1,-1)	exponent
Dhalf		c(0.5,0.5,0.5)	proportion of maximum quality in patch for which there is 0.5 of maximum impact
Imax		c(0.01, 0.01, 0.01)	maximum proportional impact on whole cell (this might vary if it is for variable storms)
FindDq		c(TRUE, TRUE, TRUE)	if a shape of the curve is to be found given the following:
PC		c(0.9,0.9,0.9)	the proportion of the maximum impact
Dpc		c(0.7,0.7,0.7)	value of disturbance for which there is PC of maximum impact
Dname		"Longitude"	

#### Fish

Parameter	List Parameters	Possible values	Description
Corr		1	Positive or negative unit to indicate correlation with habitat 1
Xlim		1	For positive correlations, the value of quality of the primary habitat for which the maximum value of the new habitat is achieved and remains thereafter
Exp		3	Exponent of the relationship between a new habitat and the primary habitat
PropYmaxBgnd		0	Minimum prop of max quality of the new habitat i.e. background quality across the map
Ylim		1	Limit to Y in considering relationship to X
CV		0.2	CV for within cell variability for each habitat
Scaledensity		TRUE	Scale density of fish in each cell to preserve a set abundance in the arena
ArenaAbundance		Number of Cells	Abundance of fish in the arena

#### Fishery catch and observations

Parameter	List Parameters	Possible values	Description
HobsParams	List		Parameters for observations of each habitat (one element for each habitat)
capture	List		Ogive of probability of capturing sample of habitat
Q50		c(0.3,0.3,0.3)	Habitat Quality for which there is probability of 0.5 of capture
Qto95		c(0.2,0.2,0.2)	Habitat Quality to be added to Q50 for which there is probability of 0.95 of capture
retain	List		Ogive of probability of retaining the caught sample of habitat and observing it on deck
Q50		c(1.0,1.1)	Habitat Quality for which there is probability of 0.5 of retention
Qto95		c(0.2,0.2,0.2)	Habitat Quality to be added to Q50 for which there is probability of 0.95 of retention
HobsQtyParams	List		Quantity observed on deck is a lognormal function of the quality of the habitat at the time
CV		c(0.2,0.2,0.2)	CV of lognormal function
FisheryCatchParams	List		
Fq		1	Catchability
CV		0.2	CV of catch

#### Management Measures

Parameter	Possible values	Description
CloseLocOnStrikes	2	Number of strikes required at location to have it closed on first level of critical VME units
LimitToNYearsInAssessment	FALSE	put number of years here if only using most recent N years in assessment else put FALSE
CloseCellOnPropStrikes	1.0	proportion of locations in cell hitting critical VME units at least once
HabVMEUnit	c(0.15,0.15,0.15)	quantity that constitutes VME unit for each habitat
PoolVMEUnits	FALSE	logical - sum VME units across habitat types (if this occurs then HabCritVME will have only one habitat
HabCritVME	c(3,3,3 .6,6,6)	first level of VME units to indicate one strike second level to result in automatic closure
RestartObsAnnually	TRUE	if TRUE then assessment data is deleted at the end of each year. if FALSE then the assessment data is continually appended with new reports and reviewed for repeat strikes at locations

Simulation		
Parameter	Possible values	Description
Trials	100	Number of trials in simulation
TrialInitial	List	Initial attributes for each trial
HabQ	All 1	Habitat quality - prop of Quality limit (one row per habitat)
Years	100	Number of years per trial
FishRedistribute	FALSE	Logical - if TRUE - redistribute fish at the beginning of each year according to quality of primary habitat
Periods	1	Number of reporting periods in a year - available to have management operate after each reporting period (currently inactive)
Shots	1000	Number of shots in a reporting period